DELMAR'S

Standard Textbook of Electricity

FIFTH EDITION

Stephen L. Herman

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Delmar's Standard Textbook of Electricity, 5th Edition
Stephen L. Herman

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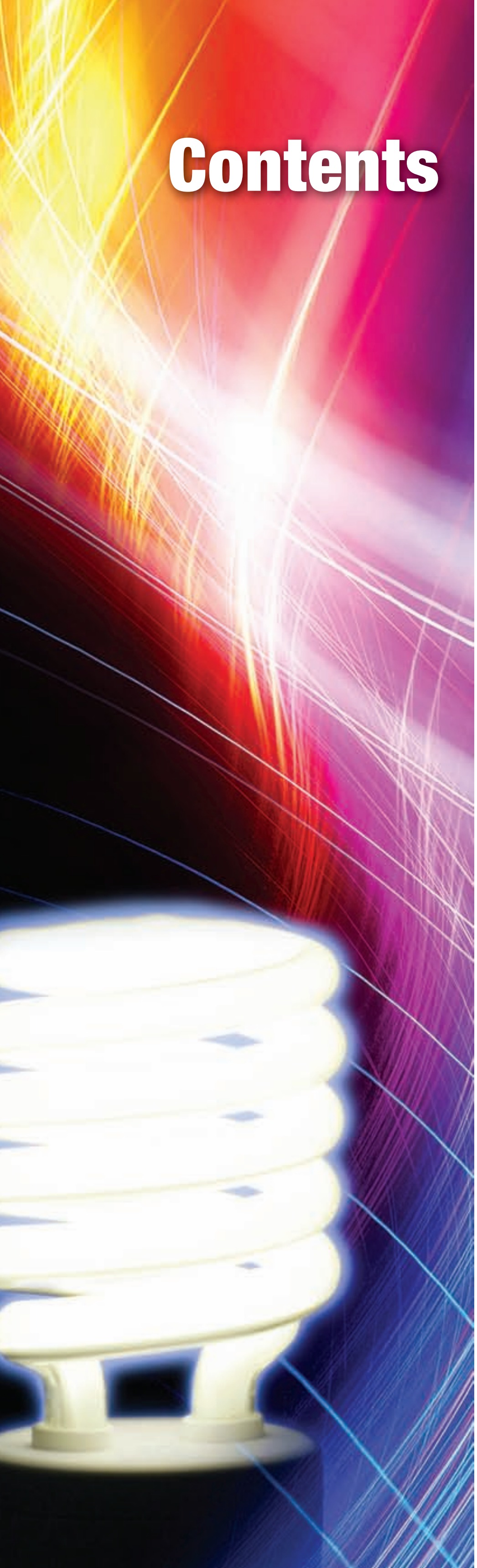

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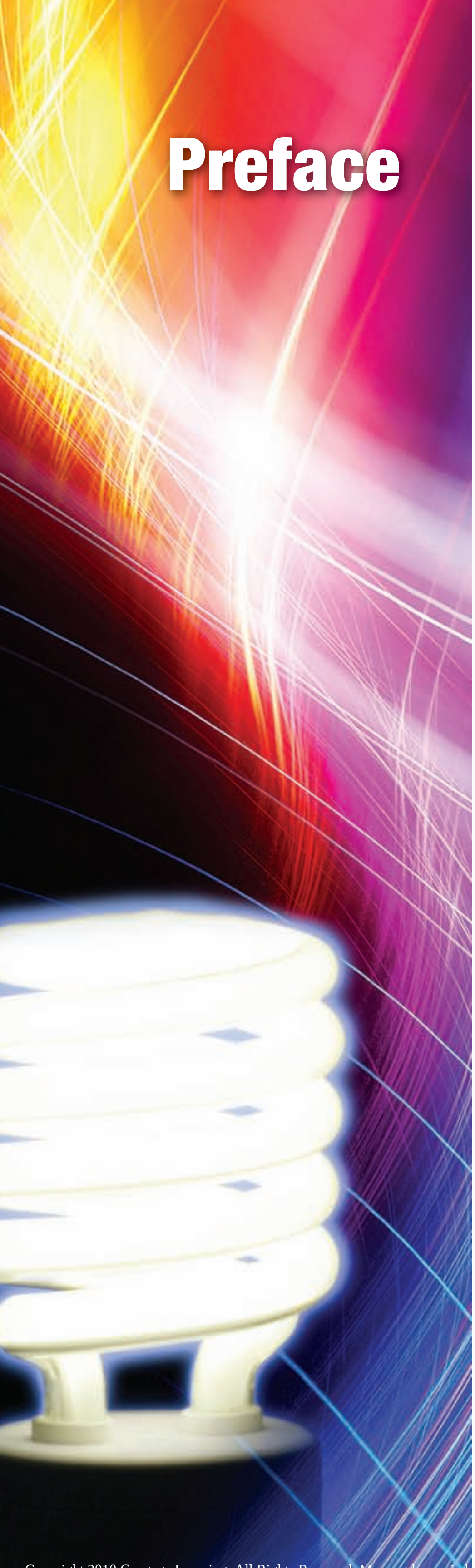
To my wife, Debbie, God's greatest gift to me.

Preface



Intended Use

Delmar's Standard Textbook of Electricity, 5th edition, is intended for students in electrical trade programs at high schools and community colleges, as well as those in industry training. It assumes that the reader has had no prior knowledge of electricity but also provides enough comprehensive coverage to be used as a reference tool for experienced electricians.

Subject & Approach

The content itself is presented as a blend of the practical and theoretical. It not only explains the different concepts relating to electrical theory but also provides many practical examples of how to do many of the common tasks the industrial electrician must perform. An extensive art program containing full color photographs and line drawings, as well as the inclusion of practical exercises for the student, also serve to further clarify theoretical concepts.

Design of Text

The subject matter has been divided into 34 separate units—each designed to "stand alone." The "stand alone" concept permits the information to be presented in almost any sequence the instructor desires, as teaching techniques vary from one instructor to another. The information is also presented in this manner to allow students and instructors quick reference on a particular subject.

Math Level

The math level has been kept to basic algebra and trigonometry, and Appendix B contains a section of electrical formulas—all divided into groups that are related to a particular application. Unit 15 of the text provides an introduction to basic trigonometry and vectors for those students weak in the subject.

A Note about Calculations

Delmar's Standard Textbook of Electricity, 5th edition, like all other scientific texts, contains numerous mathematical equations and calculations. Students often become concerned if their answers to problems are not exactly the same as the solutions given in the text. The primary reason for a discrepancy is the rounding off of values. Different scientific calculators carry out numbers to different places, depending on the manufacturer and model. Some calculators carry numbers to 8 places, some to 10 places, and some to 12 places. There may also be times when numbers that are reentered into the calculator are carried to only 2 or 3 decimal places of accuracy. For example, the numbers shown below will be multiplied with a calculator that carries numbers out to 8 places of accuracy:

$$3.21 \times 34.6 \times 4.32 \times 0.021 \times 3.098 \times 0.467$$

The answer is 14.577480.

The same problem will again be multiplied, but this time each answer will be reentered before it is multiplied by the next number. Each time the answer is reentered, it will be rounded off to 3 places after the decimal. If the fourth number after the decimal is 5 or greater, the third decimal place will be rounded up. If the fourth number is less than 5, it will be rounded down. The answer is 14.577405.

The same set of numbers will again be multiplied, but this time each answer will be reentered after rounding off the number to one place after the decimal. The answer is 14.617100.

Notice that all three answers are different, but all three are essentially correct. The most accurate answer is 14.577480, and the least accurate answer is 14.617100. Although these answers may look substantially different, they are within approximately 1% of each other.

Another consideration is problems that contain multiple steps. The more steps it takes to solve a problem, the more chance there is for inaccuracy. In most instances in this text, the answers were left in the display of the calculator, which permits the greatest degree of accuracy. When numbers had to be reentered, they were taken to 3 places of accuracy. When you work a problem in this text and your answer is different, consider the degree of difference before concluding that your answer is incorrect.

New to this Edition

The fifth edition of *Delmar's Standard Textbook of Electricity* continues to remain true to the comprehensive nature and visually appealing style that are its trademark features but will now offer more emphasis on the practical approach to electrical theory. New to this edition:

- ***Explanation of the American Wire Gauge measurement used throughout industry***

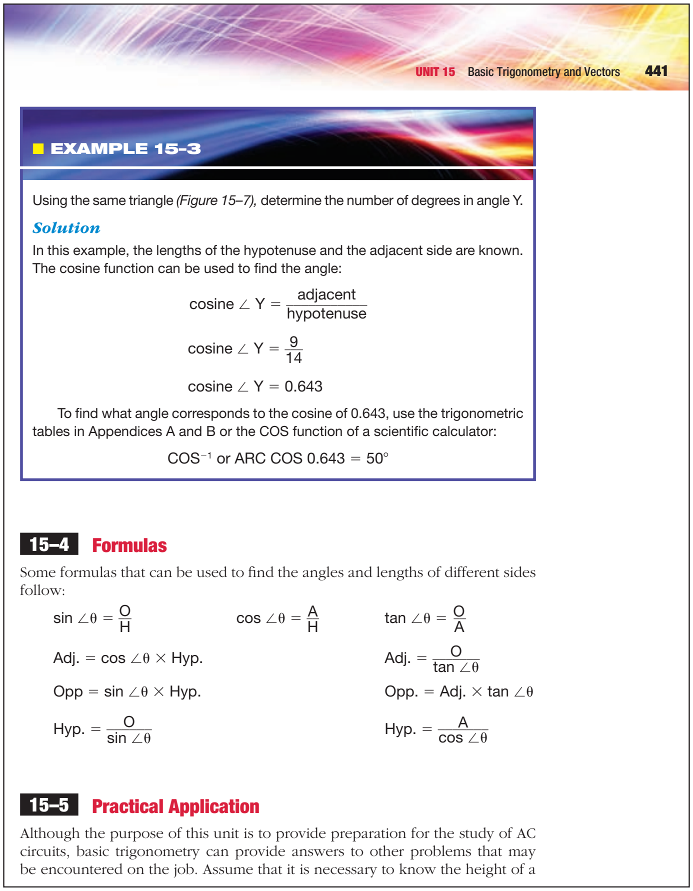
- ***Extended coverage of the effects of temperature on conductor resistance***
- ***Coverage of fuel cells***
- ***The addition of constant-current transformers***
- ***Coverage of parallel transformer connections***
- ***Energy saving "Green Tips" where applicable***
- ***New Introduction***
  "Electrical Occupations" contains information about electrical personnel, building codes, and solar and wind energy.

Features of The Text

- ***"Safety Overview"***
  At the beginning of Section I, Safety Overview provides information on general safety rules, personal protective equipment, potential job hazards, lock-out/tag-out procedures, GFCI, Grounding—and more! Students are acquainted with the all important safety concerns applicable to working in a lab and on the work site.
- ***"Cautions"***
  Author highlights text where students should be aware of potential risks in working with various types of electrical equipment.

Caution: The **ammeter**, unlike the voltmeter, is a very low-impedance device. The ammeter is used to measure current and must be connected in series with the load to permit the load to limit the current flow *(Figure 10–13).* ■

- ***Math Presentation***
  Section on vectors in Unit 17 is presented earlier in the text in Unit 15, *Basic Trigonometry,* providing a foundation for students as they work through math equations.



UNIT 15 Basic Trigonometry and Vectors 441

■ EXAMPLE 15-3

Using the same triangle *(Figure 15–7)*, determine the number of degrees in angle Y.

Solution

In this example, the lengths of the hypotenuse and the adjacent side are known. The cosine function can be used to find the angle:

$$\text{cosine} \angle Y = \frac{\text{adjacent}}{\text{hypotenuse}}$$

$$\text{cosine} \angle Y = \frac{9}{14}$$

$$\text{cosine} \angle Y = 0.643$$

To find what angle corresponds to the cosine of 0.643, use the trigonometric tables in Appendices A and B or the COS function of a scientific calculator:

$$\text{COS}^{-1} \text{ or ARC COS } 0.643 = 50°$$

15–4 Formulas

Some formulas that can be used to find the angles and lengths of different sides follow:

$$\sin \angle\theta = \frac{O}{H} \qquad \cos \angle\theta = \frac{A}{H} \qquad \tan \angle\theta = \frac{O}{A}$$

$$\text{Adj.} = \cos \angle\theta \times \text{Hyp.} \qquad \text{Adj.} = \frac{O}{\tan \angle\theta}$$

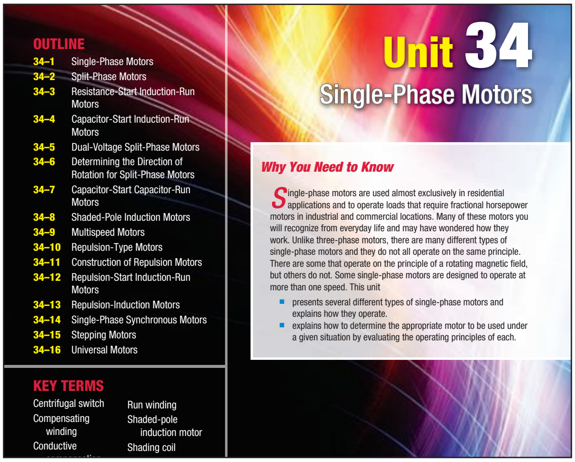
$$\text{Opp} = \sin \angle\theta \times \text{Hyp.} \qquad \text{Opp.} = \text{Adj.} \times \tan \angle\theta$$

$$\text{Hyp.} = \frac{O}{\sin \angle\theta} \qquad \text{Hyp.} = \frac{A}{\cos \angle\theta}$$

15–5 Practical Application

Although the purpose of this unit is to provide preparation for the study of AC circuits, basic trigonometry can provide answers to other problems that may be encountered on the job. Assume that it is necessary to know the height of a

- ***"Why You Need to Know"***
  Boxed articles at the beginning of each unit explain to students the importance of learning the material presented in each unit, and how it may apply to actual job situations.



OUTLINE
34–1 Single-Phase Motors
34–2 Split-Phase Motors
34–3 Resistance-Start Induction-Run Motors
34–4 Capacitor-Start Induction-Run Motors
34–5 Dual-Voltage Split-Phase Motors
34–6 Determining the Direction of Rotation for Split-Phase Motors
34–7 Capacitor-Start Capacitor-Run Motors
34–8 Shaded-Pole Induction Motors
34–9 Multispeed Motors
34–10 Repulsion-Type Motors
34–11 Construction of Repulsion Motors
34–12 Repulsion-Start Induction-Run Motors
34–13 Repulsion-Induction Motors
34–14 Single-Phase Synchronous Motors
34–15 Stepping Motors
34–16 Universal Motors

KEY TERMS
Centrifugal switch
Compensating winding
Conductive
Run winding
Shaded-pole induction motor
Shading coil

Unit 34
Single-Phase Motors

Why You Need to Know

Single-phase motors are used almost exclusively in residential applications and to operate loads that require fractional horsepower motors in industrial and commercial locations. Many of these motors you will recognize from everyday life and may have wondered how they work. Unlike three-phase motors, there are many different types of single-phase motors and they do not all operate on the same principle. There are some that operate on the principle of a rotating magnetic field, but others do not. Some single-phase motors are designed to operate at more than one speed. This unit

- presents several different types of single-phase motors and explains how they operate.
- explains how to determine the appropriate motor to be used under a given situation by evaluating the operating principles of each.

- ***"Practical Applications"***
  Word problems step the students through potential situations on the job and encourage them to develop critical thinking skills.

Practical Applications

An office building uses a bank of 63 lead-acid cells connected in series with a capacity of 80 amp-hours each to provide battery backup for their computers. The lead-acid cells are to be replaced with nickel-metal hydride cells with a capacity of 40 amp-hours each. How many nickel-metal hydride cells will be required to replace the lead-acid cells and how should they be connected? ■

- ***DVD Correlation***
  Units are highlighted where material can be viewed on the accompanying DVD series, providing another source of learning for the student: ***DC Electrical Theory, AC Electrical Theory, Single-PhaseTransformers & Electrical Machines, Three-Phase Circuits & Electrical Machines***

- ***Text Design***
  A fresh design creates a text that makes it even easier to navigate through content, serving to facilitate learning for students.

- ***New, Up-to-Date Art***
  Approximately 32 new four-color photos and line illustrations combined bring text up to date, keeping students aware of the latest technology in the industry.

- ***Dedication to Technical Accuracy and Consistency***
  Text was thoroughly reviewed for technical accuracy and consistency, ensuring existing errors were corrected, enabling students to readily grasp more difficult concepts.

Supplement Package

- ***Lab-Volt Manual*** provides experiments for students to test and troubleshoot key concepts presented in the text, using Lab-volt equipment. (Order #: 1-1115-3916-2).
  Also available: The Complete Laboratory Manual for Electricity, by Steve Herman. This manual is designed to be conducted with common lab equipment. (Order #: 1-4283-2430-5).

- ***Instructor Resource (CD-ROM for Instructors)***
  (Order #: 1-1115-3916-2).
  Instructor Guide contains answers to all review questions and practical applications contained within the text, as well as practice exams.
  - *PowerPoint* presentations provide a thorough review of all major concepts presented in each unit, featuring four-color photos and line illustrations from the text. The fifth edition contains numerous PowerPoint presentations not available before.
  - *Computerized Testbank* offered in *ExamView 4.0* contains approximately 700 questions for instructors to test student knowledge as they progress through the text. Allows instructors to edit the exams and add their own questions.
  - *Image Library* consists of all the images from the text in electronic format, allowing instructors to create their own classroom presentations.
  - *Video Clips* drawn from each video provide key lessons from the series.
  - *Instructors Guide & Solutions to Lab-Volt Manual* is in Word format.

  To access additional course materials including CourseMate, please visit www.cengagebrain.com. At the CengageBrain.com home page, search for the ISBN of your title (from the back cover of your book) using the search box at the top of the page. This will take you to the product page where these resources can be found.

- ***A DVD Set*** brings important concepts to life through easy-to-understand explanations and examples, professional graphics and animations, and a necessary emphasis on safety. Videos run approximately 20 minutes. The DVDs are interactive and provide test questions and remediation.

  DC Electrical Theory DVD (4 videos) includes Basic Electricity, Series & Parallel Circuits, Combination Circuits, and Small Sources of Electricity.

  AC Electrical Theory DVD (5 videos) includes Alternating Current, Inductance, Capacitors, Capacitors in AC Circuits, and Series Circuits.

  Single-Phase Transformers & Electrical Machines DVD (4 videos) includes Single-Phase Transformers; DC Machines; Single-Phase Motors, Part I; Single-Phase Motors, Part II.

  Three-Phase Circuits & Electrical Machines DVD (4 videos) includes Three-Phase Circuits; Three-Phase Transformers; Three-Phase Motors, Part I; Three-Phase Motors, Part II.

- ***Blackboard supplement*** features include chapter objectives, practice tests, glossary, and links to relevant websites. (Order #: 1-1115-3918-9).

Electrical Course Notes: This is a 6 panel brochure outlining the most common key concepts and formulas used when studying electrical theory. Order #: 1-1115-3923-5

CourseMate for Delmar's Standard Textbook of Electricity, 5E: This interactive and assignable web based solutions includes a CLeBook, Unit slides in PowerPoint, quizzes, animations, glossary, and engagement tracker.

A Note about the Lab Manuals

The two laboratory manuals, entitled *Experiments in Electricity for Use with Lab-Volt EMS Equipment* and *The Complete Laboratory Manual for Electricity, 3E,* provide extensive opportunities for students to apply what they have learned. Both manuals contain multiple hands-on experiments for each unit of the textbook and have been extensively field-tested to ensure that all the experiments will work as planned. The engineers at Lab-Volt conducted each of the experiments in *Experiments in Electricity for Use with Lab-Volt EMS Equipment,* and, following their testing, Lab-Volt has endorsed this manual. It is the manual they recommend to their customers. *The Complete Laboratory Manual for Electricity,* was field-tested at the Shreveport-Bossier Regional Technical School under the direction of Richard Cameron.

About the Author

Stephen L. Herman has been both a teacher of industrial electricity and an industrial electrician for many years. His formal training was obtained at Catawba Valley Technical College in Hickory, North Carolina. Mr. Herman has worked as a maintenance electrician for Superior Cable Corp. and as a class "A" electrician for National Liberty Pipe and Tube Co. During those years of experience, Mr. Herman learned to combine his theoretical knowledge of electricity with practical application. The books he has authored reflect his strong belief that a working electrician must have a practical knowledge of both theory and experience to be successful.

Mr. Herman was the Electrical Installation and Maintenance instructor at Randolph Technical College in Asheboro, North Carolina, for 9 years. After a return to industry, he became the lead instructor of the Electrical Technology Curriculum at Lee College in Baytown, Texas. He retired from Lee College after 20 years of service and, at present, resides in Pittsburg, Texas, with his wife. He continues to stay active in the industry, write, and update his books.

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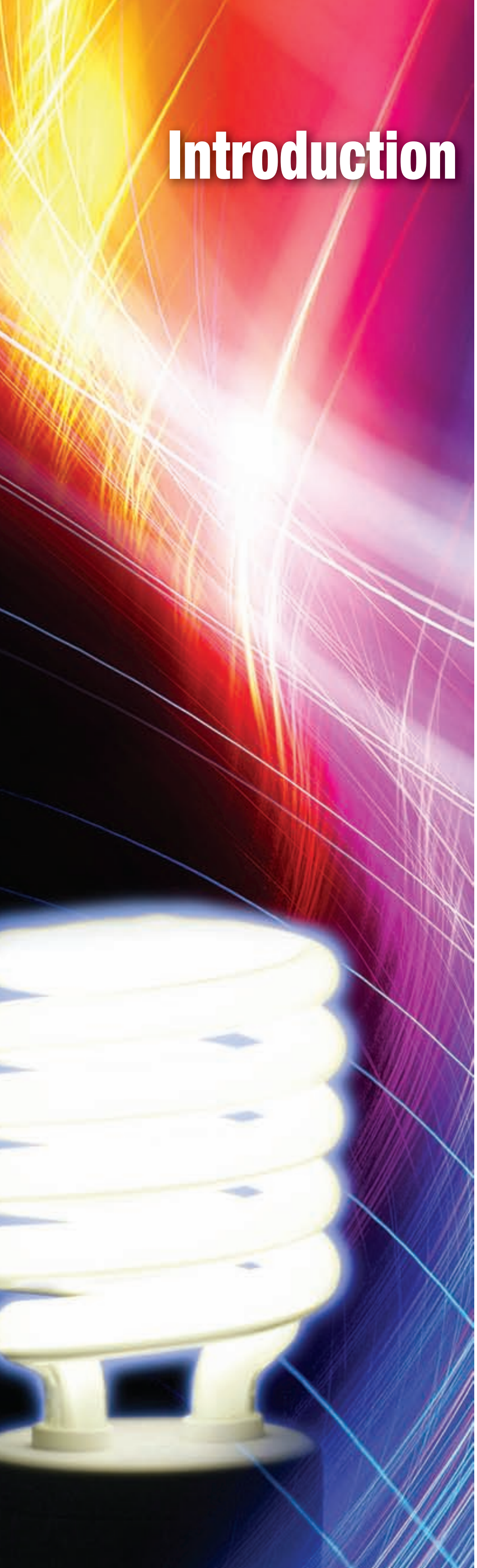
Introduction



Electrical Occupations

Organization of the Industry

The electrical industry is one of the largest in the United States and Canada. In 2008, electricians held about 692,000 jobs. Electrical contracting firms employed about 65% of the wage and salaried workers. The remainder worked as electricians in other related industries. About 9% of the electricians were self-employed. The opportunity for employment and advancement as an electrician is one of the highest of any industry. Basically, the entire country runs on electricity. Industry, commercial locations, and homes all employ electricity as the main source of power. It has been estimated that between 2008 and 2018 the need for qualified electricians will increase at a rate of about 12%. That represents an annual increase of over 8000 electricians over the next 10 years. The lay-off rate of electricians is one of the lowest of any occupation. If industry operates, it will require electricians to keep it running.

Electrical Personnel

Electricians can generally be divided into several categories, depending on their specific area of employment. Each of these categories may require special skills.

- ***Construction***
  Electricians working in the construction industry generally require a basic knowledge of electrical theory and an extensive knowledge of *National Electrical Code* requirements and wiring practices. Electricians in the construction area can generally be divided into helpers, journeymen, and masters. Many states require tests for journeymen and master levels.

- ***Industrial Electricians***
  Industrial electricians are generally concerned with maintaining equipment that has already been installed. Electricians in an industrial environment require an extensive knowledge of electrical theory and *National Electrical Code* requirements for installation of motors, capacitor banks, and transformers. Industrial electricians should also possess a basic knowledge of electronics and

electronic devices. Modern industry employs many electronic devices, such as variable frequency drives, solid state controls for direct current motors, and programmable logic controllers. Another area of concern for most industrial electricians is motor controls. Motor control systems are generally either relay logic or electronic in the form of programmable logic controllers or distributive control systems.

- ***Instrumentation Technicians***
  Instrumentation technicians calibrate and maintain devices that sense such quantities as temperature, pressure, liquid level, flow rate, and others. These people should have an extensive knowledge of electrical theory, especially as it pertains to low-voltage and closed-loop systems.

- ***Related Industries***
  The fields related to the electrical industry are too numerous to mention but include air conditioning and refrigeration, aircraft electronics, automotive, cable TV, broadcast media, energy and utilities, and home appliance and repair, as well as many, many others. The opportunity for employment in the electrical field is almost unlimited.

Union and Nonunion Employees

The largest percentage of electricians are nonunion employees. Many construction electricians receive training at various trade and technical schools. Some employers also sponsor apprenticeship programs. Apprenticeship-type programs generally require the electrician to work on the job as well as attend classes. The advantage to apprenticeship training is that it permits a person to earn money while he or she attends class. The disadvantage is that it can create an extremely busy schedule. Most industrial electricians, and those in related fields, require special training at a trade or technical school.

The largest electrician's union is the International Brotherhood of Electrical Workers (IBEW). The construction electricians who belong to the IBEW generally receive apprenticeship-type training for an organization called the National Joint Apprenticeship Training Committee (NJATC). Union electricians who work in related fields generally belong to unions organized for their particular industry, such as United Auto Workers or United Steel Workers.

Apprentices, whether union or nonunion, attend classes several hours a week and work on the job under the supervision of a journeyman. Most journeymen have completed their apprenticeship training and a set number of hours of practical work, and are required to pass an examination to become a journeyman. Journeymen work under the supervision of a master electrician. The master is ultimately responsible for the work performed and is answerable to the architect or owner. Most states require not only that a master pass a very rigorous examination but also be bonded for a particular sum of money, depending on the size of the job he or she bids on.

Ethics

Probably the greatest document concerning ethical behavior was given to a man named Moses on top of a mountain several thousand years ago and is called the Ten Commandments. Ethics are the principles by which behavior is judged to be right or wrong. There is an old saying stating that the best advertisement is word of mouth. This type of advertisement, however, can be a two-edged sword. People who do poor work, charge for work that was not done, make promises that are never kept, and cheat people at every opportunity gain a reputation that eventually catches up with them.

People who do an honest day's work for an honest wage, keep promises, and deal fairly with other people gain a reputation that will lead to success. Many years ago I worked for a man who had a business of rebuilding engines. He charged about twice the going rate of any other person in town and had more business than he could handle. I once asked him how he could charge more than anyone else and still have more business than anyone else. His answer was simple. He said, "There are two ways by which a business can be known. One is as the cheapest in town and the other is as the best in town. I'm the best in town." Most people are willing to pay more for a person that has a reputation for doing quality work and dealing honestly with customers.

Appearance

Appearance plays a major role in how a person is perceived. The old saying that first impressions are the most important is true. This doesn't mean that formal office attire is required to make a good impression on a prospective customer, but a professional person is expected to look professional. A person who wears clean work clothes and drives a relatively clean vehicle makes a much better impression than someone who shows up in filthy clothes with shirttail hanging out and pants sagging almost to the knees.

Communication

Communication skills are extremely important on any job. These skills can be divided into several areas such as speaking, listening, and writing.

Speaking: Speaking well is probably one of the most important skills for obtaining a successful career in any field. Generally, one of the first impressions you make concerns your ability to speak properly. Even though slang is widely used among friends, family, and the media, a person who uses proper English gives the impression of being educated, informed, and professional.

The ability to speak also involves communicating with people on the job, whether that person is a journeyman or an employer. The ability to explain clearly how a job was done or why it was done a certain way is also important, as it is often necessary to communicate with people who have no knowledge of the electrical field. The ability to explain to a homeowner

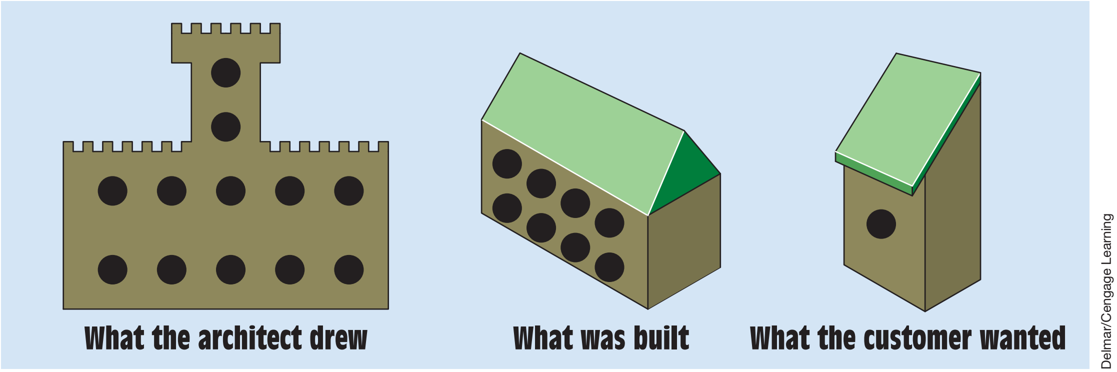


FIGURE OCCUPATIONS 1 Listening to the customer can save money and time.

why a receptacle or switch should or should not be placed in a particular location is important.

Listening: Listening is probably the most understated skill concerning communication. You should not only listen to what a person wants but also make sure you *understand* what he or she is saying. Not understanding what a person wants can lead to extremely costly mistakes. The most costly work is that which has to be redone because of a misunderstanding. An example of how misunderstandings can lead to costly mistakes is shown in *Figure Occupations 1.*

Writing: Many jobs require the electrician to fill out work reports that can include a description of the job, the materials used, and the time required to complete the job. This is especially true of a person in charge of other workers, such as a journeyman.

Maintenance electricians in an industrial environment generally submit a report on the maintenance performed on a particular machine. The report commonly includes the particular machine, the problem encountered, the materials necessary for repair, and the time spent in troubleshooting and repair.

Working on a Team

Teamwork is essential on most construction jobs. The typical construction job may include people that pour the concrete foundation; carpenters; brick masons; stone masons; plumbers; landscapers; people that install flooring and carpet; air-conditioning and refrigeration contractors; and, of course, electricians. One of the key elements to a successful team effort is communication. If conduit is to be run under the slab, it is better to communicate with the people doing the foundation and inform them that conduit needs to be run before the slab is poured.

Be respectful of other trades. If an electrical outlet box is in the way of a sewer line, the plumber may ask that it be moved. It is much easier to move an outlet box than it is to reroute a sewer line. If electrical boxes are to be placed in an outside brick wall, ask the brick mason how he would like the box to be placed. A little respect for other trades plus communication can solve many problems before they happen.

If possible, help other people. If you are already in an attic and the air-conditioning contractor asks whether you would be willing to do a small job that would save him time and effort, it is good working relations to do so. Grudges and hard feelings do not happen in a work setting where kindness is practiced.

Building Codes

Many cities, counties, and states have their own building codes that supersede the *National Electrical Code*. The *National Electrical Code* is law only if the local authority has adopted it as law. Always check local codes before beginning a construction project. Local codes often specify the manner in which wiring is to be installed and the size or type of wire that must be used for a particular application.

Green Building

"Green building" basically means making buildings more energy efficient. This can encompass many areas of the construction such as using "low E" energy-efficient windows, adding extra insulation, adding solar collectors to assist the water heater, and installing solar panels and/or wind generators to assist the electrical service. For the electrician, it may be installing larger wire than necessary to help overcome voltage drop, or installing energy-efficient appliances such as heat pump–type water heaters. These water heaters use about half the amount of power of a standard electric water heater. Energy-efficient appliances are generally identified by an Energy Star label. Energy Star is a government-backed symbol awarded to products that are considered energy efficient. Energy Star was established to reduce greenhouse gas emissions and other pollutants caused by inefficient use of energy, and to aid consumers in identifying and purchasing energy-efficient products that will save money without sacrificing performance, features, or comfort.

Before a product can receive an Energy Star label, it must meet certain requirements set forth in Energy Star product specifications:

- Product categories must produce significant energy savings nationwide.
- Qualified products must deliver the features and performance demanded by customers as well as increase energy efficiency.
- If the qualified product cost more than a conventional, less-efficient counterpart, purchasers must be able to recover their investment in increased energy efficiency through utility bill savings, within a reasonable period of time.

- Energy efficiency must be achievable through broadly available, nonproprietary technologies offered by more than one manufacturer.
- Product energy consumption and performance must be measurable and verified with testing.
- Labeling should effectively differentiate products and be clearly visible to purchasers.

Solar Energy

One of the primary sources of green energy is solar power. Solar energy is the primary source of heating water in many countries and can be as simple as a dark colored container mounted on the roof of a structure, *Figure Occupations 2*. Other types of solar water heaters involve a solar collector, a special tank that contains a heat exchanger, and related equipment, *Figure Occupations 3*. Most of these types of water heaters contain backup electric heating elements for cloudy weather when the solar collector cannot supply enough energy to heat the water.

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FIGURE OCCUPATIONS 2 Solar water heaters mounted on a roof.

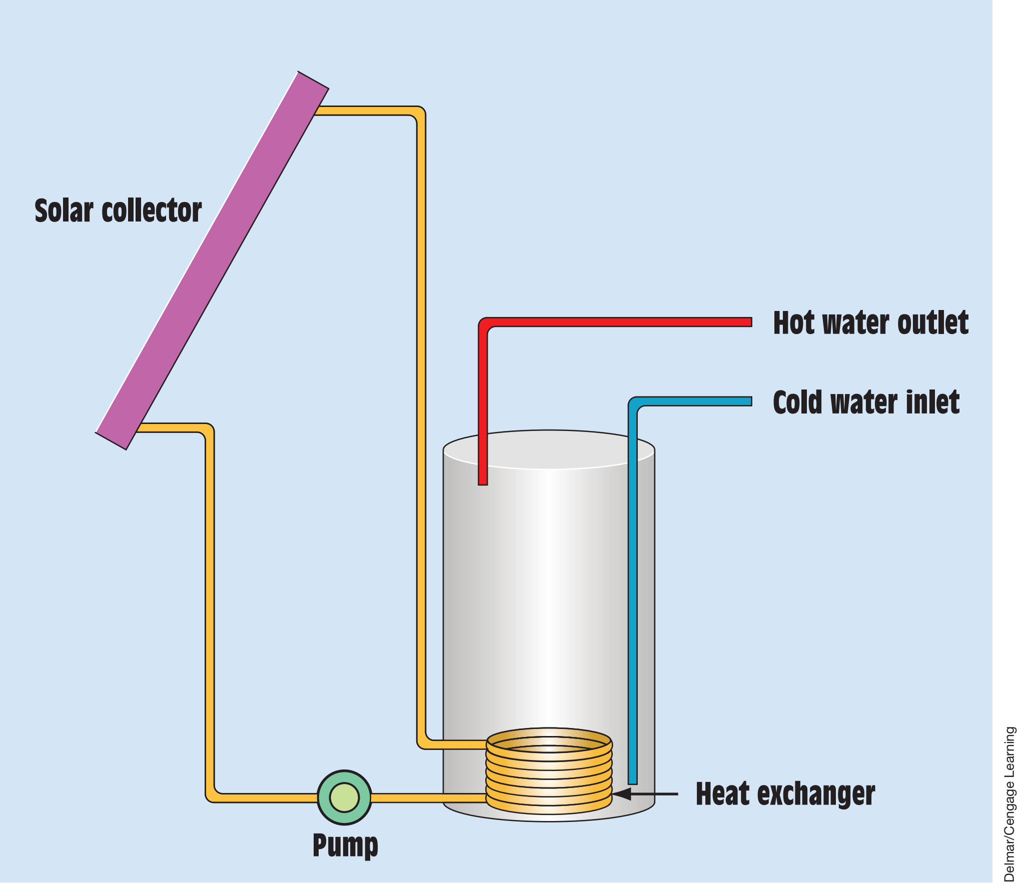


FIGURE OCCUPATIONS 3 Some solar water heaters use a solar panel and special tank with a heat exchanger.

Some solar systems generate electricity and are generally called PV (photovoltaic) systems. In these types of systems solar panels are mounted on the roof of a dwelling or in an open area on the ground, *Figure Occupations 4*. Photovoltaic cells generate direct current, which must be changed into alternating current by an inverter, *Figure Occupations 5*. The home remains connected to the utility company at all times. The solar panels augment the incoming power to help reduce the energy supplied by the utility company. There are various methods of supplying power to the utility company, depending on the requirements of the utility company and state laws. Some systems cause the electric meter to run backward during times that the solar panels are producing more energy than is being supplied by the utility company. Other systems require the use of two separate meters, *Figure Occupations 6*. One records the amount of power supplied by the utility company and the other records the amount of power supplied by the solar cells. The utility company then purchases the power from the homeowner or in some cases gives the homeowner credit

Courtesy of Solar Community

FIGURE OCCUPATIONS 4 Four solar panels are often mounted on the roof or in an open area.

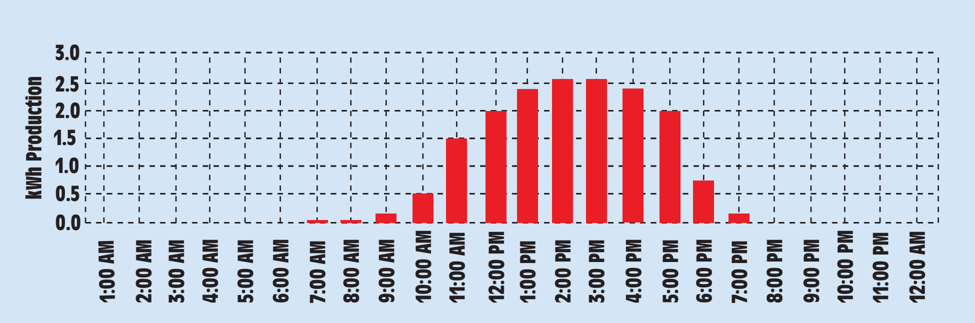
for the amount of power generated. Other systems employ batteries to store the electricity produced by the solar panels. An uninterruptable power supply (UPS) converts the direct current into alternating current. In the event of a power failure, the UPS continues to supply power from the storage batteries.

Courtesy of Solar Community

FIGURE OCCUPATIONS 5 Inverter changes the direct current produced by the solar cells into alternating current.

Courtesy of Solar Community

FIGURE OCCUPATIONS 6 One meters records the power supplied by the utility company, and another records the amount of power supplied by the solar panels.



Courtesy of Solar Community

FIGURE OCCUPATIONS 7 Generation of electric power over a 24-hour period.

The amount of electricity produced by the solar panels is directly proportional to the intensity of sunlight striking the panels. The graph shown in *Figure Occupations 7* illustrates the power output over a 24-hour period. The information was gathered during the month of March. Solar cells have a very long life span, generally considered to be 50 years or more. Most manufacturers of solar panels cover the cells with a material that is designed to remain clear in direct sunlight and is strong enough to withstand the average hail storm. Solar panels connect cells in series and parallel to obtain the desired voltage and current capacity.

Regardless of the type of system, there are generally specific procedures that must be followed during the installation of solar systems. Special circuit breakers designed for direct current and high amperage interrupt capability are often required. Manufacturers' recommendations as well as national and local electrical codes should be followed.

Wind Power

Another widely used form of "Green" energy is wind. Wind is actually a product of solar energy. The Sun heats different areas of the Earth's surface at different rates. Hot air rises at a faster rate than cool air. As the hot air rises, cool air rushes in to replace the void left by the rising hot air, and wind is created. Air has mass, and moving air can contain a lot of energy. Wind generators convert the kinetic energy of moving air into electricity. Wind energy increases by the cube of the speed, which means that each time the wind speed doubles, the amount of energy increases eight times. This is the reason that the shape of many automobiles is designed to move through the air with less friction. The wind resistance of an automobile traveling at 60 miles per hour will be eight times greater than when traveling at 30 miles per hour.

Wind generators are often referred to as wind turbines. There are two basic designs of wind turbines, the horizontal axis and the vertical axis, *Figure*

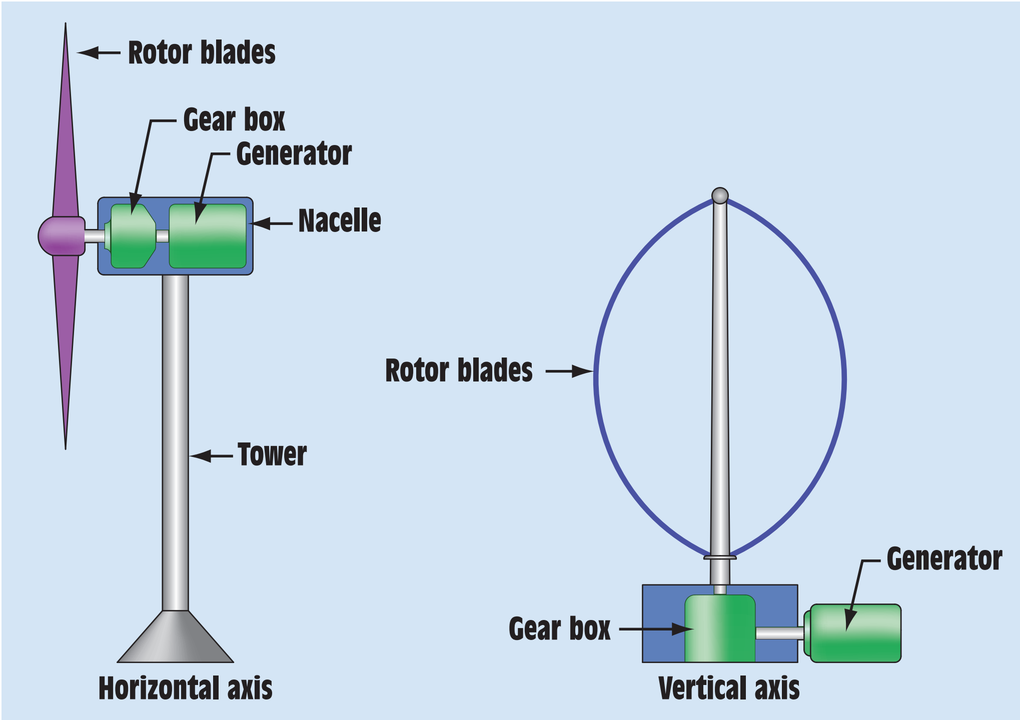


FIGURE OCCUPATIONS 8 Wind turbine types.

Occupations 8. Vertical axis turbines are often called "egg beaters." The main advantage of vertical axis turbines is that they are omnidirectional, meaning that they will operate regardless of wind direction. Although horizontal axis turbines must turn to face the wind, they are mostly used for producing electricity. The size of wind turbines can vary greatly depending on the amount of electricity they are intended to produce. Utility scale turbines used in land-based wind farms, *Figure Occupations 9,* can have rotor diameters that range

FIGURE OCCUPATIONS 9 Wind farm.

from 50 meters (164 feet) to 90 meters (295 feet). The tower height is generally the same as the rotor diameter. Utility wind turbines generally feed the electricity they produce directly into the power grid to aid other electricity-generating plants that use fossil fuels.

Wind turbines intended for residential or small commercial use are much smaller. Most have rotor diameters of 8 meters (26 feet) or smaller and are mounted on towers of 40 meters (131 feet) or less. As with solar installations, wind-powered systems can be installed to connect directly to the power grid or to charge a bank of batteries. An inverter is used to convert the direct current of the batteries into alternating current to supply the home. Inverters used to couple the wind turbine to the power line must be able to maintain a steady power flow with varying wind speeds and varying voltages. They must also be able to shape the waveform to that of a sine wave, *Figure Occupations 10*. Similar to solar installations, some wind-powered systems cause the electric

Courtesy of Diversified Technology, Inc.

FIGURE OCCUPATIONS 10 12kW Wind Power Inverter meter to run backward when it is producing more power than is required by the home. Some utility companies will give credit for the amount of power generated, and some will purchase the power from the customer. Other utilities require the use of two separate meters to determine the amount of wind power produced.

As with solar systems, when installing a wind-powered system, manufacturers' instructions and utility requirements should be followed. Before installing a wind-powered system, check to make certain that the area has a high enough average wind speed to justify the cost of the system.

Lighting

Electric lighting began in 1879 when Thomas Edison invented the first incandescent lamp. He employed the use of a carbon filament that was heated to a temperature that produced a dim light by today's standards. In 1906, the incandescent lamp was improved by replacing the carbon filament with one made of tungsten. Tungsten could be heated to a much higher temperature and therefore could produce a much brighter light. Incandescent lamps today still use tungsten filaments. Incandescent lamps have the advantage of being inexpensive to purchase, but they also have a disadvantage in that they are very energy inefficient. These lamps are basically room heaters that produce light as a byproduct. At best, incandescent lamps are about 5% efficient, which means that a 100-watt lamp actually produces about 95 watts of heat and about 5 watts of light. They consume about 400% more energy to produce the same amount light as a standard fluorescent lamp.

Light is measured in *lumens.* The lumens, a metric measure of light intensity as perceived by the human eye, is based on the English measurement of a candela. Basically, a light source that uniformly radiates 1 candela in all directions is equal to 4π lumens. Lighting efficiency is measured by the lumens produced by 1 watt of electricity (lumens per watt). The chart in *Figure Occupations 11* lists the average lumens per watt for different types of lighting. The actual light output per watt can vary greatly for each type of lamp, depending on many conditions such as temperature, age, wattage, and so on. The range is listed for each type.

The chart indicates that some types are much more energy efficient than others, but all are not suited for use inside buildings. High-pressure sodium is the most efficient, but it has a very orange color, making it unsuitable for many applications. These lamps are generally used in outdoor applications such as parking lots and street lamps. Metal halide is also very efficient and has a near white color. These lamps are often used in large buildings like factories, warehouses, and commercial locations such as building supply stores. Florescent lighting is probably the type most used for homes, office buildings, and retail stores. Compact fluorescent lamps are replacing incandescent lamps

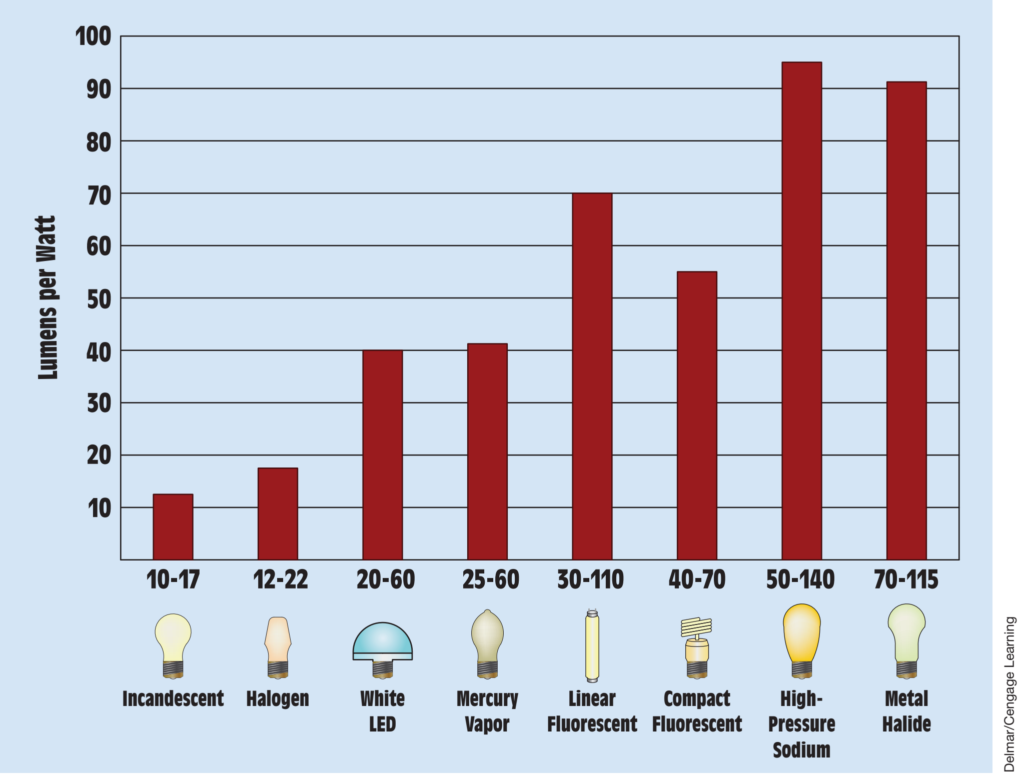


FIGURE OCCUPATIONS 11 Efficiencies of different types of lighting.

in many homes. Although compact fluorescent lamps have an initial cost that is greater than incandescent lamps, they use about one-fourth the energy to produce a similar amount of light, and their average life expectancy is about 10 times longer. Because compact fluorescent lamps are more energy efficient, they produce less heat for the same amount of light, reducing the load on air-conditioning systems. Over the life expectancy of the lamp, the average cost of the compact fluorescent lamp will be less than a similar incandescent lamp.

Summary

The electrical field offers many avenues that can lead to success. Most electricians work in the construction industry, but many are employed as maintenance technicians in industry and other related fields. The demand for qualified electricians is expected to increase at a rate of over 8000 new jobs per year over the next 10 years. The lay-off rate for electricians is one of the lowest in the country. Electricity is the power that operates homes, businesses, and industry. If industry runs, it will require electricians to keep it running.

Safety, Basic Electricity, and Ohm's Law

Courtesy of Getty Images, Inc.

Safety Overview

OUTLINE

KEY TERMS

Artificial respiration
Cardiopulmonary resuscitation (CPR)
Confined spaces
De-energized circuit
Disconnect
Energized circuit
Fibrillation
Fire-retardant clothing
Horseplay
Idiot proofing
Lockout and tagout
Material safety data sheets (MSDS)
Meter
Milliamperes (mA)
Occupational Safety and Health Administration (OSHA)
Scaffolds

Why You Need to Know

Safety is the job of each individual. You should be concerned not only with your own safety but also with the safety of others around you. This is especially true for persons employed in the electrical field. Some general rules should be followed when working with electric equipment or circuits.

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Objectives

After studying this unit, you should be able to

- state basic safety rules.
- describe the effects of electric current on the body.
- discuss the origin and responsibilities of OSHA.
- discuss material safety data sheets.
- discuss lockout and tagout procedures.
- discuss types of protective clothing.
- explain how to properly place a straight ladder against a structure.
- discuss different types of scaffolds.
- discuss classes of fires.
- discuss ground-fault circuit interrupters.
- discuss the importance of grounding.

S–1 General Safety Rules

Never Work on an Energized Circuit If the Power Can Be Disconnected

When possible, use the following three-step check to make certain that power is turned off:

1. Test the **meter** on a known live circuit to make sure the meter is operating.
2. Test the circuit that is to become the **de-energized circuit** with the meter.
3. Test the meter on the known live circuit again to make certain the meter is still operating.

Install a warning tag at the point of disconnection so people will not restore power to the circuit. If possible, use a lock to prevent anyone from turning the power back on.

Think

Of all the rules concerning safety, this one is probably the most important. No amount of safeguarding or **idiot proofing** a piece of equipment can protect a person as well as taking time to think before acting. Many technicians have been killed by supposedly "dead" circuits. Do not depend on circuit breakers, fuses, or someone else to open a circuit. Test it yourself before you touch it. If you are working on high-voltage equipment, use insulated gloves and meter probes to measure the voltage being tested. *Think* before you touch something that could cost you your life.

Avoid Horseplay

Jokes and **horseplay** have a time and place, but not when someone is working on an electric circuit or a piece of moving machinery. Do not be the cause of someone's being injured or killed, and do not let someone else be the cause of your being injured or killed.

Do Not Work Alone

This is especially true when working in a hazardous location or on a live circuit. Have someone with you who can turn off the power or give **artificial respiration** and/or **cardiopulmonary resuscitation (CPR).** Several electric shocks can cause breathing difficulties and can cause the heart to go into fibrillation.

Work with One Hand When Possible

The worst kind of electric shock occurs when the current path is from one hand to the other, which permits the current to pass directly through the heart. A person can survive a severe shock between the hand and foot that would cause death if the current path were from one hand to the other.

Learn First Aid

Anyone working on electric equipment, especially those working with voltages greater than 50 volts, should make an effort to learn first aid. A knowledge of first aid, especially CPR, may save your own or someone else's life.

Avoid Alcohol and Drugs

The use of alcohol and drugs has no place on a work site. Alcohol and drugs are not only dangerous to users and those who work around them; they also cost industry millions of dollars a year. Alcohol and drug abusers kill thousands of people on the highways each year and are just as dangerous on a work site as they are behind the wheel of a vehicle. Many industries have instituted testing policies to screen for alcohol and drugs. A person who tests positive generally receives a warning the first time and is fired the second time.

S–2 Effects of Electric Current on the Body

Most people have heard that it is not the voltage that kills but the current. This is true, but do not be misled into thinking that voltage cannot harm you. Voltage is the force that pushes the current though the circuit. It can be compared to the pressure that pushes water through a pipe. The more pressure available, the greater the volume of water flowing through the pipe. Students often ask how much current will flow through the body at a particular voltage. There is no easy answer to this question. The amount of current that can flow at a particular voltage is determined by the resistance of the current path. Different people have different resistances. A body has less resistance on a hot day when sweating, because salt water is a very good conductor. What one eats and drinks for lunch can have an effect on the body's resistance, as can the length of the current path. Is the current path between two hands or from one hand to one foot? All these factors affect body resistance.

Figure S–1 illustrates the effects of different amounts of current on the body. This chart is general—some people may have less tolerance to electricity and others may have a greater tolerance.

A current of 2 to 3 **milliamperes (mA)** (0.002 to 0.003 amperes) usually causes a slight tingling sensation, which increases as current increases and becomes very noticeable at about 10 milliamperes (0.010 amperes). The tingling sensation is very painful at about 20 milliamperes. Currents between 20 and 30 milliamperes cause a person to seize the line and be unable to let go of the circuit. Currents between 30 and 40 milliamperes cause muscular paralysis, and those between 40 and 60 milliamperes cause breathing difficulty. When the current increases to about 100 milliamperes, breathing is extremely difficult. Currents from 100 to 200 milliamperes generally cause death because the heart usually goes into **fibrillation,** a condition in which the heart begins to "quiver" and the pumping action stops. Currents above 200 milliamperes cause the heart to squeeze shut. When the current is removed, the heart usually returns to a normal pumping action. This is the operating principle of a defibrillator. The voltage considered to be the most dangerous to work with is 120 volts, because that generally causes a current flow of between 100 and 200 milliamperes through most people's bodies. Large amounts of current can cause severe electric burns that are often very serious because they occur on the inside of the body. The exterior of the body may not look seriously burned, but the inside may be severely burned.

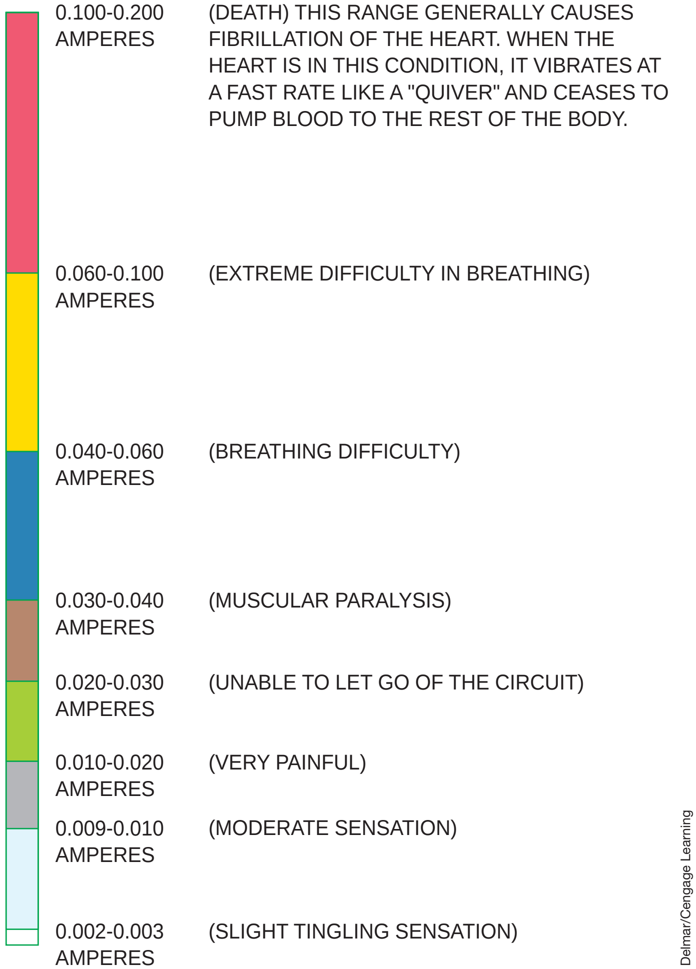


FIGURE S–1 The effects of electric current on the body.

S–3 On the Job

OSHA

OSHA is an acronym for **Occupational Safety and Health Administration,** U.S. Department of Labor. Created by congress in 1971, its mission is to ensure safe and healthful workplaces in the United States. Since its creation, workplace fatalities have been cut in half, and occupational injury and illness rates have declined by 40%. Enforcement of OSHA regulations is the responsibility of the Secretary of Labor.

OSHA standards cover many areas, such as the handling of hazardous materials, fall protection, protective clothing, and hearing and eye protection. Part 1910, Subpart S, deals mainly with the regulations concerning electrical safety. These regulations are available in books and can be accessed at the OSHA website on the Internet at *http://www.osha.org*.

Hazardous Materials

It may become necessary to deal with some type of hazardous material. A hazardous material or substance is any substance to which exposure may result in adverse effects on the health or safety of employees. Hazardous materials may be chemical, biological, or nuclear. OSHA sets standards for dealing with many types of hazardous materials. The required response is determined by the type of hazard associated with the material. Hazardous materials are required to be listed as such. Much information concerning hazardous materials is generally found on **material safety data sheets (MSDS).** (A sample MSDS is included at the end of the unit.) If you are working in an area that contains hazardous substances, always read any information concerning the handling of the material and any safety precautions that should be observed. After a problem exists is not the time to start looking for information on what to do.

Some hazardous materials require a hazardous materials (HAZMAT) response team to handle any problems. A HAZMAT team is any group of employees designated by the employer who are expected to handle and control an actual or potential leak or spill of a hazardous material. They are expected to work in close proximity to the material. A HAZMAT team is not always a fire brigade, and a fire brigade may not necessarily have a HAZMAT team. On the other hand, a HAZMAT team may be part of a fire brigade or fire department.

Employer Responsibilities

Section 5(a)1 of the Occupational Safety and Health Act basically states that employers must furnish each of their employees a place of employment that is free of recognized hazards that are likely to cause death or serious injury. This places the responsibility for compliance on employers. Employers must identify hazards or potential hazards within the work site and eliminate them, control them, or provide employees with suitable protection from them. It is the employee's responsibility to follow the safety procedures set up by the employer.

To help facilitate these safety standards and procedures, OSHA requires that an employer have a competent person oversee implementation and enforcement of these standards and procedures. This person must be able to recognize unsafe or dangerous conditions and have the authority to correct or eliminate them. This person also has the authority to stop work or shut down a work site until safety regulations are met.

MSDS

MSDS stands for material safety data sheets, which are provided with many products. They generally warn users of any hazards associated with the product. They outline the physical and chemical properties of the product; list precautions that should be taken when using the product; and list any potential health hazards, storage consideration, flammability, reactivity, and, in some instances, radioactivity. They sometimes list the name, address, and telephone number of the manufacturer; the MSDS date and emergency telephone numbers; and, usually, information on first aid procedures to use if the product is swallowed or comes in contact with the skin. Safety data sheets can be found on many home products such as cleaning products, insecticides, and flammable liquids.

Trenches

It is often necessary to dig trenches to bury conduit. Under some conditions, these trenches can be deep enough to bury a person if a cave-in should occur. Safety regulations for the shoring of trenches is found in OSHA Standard 1926, Subpart P, App C, titled "Timber Shoring for Trenches." These procedures and regulations are federally mandated and must be followed. Some general safety rules also should be followed:

1. Do not walk close to trenches unless it is necessary. This can cause the dirt to loosen and increase the possibility of a cave-in.
2. Do not jump over trenches if it is possible to walk around them.
3. Place barricades around trenches *(Figure S–2)*.
4. Use ladders to enter and exit trenches.

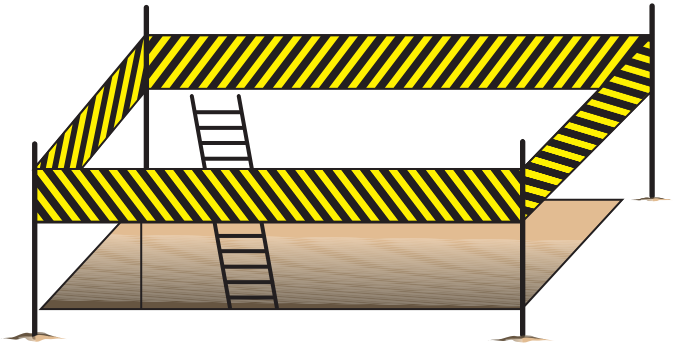


FIGURE S–2 Place a barricade around a trench and use a ladder to enter and exit the trench.

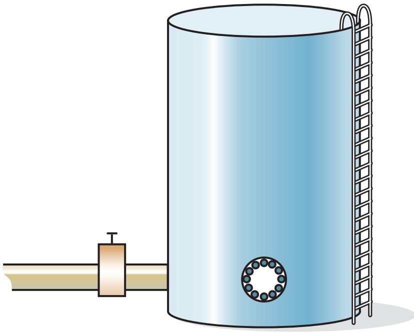


FIGURE S–3 A confined space is any space having a limited means of entrance or exit.

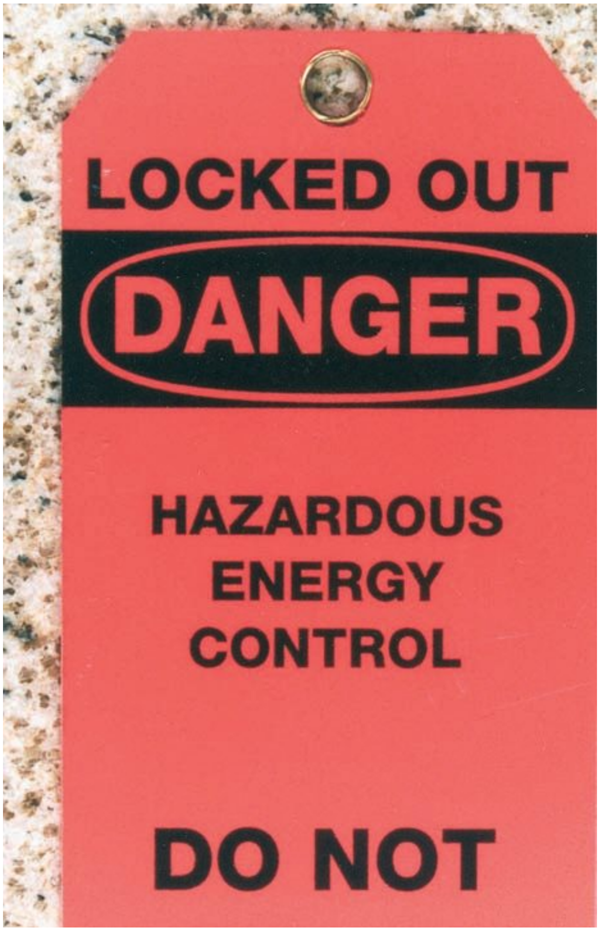
Confined Spaces

Confined spaces have a limited means of entrance or exit *(Figure S–3)*. They can be very hazardous workplaces, often containing atmospheres that are extremely harmful or deadly. Confined spaces are very difficult to ventilate because of their limited openings. It is often necessary for a worker to wear special clothing and use a separate air supply to work there. OSHA Section 12, "Confined Space Hazards," lists rules and regulations for working in a confined space. In addition, many industries have written procedures that must be followed when working in confined spaces. Some general rules include the following:

1. Have a person stationed outside the confined space to watch the person or persons working inside. The outside person should stay in voice or visual contact with the inside workers at all times. He or she should check air sample readings and monitor oxygen and explosive gas levels.
2. The outside person should never enter the space, even in an emergency, but should contact the proper emergency personnel. If he or she should enter the space and become incapacitated, there would be no one available to call for help.
3. Use only electric equipment and tools that are approved for the atmosphere found inside the confined area. It may be necessary to obtain a burning permit to operate tools that have open brushes and that spark when they are operated.
4. As a general rule, a person working in a confined space should wear a harness with a lanyard that extends to the outside person, so the outside person could pull him or her to safety if necessary.

Lockout and Tagout Procedures

Lockout and tagout procedures are generally employed to prevent someone from energizing a piece of equipment by mistake. This could apply to switches, circuit breakers, or valves. Most industries have their own internal



Delmar/Cengage Learning

FIGURE S–4 Safety tag used to tagout equipment.

Delmar/Cengage Learning

FIGURE S–5 The equipment can be locked out by several different people.

policies and procedures. Some require that a tag similar to the one shown in *Figure S–4* be placed on the piece of equipment being serviced; some also require that the equipment be locked out with a padlock. The person performing the work places the lock on the equipment and keeps the key in his or her possession. A device that permits the use of multiple padlocks and a safety tag is shown in *Figure S–5*. This is used when more than one person is working on the same piece of equipment. Violating lockout and tagout procedures is considered an extremely serious offense in most industries and often results in immediate termination of employment. As a general rule, there are no first-time warnings.

After locking out and tagging a piece of equipment, it should be tested to make certain that it is truly de-energized before working on it. A simple three-step procedure is generally recommended for making certain that a piece of electric equipment is de-energized. A voltage tester or voltmeter that has a high enough range to safely test the voltage is employed. The procedure is as follows:

1. Test the voltage tester or voltmeter on a known energized circuit to make certain the tester is working properly.
2. Test the circuit you intend to work on with the voltage tester or voltmeter to make sure that it is truly de-energized.
3. Test the voltage tester or voltmeter on a known energized circuit to make sure that the tester is still working properly.

This simple procedure helps to eliminate the possibility of a faulty piece of equipment indicating that a circuit is de-energized when it is not.

S–4 Protective Clothing

Maintenance and construction workers alike are usually required to wear certain articles of protective clothing, dictated by the environment of the work area and the job being performed.

Head Protection

Some type of head protection is required on almost any work site. A typical electrician's hard hat, made of nonconductive plastic, is shown in *Figure S–6*. It has a pair of safety goggles attached that can be used when desired or necessary.

Delmar/Cengage Learning

FIGURE S–6 Typical electrician's hard hat with attached safety goggles.

FIGURE S–7 Safety glasses provide side protection.

Eye Protection

Eye protection is another piece of safety gear required on almost all work sites. Eye protection can come in different forms, ranging from the goggles shown in *Figure S–6* to the safety glasses with side shields shown in *Figure S–7*. Common safety glasses may or may not be prescription glasses, but almost all provide side protection *(Figure S–7)*. Sometimes a full face shield may be required.

Hearing Protection

Section III, Chapter 5, of the OSHA Technical Manual includes requirements concerning hearing protection. The need for hearing protection is based on the ambient sound level of the work site or the industrial location. Workers are usually required to wear some type of hearing protection when working in certain areas, usually in the form of earplugs or earmuffs.

Fire-Retardant Clothing

Special clothing made of fire-retardant material is required in some areas, generally certain industries as opposed to all work sites. **Fire-retardant clothing** is often required for maintenance personnel who work with high-power sources such as transformer installations and motor-control centers. An arc flash in a motor-control center can easily catch a person's clothes on fire. The typical motor-control center can produce enough energy during an arc flash to kill a person 30 feet away.

FIGURE S–8 Leather gloves with rubber inserts.

FIGURE S–9 Kevlar gloves protect against cuts.

Gloves

Another common article of safety clothing is gloves. Electricians often wear leather gloves with rubber inserts when it is necessary to work on energized circuits *(Figure S–8)*. These gloves are usually rated for a certain amount of voltage. They should be inspected for holes or tears before they are used. Kevlar gloves *(Figure S–9)* help protect against cuts when stripping cable with a sharp blade.

Safety Harness

Safety harnesses provide protection from falling. They buckle around the upper body with leg, shoulder, and chest straps; and the back has a heavy metal D-ring *(Figure S–10)*. A section of rope approximately 6 feet in length, called

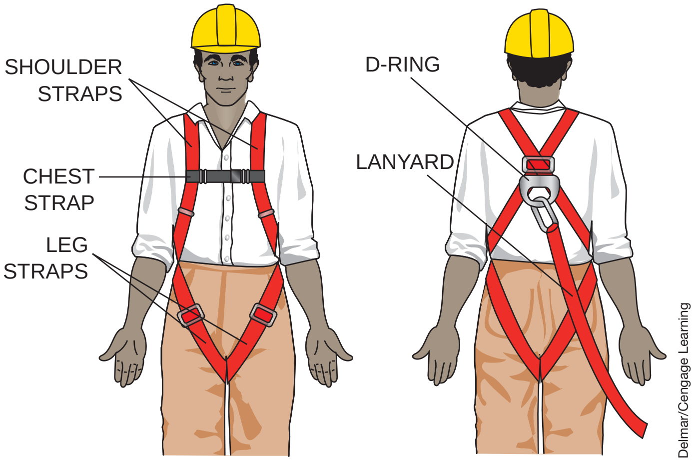


FIGURE S–10 Typical safety harness.

a lanyard, is attached to the D-ring and secured to a stable structure above the worker. If the worker falls, the lanyard limits the distance he or she can drop. A safety harness should be worn:

1. When working more than 6 feet above the ground or floor
2. When working near a hole or drop-off
3. When working on high scaffolding

A safety harness is shown in *Figure S–11*.

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FIGURE S–11 Safety harness.

S–5 Ladders and Scaffolds

It is often necessary to work in an elevated location. When this is the case, ladders or scaffolds are employed. **Scaffolds** generally provide the safest elevated working platforms. They are commonly assembled on the work site from standard sections *(Figure S–12)*. The bottom sections usually contain adjustable feet that can be used to level the sections. Two end sections are connected by X braces that form a rigid work platform *(Figure S–13)*. Sections of scaffolding are stacked on top of each other to reach the desired height.

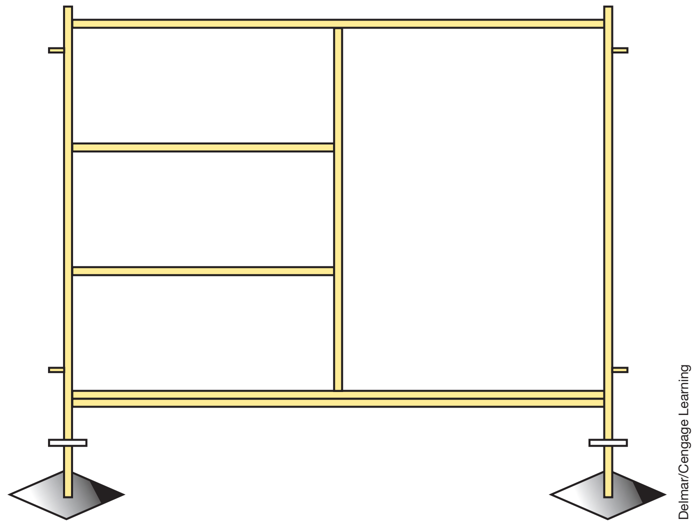

FIGURE S–12 Typical section of scaffolding.

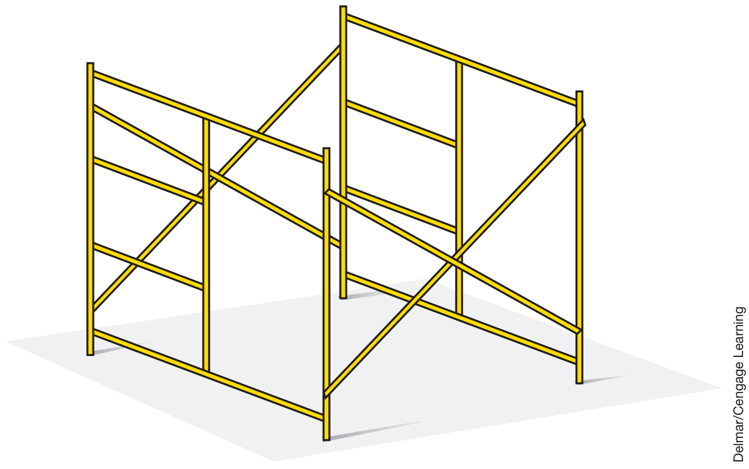

FIGURE S–13 X braces connect scaffolding sections together.

Rolling Scaffolds

Rolling scaffolds are used in areas that contain level floors, such as inside a building. The major difference between a rolling scaffold and those discussed previously is that it is equipped with wheels on the bottom section that permit it to be moved from one position to another. The wheels usually contain a mechanism that permits them to be locked after the scaffold is rolled to the desired location.

Hanging or Suspended Scaffolds

Hanging or suspended scaffolds are suspended by cables from a support structure. They are generally used on the sides of buildings to raise and lower workers by using hand cranks or electric motors.

Straight Ladders

Ladders can be divided into two main types, straight and step. Straight ladders are constructed by placing rungs between two parallel rails *(Figure S–14)*. They generally contain safety feet on one end that help prevent the ladder from slipping. Ladders used for electrical work are usually wood or fiberglass; aluminum ladders are avoided because they conduct electricity. Regardless of the type of ladder used, you should check its load capacity before using it. This information is found on the side of the ladder. Load capacities of 200 pounds, 250 pounds, and 300 pounds are common. Do not use a ladder that does not have enough load capacity to support your weight plus the weight of your tools and the weight of any object you are taking up the ladder with you.

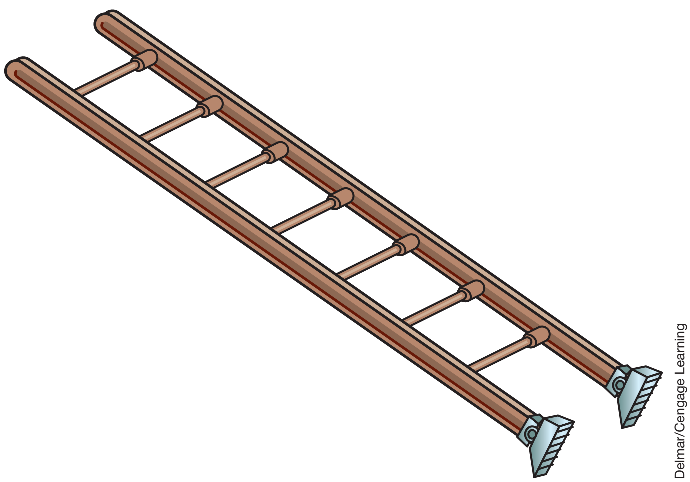

FIGURE S–14 Straight ladder.

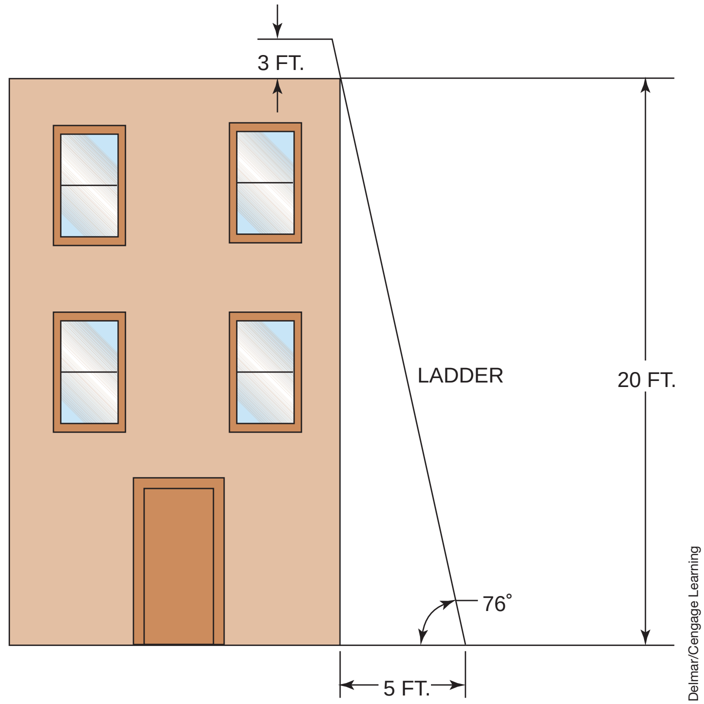

FIGURE S–15 A ladder should be placed at an angle of approximately 76°.

Straight ladders should be placed against the side of a building or other structure at an angle of approximately 76° *(Figure S–15)*. This can be accomplished by moving the base of the ladder away from the structure a distance equal to one-fourth the height of the ladder. If the ladder is 20 feet high, it should be placed 5 feet from the base of the structure. If the ladder is to provide access to the top of the structure, it should extend 3 feet above the structure.

Step Ladders

Step ladders are self-supporting, constructed of two sections hinged at the top *(Figure S–16)*. The front section has two rails and steps, the rear portion two rails and braces. Like straight ladders, step ladders are designed to withstand a certain load capacity. Always check the load capacity before using a ladder. As a general rule, ladder manufacturers recommend that the top step not be used because of the danger of becoming unbalanced and falling. Many people mistakenly think the top step is the top of the ladder, but it is actually the last step before the ladder top.

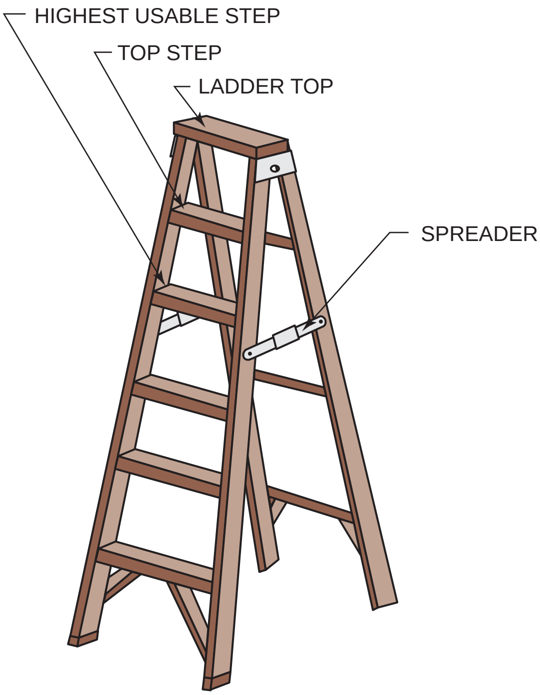

FIGURE S–16 Typical step ladder.

S–6 Fires

For a fire to burn, it must have three things: fuel, heat, and oxygen. Fuel is anything that can burn, including materials such as wood, paper, cloth, combustible dusts, and even some metals. Different materials require different amounts of heat for combustion to take place. If the temperature of any material is below its combustion temperature, it will not burn. Oxygen must be present for combustion to take place. If a fire is denied oxygen, it will extinguish.

Fires are divided into four classes: A, B, C, and D. Class A fires involve common combustible materials such as wood or paper. They are often extinguished by lowering the temperature of the fuel below the combustion temperature. Class A fire extinguishers often use water to extinguish a fire. A fire extinguisher listed as Class A only should never be used on an electrical fire.

Class B fires involve fuels such as grease, combustible liquids, or gases. A Class B fire extinguisher generally employs carbon dioxide (CO_2), which greatly lowers the temperature of the fuel and deprives the fire of oxygen. Carbon dioxide extinguishers are often used on electrical fires, because they do not destroy surrounding equipment by coating it with a dry powder.

Class C fires involve energized electric equipment. A Class C fire extinguisher usually uses a dry powder to smother the fire. Many fire extinguishers can be used on multiple types of fires; for example, an extinguisher labeled ABC could be used on any of the three classes of fire. The important thing to remember is never to use an extinguisher on a fire for which it is not rated. Using a Class A extinguisher filled with water on an electrical fire could be fatal.

Class D fires consist of burning metal. Spraying water on some burning metals can actually cause the fire to increase. Class D extinguishers place a powder on top of the burning metal that forms a crust to cut off the oxygen supply to the metal. Some metals cannot be extinguished by placing powder on them, in which case the powder should be used to help prevent the fire from spreading to other combustible materials.

S–7 Ground-Fault Circuit Interrupters

Ground-fault circuit interrupters (GFCI) are used to prevent people from being electrocuted. They work by sensing the amount of current flow on both the ungrounded (hot) and grounded (neutral) conductors supplying power to a device. In theory, the amount of current in both conductors should be equal but opposite in polarity *(Figure S–17)*. In this example, a current of 10 amperes flows in both the hot and neutral conductors.

A ground fault occurs when a path to ground other than the intended path is established *(Figure S–18)*. Assume that a person comes in contact with a defective electric appliance. If the person is grounded, a current path can be

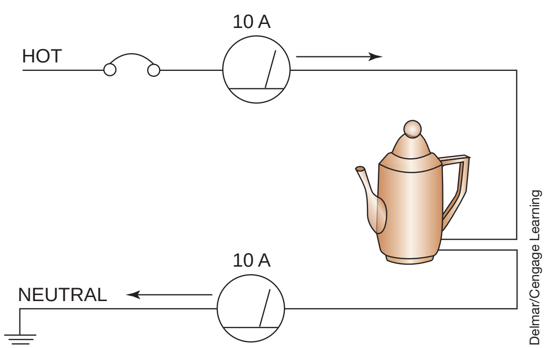

FIGURE S–17 The current in both the "hot" and neutral conductors should be the same, but flowing in opposite directions.

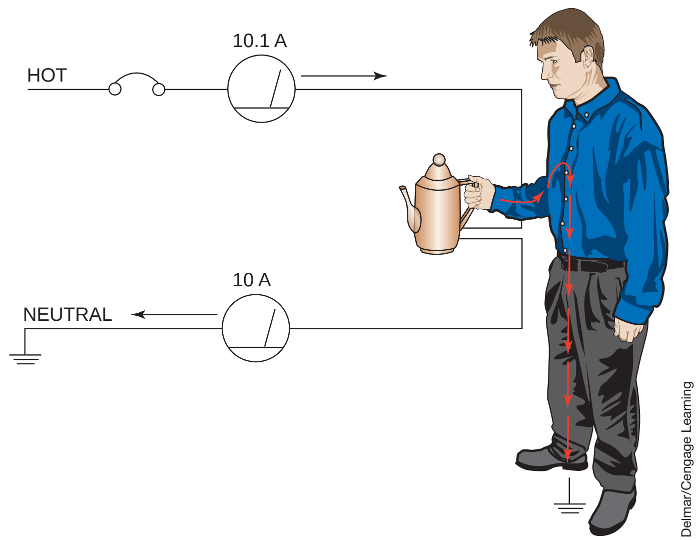

FIGURE S–18 A ground fault occurs when a path to ground other than the intended path is established.

established through the person's body. In the example shown in *Figure S–18*, it is assumed that a current of 0.1 ampere is flowing through the person. This means that the hot conductor now has a current of 10.1 amperes, but the neutral conductor has a current of only 10 amperes. The GFCI is designed to detect this current difference to protect personnel by opening the circuit when it detects a current difference of approximately 5 milliamperes (0.005 ampere). The *National Electrical Code*® *(NEC*®*) 210.8* lists places where ground-fault protection is required in dwellings. The *National Electrical Code* and *NEC* are registered trademarks of the National Fire Protection Association, Quincy, MA.

GFCI Devices

Several devices can be used to provide ground-fault protection, including the ground-fault circuit breaker *(Figure S–19)*. The circuit breaker provides ground-fault protection for an entire circuit, so any device connected to the circuit is ground-fault protected. A second method of protection, ground-fault receptacles *(Figure S–20)*, provide protection at the point of attachment. They have some

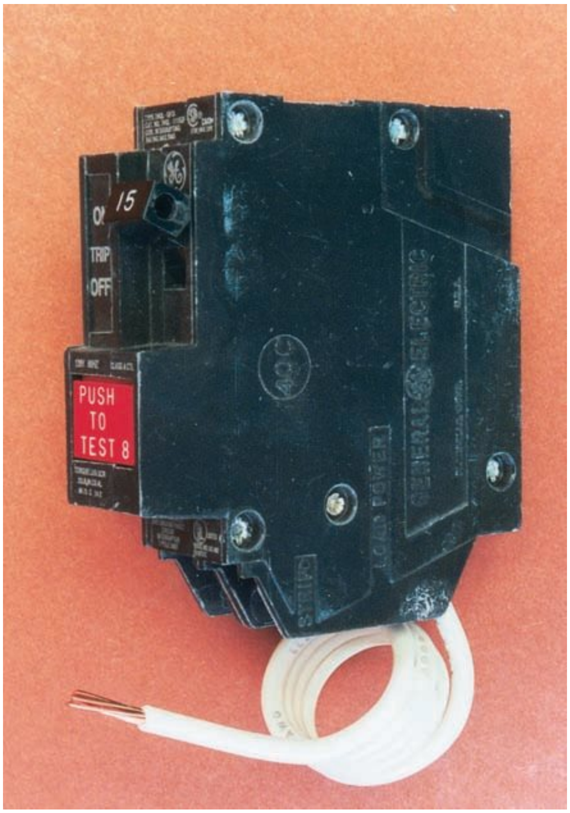

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FIGURE S–19 Ground-fault circuit breaker.

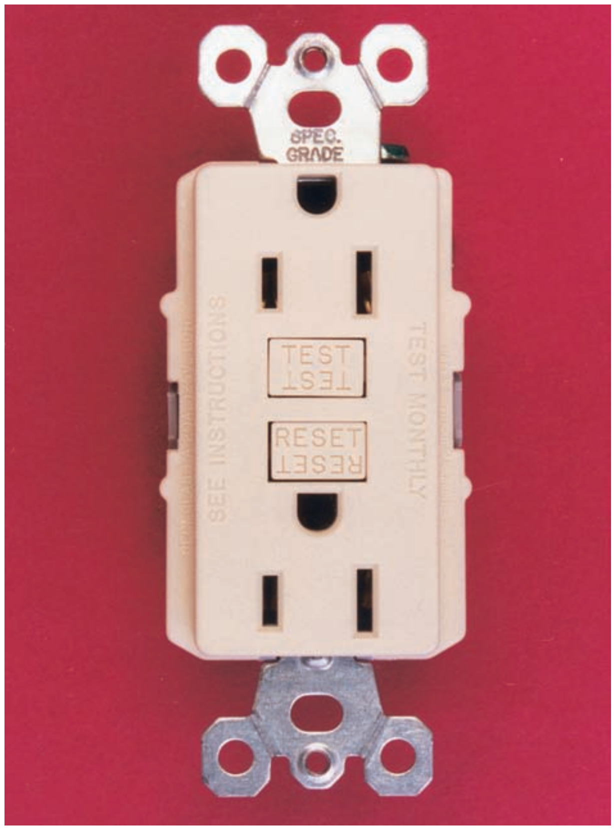

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FIGURE S–20 Ground-fault receptacle.

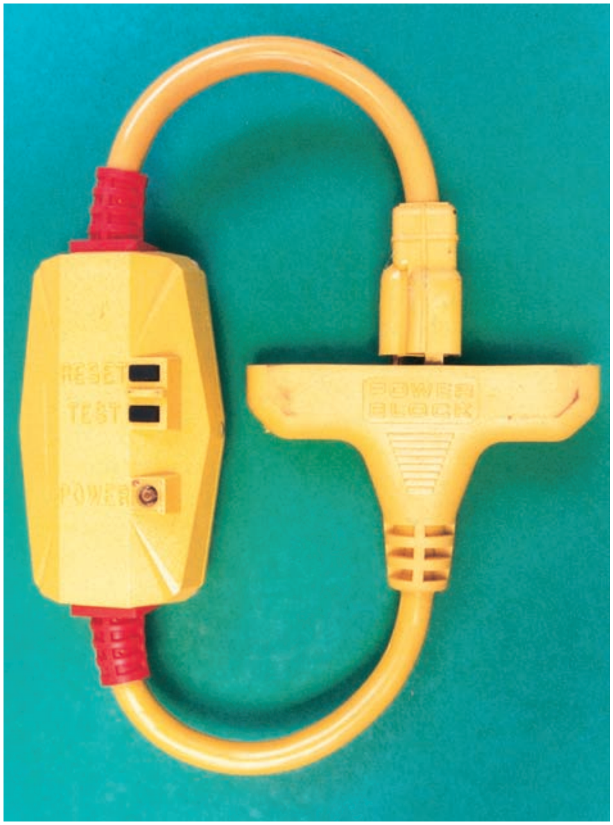

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FIGURE S–21 Ground-fault extension.

advantages over the GFCI circuit breaker. They can be connected so that they protect only the devices connected to them and do not protect any other outlets on the same circuit, or they can be connected so they provide protection to other outlets. Another advantage is that, because they are located at the point of attachment for the device, there is no stray capacitance loss between the panel box and the equipment being protected. Long wire runs often cause nuisance tripping of GFCI circuit breakers. A third ground-fault protective device is the GFCI extension cord *(Figure S–21)*. It can be connected into any standard electric outlet, and any devices connected to it are then ground-fault protected.

S–8 Arc-Fault Circuit Interrupters (AFCIs)

Arc-fault circuit interrupters are similar to ground fault circuit interrupters in that they are designed to protect people from a particular hazard. Where the ground fault interrupter is designed to protect against electrocution, the arc-fault interrupter is intended to protect against fire. Studies have shown that one-third of electrical related fires are caused by an arc-fault condition. At present, the *National Electrical Code* requires that arc-fault circuit interrupters be used on all 120-volt, single-phase, 15- and 20-ampere circuits installed in dwelling units supplying power to family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, or similar rooms or areas.

An arc-fault is a plasma flame that can develop temperatures in excess of 6000°C (10,832°F). Arc faults occur when an intermittent gap between two conductors or a conductor and ground permits current to "jump" between the two conductive surfaces. There are two basic types of arc faults, the parallel and the series.

Parallel Arc Faults

Parallel arc faults are caused by two conductors becoming shorted together *(Figure S–22)*. A prime example of this is when the insulation of a lamp cord or extension cord has become damaged and permits the two conductors to short together. The current in this type of fault is limited by the resistance of the conductors in the circuit. The current in this type of fault is generally much higher than the rated current of a typical thermomagnetic circuit breaker. A continuous short will usually cause the circuit breaker to trip almost immediately because it will activate the magnetic part of the circuit breaker, but an intermittent short may take some time to heat the thermal part of the circuit

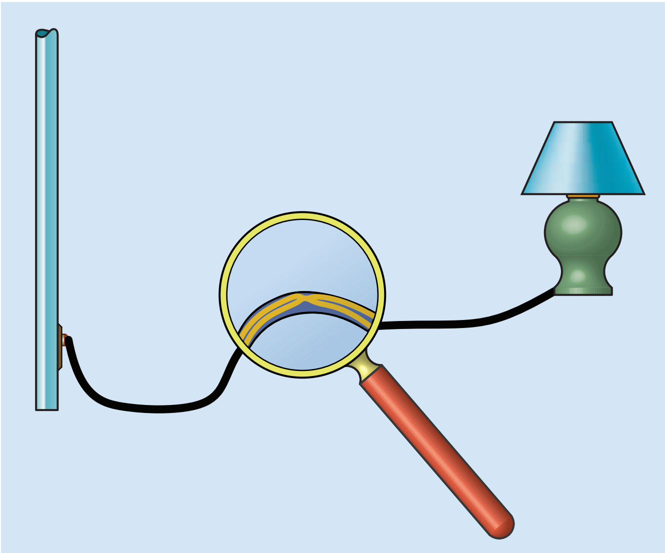

FIGURE S–22 Parallel arc faults are caused by two conductors touching.

breaker enough to cause it to trip open. Thermal/magnetic type circuit breakers are generally effective in protecting against this type of arc fault, but cords with small-size conductors, such as lamp and small extension cords, can add enough resistance to the circuit to permit the condition to exist long enough to produce sufficient heat to start a fire.

Parallel arc faults can be more hazardous than series arc faults because they generate a greater amount of heat. Arc faults of this type often cause hot metal to be ejected into combustible material. Parallel arc faults, however, generally produce peak currents that are well above the normal current rating of a circuit breaker. This permits the electronic circuits in the arc-fault circuit interrupter to detect them very quickly and trip the breaker in a fraction of a second.

Series Arc Faults

Series arc faults are generally caused by loose connections. A loose screw on an outlet terminal, or an improperly made wire nut connection, is a prime example of this type of problem. They are called series arc faults because the circuit contains some type of current-limiting resistance connected in series with the arc *(Figure S–23)*. Although the amount of electrical energy converted into heat is less than that of a parallel arc fault, series arc faults can be more dangerous. The fact that the current is limited by some type of load keeps the current below the thermal and magnetic trip rating of a common thermo/magnetic circuit breaker. Because the peak arc current is never greater than the normal steady current flow, series arcing is more difficult to detect than parallel arcing.

When the current of an arc remains below the normal range of a common thermomagnetic circuit breaker, it cannot provide protection. If a hair dryer, for

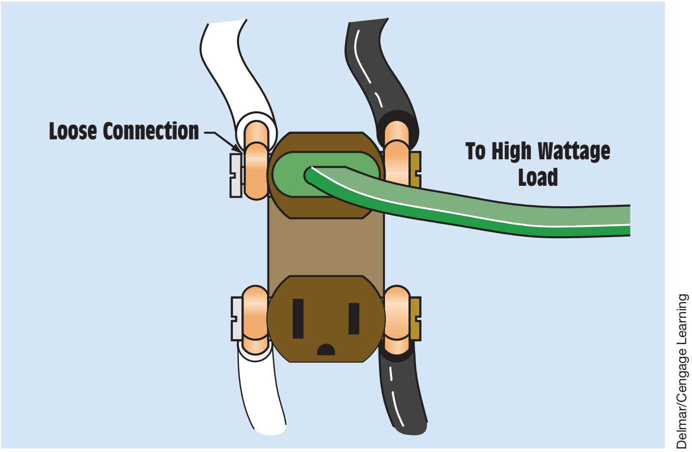

FIGURE S–23 Series arc-faults are generally caused by bad connections.

example, normally has a current draw of 12 amperes, but the wall outlet has a loose screw at one terminal so that the circuit makes connection only half of the time, the average circuit current is 6 amperes. This is well below the trip rating of a common circuit breaker. A 6-ampere arc, however, can produce a tremendous amount of heat in a small area.

Arc-Fault Detection

There are conditions where arcing in an electric circuit is normal, such as these:

- Turning a light switch on or off
- Switching on or off of a motor relay
- Plugging in an appliance that is already turned on
- Changing a light bulb with the power turned on
- Arcing caused by motors that contain a commutator and brushes

The arc-fault circuit interrupter is designed to be able to distinguish between normally occurring arcs and an arc fault. An arc caused by a toggle switch being used to turn a light on or off will produce a current spike of short duration, as shown in *Figure S–24*. An arc fault, however, is an intermittent

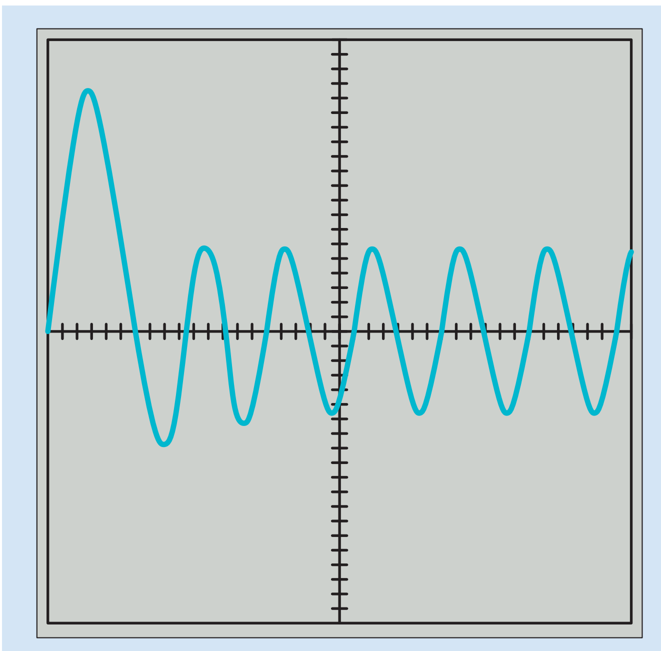

FIGURE S–24 Current spike produced by turning a light on or off.

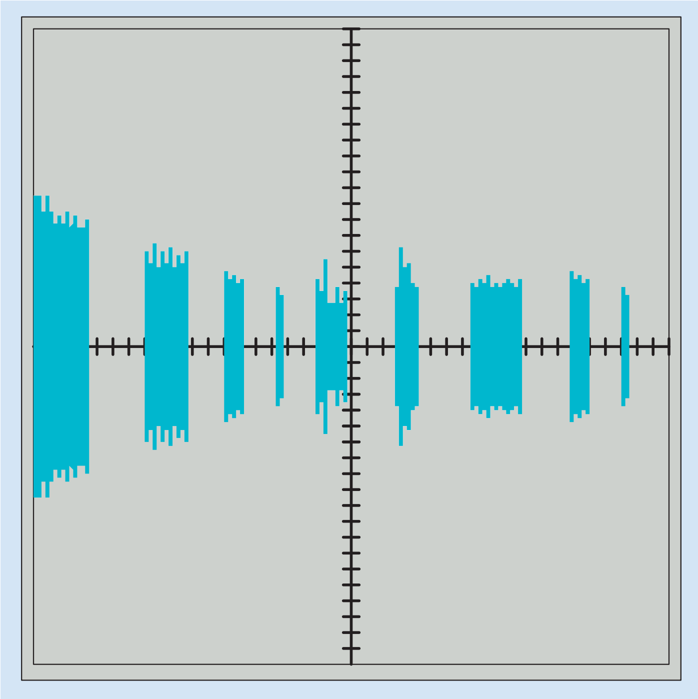

FIGURE S–25 Waveform produced by typical arc fault.

connection and will generally produce current spikes of various magnitudes and lengths of time *(Figure S–25)*.

In order for an arc-fault circuit interrupter to determine the difference between a normally occurring arc and an arc fault, a microprocessor and other related electronic components are employed to detect these differences. The AFCI contains current and temperature sensors as well as a microprocessor and nonvolatile (retains its information when power is switched off) memory. The current and temperature sensors permit the AFCI to operate as a normal circuit breaker in the event of a circuit overload or short circuit. The microprocessor continuously monitors the current and compares the waveform to information stored in the memory. The microprocessor is monitoring the current for the magnitude, duration, and length of time between pulses, not for a particular waveform. For this reason, there are some appliances that can produce waveforms similar to that of an arc fault and may cause the AFCI to trip. Appliances containing motors that employ the use of brushes and a commutator, such as vacuum cleaners and hand drills, will produce a similar waveform.

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FIGURE S–26 Arc-fault circuit breaker.

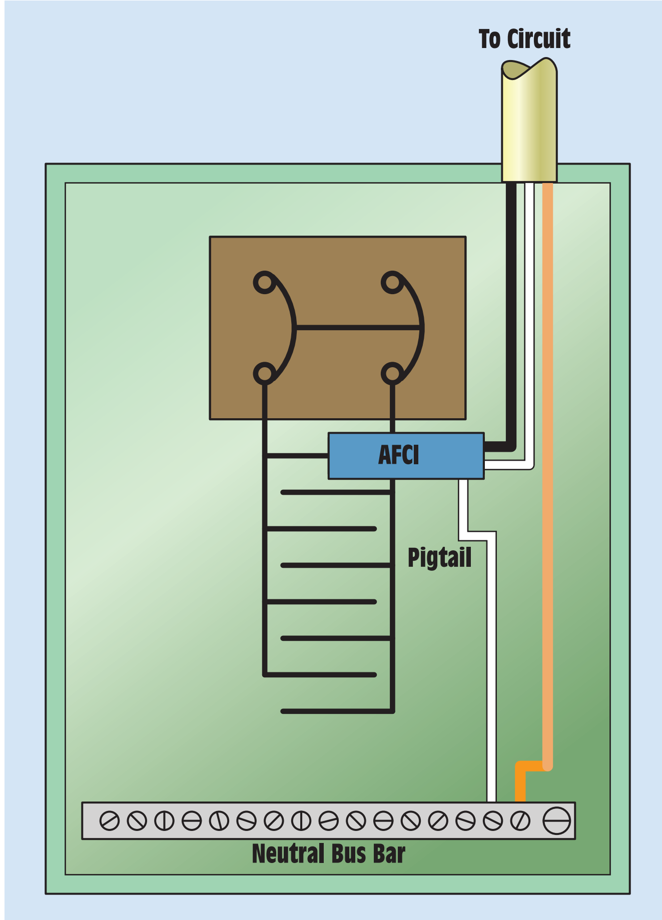

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FIGURE S–27 The arc-fault interrupter connects in the same manner as a ground-fault interrupter.

Connecting an Arc-Fault Circuit Interrupter

The AFCI is connected in the same manner as a ground fault circuit breaker. The AFCI contains a white pigtail *(Figure S–26)* that is connected to the neutral bus bar in the panel box. Both the neutral and hot or ungrounded conductors of the branch circuit are connected to the arc-fault circuit breaker. The circuit breaker contains a silver-colored and a brass-colored screw. The neutral or white wire of the branch circuit is inserted under the silver screw, and the black wire is inserted under the brass screw *(Figure S–27)*. A rocker switch located on the front of the AFCI permits the breaker to be tested for both short and arc condition. In addition to the manual test switch, the microprocessor performs a self-test about once every 10 minutes.

S–9 Grounding

Grounding is one the most important safety considerations in the electrical field. Grounding provides a low resistance path to ground to prevent conductive objects from existing at a high potential. Many electric appliances are provided with a three-wire cord. The third prong is connected to the case of the appliance and forces the case to exist at ground potential. If an ungrounded conductor comes in contact with the case, the grounding conductors conduct the current directly to ground. The third prong on a plug should never be cut off or defeated. Grounding requirements are far too numerous to list in this chapter, but *NEC 250* covers the requirements for the grounding of electrical systems.

Summary

- Never work on an **energized circuit** if the power can be **disconnected**.
- The most important rule of safety is to think.
- Avoid horseplay.
- Do not work alone.
- Work with one hand when possible.
- Learn first aid and CPR.
- A current of 100 to 200 milliamperes passing through the heart generally causes death.
- The mission of OSHA is to ensure safe and healthy workplaces in the United States.
- Avoid using alcohol and drugs in the workplace.
- Do not walk close to trenches unless it is necessary.
- Do not jump over trenches if it is possible to walk around them.
- Place barricades around trenches.
- Use ladders to enter and exit trenches.
- When working in confined spaces, an outside person should keep in constant contact with people inside the space.
- Lockout and tagout procedures are used to prevent someone from energizing a circuit by mistake.
- Scaffolds generally provide the safest elevated working platforms.

- The bottom of a straight ladder should be placed at a distance from the wall that is equal to one fourth the height of the ladder.
- Fires can be divided into four classes: Class A is common items such as wood and paper; Class B is grease, liquids, and gases; Class C is energized electric equipment; and Class D is metals.
- Ground-fault circuit interrupters are used to protect people from electric shock.
- GFCI protectors open the circuit when approximately 5 milliamperes of ground-fault current are sensed.
- Arc-fault interrupters protect against electrical fires by sensing an arc-fault condition. Arc-fault circuit interrupters employ a microprocessor to sense an arc-fault condition.
- *NEC 250* lists requirements for grounding electrical systems.

Review Questions

1. What is the most important rule of electrical safety?
2. Why should a person work with only one hand when possible?
3. What range of electric current generally causes death?
4. What is fibrillation of the heart?
5. What is the operating principle of a defibrillator?
6. Who is responsible for enforcing OSHA regulations?
7. What is the mission of OSHA?
8. What is an MSDS?
9. A padlock is used to lock out a piece of equipment. Who should have the key?
10. A ladder is used to reach the top of a building 16 feet tall. What distance should the bottom of the ladder be placed from the side of the building?
11. What is a ground fault?
12. What is the approximate current at which a ground-fault detector will open the circuit?
13. Name three devices used to provide ground-fault protection.
14. What type of fire is Class B?
15. What section of the *NEC* covers grounding?

Section 1	Identity of Material		
Trade Name	OATEY HEAVY DUTY CLEAR LO-VOC PVC CEMENT		
Product Numbers	31850, 31851, 31853, 31854		
Formula	PVC Resin in Solvent Solution		
Synonyms	PVC Plastic Pipe Cement		
Firm Name & Mailing Address	OATEY CO., 4700 West 160th Street, P.O. Box 35906 Cleveland, Ohio 44135, U.S.A. http://www.oatey.com		
Oatey Phone Number	1-216-267-7100		
Emergency Phone Numbers	For Emergency First Aid call 1-303-623-5716 COLLECT. For chemical transportation emergencies ONLY, call Chemtrec at 1-800-424-9300		
Prepared By	Charles N. Bush, Ph.D.		
Section 2	**Hazardous Ingredients**		
Ingredients	***%***	***Cas Number***	***Sec 313***
Acetone	0–5%	67-64-1	No
Amorphous Fumed Silica (Nonhazardous)	1–3%	112945-52-5	No
Proprietary (Nonhazardous)	5–15%	N/A	No
PVC Resin (Nonhazardous)	10–16%	9002-86-2	No
Cyclohexanone	5–15%	108-94-1	No
Tetrahydrofuran (See SECTION 11)	30–50%	109-99-9	No
Methyl Ethyl Ketone	20–35%	78-93-3	Yes

Section 3	Known Hazards Under U.S. 29 CFR 1910.1200				
Hazards	***Yes***	***No***	***Hazards***	***Yes***	***No***
Combustible Liquid		x	Skin Hazard	x	
Flammable Liquid	x		Eye Hazard	x	
Pyrophoric Material		x	Toxic Agent	x	
Explosive Material		x	Highly Toxic Agent		x
Unstable Material		x	Sensitizer		x

TABLE S–1 Heavy Duty Clear LO-VOC PVC Cement

Hazards	*Yes*	*No*	*Hazards*	*Yes*	*No*
Water Reactive Material		x	Kidney Toxin	x	
Oxidizer		x	Reproductive Toxin	x	
Organic Peroxide		x	Blood Toxin		x
Corrosive Material		x	Nervous System Toxin	x	
Compressed Gas		x	Lung Toxin	x	
Irritant	x		Liver Toxin	x	
Carcinogen NTP/IARC/ OSHA (see SECTION 11)		x			

Section 4	**Emergency and First Aid Procedures—Call 1-303-623-5716 Collect**
Skin	If irritation arises, wash thoroughly with soap and water. Seek medical attention if irritation persists. Remove dried cement with Oatey Plumber's Hand Cleaner or baby oil.
Eyes	If material gets into eyes or if fumes cause irritation, immediately flush eyes with water for 15 minutes. If irritation persists, seek medical attention.
Inhalation	Move to fresh air. If breathing is difficult, give oxygen. If not breathing, give artificial respiration. Keep victim quiet and warm. Call a poison control center or physician immediately. If respiratory irritation occurs and does not go away, seek medical attention.
Ingestion	**DO NOT INDUCE VOMITING.** This product may be aspirated into the lungs and cause chemical pneumonitis, a potentially fatal condition. Drink water and call a poison control center or physician immediately. Avoid alcoholic beverages. Never give anything by mouth to an unconscious person.
Section 5	**Fire Fighting Measures**
Precautions	Do not use or store near heat, sparks, or flames. Do not smoke when using. Vapors may accumulate in low places and may cause flash fires.
Special Fire Fighting Procedures	**FOR SMALL FIRES:** Use dry chemical, CO_2, water or foam extinguisher. **FOR LARGE FIRES:** Evacuate area and call Fire Department immediately.

TABLE S–1 Continued

Section 6	**Accidental Release Measures**			
Spill or Leak Procedures	Remove all sources of ignition and ventilate area. Stop leak if it can be done without risk. Personnel cleaning up the spill should wear appropriate personal protective equipment, including respirators if vapor concentrations are high. Soak up spill with absorbent material such as sand, earth or other noncombusting material. Put absorbent material in covered, labeled metal containers. Contaminated absorbent material may pose the same hazards as the spilled product. See Section 13 for disposal information.			
Section 7	**Handling and Storage**			
Precautions	**HANDLING & STORAGE:** Keep away from heat, sparks and flames; store in cool, dry place. **OTHER:** Containers, even empties, will retain residue and flammable vapors.			
Section 8	**Exposure Controls/Personal Protection**			
Protective Equipment Types	**EYES:** Safety glasses with side shields. **RESPIRATORY:** NIOSH-approved canister respirator in absence of adequate ventilation. **GLOVES:** Rubber gloves are suitable for normal use of the product. For long exposures to pure solvents, chemical-resistant gloves may be required. **OTHER:** Eye wash and safety shower should be available.			
Ventilation	**LOCAL EXHAUST:** Open doors & windows. Exhaust ventilation capable of maintaining emissions at the point of use below PEL. If used in enclosed area, use exhaust fans. Exhaust fans should be explosion-proof or set up in a way that flammable concentrations of solvent vapors are not exposed to electrical fixtures or hot surfaces.			
Section 9	**Physical and Chemical Properties**			
NFPA Hazard Signal	Health 2	Stability 1	Flammability 3	Special None
HMIS Hazard Signal	Health 3	Stability 1	Flammability 4	Special None
Boiling Point	151°F/66°C			
Melting Point	N/A			
Vapor Pressure	145 mmHg @ 20°C			

TABLE S–1 Continued

Vapor Density (Air = 1)	2.5
Volatile Components	70–80%
Solubility In Water	Negligible
PH	N/A
Specific Gravity	0.95 +/–0.015
Evaporation Rate	(BUAC = 1) = 5.5 – 8.0
Appearance	Clear Liquid
Odor	Ether-Like
Will Dissolve In	Tetrahydrofuran
Material Is	Liquid

Unit 1

Atomic Structure

OUTLINE

KEY TERMS

Alternating current (AC)
Atom
Atomic number
Attraction
Bidirectional
Conductor
Direct current (DC)
Electron
Electron orbit
Element
Insulators
Matter
Molecules
Negative
Neutron
Nucleus
Positive
Proton
Repulsion
Semiconductors
Unidirectional
Valence electrons

Why You Need to Know

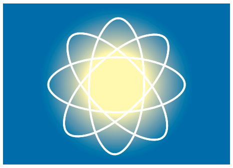
Atoms are the building blocks of the universe, and all matter is composed of them. One component of an atom is the electron, and all electrical quantities, such as voltage, current, and watts, are based on other electrical units that are derived from the measurement of electrons. A basic understanding of electron flow will remove the "mystery" of electricity and will start you on a path to a further understanding of electrical theory. This unit explains

- how electricity is produced and how those sources are divided in alternating current (AC) and direct current (DC) for utilization.
- why some materials are conductors and others are insulators.
- why a conductor becomes warm as a current flows through it.

Objectives

After studying this unit, you should be able to

- list the three principal parts of an atom.
- state the law of charges.
- discuss centripetal force.
- discuss the differences between conductors and insulators.



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Preview

Electricity is the driving force that provides most of the power for the industrialized world. It is used to light homes, cook meals, heat and cool buildings, drive motors, and supply the ignition for most automobiles. The technician who understands electricity can seek employment in almost any part of the world.

Electric sources are divided into two basic types, **direct current (DC)** and **alternating current (AC).** Direct current is **unidirectional,** which means that it flows in only one direction. The first part of this text is mainly devoted to the study of direct current. Alternating current is **bidirectional,** which means that it reverses its direction of flow at regular intervals. The latter part of this text is devoted mainly to the study of alternating current. ■

1–1 Early History of Electricity

Although the practical use of electricity has become common only within the last hundred years, it has been known as a force for much longer. The Greeks were the first to discover electricity about 2500 years ago. They noticed that when amber was rubbed with other materials, it became charged with an unknown force that had the power to attract objects such as dried leaves, feathers, bits of cloth, or other lightweight materials. The Greeks called amber *elektron*. The word *electric* was derived from it and meant "to be like amber," or to have the ability to attract other objects.

This mysterious force remained little more than a curious phenomenon until about 2000 years later, when other people began to conduct experiments. In the early 1600s, William Gilbert discovered that amber was not the only material that could be charged to attract other objects. He called materials that could be charged *electriks* and materials that could not be charged *nonelektriks*.

About 300 years ago, a few men began to study the behavior of various charged objects. In 1733, a Frenchman named Charles DuFay found that a piece of charged glass would repel some charged objects and attract others. These men soon learned that the force of **repulsion** was just as important as the force

LIST A	LIST B
Glass (rubbed on silk)	Hard rubber (rubbed on wool)
Glass (rubbed on wool or cotton)	Block of sulfur (rubbed on wool or fur)
Mica (rubbed on cloth)	Most kinds of rubber (rubbed on cloth)
Asbestos (rubbed on cloth or paper)	Sealing wax (rubbed on silk, wool, or fur)
Stick of sealing wax (rubbed on wool)	Mica (rubbed on dry wool)
	Amber (rubbed on cloth)

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FIGURE 1–1 List of charged materials.

of **attraction.** From these experiments, two lists were developed *(Figure 1–1)*. It was determined that any material in list A would attract any material in list B, that all materials in list A would repel each other, and that all materials in list B would repel each other *(Figure 1–2)*. Various names were suggested for the materials in lists A and B. Any opposite-sounding names could have been chosen, such as east and west, north and south, male and female. Benjamin

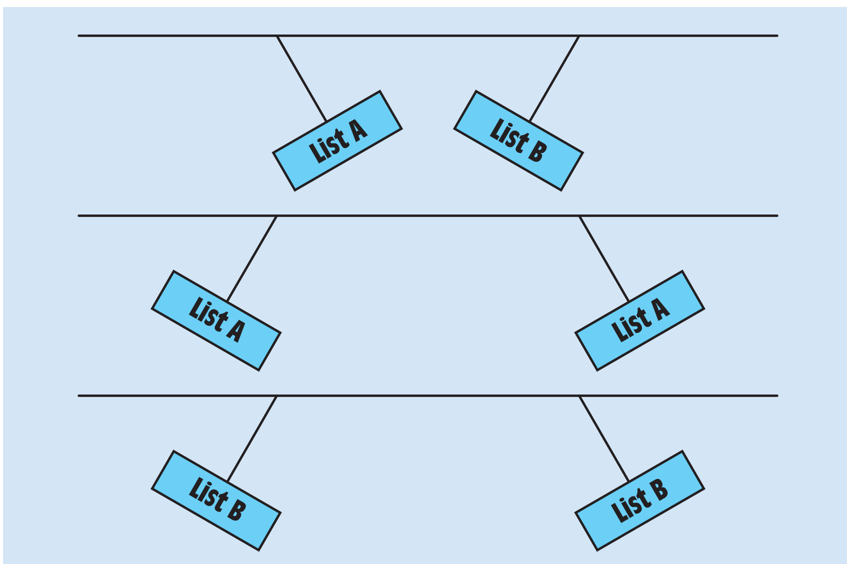

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FIGURE 1–2 Unlike charges attract and like charges repel.

Franklin named the materials in list A **positive** and the materials in list B **negative.** These names are still used today. The first item in each list was used as a standard for determining whether a charged object was positive or negative. Any object repelled by a piece of glass rubbed on silk would have a positive charge, and any item repelled by a hard rubber rod rubbed on wool would have a negative charge.

1–2 Atoms

Understanding electricity necessitates starting with the study of atoms. The **atom** is the basic building block of the universe. All **matter** is made from a combination of atoms. Matter is any substance that has mass and occupies space. Matter can exist in any of three states: solid, liquid, or gas. Water, for example, can exist as a solid in the form of ice, as a liquid, or as a gas in the form of steam *(Figure 1–3)*. An **element** is a substance that cannot be chemically divided into two or more simpler substances. A table listing both natural and artificial elements is shown in *Figure 1–4*. An atom is the smallest part of an element. The three principal parts of an atom are the **electron,** the **neutron,**

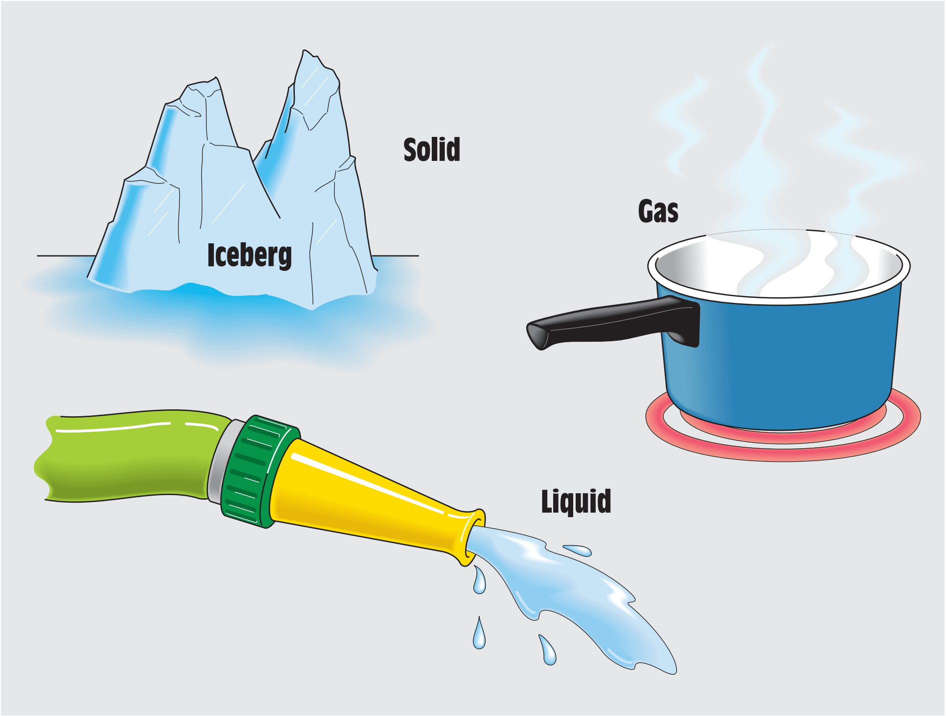

FIGURE 1–3 Water can exist in three states, depending on temperature and pressure.

ATOMIC NUMBER	NAME	VALENCE ELECTRONS	SYMBOL	ATOMIC NUMBER	NAME	VALENCE ELECTRONS	SYMBOL	ATOMIC NUMBER	NAME	VALENCE ELECTRONS	SYMBOL
1	Hydrogen	1	H	37	Rubidium	1	Rb	73	Tantalum	2	Ta
2	Helium	2	He	38	Strontium	2	Sr	74	Tungsten	2	W
3	Lithium	1	Li	39	Yttrium	2	Y	75	Rhenium	2	Re
4	Beryllum	2	Be	40	Zirconium	2	Zr	76	Osmium	2	Os
5	Boron	3	B	41	Niobium	1	Nb	77	Iridium	2	Ir
6	Carbon	4	C	42	Molybdenum	1	Mo	78	Platinum	1	Pt
7	Nitrogen	5	N	43	Technetium	2	Tc	79	Gold	1	Au
8	Oxygen	6	O	44	Ruthenium	1	Ru	80	Mercury	2	Hg
9	Fluorine	7	F	45	Rhodium	1	Rh	81	Thallium	3	Tl
10	Neon	8	Ne	46	Palladium	–	Pd	82	Lead	4	Pb
11	Sodium	1	Na	47	Silver	1	Ag	83	Bismuth	5	Bl
12	Magnesium	2	Ma	48	Cadmium	2	Cd	84	Polonium	6	Po
13	Aluminum	3	Al	49	Indium	3	In	85	Astatine	7	At
14	Silicon	4	Si	50	Tin	4	Sn	86	Radon	8	Rd
15	Phosphorus	5	P	51	Antimony	5	Sb	87	Francium	1	Fr
16	Sulfur	6	S	52	Tellurium	6	Te	88	Radium	2	Ra
17	Chlorine	7	Cl	53	Iodine	7	I	89	Actinium	2	Ac
18	Argon	8	A	54	Xenon	8	Xe	90	Thorium	2	Th
19	Potassium	1	K	55	Cesium	1	Cs	91	Protactinium	2	Pa
20	Calcium	2	Ca	56	Barium	2	Ba	92	Uranium	2	U
21	Scandium	2	Sc	57	Lanthanum	2	La				
22	Titanium	2	Ti	58	Cerium	2	Ce		Artificial Elements		
23	Vanadium	2	V	59	Praseodymium	2	Pr				
24	Chromium	1	Cr	60	Neodymium	2	Nd	93	Neptunium	2	Np
25	Manganese	2	Mn	61	Promethium	2	Pm	94	Plutonium	2	Pu
26	Iron	2	Fe	62	Samarium	2	Sm	95	Americium	2	Am
27	Cobalt	2	Co	63	Europium	2	Eu	96	Curium	2	Cm
28	Nickel	2	Ni	64	Gadolinium	2	Gd	97	Berkelium	2	Bk
29	Copper	1	Cu	65	Terbium	2	Tb	98	Californium	2	Cf
30	Zinc	2	Zn	66	Dysprosium	2	Dy	99	Einsteinium	2	E
31	Gallium	3	Ga	67	Holmium	2	Ho	100	Fermium	2	Fm
32	Germanium	4	Ge	68	Erbium	2	Er	101	Mendelevium	2	Mv
33	Arsenic	5	As	69	Thulium	2	Tm	102	Nobelium	2	No
34	Selenium	6	Se	70	Ytterbium	2	Yb	103	Lawrencium	2	Lw
35	Bromine	7	Br	71	Lutetium	2	Lu				
36	Krypton	8	Kr	72	Hafnium	2	Hf				

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FIGURE 1–4 Table of elements.

and the **proton.** Although most atoms contain these three principal parts, the smallest atom, hydrogen, does not contain a neutron *(Figure 1–5)*. Hydrogen contains one proton and one electron. The smallest atom that contains neutrons is helium *(Figure 1–6)*. Helium contains two protons, two neutrons, and two electrons. It is theorized that protons and neutrons are actually made of smaller particles called *quarks*.

Notice that the proton has a positive charge, the electron a negative charge, and the neutron no charge. The neutrons and the protons combine to form the **nucleus** of the atom. Because the neutron has no charge, the nucleus has a net positive charge. The number of protons in the nucleus determines what kind of element an atom is. Oxygen, for example, contains 8 protons in its nucleus, and gold contains 79. The **atomic number** of an element is the same as the number of protons in the nucleus. The lines of force produced by the positive charge of the proton extend outward in all directions *(Figure 1–7)*. The nucleus may or may not contain as many neutrons as protons. For example, an atom of helium contains 2 protons and 2 neutrons in its nucleus, whereas an atom of copper contains 29 protons and 35 neutrons *(Figure 1–8)*.

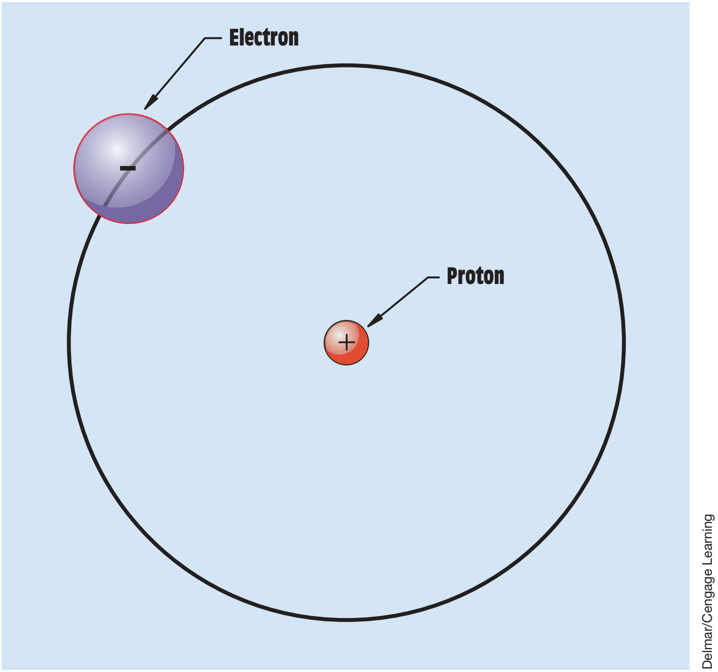

FIGURE 1–5 Hydrogen contains one proton and one electron.

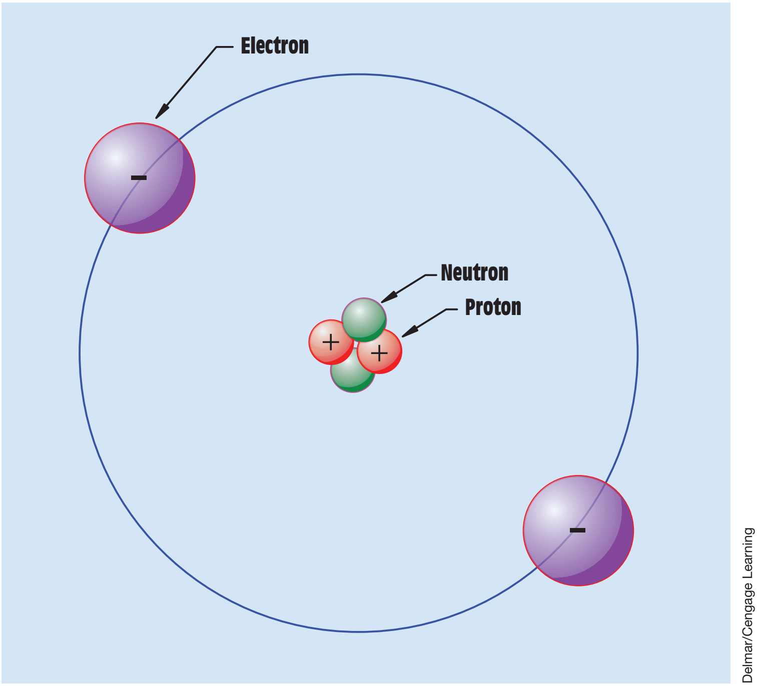

FIGURE 1–6 Helium contains two protons, two neutrons, and two electrons.

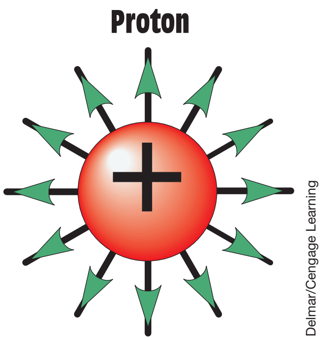

FIGURE 1–7 The lines of force extend outward.

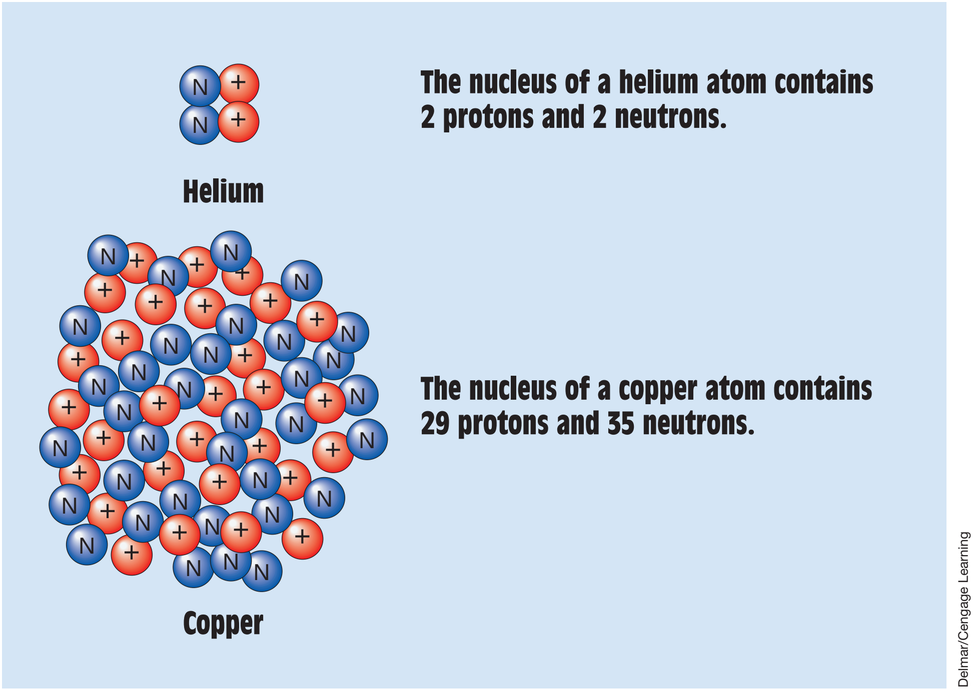

FIGURE 1–8 The nucleus may or may not contain the same number of protons and neutrons.

The electron orbits the outside of the nucleus. Notice in *Figure 1–5* that the electron is shown to be larger than the proton. Actually, an electron is about three times as large as a proton. The estimated size of a proton is 0.07 trillionth of an inch in diameter, and the estimated size of an electron is 0.22 trillionth of an inch in diameter. Although the electron is larger in size, the proton weighs about 1840 times more. Imagine comparing a soap bubble with a piece of buckshot. Compared with the electron, the proton is a very massive particle. Because the electron exhibits a negative charge, the lines of force come in from all directions *(Figure 1–9)*.

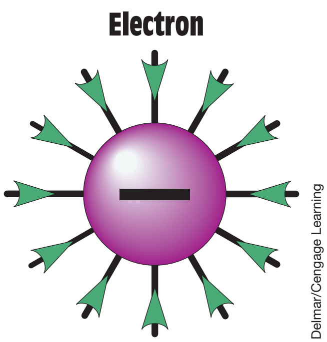

FIGURE 1–9 The lines of force come inward.

1–3 The Law of Charges

Understanding atoms necessitates first understanding a basic law of physics that states that ***opposite charges attract and like charges repel.*** In *Figure 1–10*, which illustrates this principle, charged balls are suspended from strings. Notice that the two balls that contain opposite charges are attracted to each other. The two positively charged balls and the two negatively charged balls repel each other. The reason for this is that lines of force can never cross each other. The outward-going lines of force of a positively charged object combine with the inward-going lines of force of a negatively charged object *(Figure 1–11)*. This combining produces an attraction between the two objects. If two objects with like charges come close to

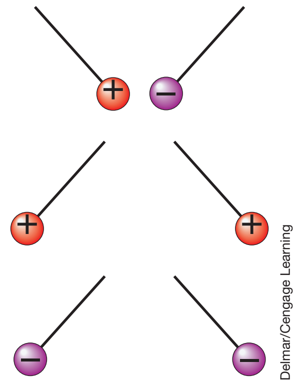

FIGURE 1–10 Unlike charges attract and like charges repel.

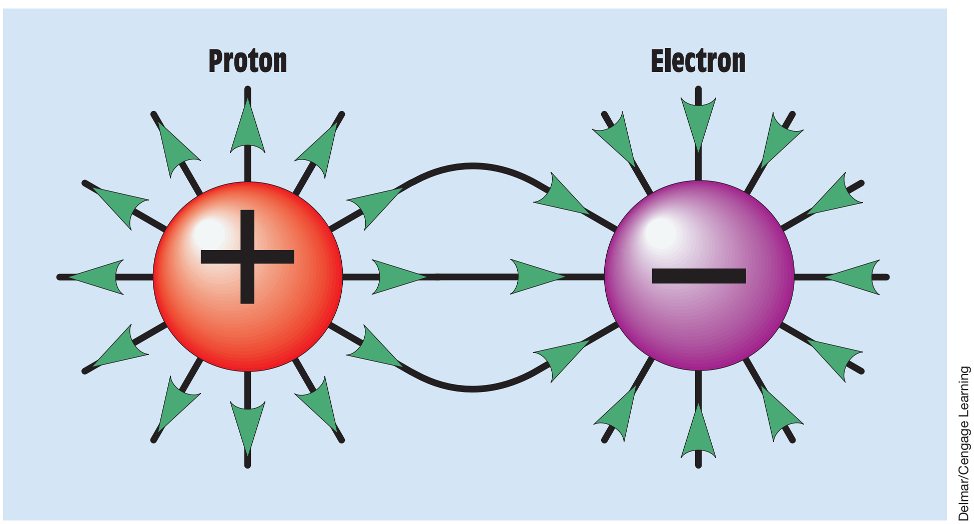

FIGURE 1–11 Unlike charges attract each other.

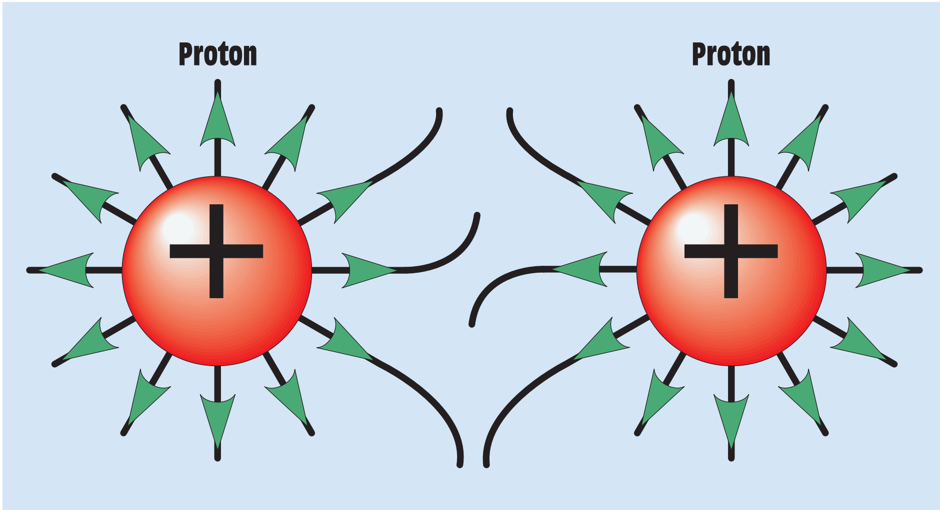

FIGURE 1–12 Like charges repel each other.

each other, the lines of force repel *(Figure 1–12)*. Because the nucleus has a net positive charge and the electron has a negative charge, the electron is attracted to the nucleus.

Because the nucleus of an atom is formed from the combination of protons and neutrons, one may ask why the protons of the nucleus do not repel each other because they all have the same charge. Two theories attempt to explain this. The first theory asserted that the force of gravity held the nucleus together. Neutrons, like protons, are extremely massive particles. It was first theorized that the gravitational attraction caused by their mass overcame the repelling force of the positive charges. By the mid-1930s, however, it was known that the force of gravity could not hold the nucleus together. According to Coulomb's law, the electromagnetic force in helium is about 1.1×10^{36} times greater than the gravitational force as determined by Newton's law. In 1947, the Japanese physicist Hideki Yukawa identified a subatomic particle that acts as a mediator to hold the nucleus together. The particle is a quark known as a *gluon*. The force of the gluon is about 10^2 times stronger than the electromagnetic force.

1–4 Structure of the Atom

In 1808, a scientist named John Dalton proposed that all matter was composed of atoms. Although the assumptions that Dalton used to prove his theory were later found to be factually incorrect, the idea that all matter is composed of atoms was adopted by most of the scientific world. Then in 1897, J.J. Thomson discovered the electron. Thomson determined that electrons have a negative charge and that they have very little mass compared to the atom. He proposed that atoms have a large positively charged massive body with negatively charged electrons scattered throughout it. Thomson also proposed that the negative charge of the electrons exactly balanced the positive charge of the large mass, causing the atom to have a net charge of zero. Thomson's model of the atom proposed that electrons existed in a random manner within the atom, much like firing BBs from a BB gun into a slab of cheese. This was referred to as the plum pudding model of the atom.

In 1913, a Danish scientist named Neils Bohr presented the most accepted theory concerning the structure of an atom. In the Bohr model, electrons exist in specific or "allowed" orbits around the nucleus in much the same way that planets orbit the Sun *(Figure 1–13)*. The orbit in which the electron exists is

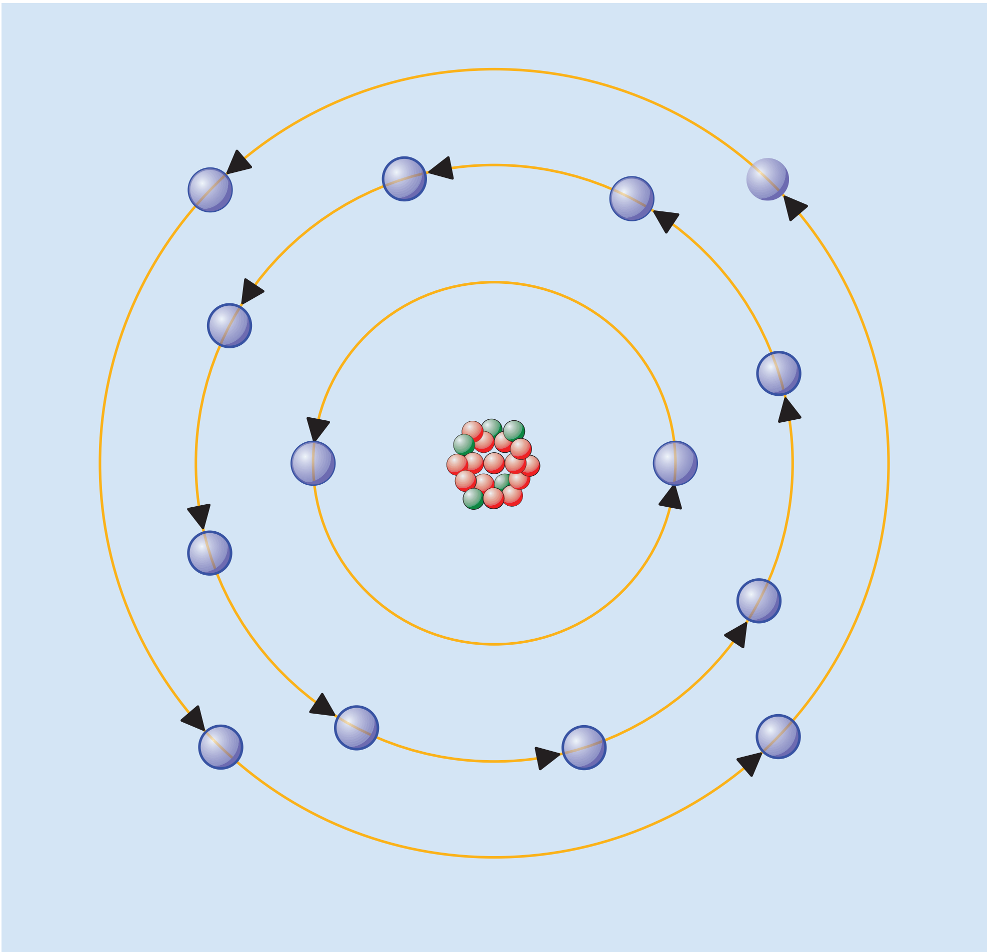

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FIGURE 1–13 Bohr's model of the atom proposed that electrons orbit the nucleus in much the same way that planets orbit the Sun.

determined by the electron's mass times its speed times the radius of the orbit. These factors must equal the positive force of the nucleus. In theory there can be an infinite number of allowed orbits.

When an electron receives enough energy from some other source, it "quantum jumps" into a higher allowed orbit. Electrons, however, tend to return to a lower allowed orbit. When this occurs, the electron emits the excess energy as a single photon of electromagnetic energy.

1–5 Electron Orbits

Each **electron orbit** of an atom contains a set number of electrons *(Figure 1–14)*. The number of electrons that can be contained in any one orbit, or shell, is found by the formula ($2N^2$). The letter *N* represents the number of the orbit, or shell. For example, the first orbit can hold no more than 2 electrons:

$$2 \times (1)^2 \text{ or}$$
$$2 \times 1 = 2$$

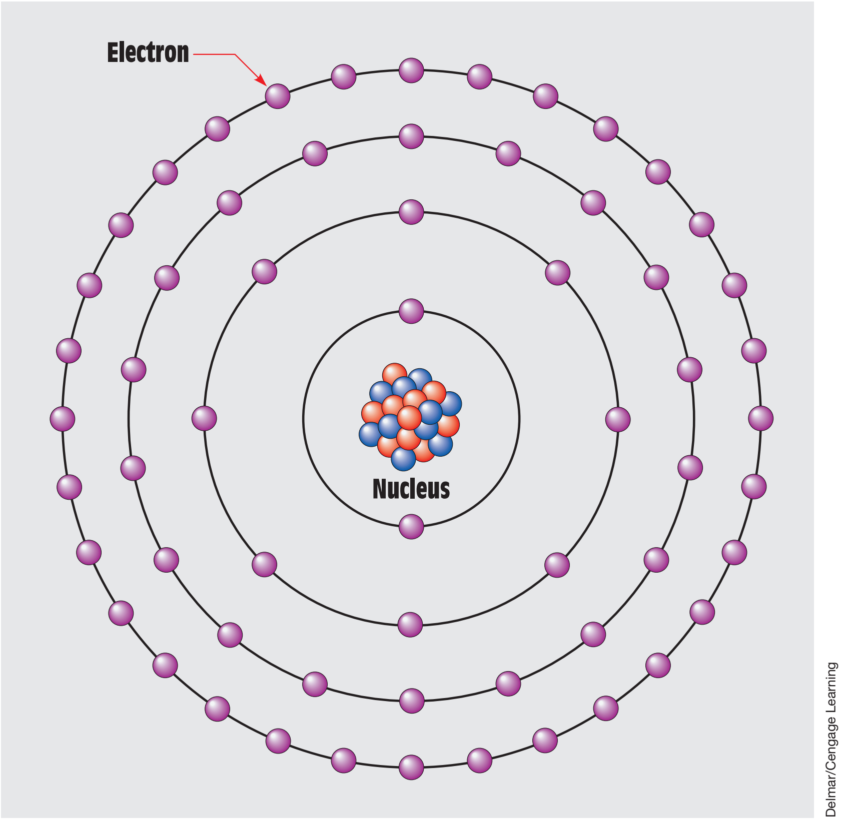

FIGURE 1–14 Electron orbits.

The second orbit can hold no more than 8 electrons:

$$2 \times (2)^2 \text{ or}$$
$$2 \times 4 = 8$$

The third orbit can contain no more than 18 electrons:

$$2 \times (3)^2 \text{ or}$$
$$2 \times 9 = 18$$

The fourth and fifth orbits cannot hold more than 32 electrons. Thirty-two is the maximum number of electrons that can be contained in any orbit:

$$2 \times (4)^2 \text{ or}$$
$$2 \times 16 = 32$$

Although atoms are often drawn flat, as illustrated in *Figure 1–14*, electrons orbit the nucleus in a spherical fashion, as shown in *Figure 1–15*. Electrons travel at such a high rate of speed that they form a shell around the nucleus. For this reason, electron orbits are often referred to as *shells*.

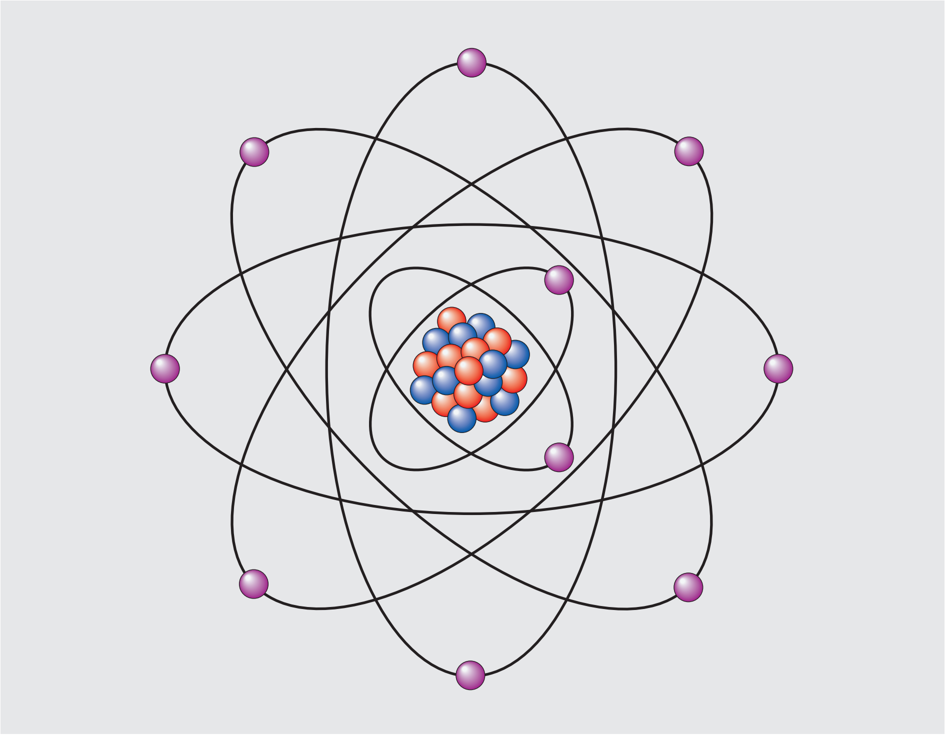

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FIGURE 1–15 Electrons orbit the nucleus in a circular fashion.

1–6 Valence Electrons

The outer shell of an atom is known as the *valence shell*. Any electrons located in the outer shell of an atom are known as **valence electrons** *(Figure 1–16)*. The valence shell of an atom cannot hold more than eight electrons. The valence electrons are of primary concern in the study of electricity because these electrons explain much of electrical theory. A **conductor,** for instance, is made from a material that contains between one and three valence electrons. Atoms with one, two, or three valence electrons are unstable and can be made to give up these electrons with little effort. Conductors are materials that permit electrons to flow through them easily. When an atom has only one or two valence electrons, these electrons are loosely held by the atom and are easily given up for current flow. Silver, copper, and gold all contain one valence electron and are excellent conductors of electricity. Silver is the best natural conductor of electricity, followed by copper, gold, and

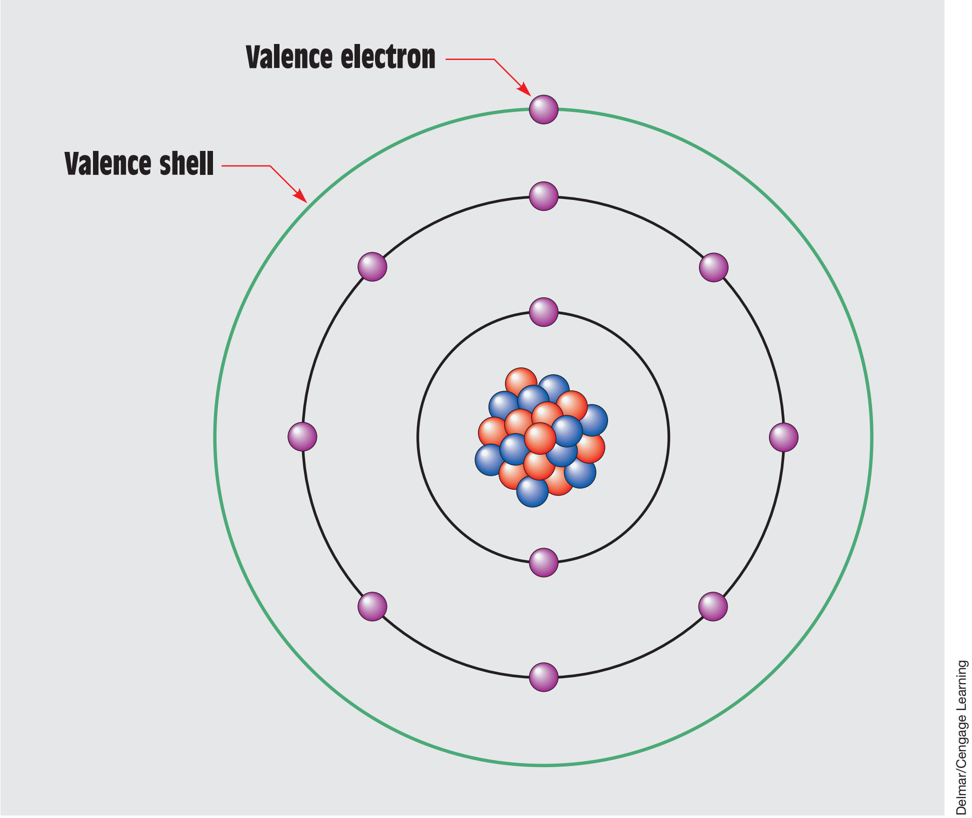

FIGURE 1–16 The electrons located in the outer orbit of an atom are valence electrons.

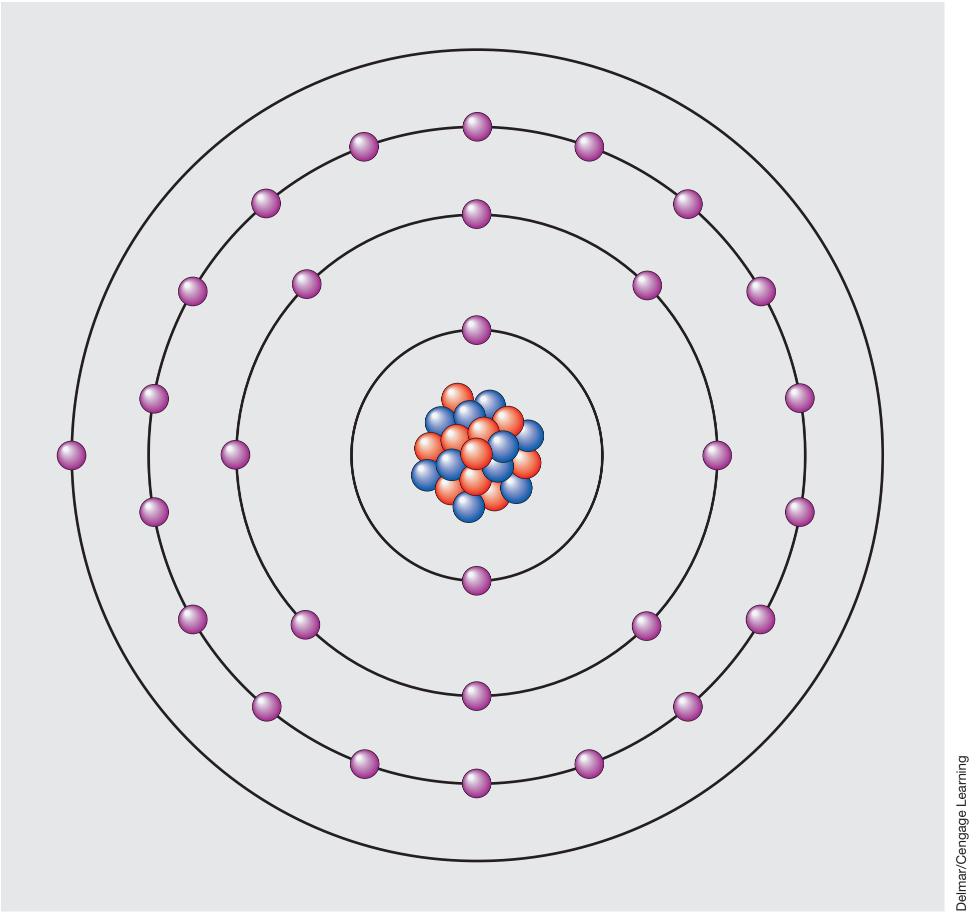

FIGURE 1–17 A copper atom contains 29 electrons and has 1 valence electron.

aluminum. An atom of copper is shown in *Figure 1–17*. Although it is known that atoms containing few valence electrons are the best conductors, it is not known why some of these materials are better conductors than others. Copper, gold, platinum, and silver all contain only one valence electron. Silver, however, conducts electricity more readily than any of the others. Aluminum, which contains three valence electrons, is a better conductor than platinum, which contains only one valence electron.

1–7 Electron Flow

Electrical current is the flow of electrons. There are several theories concerning how electrons are made to flow through a conductor. One theory is generally referred to as the *bump theory*. It states that current flow is produced when an

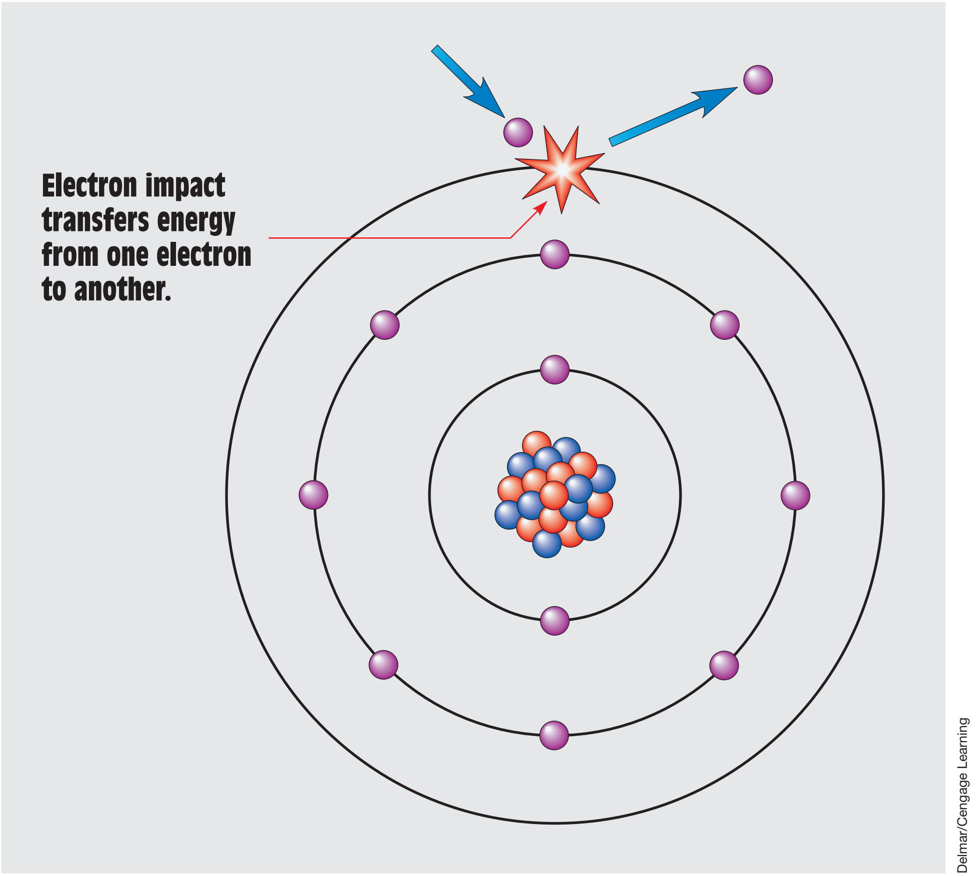

FIGURE 1–18 An electron of one atom knocks an electron of another atom out of orbit.

electron from one atom knocks electrons of another atom out of orbit. *Figure 1–18* illustrates this action. When an atom contains only one valence electron, that electron is easily given up when struck by another electron. The striking electron gives its energy to the electron being struck. The striking electron may settle into orbit around the atom, and the electron that was struck moves off to strike another electron. This same effect can be seen in the game of pool. If the moving cue ball strikes a stationary ball exactly right, the energy of the cue ball is given to the stationary ball. The stationary ball then moves off with the cue ball's energy, and the cue ball stops moving *(Figure 1–19)*. The additional energy causes the electron to move out of orbit and become a free electron. After traveling a short distance, the electron enters the valence orbit of a different atom. When it returns to orbit, some or all of the gained energy is released in the form of heat, which is why conductors become warm when

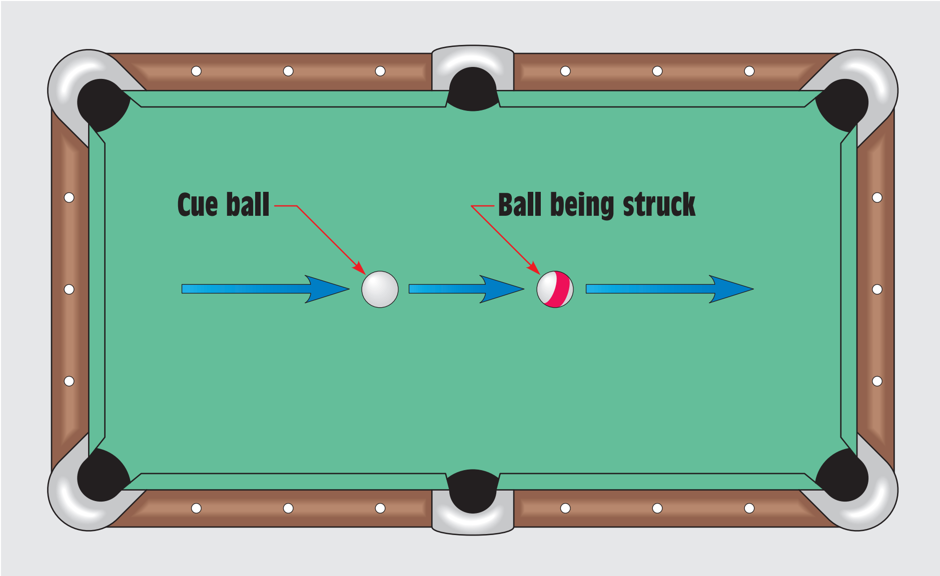

FIGURE 1–19 The energy of the cue ball is given to the ball being struck.

current flows through them. If too much current flows in a conductor, it may become hot enough to cause a fire.

If an atom containing two valence electrons is struck by a moving electron, the energy of the striking electron is divided between the two valence electrons *(Figure 1–20)*. If the valence electrons are knocked out of orbit, they contain only half the energy of the striking electron. This effect can also be seen in the game of pool *(Figure 1–21)*. If a moving cue ball strikes two stationary balls at the same time, the energy of the cue ball is divided between the two stationary balls. Both stationary balls will move but with only half the energy of the cue ball.

Other theories deal with the fact that all electric power sources produce a positive terminal and a negative terminal. The negative terminal is created by causing an excess of electrons to form at that terminal, and the positive terminal is created by removing a large number of electrons from that terminal *(Figure 1–22)*. Different methods can be employed to produce the excess of electrons at one terminal and deficiency of electrons at the other, but when a circuit is completed between the two terminals, negative electrons are repelled away from the negative terminal and attracted to the positive *(Figure 1–23)*. The greater the difference in the number of electrons between the negative and positive terminals, the greater the force of repulsion and attraction.

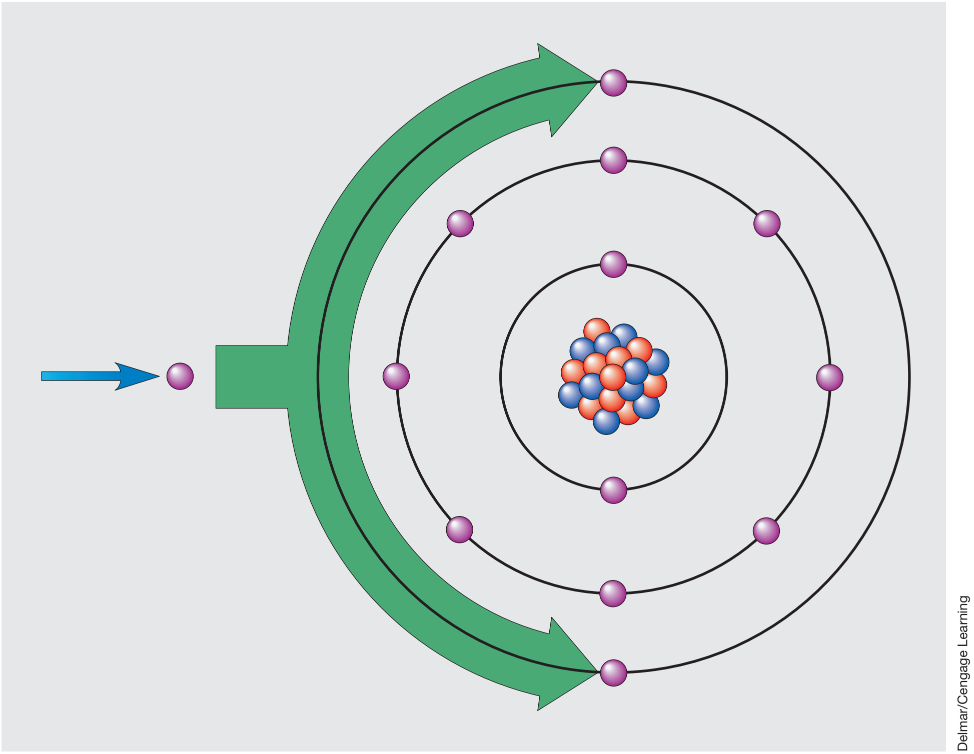

FIGURE 1–20 The energy of the striking electron is divided.

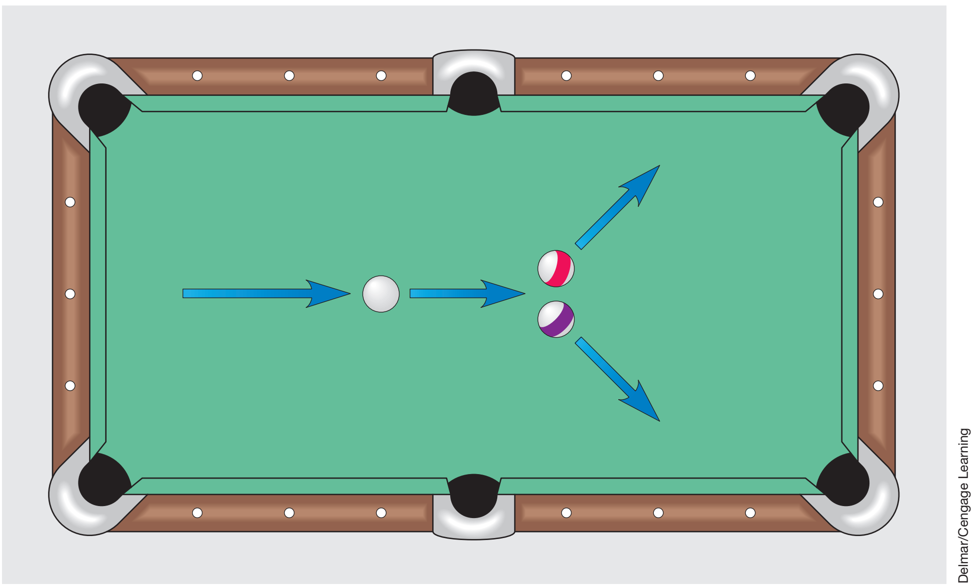

FIGURE 1–21 The energy of the cue ball is divided between the two other balls.

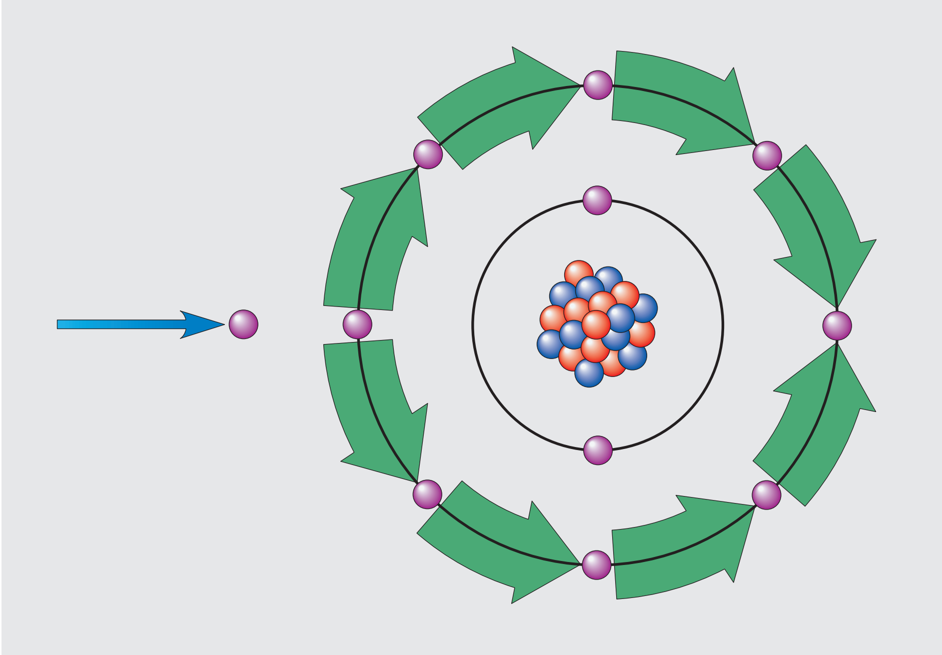

FIGURE 1–24 The energy of the striking electron is divided among the eight electrons.

1–8 Insulators

Materials containing seven or eight valence electrons are known as **insulators.** Insulators are materials that resist the flow of electricity. When the valence shell of an atom is full or almost full, the electrons are held tightly and are not given up easily. Some good examples of insulator materials are rubber, plastic, glass, and wood. *Figure 1–24* illustrates what happens when a moving electron strikes an atom containing eight valence electrons. The energy of the moving electron is divided so many times that it has little effect on the atom. Any atom that has seven or eight valence electrons is extremely stable and does not easily give up an electron.

1–9 Semiconductors

Semiconductors are materials that are neither good conductors nor good insulators. They contain four valence electrons *(Figure 1–25)* and are characterized by the fact that as they are heated, their resistance decreases. Heat has the opposite effect on conductors, whose resistance *increases* with an

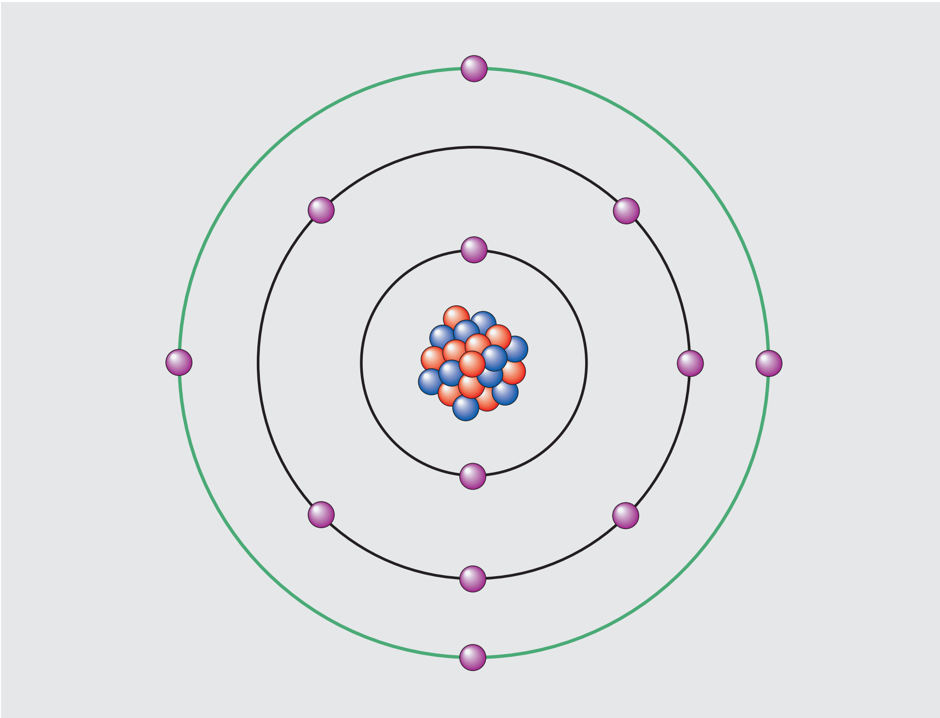

FIGURE 1–25 Semiconductors contain four valence electrons.

increase of temperature. Semiconductors have become extremely important in the electrical industry since the invention of the transistor in 1947. All solid-state devices such as diodes, transistors, and integrated circuits are made from combinations of semiconductor materials. The two most common materials used in the production of electronic components are silicon and germanium. Of the two, silicon is used more often because of its ability to withstand heat. Before any pure semiconductor can be used to construct an electronic device, it must be mixed or "doped" with an impurity.

1–10 Molecules

Although all matter is made from atoms, atoms should not be confused with **molecules,** which are the smallest part of a compound. Water, for example, is a compound, not an element. The smallest particle of water is a molecule made of two atoms of hydrogen and one atom of oxygen, H_2O *(Figure 1–26)*. If the molecule of water is broken apart, it becomes two hydrogen atoms and one oxygen atom and is no longer water.

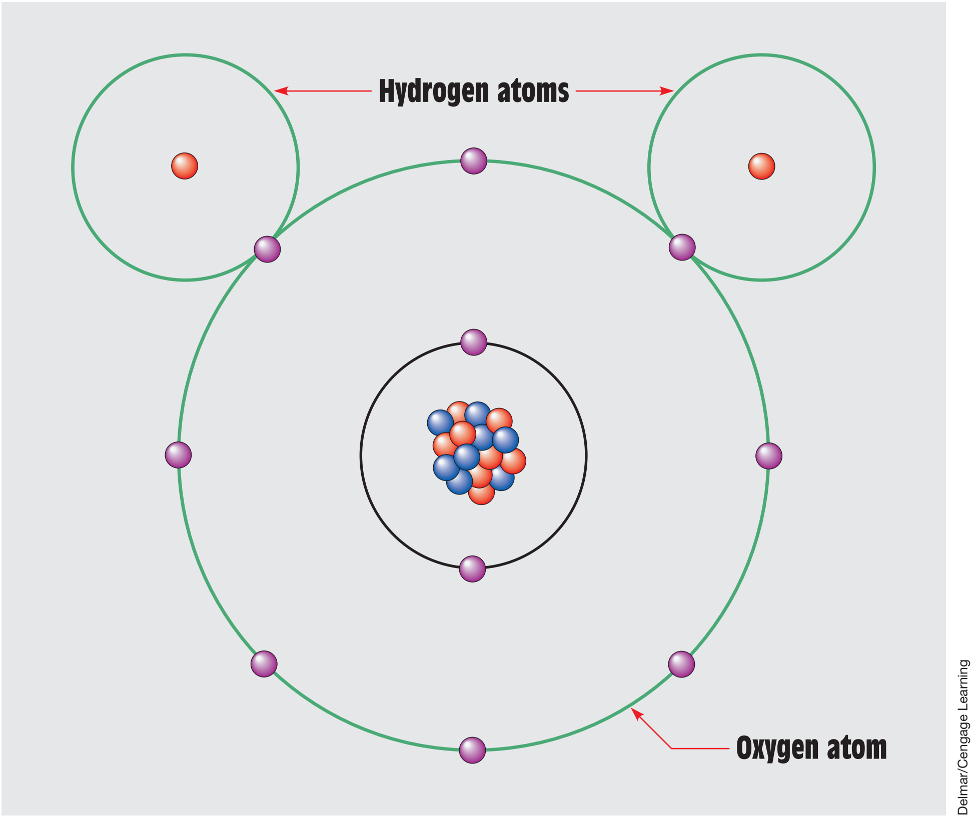

FIGURE 1–26 A water molecule.

1–11 Methods of Producing Electricity

So far in this unit, it has been discussed that electricity is a flow of electrons. There are six basic methods for producing electricity:

1. Magnetism
2. Chemical action
3. Pressure
4. Heat
5. Friction
6. Light

Of the six methods listed, magnetism is the most common method used to produce electricity. Electromagnetic induction is the operating principle of all generators and alternators. These principles are covered fully later in this text.

The second most common method of producing electricity is chemical action. The chemical production of electricity involves the movement of entire ions instead of just electrons. The principles of conduction in liquids are discussed in Unit 12 and Unit 13.

The production of electricity by pressure involves the striking, bending, or twisting of certain crystals. This effect is referred to as the *piezo* electric effect. The word *piezo* is derived from a Greek word meaning "pressure."

Producing electricity with heat is referred to as the *Seebeck* effect. The Seebeck effect is the operating principle of thermocouples. Thermocouples are discussed in Unit 13.

Static charges are probably the best example of producing electricity by friction. A static charge occurs when certain materials are rubbed together and electrons are transferred from one object to the other. Static electricity is discussed in Unit 3.

Producing electricity from light involves the use of particles called *photons*. In theory, photons are massless particles of pure energy. Photons can be produced when electrons are forced to change to a lower energy level. This is the operating principle of gas-filled lights such as sodium vapor, mercury vapor, and so on. Electricity can be produced by photons when they strike a semiconductor material. The energy of the photon is given to an electron, forcing it to move out of orbit. This is the operating principle of *photovoltaic* devices called *solar cells*. Solar cells are discussed in Unit 13. Other photo-operated devices are *photoemissive* and *photoconductive*. Photoemissive devices include photodiodes, phototransistors, photoSCRs, and so on. These devices are generally used to sense light when the speed of operation is imperative. Photoconductive devices change resistance with a change of light. The most common photoconductive device is the cad cell *(Figure 1–27)*. Cad cells exhibit a resistance

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FIGURE 1–27 Cad cell.

of about 50 ohms (Ω) in direct sunlight and several hundred thousand ohms in darkness.

1–12 Electrical Effects

With the exception of friction, electricity can be used to cause the same effects that produce it:

1. Magnetism
2. Chemical reactions
3. Pressure
4. Heat
5. Light

Anytime an electric current flows through a conductor, a magnetic field is created around the conductor. This principle is discussed in Unit 4.

Electricity can be used to produce certain chemical reactions, such as electroplating. Electroplating is accomplished by placing a base metal and a pure metal in a chemical solution. An object can be copper plated, for example, by placing a base metal object and a piece of pure copper in a solution of cuprous cyanide. The object to be plated is connected to the negative electrode, and the pure copper is connected to the positive electrode. Atoms of copper are transferred through the solution and deposited on the object to be plated.

Another example of electricity producing chemical reactions can be seen in the process of *electrolysis*. Electrolysis is the process of separating elements electrically. These principles are discussed in Unit 12.

Just as the twisting or bending of certain crystals can produce electricity, electricity can cause certain crystals to bend or twist. When electricity is applied to a certain size and shape of quartz crystal, the crystal vibrates at a certain rate. This principle has been used in crystal radios for many years. If an electric current is applied to a piece of Rochelle salt crystal, the crystal vibrates. This is the operating principle of a crystal earphone *(Figure 1–28)*.

As discussed previously in this unit, when electrons enter a valence orbit, heat is often produced. This is the reason that conductors become warm as current flows through them. This is also the operating principle of many heat-producing devices such as electric ranges, electric irons, electric heaters, and so on.

Light is produced when electrons move to a lower orbit and produce a photon. When electric current is applied to certain conductors, they not only become hot, but they also emit photons of light. Incandescent lamps use this principle of operation. When electric current is applied to the filament of an incandescent lamp, most of the electrical energy is converted into heat, but part of it produces photons of light. Incandescent lamps, however, are very

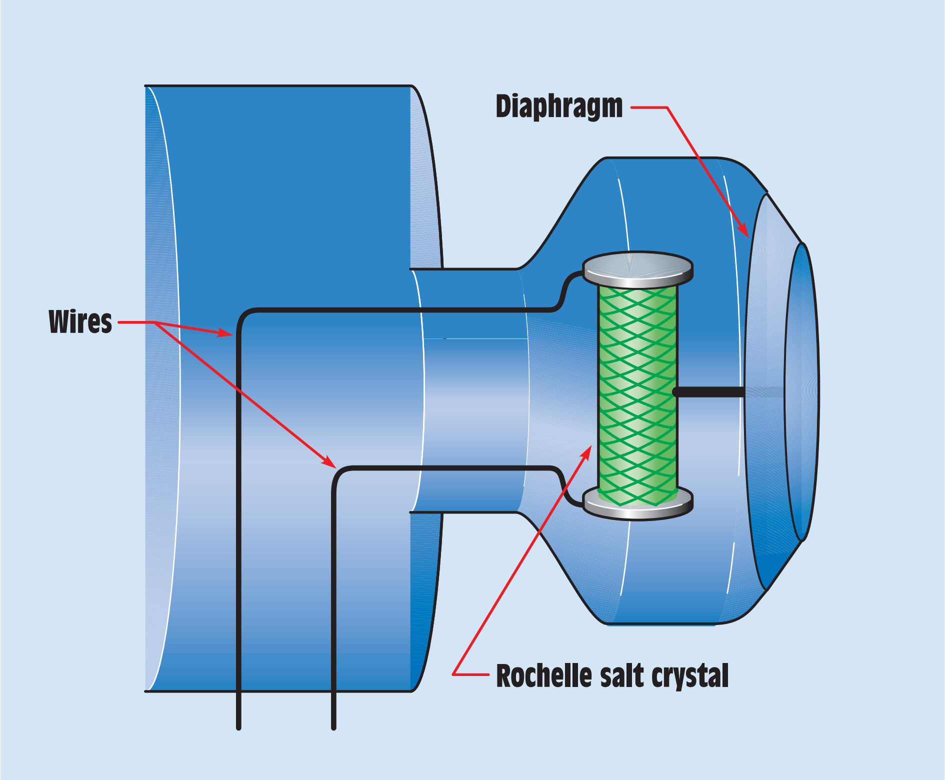

FIGURE 1–28 Producing sound with electricity.

inefficient. The typical 100-watt lamp produces about 95 watts of heat and 5 watts of light. Other lighting sources such as sodium vapor, mercury vapor, and fluorescent are much more efficient. Some semiconductor devices can be used to produce light without heat. Light-emitting diodes are a good example of these devices.

Summary

- The atom is the smallest part of an element.
- The three principal parts of an atom are the proton, the electron, and the neutron.
- Protons have a positive charge, electrons a negative charge, and neutrons no charge.
- Valence electrons are located in the outer orbit of an atom.
- Conductors are materials that provide an easy path for electron flow.

- Conductors are made from materials that contain from one to three valence electrons.
- Insulators are materials that do not provide an easy path for the flow of electrons.
- Insulators are generally made from materials containing seven or eight valence electrons.
- Semiconductors contain four valence electrons.
- Semiconductors are used in the construction of all solid-state devices such as diodes, transistors, and integrated circuits.
- A molecule is the smallest part of a compound.
- Six basic methods for producing electricity are magnetism, chemical action, light, heat, pressure, and friction.
- Five basic effects that can be caused by electricity are magnetism, chemical reactions, light, heat, and pressure.
- A photon is a massless particle of pure energy.
- Photons can be produced when electrons move from one energy level to another.

Review Questions

1. What are the three principal parts of an atom, and what charge does each carry?
2. How many times larger is an electron than a proton?
3. How many times more does a proton weigh than an electron?
4. State the law of charges.
5. What force keeps an electron in orbit around the nucleus of an atom?
6. How many valence electrons are generally contained in materials used for conductors?
7. How many valence electrons are generally contained in materials used for insulators?
8. What is electricity?
9. What is a gluon?
10. It is theorized that protons and neutrons are actually formed from a combination of smaller particles. What are these particles called?

Unit 2

Electrical Quantities and Ohm's Law

OUTLINE

KEY TERMS

Ampere (A)
British thermal unit (Btu)
Complete path
Conventional current flow theory
Coulomb (C)
Electromotive force (EMF)
Electron flow theory
Grounding conductor
Horsepower (hp)
Impedance
Joule
Neutral conductor
Ohm (Ω)
Ohm's law
Potential difference
Power
Resistance
Volt (V)
Watt (W)

Why You Need to Know

Anyone working in the electrical field must know and understand the basic units used to measure electric power. To accomplish this, it is important to understand how electricity works and is evaluated. In order to work with electric components and control devices in the field, you must know the electrical measuring terms and how to apply these terms. This unit presents

- the difference between voltage and current. You will discover, for example, that voltage is actually the force that pushes the electrons through a conductor. Voltage cannot flow, but it can cause current to flow.
- current. This is a quantity of electrons moving through a conductor within a certain length of time. Current, or amperes, is the actual amount of electricity that flows through the circuit. If it were possible to cut a wire and catch electricity in a container, you would have a container full of electrons.
- watts. This is a measure of power. It is basically the rate at which electrical energy is being converted into some other form. It is also the measurement used by the power company to charge its customers for the amount of energy consumed.
- Ohm's law. This is the basis for all electrical calculations. Ohm's law is a method of mathematically determining electrical quantities when other quantities are known. It is possible, for example, to determine the amount of current that will flow in a circuit if the resistance in the circuit and the voltage applied to it are known.
- a discussion of the similarity of electricity and water systems.

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Objectives

After studying this unit, you should be able to

- define a coulomb.
- define an ampere.
- define a volt.
- define an ohm.
- define a watt.
- calculate different electrical values using Ohm's law.
- discuss different types of electric circuits.
- select the proper Ohm's law formula from a chart.

Preview

Electricity has a standard set of values. Before one can work with electricity, one must know these values and how to use them. Because the values of electrical measurement have been standardized, they are understood by everyone who uses them. For instance, carpenters use a standard system for measuring length, such as the inch, foot, meter, or centimeter. Imagine what a house would look like that was constructed by two carpenters who used different lengths of measure for an inch or foot. The same holds true for people who work with electricity. The standards of measurement must be the same for everyone. Meters should be calibrated to indicate the same quantity of current flow or voltage or resistance. A volt, an ampere, or an ohm is the same everywhere in the world. ■

2–1 The Coulomb

A **coulomb** is a quantity measurement for electrons. One coulomb contains 6.25×10^{18}, or 6,250,000,000,000,000,000 electrons. To better understand the number of electrons contained in a coulomb, think of comparing one second to 200 billion years. Because the coulomb is a quantity measurement, it is similar to a quart, a gallon, or a liter. It takes a certain amount of liquid to equal a liter, just as it takes a certain amount of electrons to equal a coulomb.

The coulomb is named for a French scientist who lived in the 1700s named Charles Augustin de Coulomb. Coulomb experimented with electrostatic charges and developed a law dealing with the attraction and repulsion of these forces. The law, known as ***Coulomb's law of electrostatic charges, states that the force of electrostatic attraction or repulsion is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.*** The number of electrons contained in the coulomb was determined by the average charge of an electron. The symbol for coulomb is the letter *C*. It is the System Internationale (SI) unit of electric charge. A coulomb is defined as the charge transferred by a current of 1 ampere in one second.

2–2 The Ampere

The **ampere** is named for André Ampère, a scientist who lived from the late 1700s to the early 1800s. Ampère is most famous for his work dealing with electromagnetism, which is discussed in a later unit. The ampere (A) is equal to 1 coulomb per second. Notice that the definition of an ampere involves a quantity measurement, the coulomb, and a time measurement, the second. One ampere of current flows through a wire when 1 coulomb flows past a point in one second *(Figure 2–1)*. The ampere is a measurement of the amount of electricity that is flowing through a circuit. In a water system, it would be comparable to gallons per minute or gallons per second *(Figure 2–2)*. The letter *I*, which stands for intensity of current, and the letter *A,* which stands for ampere, are both used to represent current flow in algebraic formulas. This text uses the letter *I* in formulas to represent current.

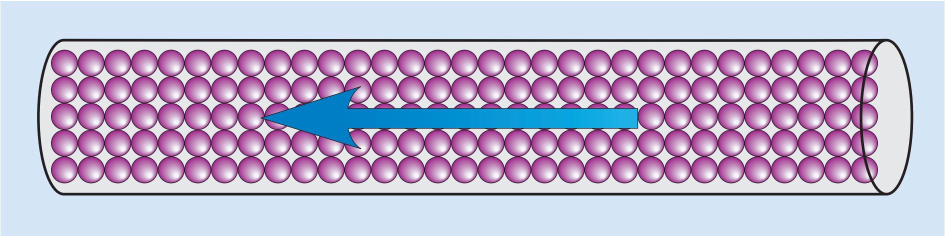

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FIGURE 2–1 One ampere equals one coulomb per second.

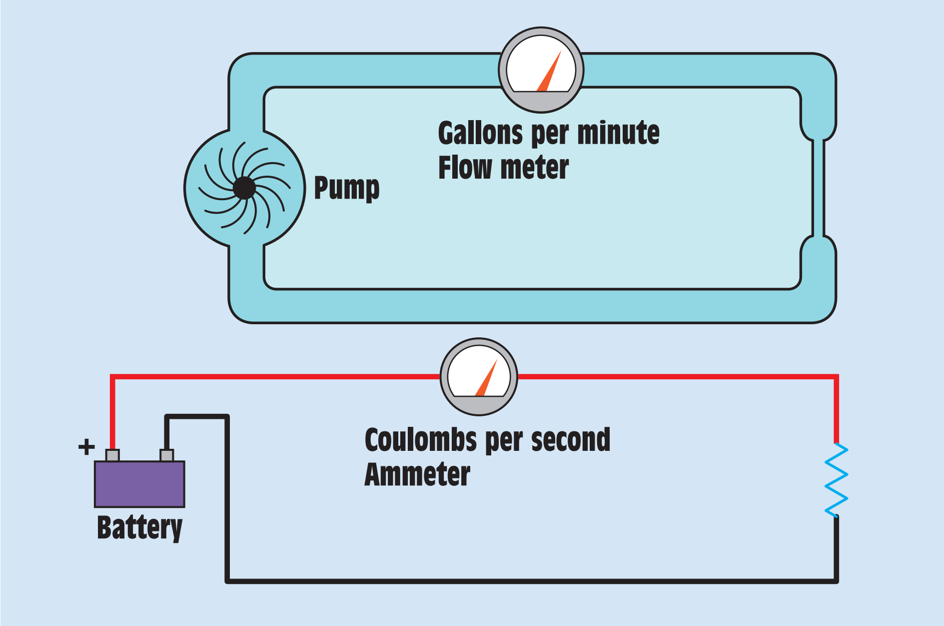

FIGURE 2–2 Current in an electric circuit can be compared to flow rate in a water system.

2–3 The Electron Flow Theory

There are actually two theories concerning current flow. One theory is known as the **electron flow theory** and states that because electrons are negative particles, current flows from the most negative point in the circuit to the most positive. The electron flow theory is the more widely accepted as being correct and is used throughout this text.

2–4 The Conventional Current Flow Theory

The second theory, known as the **conventional current flow theory,** is older than the electron flow theory and states that current flows from the most positive point to the most negative. Although it has been established almost to a certainty that the electron flow theory is correct, the conventional current flow theory is still widely used for several reasons. Most electronic circuits use the negative terminal as ground or common. When the negative terminal is used as ground, the positive terminal is considered to be above ground, or hot. It is easier for most people to think of something flowing down rather than up, or from a point above ground to

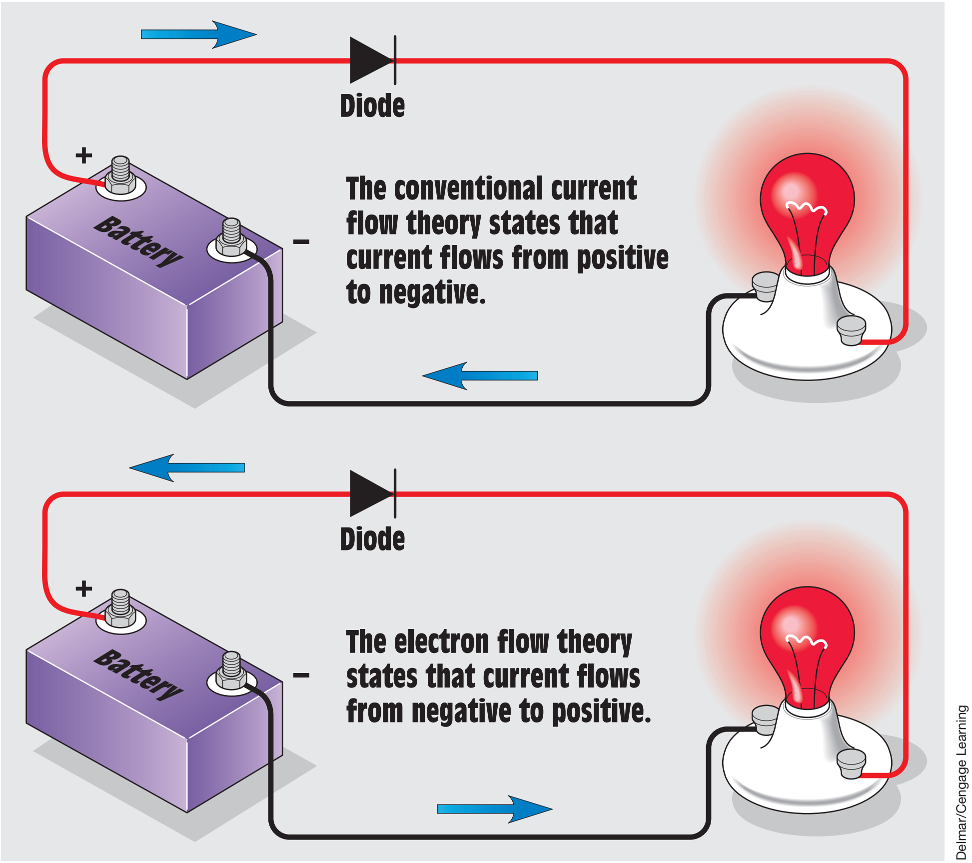

FIGURE 2–3 Conventional current flow theory and electron flow theory.

ground. An automobile electric system is a good example of this type of circuit. Most people consider the positive battery terminal to be the hot terminal.

Many people who work in the electronics field prefer the conventional current flow theory because all the arrows on the semiconductor symbols point in the direction of conventional current flow. If the electron flow theory is used, it must be assumed that current flows against the arrow *(Figure 2–3)*. Another reason that many people prefer using the conventional current flow theory is that most electronic schematics are drawn in a manner that assumes that current flows from the more positive to the more negative source. In *Figure 2–4,* the positive voltage point is shown at the top of the schematic and the negative (ground) is shown at the bottom. When tracing the flow of current through a circuit, most people find it easier to go from top to bottom than from bottom to top.

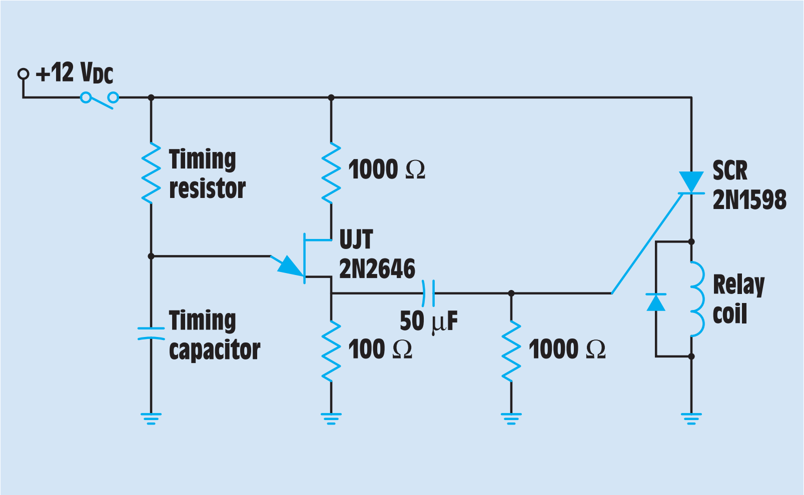

FIGURE 2–4 On-delay timer.

2–5 Speed of Current

To determine the speed of current flow through a wire, one must first establish exactly what is being measured. As stated previously, current is a flow of electrons through a conductive substance. Assume for a moment that it is possible to remove a single electron from a wire and identify it by painting it red. If it were possible to observe the progress of the identified electron as it moved from atom to atom, it would be seen that a single electron moves rather slowly *(Figure 2–5)*. It is estimated that a single electron moves at a rate of about 3 inches per hour at 1 ampere of current flow.

Another factor that must be considered is whether the circuit is DC, AC, or radio waves. Radio waves move at approximately the speed of light, which is

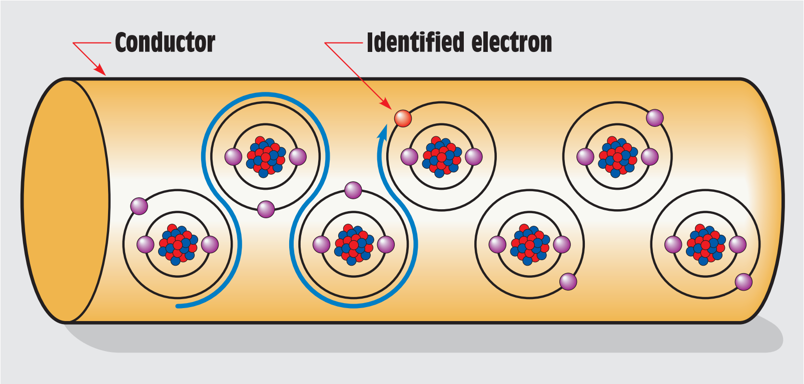

FIGURE 2–5 Electrons moving from atom to atom.

186,000 miles per second or 300,000,000 meters per second. The velocity of AC through a conductor is less than the speed of light because magnetic fields travel more slowly in material dielectrics than they do through free air. The formula shown can be used to calculate the wavelength of a signal traveling through a conductor. Wavelength is the distance that current travels during one AC cycle. Wavelength is discussed more fully in Unit 15.

$$L = \frac{984\ V}{f}$$

where

L = length in feet
V = velocity factor
f = frequency in megahertz (MHz)

The velocity factor is determined by the type of conductor. *Table 2–1* gives the velocity factor for several different types of coaxial cables and parallel conductors.

How many feet would a 5-MHz signal travel through a conductor with a velocity factor of 0.66 during one AC cycle?

$$L = \frac{984 \times 0.66}{5}$$

$$L = 129.888 \text{ feet}$$

Description or Type Number	Velocity Factor	Characteristic Impedance	Capacitance per Foot
Coaxial Cable			
RG–8A/U	0.66	53	29.5 pF
RG–58A/U	0.66	53	28.5 pF
RG–17A/U	0.66	50	30 pF
RG–11A/U	0.66	75	20.5 pF
RG59A/U	0.66	73	21 pF
Parallel Conductors			
Air Insulated	0.975	200–600	—
214–023	0.71	75	20 pF
214–056	0.82	300	5.8 pF
214–076	0.84	300	3.9 pF
214–022	0.85	300	3 pF

TABLE 2–1 Data for Different Types of Transmission Lines

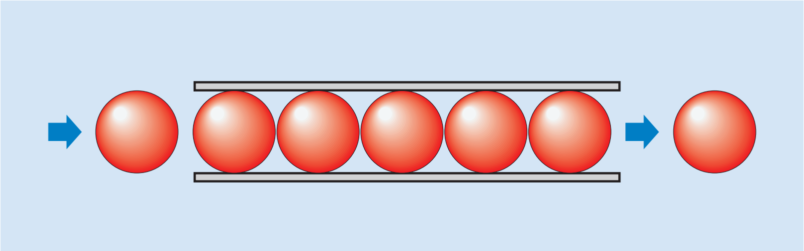

FIGURE 2–6 When a ball is pushed into one end, another ball is forced out the other end. This basic principle causes the instantaneous effect of electric impulses.

In a DC circuit, the impulse of electricity can appear to be faster than the speed of light. Assume for a moment that a pipe has been filled with table-tennis balls *(Figure 2–6)*. If a ball is forced into the end of the pipe, the ball at the other end will be forced out. Each time a ball enters one end of the pipe, another ball is forced out the other end. This principle is also true for electrons in a wire. There are billions of electrons in a wire. If an electron enters one end of a wire, another electron is forced out the other end. Assume that a wire is long enough to be wound around the earth 10 times. If a power source and a switch were connected at one end of the wire and a light at the other end *(Figure 2–7)*, the light would turn on the moment the switch was closed. It would take light approximately 1.3 seconds to travel around the earth 10 times.

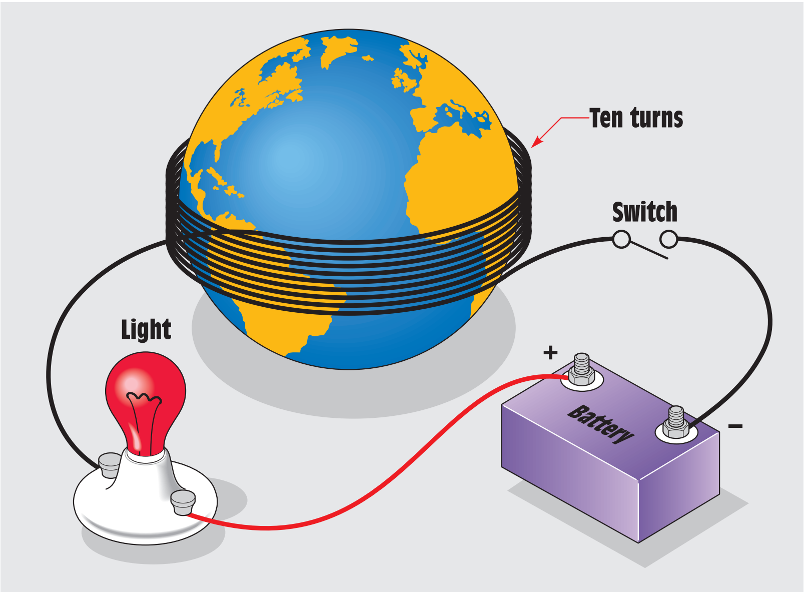

FIGURE 2–7 The impulse of electricity can appear to travel faster than light.

2–6 Basic Electric Circuits

A **complete path** must exist before current can flow through a circuit *(Figure 2–8)*. A complete circuit is often referred to as a *closed circuit*, because the power source, conductors, and load form a closed loop. In *Figure 2–8,* a lamp is used as the load. The load offers resistance to the circuit and limits the amount of current that can flow. If the switch is opened, there is no longer a closed loop and no current can flow. This is often referred to as an incomplete, or open, circuit.

Another type of circuit is the short circuit, which has very little or no resistance. It generally occurs when the conductors leading from and back to the power source become connected *(Figure 2–9)*. In this example, a separate current path has been established that bypasses the load. Because the load is the device that limits the flow of current, when it is bypassed, an excessive amount of current can flow. Short circuits generally cause a fuse to blow or a circuit breaker to open. If the circuit has not been protected by a fuse or circuit breaker, a short circuit can damage equipment, melt wires, and start fires.

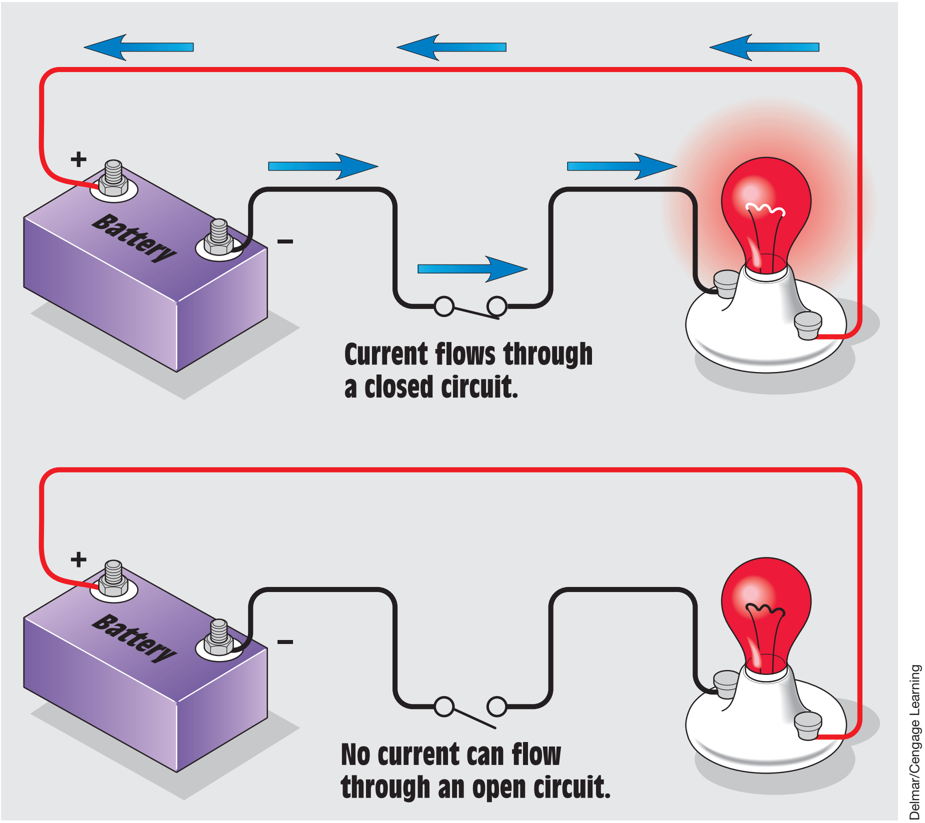

FIGURE 2–8 Current flows only through a closed circuit.

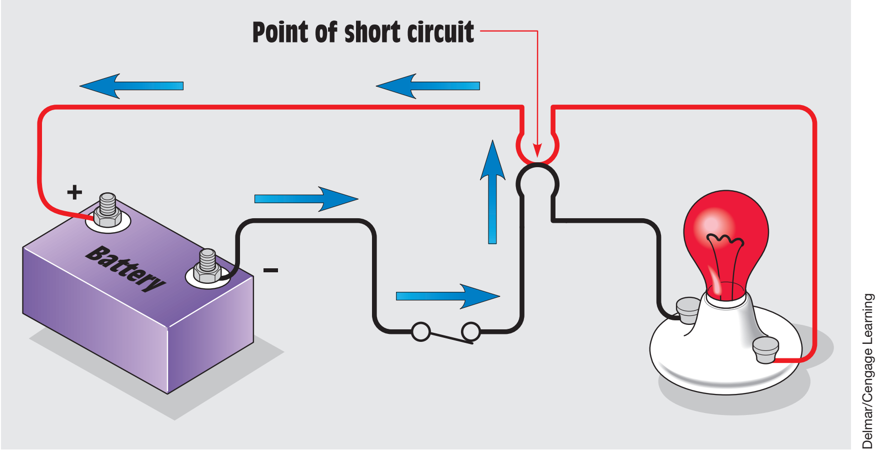

FIGURE 2–9 A short circuit bypasses the load and permits too much current to flow.

Another type of circuit, one that is often confused with a short circuit, is a grounded circuit. Grounded circuits can also cause an excessive amount of current flow. They occur when a path other than the one intended is established to ground. Many circuits contain an extra conductor called the **grounding conductor.** A typical 120-volt appliance circuit is shown in *Figure 2–10*. In this circuit, the ungrounded, or hot, conductor is connected to the fuse or circuit breaker. The hot conductor supplies power to the load. The grounded conductor, or **neutral conductor,** provides the return path and completes the circuit back to the power source. The grounding conductor is generally connected to the case of the appliance to provide a low-resistance path to ground. Although both the neutral and grounding conductors are grounded at the power source,

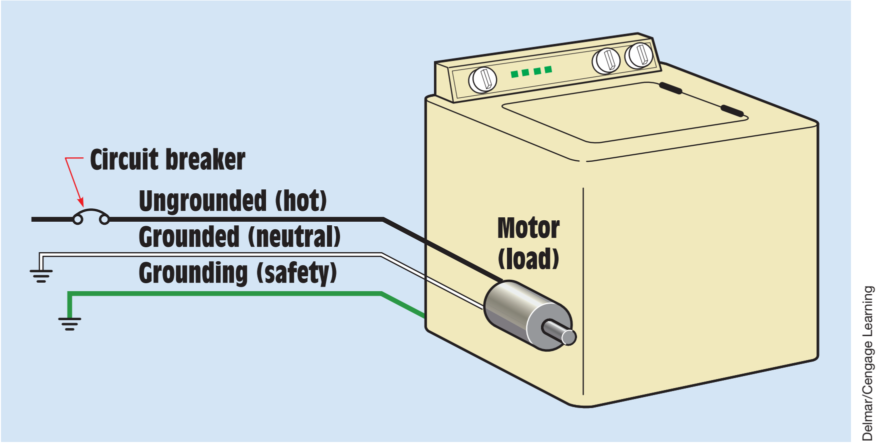

FIGURE 2–10 120-V appliance circuit.

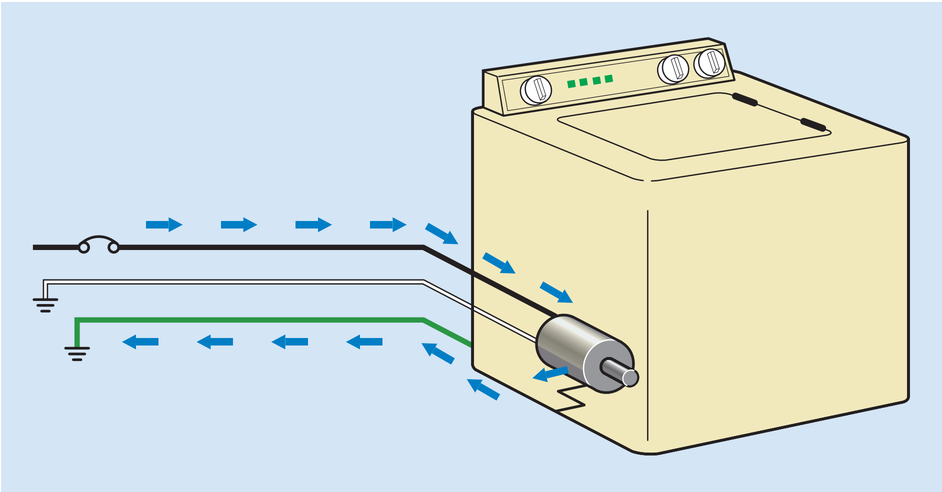

FIGURE 2–11 The grounding conductor provides a low-resistance path to ground.

the grounding conductor is not considered to be a circuit conductor, because current will flow through the grounding conductor only when a circuit fault develops. In normal operation, current flows through the hot and neutral conductors only.

The grounding conductor is used to help prevent a shock hazard in the event that the ungrounded, or hot, conductor comes in contact with the case or frame of the appliance *(Figure 2–11)*. This condition can occur in several ways. In this example, assume that the motor winding becomes damaged and makes connection to the frame of the motor. Because the frame of the motor is connected to the frame of the appliance, the grounding conductor provides a circuit path to ground. If enough current flows, the circuit breaker will open. Without a grounding conductor connected to the frame of the appliance, the frame would become hot (in the electrical sense) and anyone touching the case and a grounded point, such as a water line, would complete the circuit to ground. The resulting shock could be fatal. For this reason, the grounding prong of a plug should never be cut off or bypassed.

2–7 The Volt

Voltage is defined as the potential difference between two points of a conducting wire carrying a constant current of 1 ampere when the power dissipated between these points is 1 watt. Voltage is also referred to as **potential difference** or **electromotive force (EMF).** It is the force that pushes the electrons through a wire and is often referred to as electrical pressure. A **volt** is the amount of potential necessary to cause 1 coulomb to produce 1 joule of work. One thing to remember is that voltage cannot flow. Voltage in an electrical

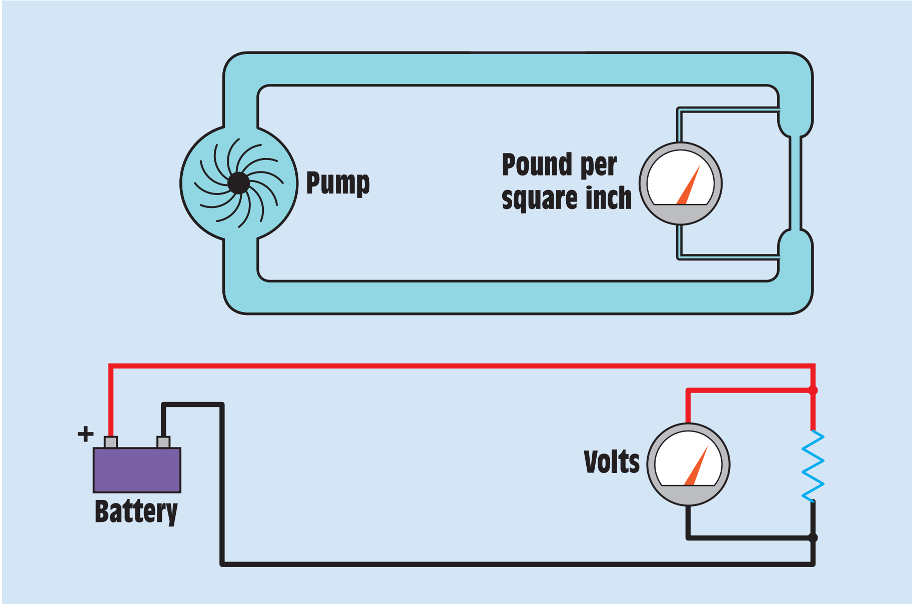

FIGURE 2–12 Voltage in an electric circuit can be compared to pressure in a water system.

circuit is like pressure in a water system *(Figure 2–12)*. To say that voltage flows through a circuit is like saying that pressure flows through a pipe. Pressure can push water through a pipe, and it is correct to say that water flows through a pipe, but it is not correct to say that pressure flows through a pipe. The same is true for voltage. Voltage pushes current through a wire, but voltage cannot flow through a wire.

Voltage is often thought of as the potential to do something. For this reason it is frequently referred to as potential, especially in older publications and service manuals. Voltage must be present before current can flow, just as pressure must be present before water can flow. A voltage, or potential, of 120 volts is present at a common wall outlet, but there is no flow until some device is connected and a complete circuit exists. The same is true in a water system. Pressure is present, but water cannot flow until the valve is opened and a path is provided to a region of lower pressure. The letter *E*, which stands for EMF, or the letter *V*, which stands for volt, can be used to represent voltage in an algebraic formula. This text uses the letter *E* to represent voltage in an algebraic formula.

2–8 The Ohm

An **ohm** is the unit of **resistance** to current flow. It was named after the German scientist Georg S. Ohm. The symbol used to represent an ohm, or resistance, is the Greek letter omega (Ω). The letter *R*, which stands for resistance, is used to

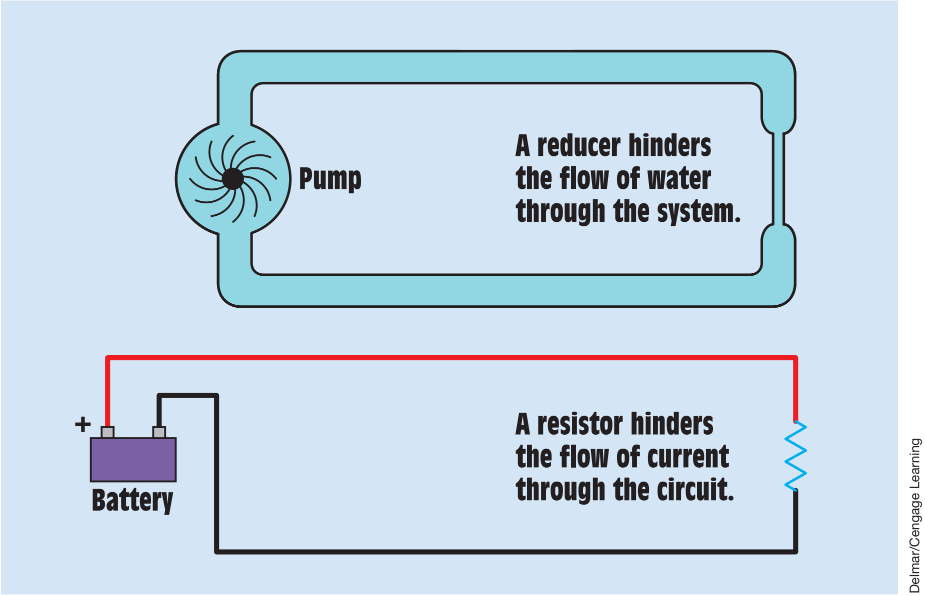

FIGURE 2–13 A resistor in an electric circuit can be compared to a reducer in a water system.

represent ohms in an algebraic formula. An ohm is the amount of resistance that allows 1 ampere of current to flow when the applied voltage is 1 volt. Without resistance, every electric circuit would be a short circuit. All electric loads, such as heating elements, lamps, motors, transformers, and so on, are measured in ohms. In a water system, a reducer can be used to control the flow of water; in an electric circuit, a resistor can be used to control the flow of electrons *(Figure 2–13)*.

To understand the effect of resistance on an electric circuit, imagine a person running along a beach. As long as the runner stays on the hard, compact sand, he or she can run easily along the beach. Likewise, current can flow easily through a good conductive material, such as a copper wire. Now imagine that the runner wades out into the water until it is knee deep. He or she will no longer be able to run along the beach as easily because of the resistance of the water. Now imagine that the runner wades out into the water until it is waist deep. His or her ability to run along the beach will be hindered to a greater extent because of the increased resistance of the water against his or her body. The same is true for resistance in an electric circuit. The higher the resistance, the greater the hindrance to current flow.

Another fact an electrician should be aware of is that any time current flows through a resistance, heat is produced *(Figure 2–14)*. That is why a wire becomes warm when current flows through it. The elements of an electric range become hot, and the filament of an incandescent lamp becomes extremely hot because of resistance.

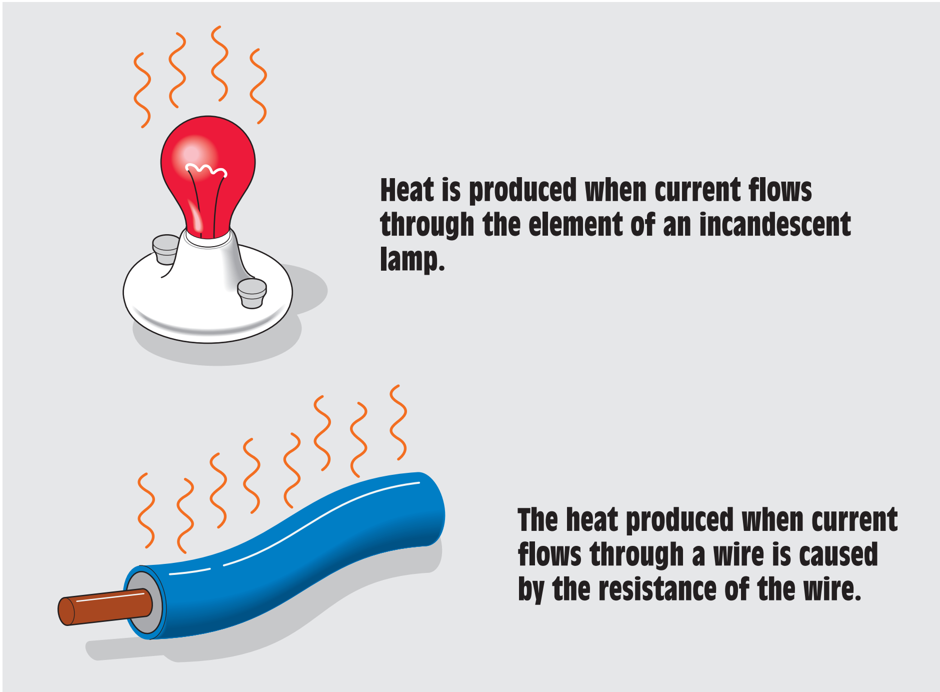

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FIGURE 2–14 Heat is produced when current flows through resistance.

Another term similar in meaning to resistance is **impedance.** Impedance is most often used in calculations of AC rather than DC. Impedance is discussed to a greater extent later in this text.

GREEN TIP: Larger wire size will result in less resistance. Less resistance reduces the voltage drop and consequently the amount of power loss due to heating the conductor. ■

2–9 The Watt

Wattage is a measure of the amount of power that is being used in a circuit. The **watt** was named in honor of the English scientist James Watt. In an algebraic formula, wattage is generally represented either by the letter *P*, for power, or *W*, for watts. It is proportional to the amount of voltage and the amount of current flow. To understand watts, return to the example of the water system. Assume that a water pump has a pressure of 120 pounds per square inch (PSI) and causes a flow rate of 1 gallon per second. Now assume that this water is

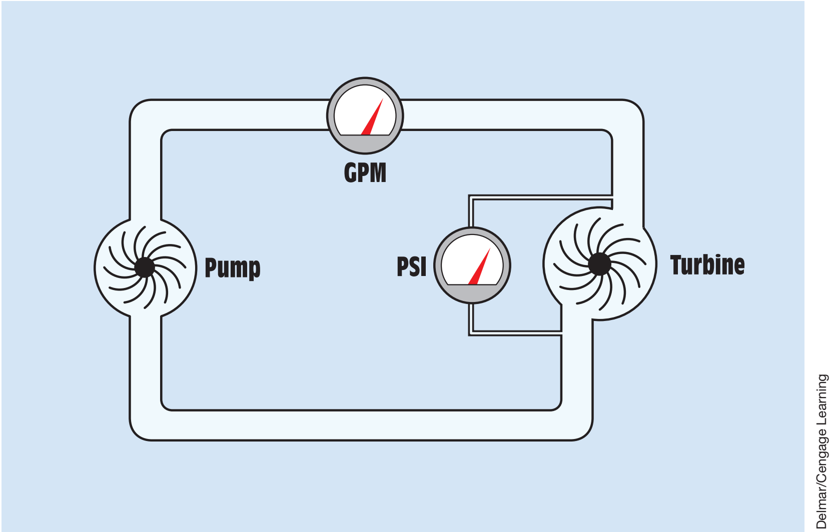

FIGURE 2–15 Force equals flow rate times pressure.

used to drive a turbine, as shown in *Figure 2–15.* The turning force or torque developed by the turbine is proportional to the amount of water flow and the pressure forcing it against the turbine blades. If the pressure is increased and the flow rate remains constant, the water will strike the turbine blades with greater force and the torque will increase. If the pressure remains constant and a greater volume of water is permitted to flow, the turbine blades will be struck by more pounds of water in the same amount of time and torque will again increase. As you can see, the torque developed by the turbine is proportional to both the pressure and the flow rate of the water.

The power of an electric circuit is very similar. *Figure 2–16* shows a resistor connected to a circuit with a voltage of 120 volts and a current flow of 1 ampere.

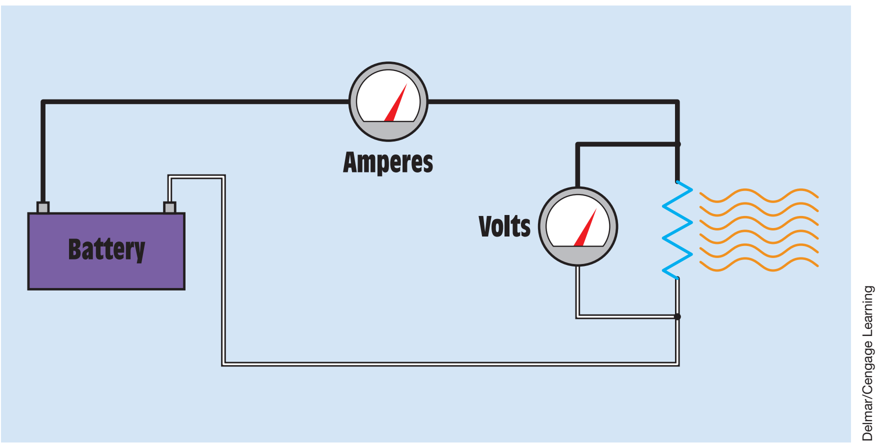

FIGURE 2–16 Amperes times volts equals watts.

The resistor shown represents an electric heating element. When 120 volts force a current of 1 ampere through it, the heating element will produce 120 watts of heat (120 V × 1 A = 120 W). If the voltage is increased to 240 volts, but the current remains constant, the element will produce 240 watts of heat (240 V × 1 A = 240 W). If the voltage remains at 120 volts, but the current is increased to 2 amperes, the heating element will again produce 240 watts (120 V × 2 A = 240 W). Notice that the amount of power used by the heating element is determined by the amount of current flow and the voltage driving it.

An important concept concerning **power** in an electric circuit is that before true power, or watts, can exist, there must be some type of energy change or conversion. In other words, electric energy must be changed or converted into some other form of energy before there can be power or watts. It makes no difference whether electric energy is converted into heat energy or mechanical energy; there must be some form of energy conversion before watts can exist.

2–10 Other Measures of Power

The watt is not the only unit of power measure. Many years ago, James Watt decided that in order to sell his steam engines, he would have to rate their power in terms that the average person could understand. He decided to compare his steam engines to the horses he hoped his engines would replace. After experimenting, Watt found that the average horse working at a steady rate could do 550 foot-pounds of work per second. A foot-pound (ft-lb) is the amount of force required to raise a 1 pound weight 1 foot. This rate of doing work is the definition of a **horsepower (hp):**

$$1 \text{ hp} = 550 \text{ ft-lb/s}$$

Horsepower can also be expressed as 33,000 foot-pounds per minute (550 ft-lb + 60 s = 33,000):

$$1 \text{ hp} = 33{,}000 \text{ ft-lb/min}$$

It was later calculated that the amount of electric energy needed to produce one horsepower was 746 watts:

$$1 \text{ hp} = 746 \text{ W}$$

Another measure of energy frequently used in the English system of measure is the **British thermal unit (Btu).** A Btu is defined as the amount of heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit. In the metric system, the calorie is used instead of the Btu to measure heat. A calorie is the amount of heat needed to raise the temperature of 1 gram of water 1 degree Celsius. The **joule** is the SI equivalent of the watt. A joule is defined as 1 newton-meter. A newton is a force of 100,000 dynes, or about

1 Horsepower =	746 watts
1 Horsepower =	550 ft-lb/s
1 Watt =	0.00134 horsepower
1 Watt =	3.412 Btu/hr
1 Wattsecond =	1 joule
1 Btu-hr =	0.293 watts
1 Cal/s =	4.19 watts
1 Ft-lb/s =	1.36 watts
1 Btu =	1050 joules
1 Joule =	0.2388 cal
1 Cal =	4.187 joules

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FIGURE 2–17 Common power units.

3-½ ounces, and a meter is about 39 inches. The joule can also be expressed as the amount of work done by 1 coulomb flowing through a potential of 1 volt, or as the amount of work done by 1 watt for 1 second:

$$1 \text{ joule} = 1 \text{ wattsecond}$$

The chart in *Figure 2–17* gives some common conversions for different quantities of energy. These quantities can be used to calculate different values.

EXAMPLE 2-1

An elevator must lift a load of 4000 lb to a height of 50 ft in 20 s. How much horsepower is required to operate the elevator?

Solution

Find the amount of work that must be performed, and then convert that to horsepower:

$$4{,}000 \text{ lb} \times 50 \text{ ft} = 200{,}000 \text{ ft-lb}$$

$$\frac{200{,}000 \text{ ft-lb}}{20 \text{ s}} = 10{,}000 \text{ ft-lb/s}$$

$$\frac{10{,}000 \text{ ft-lb/s}}{550 \text{ ft-lb/s}} = 18.18 \text{ hp}$$

EXAMPLE 2-2

A water heater contains 40 gallons of water. Water weighs 8.34 lb per gallon. The present temperature of the water is 68°F. The water must be raised to a temperature of 160°F in one hour. How much power will be required to raise the water to the desired temperature?

Solution

First determine the weight of the water in the tank, because a Btu is the amount of heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit:

$$40 \text{ gal} \times 8.34 \text{ lb per gal} = 333.6 \text{ lb}$$

The second step is to determine how many degrees of temperature the water must be raised. This amount will be the difference between the present temperature and the desired temperature:

$$160°\text{F} - 68°\text{F} = 92°\text{F}$$

The amount of heat required in Btu will be the product of the pounds of water and the desired increase in temperature:

$$333.6 \text{ lb} \times 92°\text{F} = 30{,}691.2 \text{ lb-degrees or Btu}$$

$$1 \text{ W} = 3.412 \text{ Btu/hr}$$

Therefore,

$$\frac{30.691 \text{ Btu}}{3.412 \text{ Btu/hr/w}} = 8995.1\text{w}$$

2–11 Ohm's Law

In its simplest form, **Ohm's law** states that ***it takes 1 volt to push 1 ampere through 1 ohm.*** Ohm discovered that all electric quantities are proportional to each other and can therefore be expressed as mathematical formulas. He found that if the resistance of a circuit remained constant and the voltage increased, there was a corresponding proportional increase of current. Similarly, if the resistance remained constant and the voltage decreased, there would be a proportional decrease of current. He also found that if the voltage remained constant and the resistance increased, there would be a decrease of current; and if the voltage remained constant and the resistance decreased, there would be an increase of current. This finding led Ohm to the conclusion that ***in a DC***

circuit, the current is directly proportional to the voltage and inversely proportional to the resistance.

Because Ohm's law is a statement of proportion, it can be expressed as an algebraic formula when standard values such as the volt, the ampere, and the ohm are used. The three basic Ohm's law formulas are

$$E = I \times R$$

$$I = \frac{E}{R}$$

$$R = \frac{E}{I}$$

where

E = EMF, or voltage
I = intensity of current, or amperage
R = resistance

The first formula states that the voltage can be found if the current and resistance are known. Voltage is equal to amperes multiplied by ohms. For example, assume that a circuit has a resistance of 50 ohms and a current flow through it of 2 amperes. The voltage connected to this circuit is 100 volts.

$$E = I \times R$$

$$E = 2\ \text{A} \times 50\ \Omega$$

$$E = 100\ \text{V}$$

The second formula states that the current can be found if the voltage and resistance are known. In the example shown, 120 volts are connected to a resistance of 30 ohms. The amount of current flow will be 4 amperes.

$$I = \frac{E}{R}$$

$$I = \frac{120\ \text{V}}{30\ \Omega}$$

$$I = 4\ \text{A}$$

The third formula states that if the voltage and current are known, the resistance can be found. Assume that a circuit has a voltage of 240 volts and a current flow of 10 amperes. The resistance in the circuit is 24 ohms.

$$R = \frac{E}{I}$$

$$R = \frac{240\ \text{V}}{10\ \text{A}}$$

$$R = 24\ \Omega$$

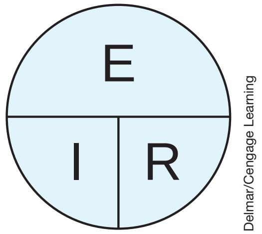

FIGURE 2–18 Chart for finding values of voltage, current, and resistance.

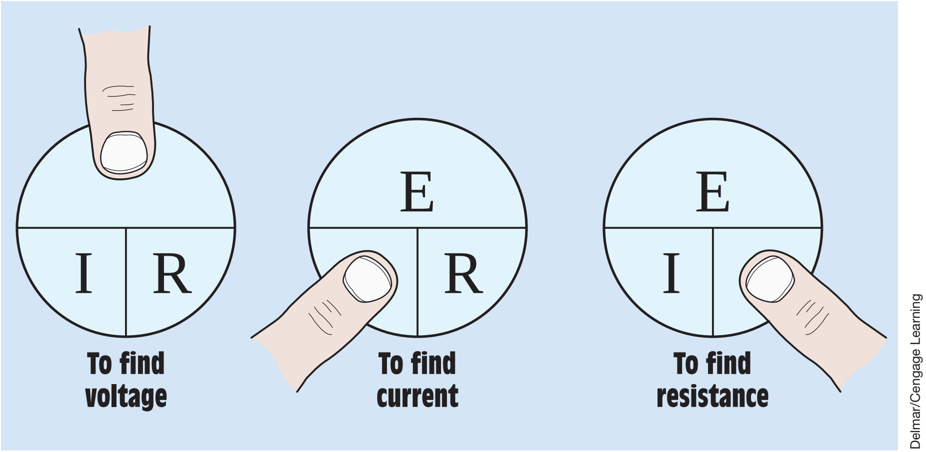

FIGURE 2–19 Using the Ohm's law chart.

Figure 2–18 shows a simple chart that can be a great help when trying to remember an Ohm's law formula. To use the chart, cover the quantity that is to be found. For example, if the voltage, E, is to be found, cover the E on the chart. The chart now shows the remaining letters IR *(Figure 2–19)*; thus, E = I × R. The same method reveals the formulas for current (I) and resistance (R).

A larger chart, which shows the formulas needed to find watts as well as voltage, amperage, and resistance, is shown in *Figure 2–20*. The letter

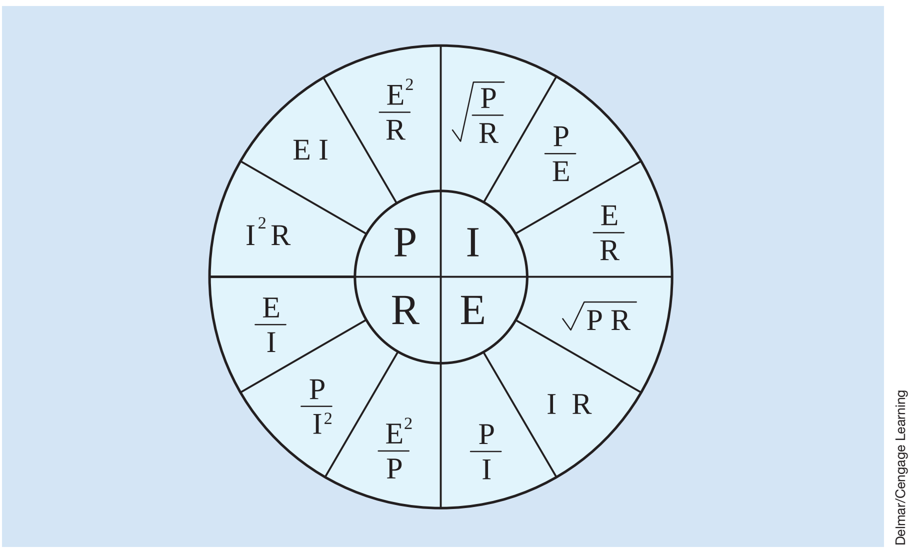

FIGURE 2–20 Formula chart for finding values of voltage, current, resistance, and power.

P (power) is used to represent the value of watts. Notice that this chart is divided into four sections and that each section contains three different formulas. To use this chart, select the section containing the quantity to be found and then choose the proper formula from the given quantities.

EXAMPLE 2-3

An electric iron is connected to 120 V and has a current draw of 8 A. How much power is used by the iron?

Solution

The quantity to be found is watts, or power. The known quantities are voltage and amperage. The proper formula to use is shown in *Figure 2–21*.

$$P = EI$$

$$P = 120\ V \times 8\ A$$

$$P = 960\ W$$

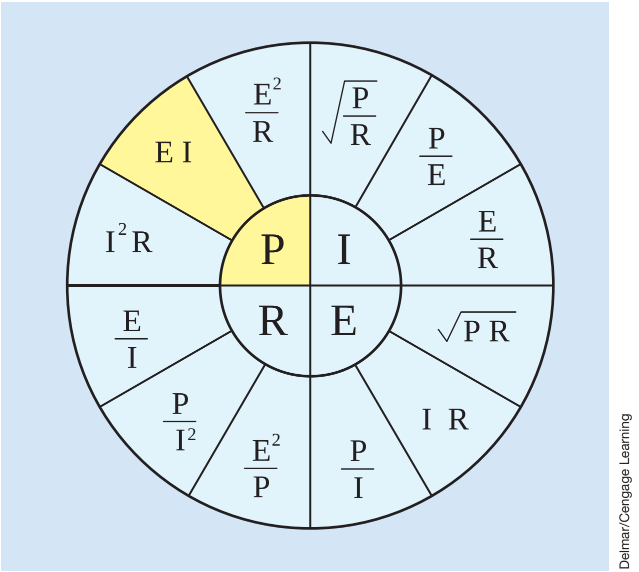

FIGURE 2–21 Finding power when voltage and current are known.

■ EXAMPLE 2-4

An electric hair dryer has a power rating of 1000 W. How much current will it draw when connected to 120 V?

Solution

The quantity to be found is amperage, or current. The known quantities are power and voltage. To solve this problem, choose the formula shown in *Figure 2–22*.

$$I = \frac{P}{E}$$

$$I = \frac{1000\text{ W}}{120\text{ V}}$$

$$I = 8.333\text{A}$$

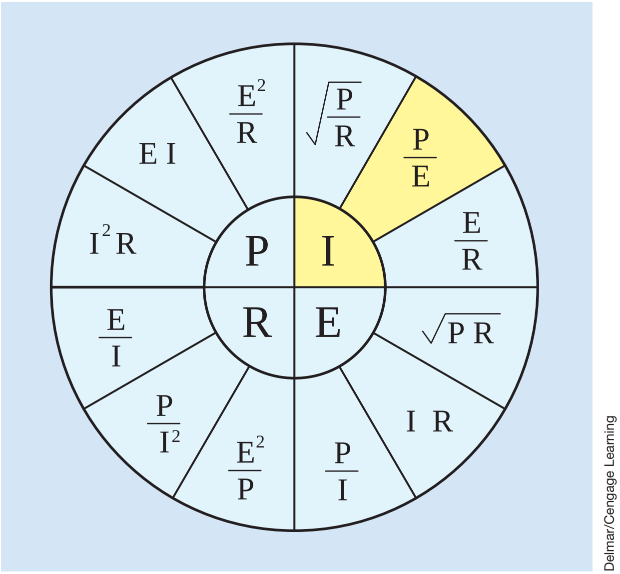

FIGURE 2–22 Finding current when power and voltage are known.

EXAMPLE 2-5

An electric hotplate has a power rating of 1440 W and a current draw of 12 A. What is the resistance of the hotplate?

Solution

The quantity to be found is resistance, and the known quantities are power and current. Use the formula shown in *Figure 2–23*.

$$R = \frac{P}{I^2}$$

$$R = \frac{1440\ W}{12\ A \times 12\ A}$$

$$R = \frac{1440\ W}{144\ A}$$

$$R = 10\ \Omega$$

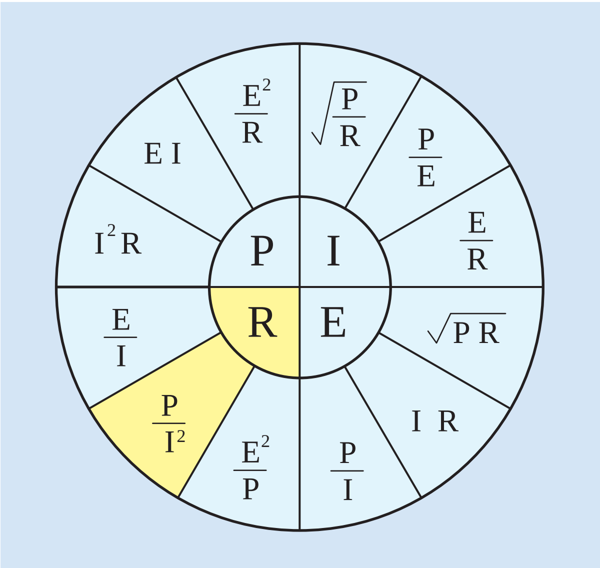

FIGURE 2–23 Finding resistance when power and current are known.

Kilo	1000
Hecto	100
Deka	10
Base unit	1
Deci	$^1/_{10}$ or 0.1
Centi	$^1/_{100}$ or 0.01
Milli	$^1/_{1000}$ or 0.001

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FIGURE 2–24 Standard metric prefixes.

2–12 Metric Prefixes

Metric prefixes are used in the electrical field just as they are in most other scientific fields. A special type of notation, known as *engineering notation*, is used in electrical measurements. Engineering notation is similar to scientific notation except that engineering notation is in steps of 1000 instead of 10. The chart in *Figure 2–24* shows standard metric prefixes. The first step above the base unit is deka, which means 10. The second prefix is hecto, which means 100, and the third prefix is kilo, which means 1000. The first prefix below the base unit is deci, which means $^1/_{10}$; the second prefix is centi, which means $^1/_{100}$; and the third is milli, which means $^1/_{1000}$.

The chart in *Figure 2–25* shows prefixes used in engineering notation. The first prefix above the base unit is kilo, or 1000; the second prefix is mega, or 1,000,000; and the third prefix is giga, or 1,000,000,000. Notice that each prefix is 1000 times greater than the previous prefix. The chart also shows that the first prefix below the base unit is milli, or $^1/_{1000}$; the second is micro, represented by the Greek mu (μ), or $^1/_{1,000,000}$; and the third is nano, or $^1/_{1,000,000,000}$.

Metric prefixes are used in almost all scientific measurements for ease of notation. It is much simpler to write a value such as 10 MΩ than it is to write 10,000,000 ohms, or to write 0.5 ns than to write 0.000,000,000, 5 second. Once the metric prefixes have been learned, measurements such as 47 kilohms (kΩ) or 50 milliamperes (mA) become commonplace to the technician.

The SI System

Note that the term *metric* is commonly used to indicate a system that employs measurements that increase or decrease in steps of 10. The prefixes just discussed are commonly referred to as *metric* units of measure. These prefixes are actually part of the SI (System Internationale) system that was adopted for

ENGINEERING UNIT	SYMBOL	MULTIPLY BY	
Tera	T	1,000,000,000,000	X 10^{12}
Giga	G	1,000,000,000	X 10^{9}
Mega	M	1,000,000	X 10^{6}
Kilo	k	1,000	X 10^{3}
Base unit		1	
Milli	m	0.001	X 10^{-3}
Micro	µ	0.000,001	X 10^{-6}
Nano	n	0.000,000,001	X 10^{-9}
Pico	p	0.000,000,000,001	X 10^{-12}

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FIGURE 2–25 Standard prefixes of engineering notation.

use in the United States in 1960 by the 11th General Conference on Weights and Measures (abbreviated CGPM from the official French name *Conference Generale des Poids et Mesures*). The intention of the SI system is to provide a worldwide standard of weights and measures. The SI system uses seven base and two supplementary units that are regarded as dimensionally independent *(Figure 2–26)*. From these base and supplementary units, other units have been derived. Some of these units commonly used in the electrical field are shown in *Figure 2–27*.

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Thermodynamic temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd
Phase angle	Radian	rad
Solid angle	Sterdian	sr

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FIGURE 2–26 SI base and supplementary units.

Quantity	Unit	Symbol	Formula
Frequency	Hertz	Hz	l/s
Force	Newton	N	$(kg \cdot m)/s^2$
Pressure, stress	Pascal	Pa	N/m^2
Energy, work, quantity of heat	Joule	J	$N \cdot m$
Power, radiant flux	Watt	W	J/s
Quantity of electricity, charge	Coulomb	C	$A \cdot s$
Electric potential, electromotive force	Volt	V	W/A
Capacitance	Farad	F	C/V
Electric resistance	Ohm	Ω	V/A
Conductance	Siemens	S	A/V
Magnetic flux	Weber	Wb	$V \cdot s$
Magnetic flux density	Tesla	T	Wb/m^2
Inductance	Henry	H	Wb/A
Luminous flux	Lumen	lm	$cd \cdot sr$
Illuminance	Lux	lx	lm/m^2

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FIGURE 2–27 Derived SI units.

Summary

- A coulomb is a quantity measurement of electrons.
- An ampere (A) is 1 coulomb per second.
- The letter *I*, which stands for intensity of current flow, is normally used in Ohm's law formulas.
- Voltage is referred to as electric pressure, potential difference, or electromotive force. An E or a V can be used to represent voltage in Ohm's law formulas.
- An ohm (Ω) is a measurement of resistance (R) in an electric circuit.
- The watt (W) is a measurement of power in an electric circuit. It is represented by either a W or a P (power) in Ohm's law formulas.
- Electric measurements are generally expressed in engineering notation.
- Engineering notation differs from scientific notation in that it uses steps of 1000 instead of steps of 10.
- Before current can flow, there must be a complete circuit.
- A short circuit has little or no resistance.

Review Questions

1. What is a coulomb?
2. What is an ampere?
3. Define voltage.
4. Define ohm.
5. Define watt.
6. An electric heating element has a resistance of 16 Ω and is connected to a voltage of 120 V. How much current will flow in this circuit?
7. How many watts of heat are being produced by the heating element in Question 6?
8. A 240-V circuit has a current flow of 20 A. How much resistance is connected in the circuit?
9. An electric motor has an apparent resistance of 15 Ω. If 8 A of current are flowing through the motor, what is the connected voltage?
10. A 240-V air-conditioning compressor has an apparent resistance of 8 Ω. How much current will flow in the circuit?
11. How much power is being used by the motor in Question 10?
12. A 5-kW electric heating unit is connected to a 240-V line. What is the current flow in the circuit?
13. If the voltage in Question 12 is reduced to 120 V, how much current would be needed to produce the same amount of power?
14. Is it less expensive to operate the electric heating unit in Question 12 on 240 V or 120 V?

Practical Applications

You are an electrician on the job. The electrical blueprint shows that eight 500-W lamps are to be installed on the same circuit. The circuit voltage is 277 V and is protected by a 20-A circuit breaker. A continuous-use circuit can be loaded to only 80% of its rating. Is a 20-A circuit large enough to carry this load? ■

Practical Applications

You have been sent to a new home. The homeowner reports that sometimes the electric furnace trips the 240-V, 60-A circuit breaker connected to it. Upon examination, you find that the furnace contains three 5000-W heating elements designed to turn on in stages. For example, when the thermostat calls for heat, the first 5000-W unit turns on. After some period of time, the second unit will turn on, and then, after another time delay, the third unit will turn on. What do you think the problem is, and what would be your recommendation for correcting it? Explain your answer. ■

Practical Applications

You are an electrician installing the wiring in a new home. The homeowner desires that a ceiling fan with light kits be installed in five different rooms. Each fan contains a light kit that can accommodate four 60-watt lamps. Each fan motor draws a current of 1.8 amperes when operated on high speed. It is assumed that each fan can operate more than three hours at a time and therefore must be considered a continuous-duty device. The fans are to be connected to a 15-ampere circuit. Because the devices are continuous duty, the circuit current must be limited to 80% of the continuous connected load. How many fans can be connected to a single 15-ampere circuit? How many circuits will be required to supply power to all five fans? ■

Practical Applications

A homeowner is installing a swimming pool. You have been asked to install a circuit to operate a 600-watt underwater light and a circulating pump. The motor nameplate reveals that the pump has a current draw of 8.5 amperes. The devices are considered continuous duty. Can the power to operate both of these devices be supplied by a single 20-ampere circuit? ■

Practice Problems

Ohm's Law

Fill in the missing values.

Volts (E)	Amperes (I)	Ohms (R)	Watts (P)
153 V	0.056 A		
	0.65 A	470 Ω	
24 V			124 W
	0.00975 A		0.035 W
		6.8 kΩ	0.86 W
460 V		72 Ω	
48 V	1.2 A		
	154 A	0.8 Ω	
277 V			760 W
	0.0043 A		0.0625 W
		130 kΩ	0.0225 W
96 V		2.2 kΩ	

Unit 3

Static Electricity

Why You Need to Know

Many processes and devices use static electricity in a productive way. Copy machines, for example, could not operate except for the principles governing static electricity. Other devices such as electronic air cleaners and paint spray operations employ static electricity. The concepts of static electricity and how it can be used or prevented are important to anyone in the electrical field. To fully understand static electricity, this unit presents

- a demonstration of electron flow and how, by adding electrons, an object is negatively charged and how, by removing electrons, an object becomes positively charged.
- an explanation of electron flow in thunderclouds and lightning. This natural element is probably the greatest example of static electricity, and in this unit you can see how it applies to the theory of positive and negative charges in nature.

OUTLINE

KEY TERMS

Electroscope
Electrostatic charges
Lightning
Lightning arrestor
Lightning bolts
Lightning rods
Nuisance static charges
Precipitators
Selenium
Static
Thundercloud
Useful static charges

Objectives

After studying this unit, you should be able to

- discuss the nature of static electricity.
- use an electroscope to determine unknown charges.
- discuss lightning protection.
- list nuisance charges of static electricity.
- list useful charges of static electricity.

Preview

Static electric charges occur often in everyday life. Almost everyone has received a shock after walking across a carpet and then touching a metal object or after sliding across a car seat and touching the door handle. Almost everyone has combed their hair with a hard rubber or plastic comb and then used the comb to attract small pieces of paper or other lightweight objects. Static electric charges cause clothes to stick together when they are taken out of a clothes dryer. Lightning is without doubt the greatest display of a static electric discharge. ■

3–1 Static Electricity

Although static charges can be a nuisance *(Figure 3–1)*, or even dangerous, they can also be beneficial. Copy machines, for example, operate on the principle of static electricity. The manufacture of sandpaper also relies on the application of static electricity. Grains of sand receive a static charge to

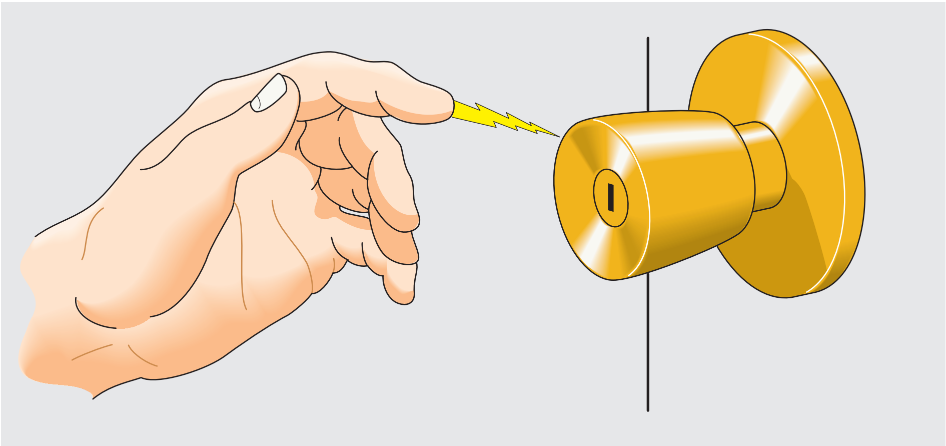

FIGURE 3–1 Static electric charges can cause a painful shock.

make them stand apart and expose a sharper edge *(Figure 3–2)*. Electronic air filters—**precipitators**—use static charges to attract small particles of smoke, dust, and pollen *(Figure 3–3)*. The precipitator uses a high-voltage DC power supply to provide a set of wires with a positive charge and a set of plates with a negative charge. As a blower circulates air through the unit, small particles

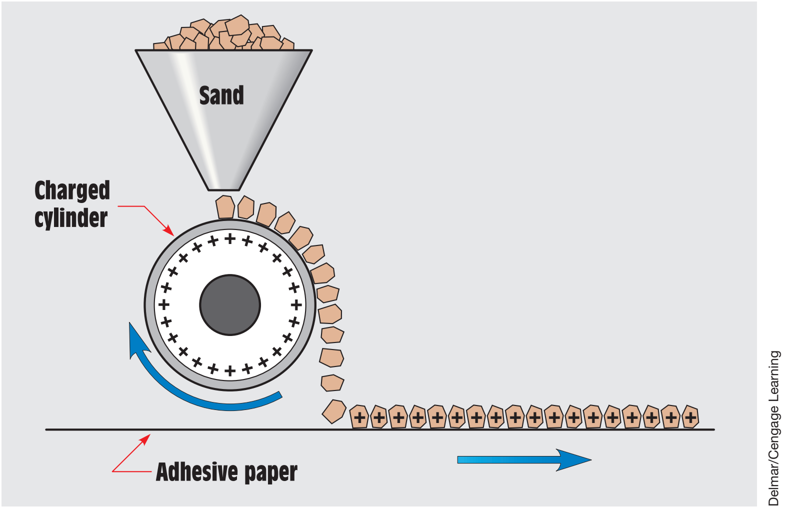

FIGURE 3–2 Grains of sand receive a charge to help them stand apart.

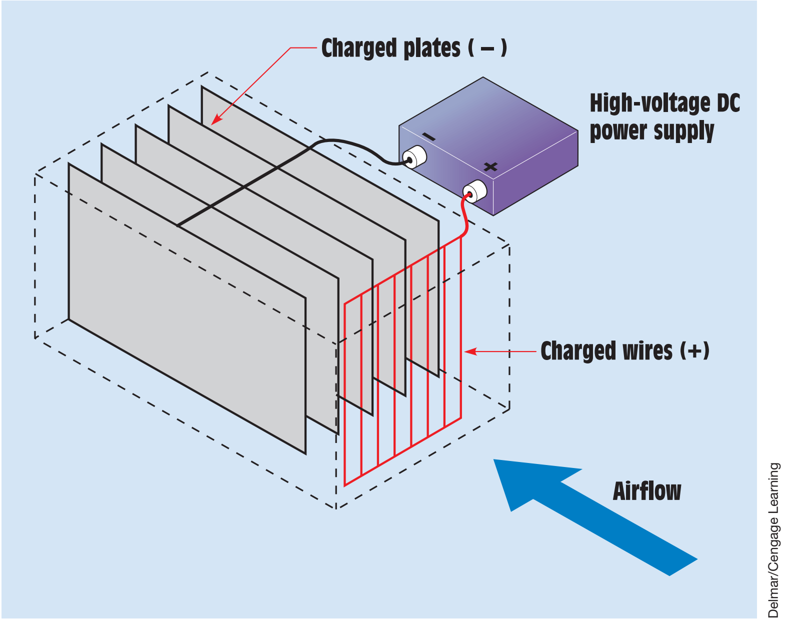

FIGURE 3–3 Electronic air cleaner.

receive a positive charge as they move across the charged wires. The charged particles are then attracted to the negative plates. The negative plates hold the particles until the unit is turned off and the plates are cleaned.

The word **static** means not moving or sitting still. Static electricity refers to electrons that are sitting still and not moving. Static electricity is therefore a charge and not a current. **Electrostatic charges** are built up on insulator materials because insulators are the only materials that can hold the electrons stationary and keep them from flowing to a different location. A static charge can be built up on a conductor only if the conductor is electrically insulated from surrounding objects. A static charge can be either positive or negative. If an object has a lack of electrons, it has a positive charge; and if it has an excess of electrons, it has a negative charge.

3–2 Charging an Object

The charge that accumulates on an object is determined by the materials used to produce the charge. If a hard rubber rod is rubbed on a piece of wool, the wool deposits excess electrons on the rod and gives it a negative charge. If a glass rod is rubbed on a piece of wool, electrons are removed from the rod, thus producing a positive charge on the rod *(Figure 3–4)*.

3–3 The Electroscope

An early electric instrument that can be used to determine the polarity of the electrostatic charge of an object is the **electroscope** *(Figure 3–5)*. An electroscope is a metal ball attached to the end of a metal rod. The other end of the rod is attached to two thin metal leaves. The metal leaves are inside a transparent container that permits the action of the leaves to be seen. The metal rod is insulated from the box. The metal leaves are placed inside a container so that air currents cannot affect their movement.

Before the electroscope can be used, it must first be charged. This is done by touching the ball with an object that has a known charge. For this example, assume that a hard rubber rod has been rubbed on a piece of wool to give it a negative charge. When the rubber rod is wiped against the metal ball, excess electrons are deposited on the metal surface of the electroscope. Because both of the metal leaves now have an excess of electrons, they repel each other, as shown in *Figure 3–6*.

Testing an Object

A charged object can now be tested to determine whether it has a positive or negative polarity. Assume that a ballpoint pen is charged by rubbing the plastic body through a person's hair. Now bring the pen close to but not touching

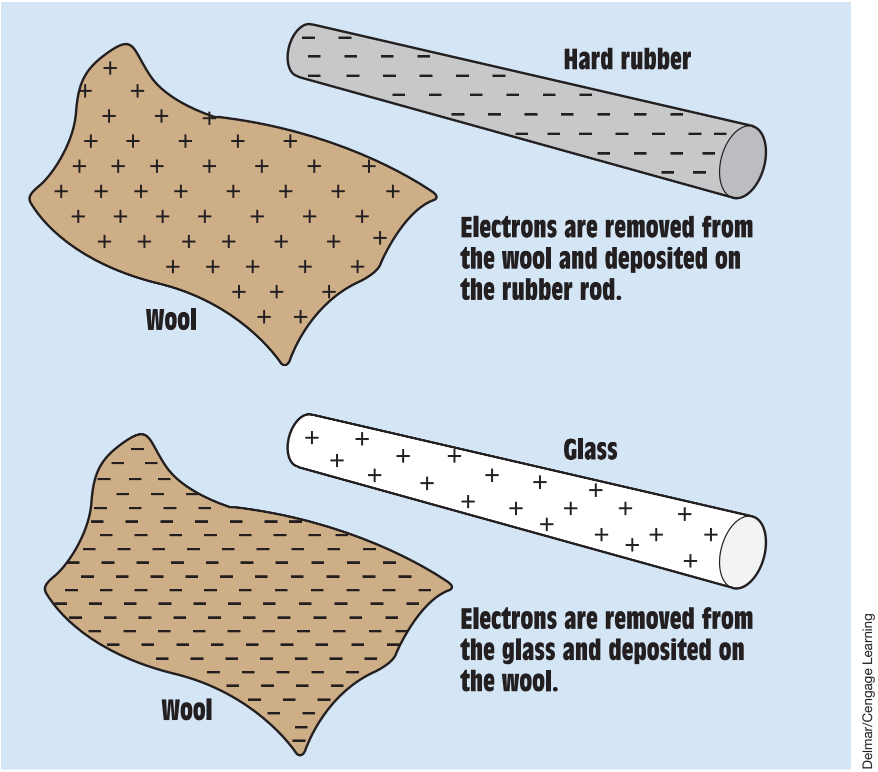

FIGURE 3–4 Producing a static charge.

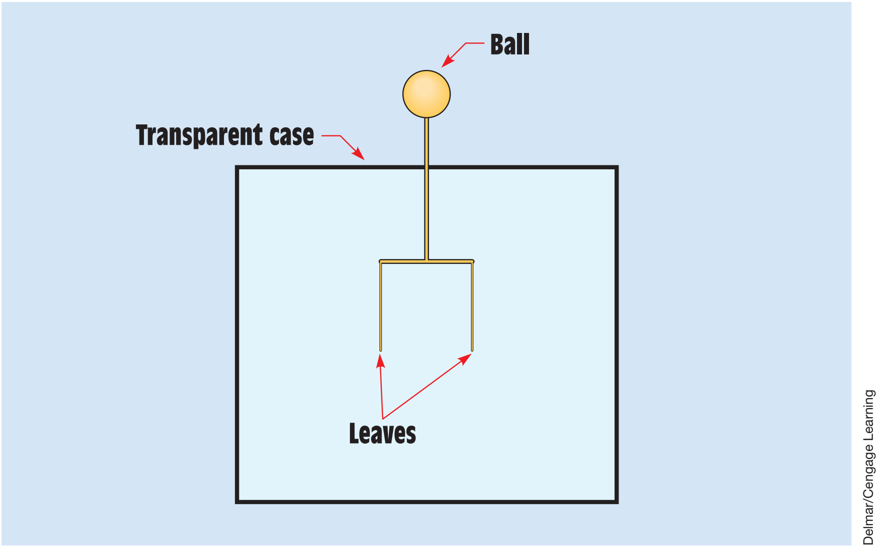

FIGURE 3–5 An electroscope.

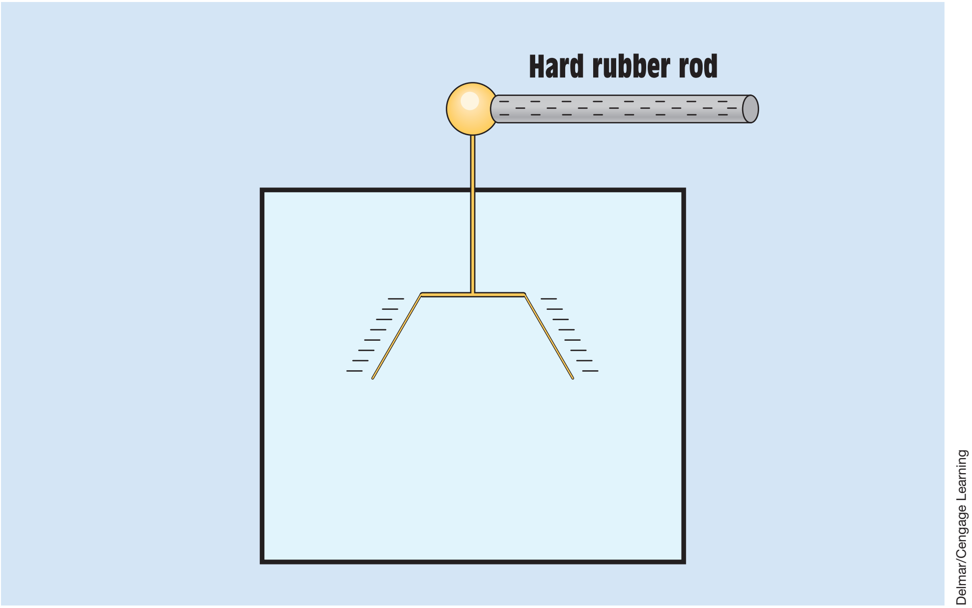

FIGURE 3–6 The electroscope is charged with a known static charge.

the ball and observe the action of the leaves. If the pen has taken on a negative charge, the leaves will move farther apart, as shown in *Figure 3–7*. The field caused by the negative electrons on the pen repels electrons from the ball. These electrons move down the rod to the leaves, causing the leaves to

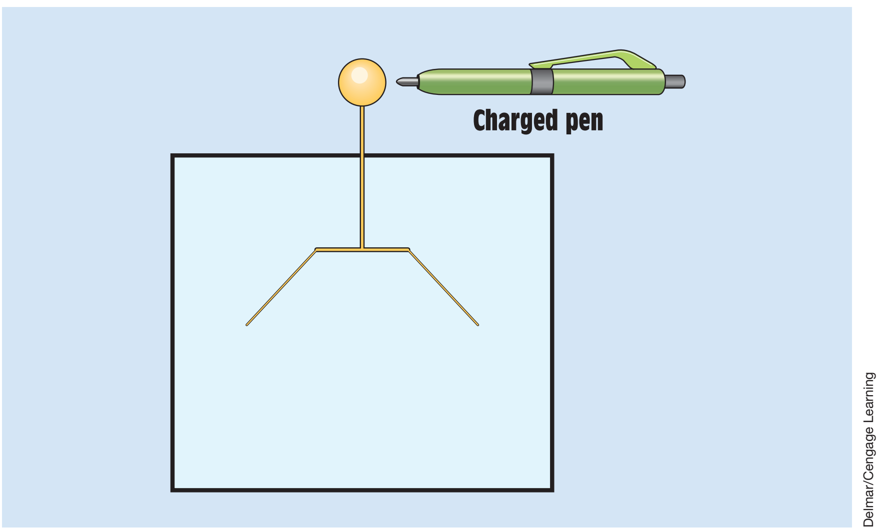

FIGURE 3–7 The leaves are deflected farther apart, indicating that the object has a negative charge.

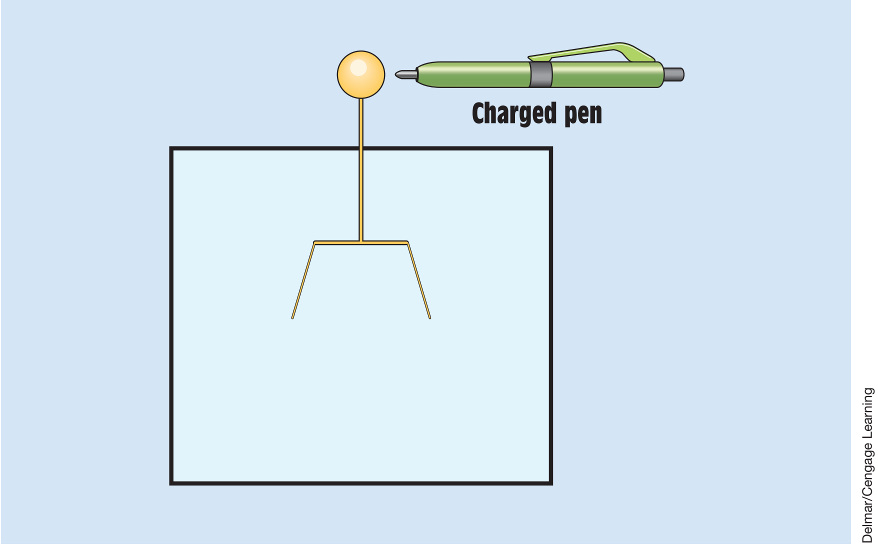

FIGURE 3–8 The leaves move closer together, indicating that the object has a positive charge.

become more negative and to repel each other more, forcing the leaves to move farther apart.

If the pen has a positive charge, the leaves will move closer together when the pen is moved near the ball *(Figure 3–8)*. This action is caused by the positive field of the pen attracting electrons. When electrons are attracted away from the leaves, they become less negative and move closer together. If the electroscope is charged with a positive charge in the beginning, a negatively charged object will cause the leaves to move closer together and a positively charged object will cause the leaves to move farther apart.

3–4 Static Electricity in Nature

When static electricity occurs in nature, it can be harmful. The best example of natural static electricity is **lightning.** A static charge builds up in clouds that contain a large amount of moisture as they move through the air. It is theorized that the movement causes a static charge to build up on the surface of drops of water. Large drops become positively charged, and small drops become negatively charged. *Figure 3–9* illustrates a typical **thundercloud.** Notice that both positive and negative charges can be contained in the same cloud. Most lightning discharges, or **lightning bolts,** occur within the cloud. Lightning discharges can also take place between different clouds, between a

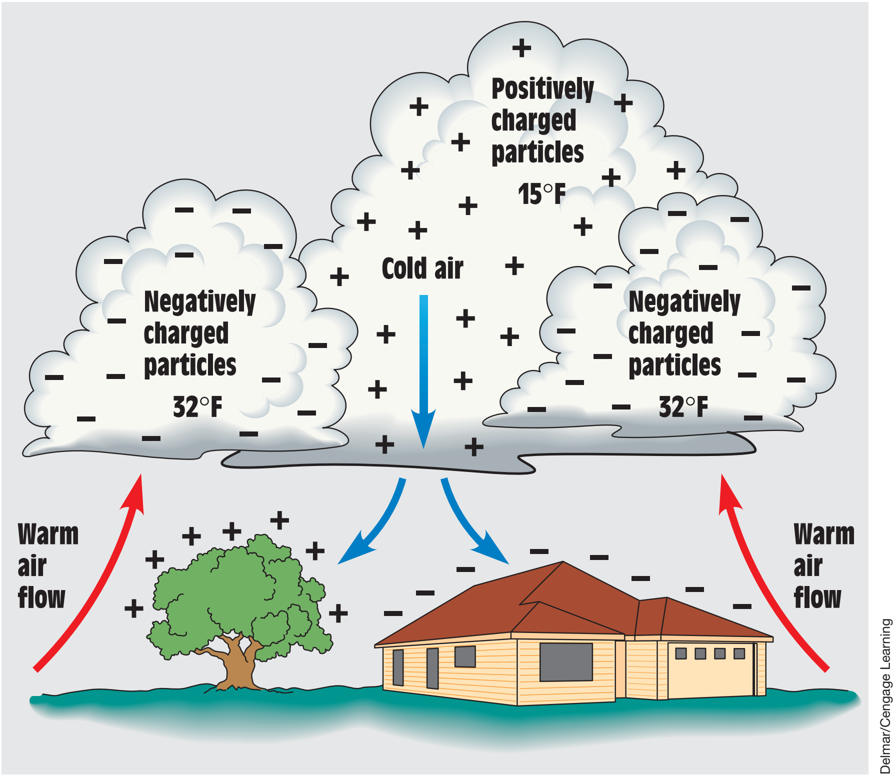

FIGURE 3–9 The typical thundercloud contains both negatively and positively charged particles.

cloud and the ground, and between the ground and the cloud *(Figure 3–10)*. Whether a lightning bolt travels from the cloud to the ground or from the ground to the cloud is determined by which contains the negative and which the positive charge. Current always flows from negative to positive. If a cloud is negative and an object on the ground is positive, the lightning discharge travels from the cloud to the ground. If the cloud has a positive charge and the object on the ground has a negative charge, the discharge travels from the ground to the cloud. A lightning bolt has an average voltage of about 15,000,000 volts.

Lightning Protection

Lightning rods are sometimes used to help protect objects from lightning. Lightning rods work by providing an easy path to ground for current flow. If the protected object is struck by a lightning bolt, the lightning rod bleeds the lightning discharge to ground before the protected object can be harmed *(Figure 3–11)*. Lightning rods were invented by Benjamin Franklin.

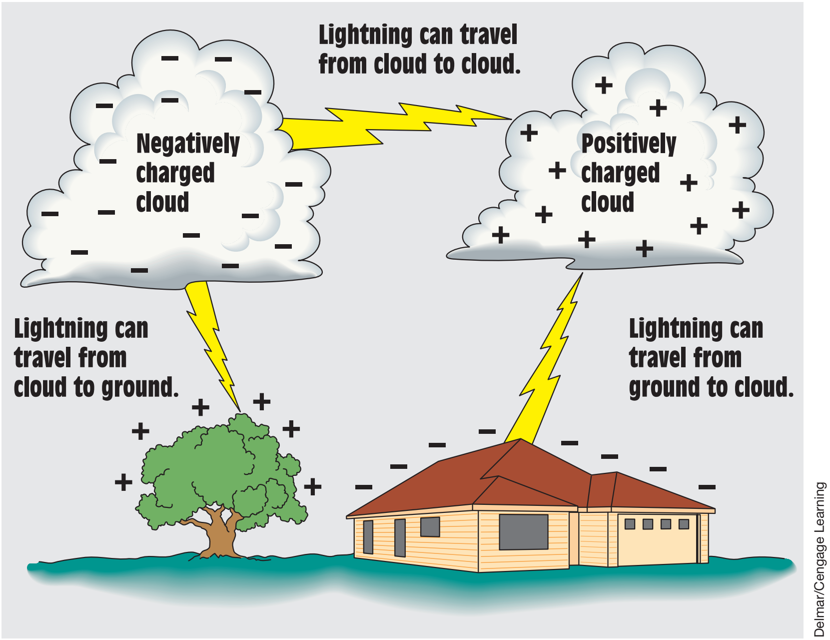

FIGURE 3–10 Lightning travels from negative to positive.

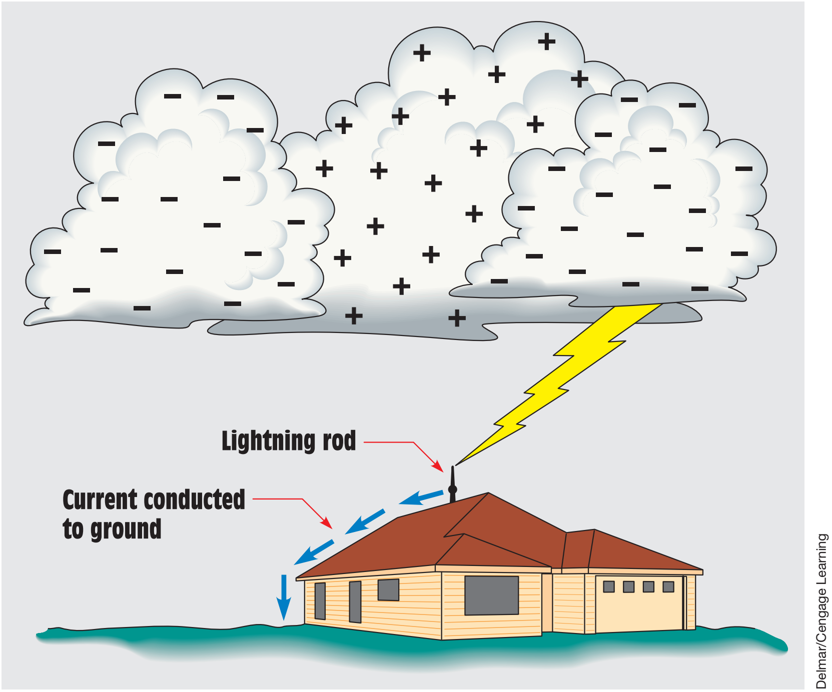

FIGURE 3–11 A lightning rod provides an easy path to ground.

Another device used for lightning protection is the **lightning arrestor.** The lightning arrestor works in a manner very similar to the lightning rod except that it is not designed to be struck by lightning itself and it does not provide a direct path to ground. The lightning arrestor is grounded at one end, and the other end is brought close to but not touching the object to be protected. If the protected object is struck, the high voltage of the lightning arcs across to the lightning arrestor and bleeds to ground.

Power lines are often protected by lightning arrestors that exhibit a very high resistance at the normal voltage of the line. If the power line is struck by lightning, the increase of voltage causes the resistance of the arrestor to decrease and conduct the lightning discharge to ground.

3–5 Nuisance Static Charges

Static charges are sometimes a nuisance. Some examples of **nuisance static charges** are listed here:

1. *The static charge that accumulates on automobiles as they move through dry air*. These static charges can cause dangerous conditions under certain circumstances. For that reason, trucks carrying flammable materials such as gasoline or propane use a drag chain. One end of the drag chain is attached to the frame of the vehicle, and the other end drags the ground. The chain is used to provide a path to ground while the vehicle is moving and to prevent a static charge from accumulating on the body of the vehicle.
2. *The static charge that accumulates on a person's body as he or she walks across a carpet*. This charge can cause a painful shock when a metal object is touched and it discharges in the form of an electric spark. Most carpets are made from man-made materials that are excellent insulators such as nylon. In the winter, the heating systems of most dwellings remove moisture from the air and cause the air to have a low humidity. The dry air combined with an insulating material provides an excellent setting for the accumulation of a static charge. This condition can generally be eliminated by the installation of a humidifier. A simple way to prevent the painful shock of a static discharge is to hold a metal object, such as a key or coin, in one hand. Touch the metal object to a grounded surface, and the static charge will arc from the metal object to ground instead of from your finger to ground.
3. *The static charge that accumulates on clothes in a dryer*. This static charge is caused by the clothes moving through the dry air. The greatest static charges generally are built up on man-made fabrics because they are the best insulators and retain electrons more readily than natural fabrics such as cotton or wool.

3–6 Useful Static Charges

Not all static charges are a nuisance. Some examples of **useful static charges** follow:

1. Static electricity is often used in spray painting. A high-voltage grid is placed in front of the spray gun. This grid has a positive charge. The object to be painted has a negative charge *(Figure 3–12)*. As the droplets of paint pass through the grid, the positive charge causes electrons to be removed from the paint droplets. The positively charged droplets are attracted to the negatively charged object. This static charge helps to prevent waste of the paint and at the same time produces a uniform finish.

2. Another device that depends on static electricity is the dry copy machine. The copy machine uses an aluminum drum coated with **selenium** *(Figure 3–13)*. Selenium is a semiconductor material that changes its conductivity with a change of light intensity. When selenium is in the presence of light, it has a very high conductivity. When it is in darkness, it has a very low conductivity.

A high-voltage wire located near the drum causes the selenium to have a positive charge as it rotates *(Figure 3–14)*. The drum is in darkness when it is charged. An image of the material to be copied is reflected on the drum by

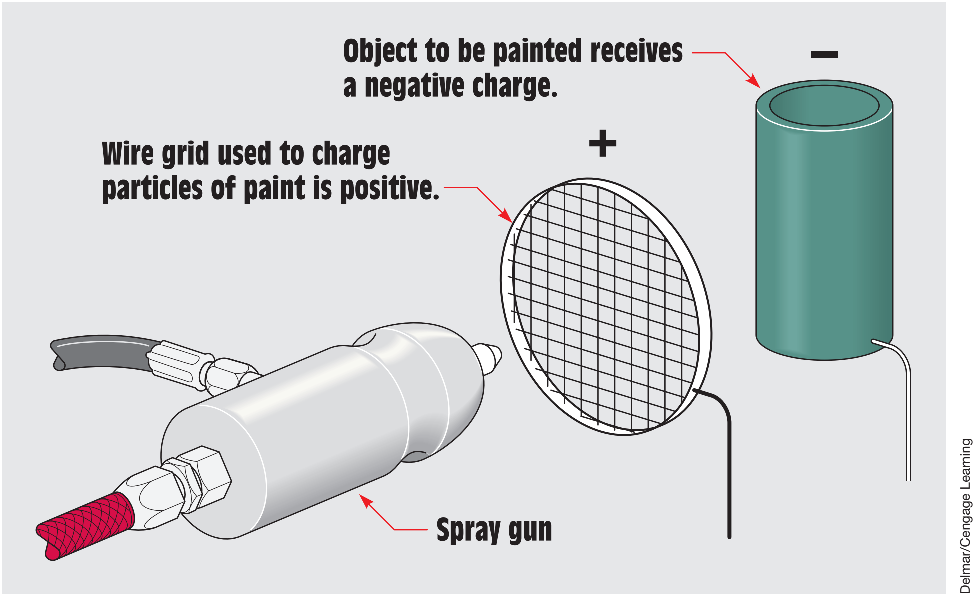

FIGURE 3–12 Static electric charges are often used in spray painting.

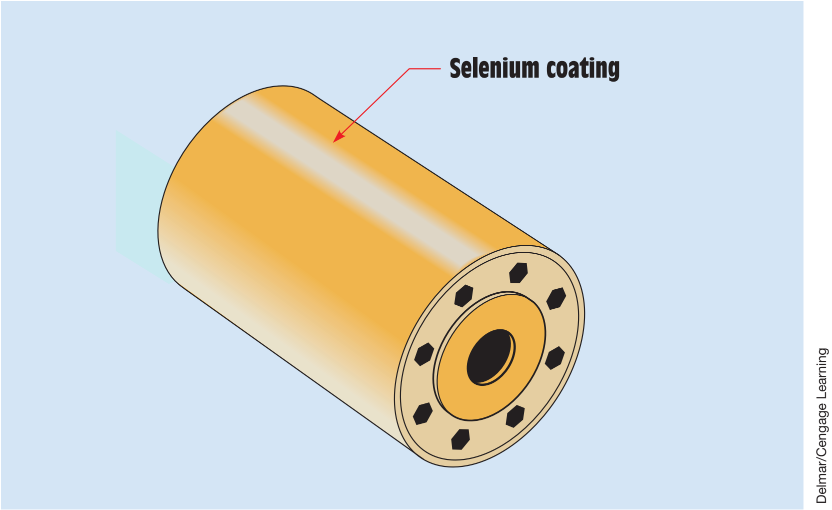

FIGURE 3–13 The drum of a copy machine is coated with selenium.

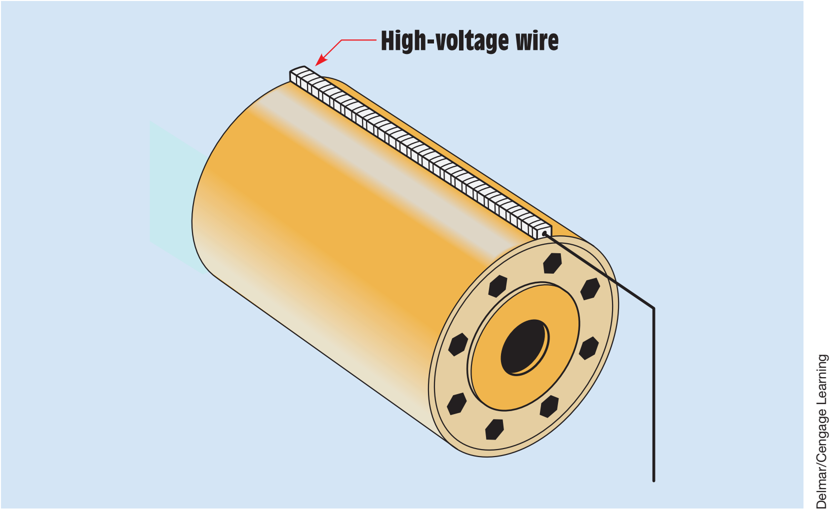

FIGURE 3–14 The drum receives a positive charge.

a system of lenses and mirrors *(Figure 3–15)*. The light portions of the paper reflect more light than the dark portions. When the reflected light strikes the drum, the conductivity of the selenium increases greatly, and negative electrons from the aluminum drum neutralize the selenium charge at that point. The dark area of the paper causes the drum to retain a positive charge.

A dark powder that has a negative charge is applied to the drum *(Figure 3–16)*. The powder is attracted to the positively charged areas on the drum. The powder on the neutral areas of the drum falls away.

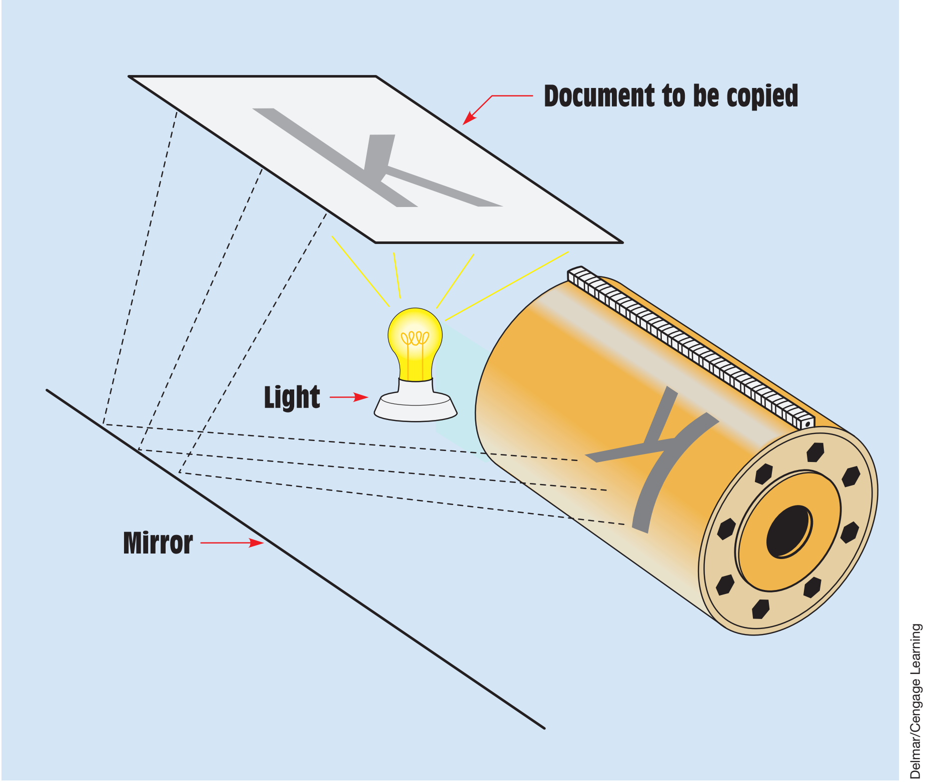

FIGURE 3–15 The image is transferred to the selenium drum.

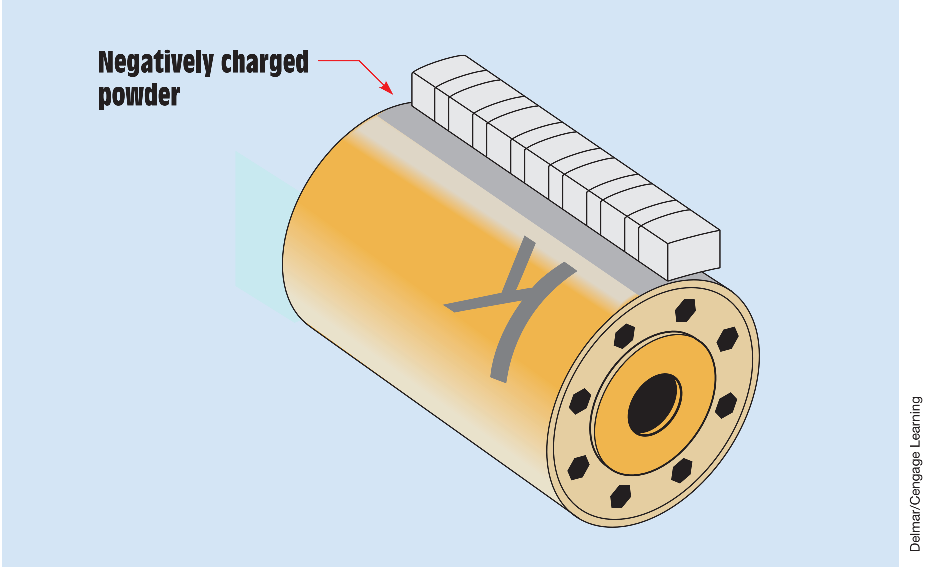

FIGURE 3–16 Negatively charged powder is applied to the positively charged drum.

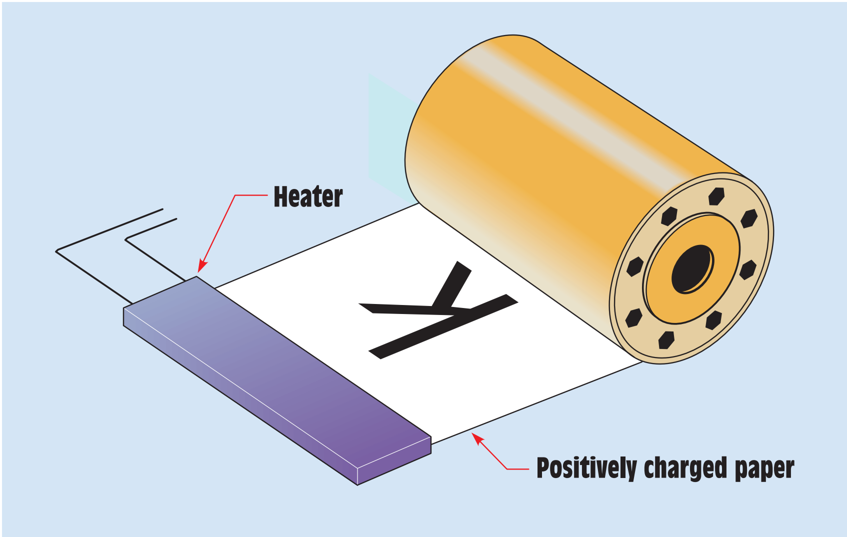

FIGURE 3–17 The negatively charged powder is attracted to the positively charged paper.

A piece of positively charged paper passes under the drum *(Figure 3–17)* and attracts the powder from the drum. The paper then passes under a heating element, which melts the powder into the paper and causes the paper to become a permanent copy of the original.

Summary

- The word *static* means not moving.
- An object can be positively charged by removing electrons from it.
- An object can be negatively charged by adding electrons to it.
- An electroscope is a device used to determine the polarity of an object.
- Static charges accumulate on insulator materials.
- Lightning is an example of a natural static charge.

Review Questions

1. Why is static electricity considered to be a charge and not a current?
2. If electrons are removed from an object, is the object positively or negatively charged?
3. Why do static charges accumulate on insulator materials only?

4. What is an electroscope?
5. An electroscope has been charged with a negative charge. An object with an unknown charge is brought close to the electroscope. The leaves of the electroscope come closer together. Does the object have a positive or a negative charge?
6. Can one thundercloud contain both positive and negative charges?
7. A thundercloud has a negative charge, and an object on the ground has a positive charge. Will the lightning discharge be from the cloud to the ground or from the ground to the cloud?
8. Name two devices used for lightning protection.
9. What type of material is used to coat the aluminum drum of a copy machine?
10. What special property does this material have that makes it useful in a copy machine?

Unit 4
Magnetism

OUTLINE

KEY TERMS

- Ampere-turns
- Demagnetized
- Electromagnets
- Electron spin patterns
- Flux
- Flux density
- Left-hand rule
- Lines of flux
- Lodestones
- Magnetic domains
- Magnetic molecules
- Magnetomotive force (mmf)
- Permanent magnets
- Permeability
- Reluctance
- Residual magnetism
- Saturation

Why You Need to Know

Magnetism and electricity are inseparable. If you have one, the other can be produced. A list of devices that operate on magnetism is almost endless. Everything from a simple compass to the largest electric motor in industry operates on magnetism. This unit presents those basic principles and discusses the most common terms used to measure magnetism:

- flux density.
- reluctance.
- ampere-turns.
- the left-hand rule regarding electromagnets.

These concepts appear many times in the study of electricity.


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Objectives

After studying this unit, you should be able to

- discuss the properties of permanent magnets.
- discuss the difference between the axis poles of the earth and the magnetic poles of the earth.
- discuss the operation of electromagnets.
- determine the polarity of an electromagnet when the direction of the current is known.
- discuss the different systems used to measure magnetism.
- define terms used to describe magnetism and magnetic quantities.

Preview

Magnetism is one of the most important phenomena in the study of electricity. It is the force used to produce most of the electrical power in the world. The force of magnetism has been known for over 2000 years. It was first discovered by the Greeks when they noticed that a certain type of stone was attracted to iron. This stone was first found in Magnesia in Asia Minor and was named magnetite. In the Dark Ages, the strange powers of the magnet were believed to be caused by evil spirits or the devil. ■

4–1 The Earth Is a Magnet

The first compass was invented when it was noticed that a piece of magnetite, a type of stone that is attracted to iron, placed on a piece of wood floating in water always aligned itself north and south *(Figure 4–1)*. Because they are always able to align themselves north and south, natural magnets became known as "leading stones"or **lodestones.** The reason that the lodestone aligned itself north and south is because the earth itself contains magnetic poles. *Figure 4–2* illustrates the positions of the true North and South Poles, or the axis, of the earth and the positions of the magnetic poles. Notice that *magnetic* north is not located at the true North Pole of the earth. This is the reason that navigators must distinguish between true north and magnetic north. The angular difference between the two is known as the *angle of declination*. Although the illustration shows the magnetic lines of force to be only on each side of the earth, the lines actually surround the entire earth like a magnetic shell.

Also notice that the magnetic north pole is located near the southern polar axis and the magnetic south pole is located near the northern polar

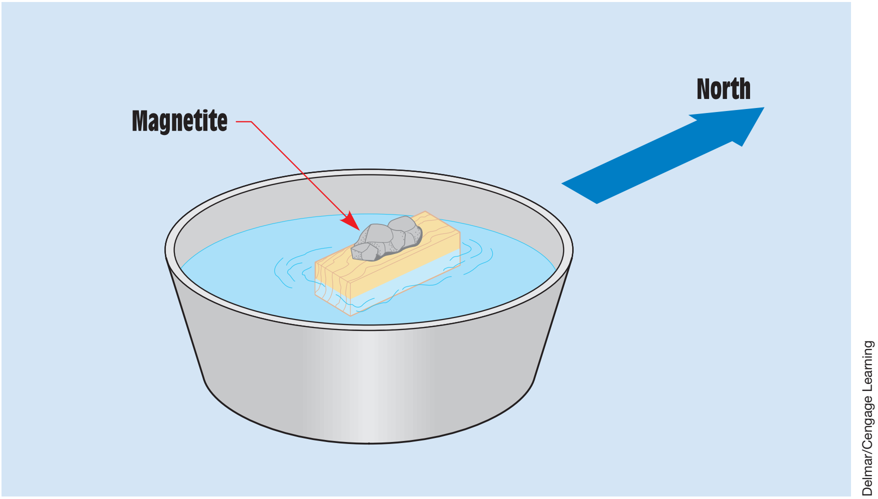

FIGURE 4–1 The first compass.

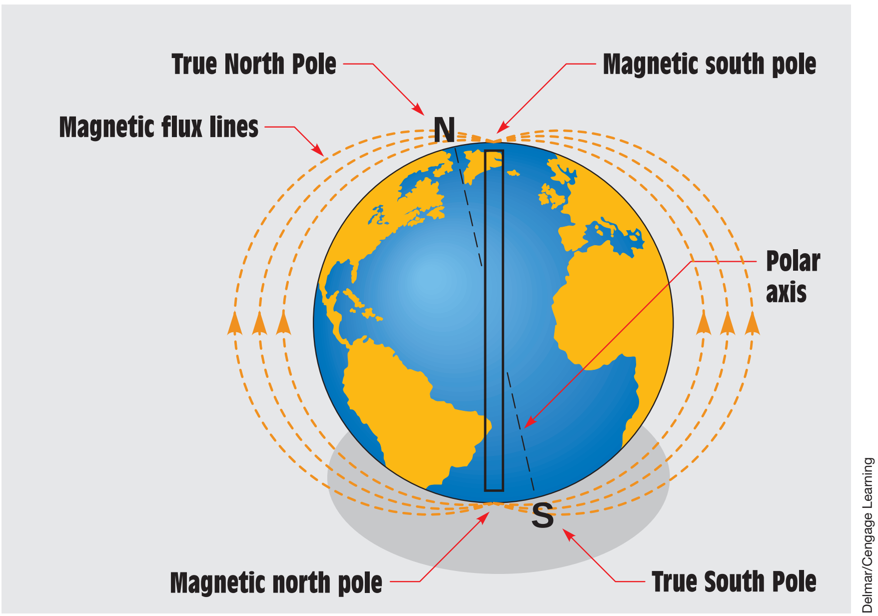

FIGURE 4–2 The earth is a magnet.

axis. The reason that the *geographic* poles (axes) are called north and south is because the north pole of a compass needle points in the direction of the north geographic pole. Because unlike magnetic poles attract, the north magnetic pole of the compass needle is attracted to the south magnetic pole of the earth.

4–2 Permanent Magnets

Permanent magnets are magnets that do not require any power or force to maintain their field. They are an excellent example of one of the basic laws of magnetism that states that ***energy is required to create a magnetic field, but no energy is required to maintain a magnetic field.*** Man-made permanent magnets are much stronger and can retain their magnetism longer than natural magnets.

4–3 The Electron Theory of Magnetism

Only three substances actually form natural magnets: iron, nickel, and cobalt. Why these materials form magnets has been the subject of complex scientific investigations, resulting in an explanation of magnetism based on **electron spin patterns.** It is believed that electrons spin on their axes as they orbit around the nucleus of the atom. This spinning motion causes each electron to become a tiny permanent magnet. Although all electrons spin, they do not all spin in the same direction. In most atoms, electrons that spin in opposite directions tend to form pairs *(Figure 4–3)*. Because the electron pairs spin in opposite directions, their magnetic effects cancel each other out as far as having any effect on distant objects. In a similar manner, two horseshoe magnets connected together would be strongly attracted to each other but would have little effect on surrounding objects *(Figure 4–4)*.

An atom of iron contains 26 electrons. Of these 26, 22 are paired and spin in opposite directions, canceling each other's magnetic effect. In the next to

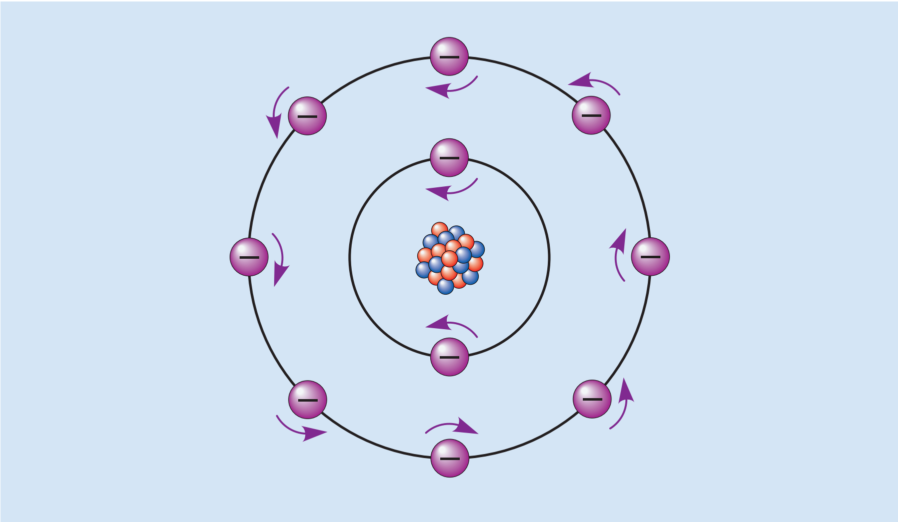
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FIGURE 4–3 Electron pairs generally spin in opposite directions.

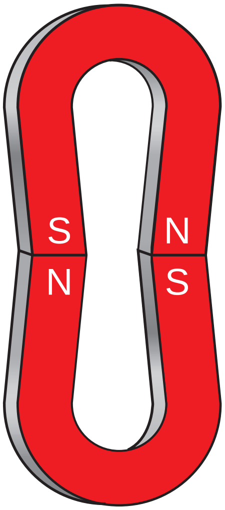

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FIGURE 4–4 Two horseshoe magnets attract each other.

the outermost shell, however, 4 electrons are not paired and spin in the same direction. These 4 electrons account for the magnetic properties of iron. At a temperature of 1420°F, or 771.1°C, the electron spin patterns rearrange themselves and iron loses its magnetic properties.

When the atoms of most materials combine to form molecules, they arrange themselves in a manner that produces a total of eight valence electrons. The electrons form a spin pattern that cancels the magnetic field of the material. When the atoms of iron, nickel, and cobalt combine, however, the magnetic field is not canceled. Their electrons combine so that they share valence electrons in such a way that their spin patterns are in the same direction, causing their magnetic fields to add instead of cancel. The additive effect forms regions in the molecular structure of the metal called **magnetic domains** or **magnetic molecules.** These magnetic domains act like small permanent magnets.

A piece of nonmagnetized metal has its molecules in a state of disarray *(Figure 4–5)*. When the metal is magnetized, its molecules align themselves in an orderly pattern *(Figure 4–6)*. In theory, each molecule of a magnetic

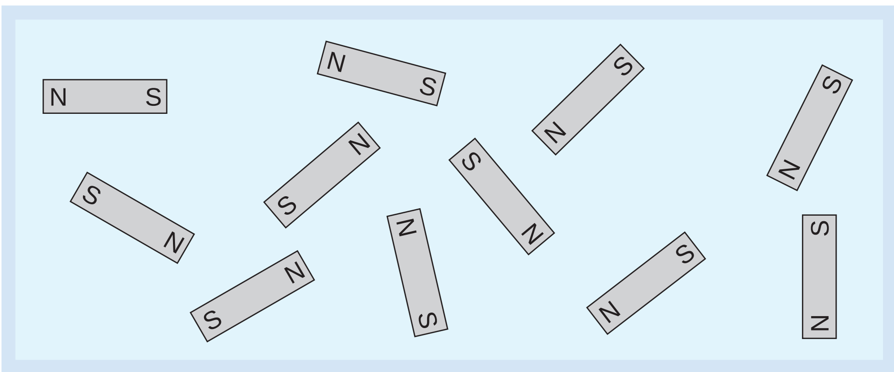

FIGURE 4–5 The atoms are disarrayed in a piece of nonmagnetized metal.

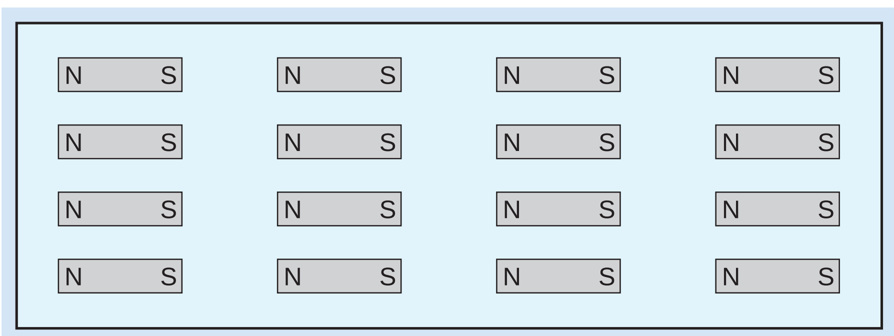

FIGURE 4–6 The atoms are aligned in an orderly fashion in a piece of magnetized metal.

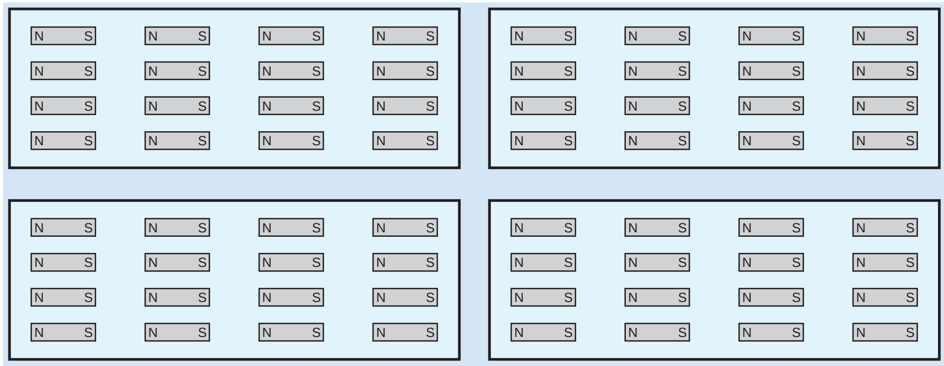

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FIGURE 4–7 When a magnet is cut apart, each piece becomes a separate magnet.

material is itself a small magnet. If a permanent magnet is cut into pieces, each piece is a separate magnet *(Figure 4–7)*.

4–4 Magnetic Materials

Magnetic materials can be divided into three basic classifications:

- *Ferromagnetic materials* are metals that are easily magnetized. Examples of these materials are iron, nickel, cobalt, and manganese.
- *Paramagnetic materials* are metals that can be magnetized, but not as easily as ferromagnetic materials. Some examples of paramagnetic materials are platinum, titanium, and chromium.
- *Diamagnetic materials* are either metal or nonmetal materials that cannot be magnetized. The magnetic lines of force tend to go around them instead of through them. Some examples of these materials are copper, brass, and antimony.

Some of the best materials for the production of permanent magnets are alloys. One of the best permanent magnet materials is Alnico 5, which is made from a combination of aluminum, nickel, cobalt, copper, and iron. Another type of permanent magnet material is made from a combination of barium ferrite and strontium ferrite. Ferrites can have an advantage in some situations because they are insulators and not conductors. They have a resistivity of approximately 1,000,000 ohm-centimeters. Barium ferrite and strontium ferrite can be powdered. The powder is heated to the melting point and then rolled and heat treated. This treatment changes the grain structure and magnetic properties of the material. The new type of material has a property more like stone than metal and is known as a *ceramic magnet*. Ceramic magnets can be powdered and mixed with rubber, plastic, or liquids. Ceramic magnetic materials mixed with liquids can be used to make magnetic ink, which is used on checks. Another frequently used magnetic material is iron oxide, which is used to make magnetic recording tape and computer disks.

4–5 Magnetic Lines of Force

Magnetic lines of force are called **flux.** The symbol used to represent flux is the Greek letter phi (Φ). Flux lines can be seen by placing a piece of cardboard on a magnet and sprinkling iron filings on the cardboard. The filings will align themselves in a pattern similar to the one shown in *Figure 4–8*. The pattern produced by the iron filings forms a two-dimensional figure, but the flux lines actually surround the entire magnet *(Figure 4–9)*. Magnetic **lines of flux** repel each other and never cross. Although magnetic lines of flux do not flow, it is assumed they are in north to south direction.

A basic law of magnetism states that ***unlike poles attract and like poles repel.*** *Figure 4–10* illustrates what happens when a piece of cardboard is placed over two magnets with their north and south poles facing each other and iron filings are sprinkled on the cardboard. The filings form a pattern showing that the magnetic lines of flux are attracted to each other. *Figure 4–11* illustrates the pattern formed by the iron filings when the cardboard is placed over two magnets with like poles facing each other. The filings show that the magnetic lines of flux repel each other.

If the opposite poles of two magnets are brought close to each other, they are attracted to each other *(Figure 4–12)*. If like poles of the two magnets are brought together, they repel each other.

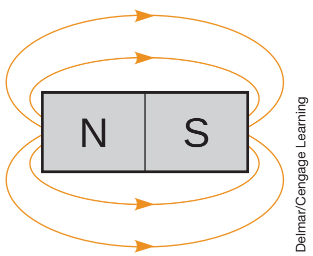

FIGURE 4–8 Magnetic lines of force are called lines of flux.

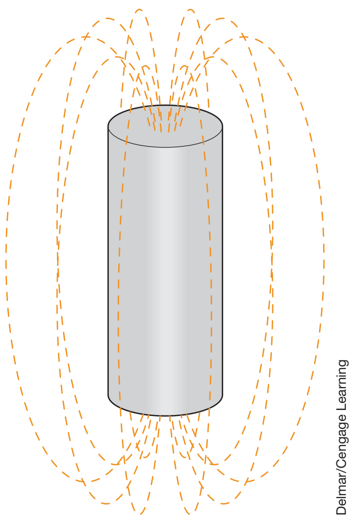

FIGURE 4–9 Magnetic lines of flux surround the entire magnet.

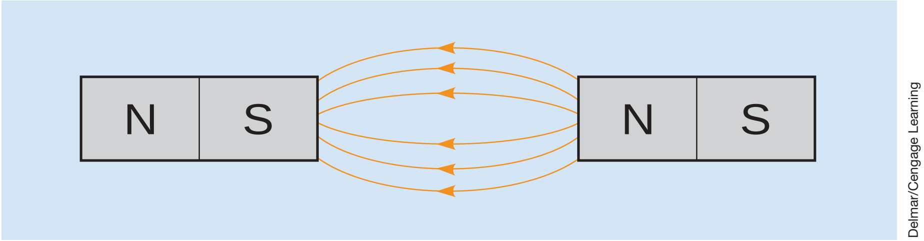

FIGURE 4–10 Opposite magnetic poles attract each other.

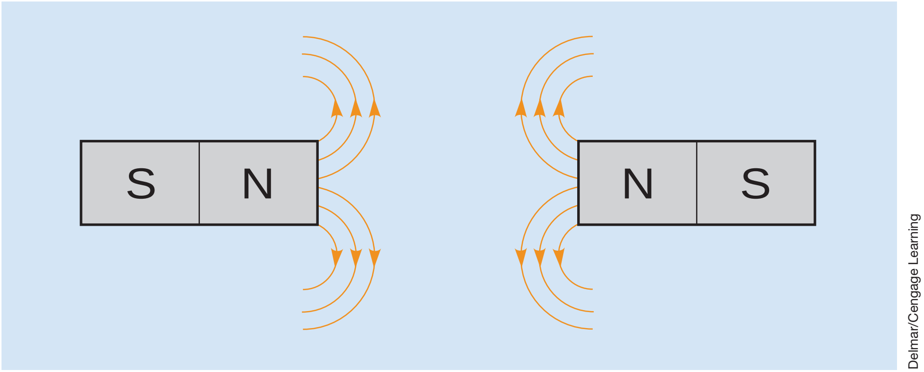

FIGURE 4–11 Like magnetic poles repel each other.

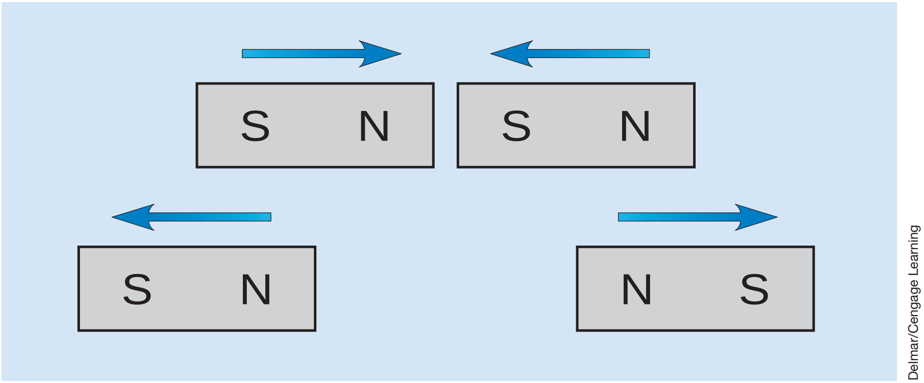

FIGURE 4–12 Opposite poles of a magnet attract, and like poles repel.

4–6 Electromagnetics

A basic law of physics states that ***whenever an electric current flows through a conductor, a magnetic field is formed around the conductor.*** **Electromagnets** depend on electric current flow to produce a magnetic field. They are generally designed to produce a magnetic field only as long as the current is flowing; they do not retain their magnetism when current flow stops. Electromagnets operate on the principle that current flowing through a conductor produces a magnetic field around the conductor *(Figure 4–13)*. If the conductor is wound into a coil *(Figure 4–14)*, the magnetic lines of flux add to produce a stronger magnetic field. A coil with 10 turns of wire produces a magnetic field that is 10 times as strong as the magnetic field around a single conductor.

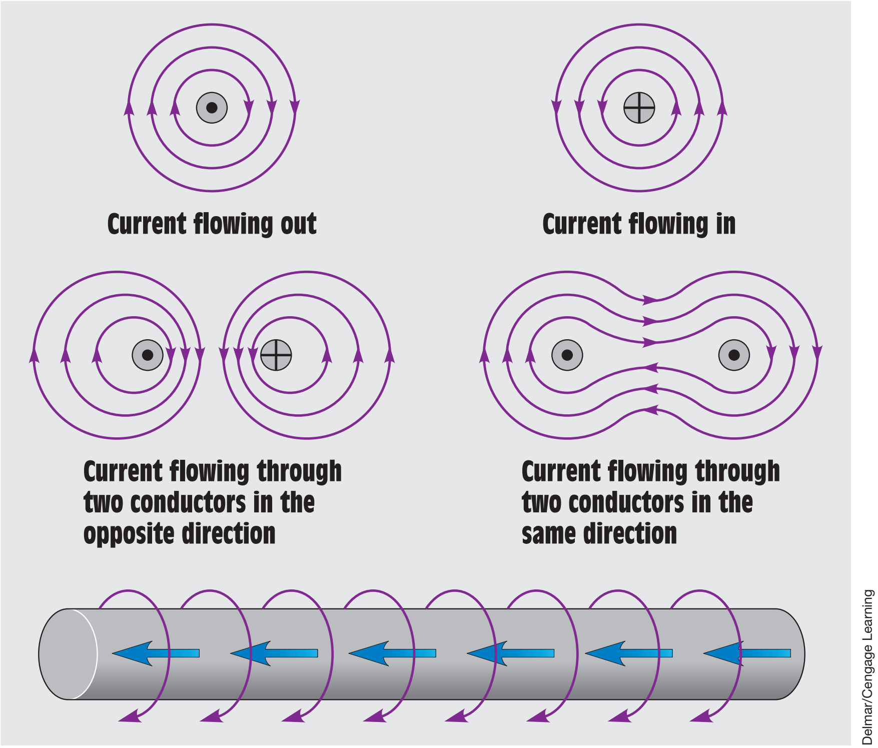

FIGURE 4–13 Current flowing through a conductor produces a magnetic field around the conductor.

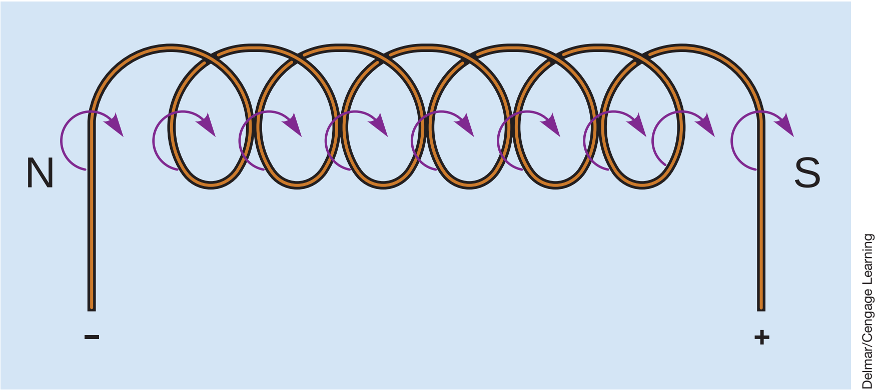

FIGURE 4–14 Winding the wire into a coil increases the strength of the magnetic field.

Another factor that affects the strength of an electromagnetic field is the amount of current flowing through the wire. An increase in current flow causes an increase in magnetic field strength. The two factors that determine the number of flux lines produced by an electromagnet are the number of turns of wire and the amount of current flow through the wire. The strength of an electromagnet is proportional to its **ampere-turns.** Ampere-turns are determined by multiplying the number of turns of wire by the current flow.

Core Material

Coils can be wound around any type of material to form an electromagnet. The base material is called the *core material*. When a coil is wound around a nonmagnetic material such as wood or plastic, it is known as an *air-core magnet*. When a coil is wound around a magnetic material such as iron or soft steel, it is known as an *iron-core magnet*. The addition of magnetic material to the center of the coil can greatly increase the strength of the magnet. If the core material causes the magnetic field to become 10 times stronger, the core material has a **permeability** of 10 *(Figure 4–15)*. Permeability is a measure of a material's ability to become magnetized. The number of flux lines produced is proportional to the ampere-turns. The magnetic core material provides an easy path for the flow of magnetic lines in much the same way a conductor provides an easy path for the flow of electrons. This increased permeability permits the flux lines to be concentrated in a smaller area, which increases the number of flux lines per square inch or per square centimeter. In a similar manner, a person using a garden hose with an adjustable nozzle attached can adjust the nozzle to spray the water in a fine mist that covers a large area or in a concentrated stream that covers a small area.

Another common magnetic measurement is **reluctance.** Reluctance is resistance to magnetism. A material such as soft iron or steel has a high permeability and low reluctance because it is easily magnetized. A material such as copper has a low permeability and high reluctance.

If the current flow in an electromagnet is continually increased, the magnet eventually reaches a point where its strength increases only slightly with an increase in current. When this condition occurs, the magnetic material is at a point of **saturation.** Saturation occurs when all the molecules of the magnetic material are lined up. Saturation is similar to pouring 5 gallons of water into a 5-gallon bucket. Once the bucket is full, it simply cannot hold any more water. If it became necessary to construct a stronger magnet, a larger piece of core material would be required.

When the current flow through the coil of a magnet is stopped, some magnetism may be left in the core material. The amount of magnetism left in a material after the magnetizing force has stopped is called **residual magnetism.** If the residual magnetism of a piece of core material is hard to remove, the

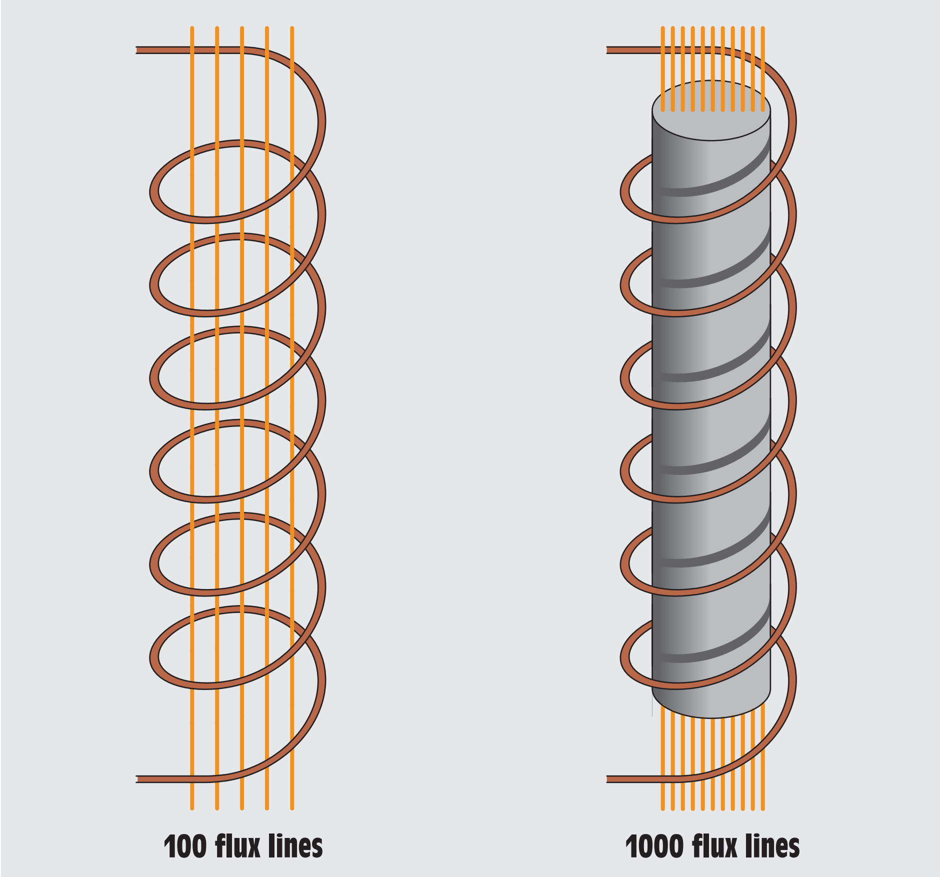

FIGURE 4–15 An iron core increases the number of flux lines per square inch.

material has a high coercive force. *Coercive force* is a measure of a material's ability to retain magnetism. A high coercive force is desirable in materials that are intended to be used as permanent magnets. A low coercive force is generally desirable for materials intended to be used as electromagnets. Coercive force is measured by determining the amount of current flow through the coil in the direction opposite to that required to remove the residual magnetism. Another term that is used to describe a material's ability to retain magnetism is *retentivity*.

4–7 Magnetic Measurement

The terms used to measure the strength of a magnetic field are determined by the system that is being used. Three different systems are used to measure magnetism: the English system, the CGS system, and the MKS or SI system.

The English System

In the English system of measure, magnetic strength is measured in a term called **flux density.** Flux density is measured in lines per square inch. As the Greek letter phi (Φ) is used to measure flux, the letter *B* is used to represent flux density. The following formula is used to determine flux density:

$$\text{B (flux density)} = \frac{\Phi \text{ (flux lines)}}{\text{A (area)}}$$

In the English system, the term used to describe the total force producing a magnetic field, or flux, is **magnetomotive force (mmf).** Magnetomotive force can be computed using the formula

$$\text{mmf} = \Phi \times \text{rel (reluctance)}$$

The following formula can be used to determine the strength of the magnet:

$$\text{Pull (in pounds)} = \frac{\text{B} \times \text{A}}{72{,}000{,}000}$$

where

$$\text{B} = \text{flux density in lines per square inch}$$
$$\text{A} = \text{area of the magnet.}$$

The CGS System

In the CGS (centimeter-gram-second) system of measurement, one magnetic line of force is known as a *maxwell*. A gauss represents a magnetic force of 1 maxwell per square centimeter. In the English or SI system, magnetomotive force is measured in ampere-turns. In the CGS system, gilberts are used to represent the same measurement. Because the main difference between these two systems of measurement is that they use different units of measure, a conversion factor can be employed to help convert one set of units to another:

$$1 \text{ gilbert} = 1.256 \text{ ampere-turns}$$

In the CGS system, a standard called the *unit magnetic pole* is used. In *Figure 4–16,* two magnets are separated by a distance of 1 centimeter. These magnets repel each other with a force of 1 dyne. The dyne is a very weak unit of force. One dyne is equal to $^1/_{27{,}800}$ of an ounce, or it requires

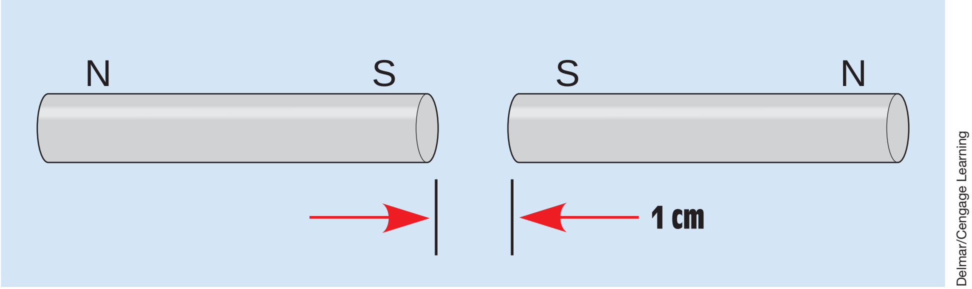

FIGURE 4–16 A unit magnetic pole produces a force of one dyne.

27,800 dynes to equal a force of 1 ounce. When the two magnets separated by a distance of 1 centimeter exert a force of 1 dyne, they are considered to be a unit magnetic pole. Magnetic force can then be determined using the formula

$$\text{Force (in dynes)} = \frac{M_1 \times M_2}{D^2}$$

where

M_1 = strength of first magnet in unit magnetic poles

M_2 = strength of second magnet in unit magnetic poles

D = distance between the poles in centimeters

The MKS or SI System

The MKS or SI system employs the units of measure of the MKS (meter-kilogram-second) system. In the SI system, the unit of force is the newton. One newton is equal to 0.2248 pounds, or it requires 4.448 newtons to equal a force of 1 pound. The weber is used to measure magnetic flux. One weber equals 100,000,000 lines of flux or 10^8 maxwells.

4–8 Magnetic Polarity

The polarity of an electromagnet can be determined using the **left-hand rule.** When the fingers of the left hand are placed around the windings in the direction of electron current flow, the thumb points to the north magnetic pole *(Figure 4–17)*. If the direction of current flow is reversed, the polarity of the magnetic field also reverses.

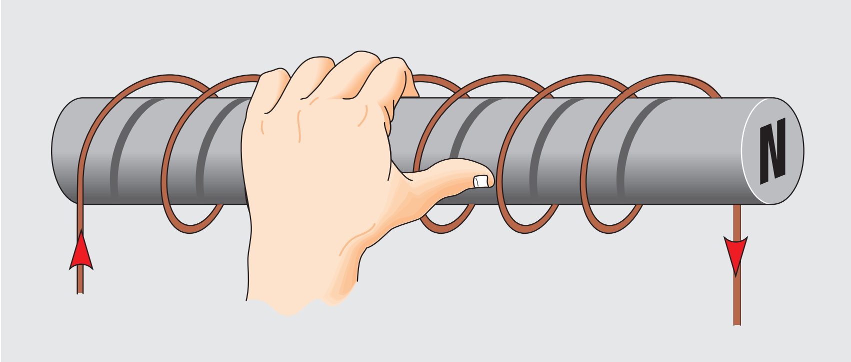

FIGURE 4–17 The left-hand rule can be used to determine the polarity of an electromagnet.

4–9 Demagnetizing

When an object is to be **demagnetized,** its molecules must be disarranged as they are in a nonmagnetized material. This can be done by placing the object in the field of a strong electromagnet connected to an AC line. Because the magnet is connected to AC, the polarity of the magnetic field reverses each time the current changes direction. The molecules of the object to be demagnetized are therefore aligned first in one direction and then in the other. If the object is pulled away from the AC magnetic field, the effect of the field becomes weaker as the object is moved farther away *(Figure 4–18)*. The weakening of the magnetic field causes the molecules of the object to

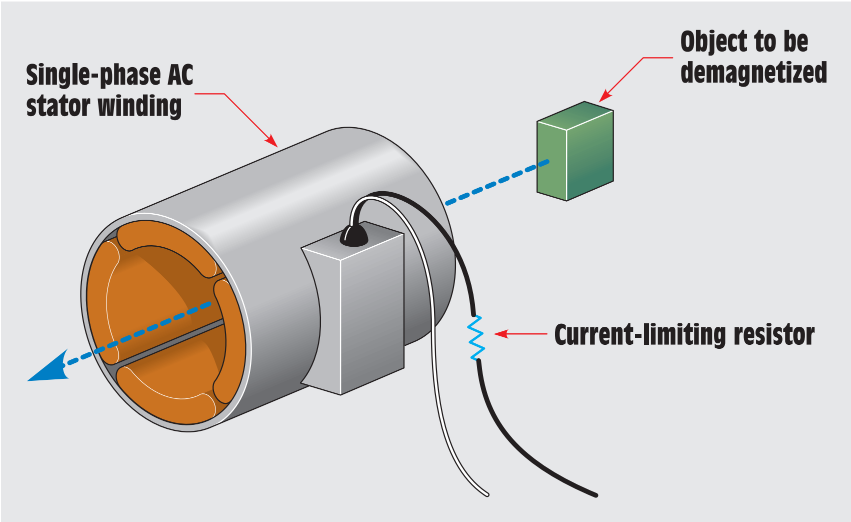

FIGURE 4–18 Demagnetizing an object.

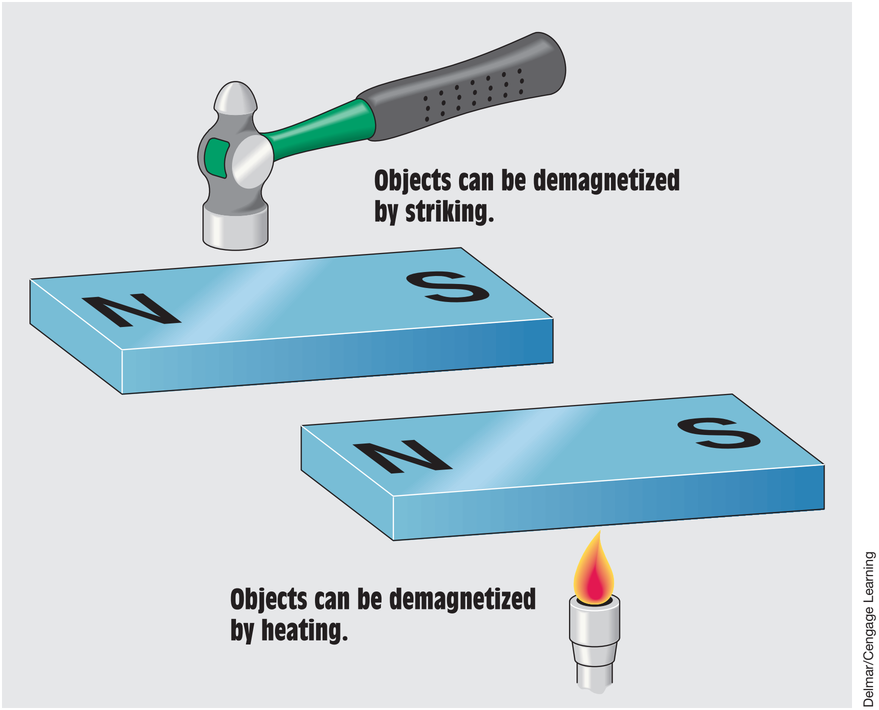

FIGURE 4–19 Other methods for demagnetizing objects.

be left in a state of disarray. The ease or difficulty with which an object can be demagnetized depends on the strength of the AC magnetic field and the coercive force of the object.

An object can be demagnetized in two other ways *(Figure 4–19)*. If a magnetized object is struck, the vibration often causes the molecules to rearrange themselves in a disordered fashion. It may be necessary to strike the object several times. Heating also demagnetizes an object. When the temperature becomes high enough, the molecules rearrange themselves in a disordered fashion.

4–10 Magnetic Devices

A list of devices that operate on magnetism would be very long indeed. Some of the more common devices are electromagnets, measuring instruments, inductors, transformers, and motors.

The Speaker

The speaker is a common device that operates on the principle of magnetism *(Figure 4–20)*. The speaker produces sound by moving a cone; the movement

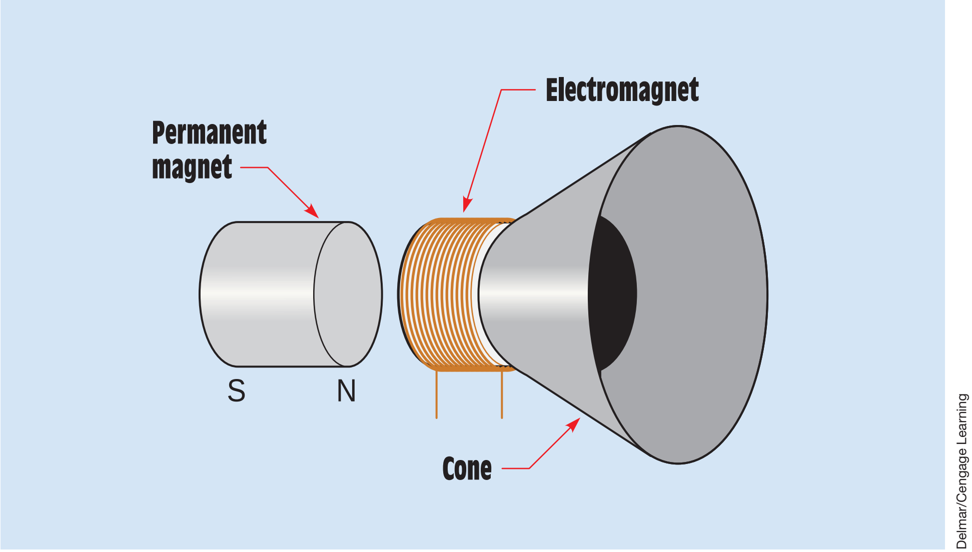

FIGURE 4–20 A speaker uses both an electromagnet and a permanent magnet.

causes a displacement of air. The tone is determined by how fast the cone vibrates. Low or bass sounds are produced by vibrations in the range of 20 cycles per second. High sounds are produced when the speaker vibrates in the range of 20,000 cycles per second.

The speaker uses two separate magnets. One is a permanent magnet, and the other is an electromagnet. The permanent magnet is held stationary, and the electromagnet is attached to the speaker cone. When current flows through the coil of the electromagnet, a magnetic field is produced. The polarity of the field is determined by the direction of current flow. When the electromagnet has a north polarity, it is repelled away from the permanent magnet, causing the speaker cone to move outward and displace air. When the current flow reverses through the coil, the electromagnet has a south polarity and is attracted to the permanent magnet. The speaker cone then moves inward and again displaces air. The number of times per second that the current through the coil reverses determines the tone of the speaker.

Summary

- Early natural magnets were known as lodestones.
- The earth has a north and a south magnetic pole.
- The magnetic poles of the earth and the axes poles are not the same.
- Like poles of a magnet repel each other, and unlike poles attract each other.

- Some materials have the ability to become better magnets than others.
- Three basic types of magnetic material are

  a. Ferromagnetic

  b. Paramagnetic

  c. Diamagnetic
- When current flows through a wire, a magnetic field is created around the wire.
- The direction of current flow through the wire determines the polarity of the magnetic field.
- The strength of an electromagnet is determined by the ampere-turns.
- The type of core material used in an electromagnet can increase its strength.
- Three different systems are used to measure magnetic values:

  a. The English system

  b. The CGS system

  c. The SI system
- An object can be demagnetized by placing it in an AC magnetic field and pulling it away, by striking, and by heating.

Review Questions

1. Is the north magnetic pole of the earth a north polarity or a south polarity?
2. What were early natural magnets known as?
3. The south pole of one magnet is brought close to the south pole of another magnet. Will the magnets repel or attract each other?
4. How can the polarity of an electromagnet be determined if the direction of current flow is known?
5. Define the following terms:

   Flux density
   Permeability
   Reluctance
   Saturation
   Coercive force
   Residual magnetism
6. A force of 1 ounce is equal to how many dynes?

Unit 5
Resistors

Why You Need to Know

Resistors are one of the primary types of electric loads, and electrical theory can be applied through the use of resistors in such formulas as Ohm's law. This concept is required when calculating field requirements and controlling heat in a circuit. It is important to learn how different types of resistors are made and some of the ways they are employed in circuits. To understand resistors, this unit covers

- how the values of different types of resistors are determined.
- how some resistors use bands of color while others employ markings.
- how some resistors are intended to dissipate large amounts of heat and should be mounted a particular way.

OUTLINE

KEY TERMS

Carbon film resistor
Color code
Composition carbon resistor
Fixed resistors
Metal film resistor
Metal glaze resistor
Multiturn variable resistors
Pot
Potentiometer
Rheostat
Short circuit
Tolerance
Variable resistor
Voltage divider
Wire-wound resistors

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Objectives

After studying this unit, you should be able to

- list the major types of fixed resistors.
- determine the resistance of a resistor using the color code.
- determine whether a resistor is operating within its power rating.
- connect a variable resistor for use as a potentiometer.

Preview

Resistors are one of the most common components found in electric circuits. The unit of measure for resistance (R) is the *ohm*, which was named for a German scientist named Georg S. Ohm. The symbol used to represent resistance is the Greek letter omega (Ω). Resistors come in various sizes, types, and ratings to accommodate the needs of almost any circuit applications. ■

5–1 Uses of Resistors

Resistors are commonly used to perform two functions in a circuit. One is to limit the flow of current through the circuit. In *Figure 5–1,* a 30-ohm resistor is connected to a 15-volt battery. The current in this circuit is limited to a value of 0.5 ampere.

$$I = \frac{E}{R}$$

$$I = \frac{15\ V}{30\ \Omega}$$

$$I = 0.5\ A$$

If this resistor were not present, the circuit current would be limited only by the resistance of the conductor, which would be very low, and a large amount of current would flow. Assume, for example, that the wire has a resistance of 0.0001 ohm. When the wire is connected across the 15-volt power source, a current of 150,000 amperes would try to flow through the circuit (15 V/0.0001 Ω = 150,000 A). This is commonly known as a **short circuit.**

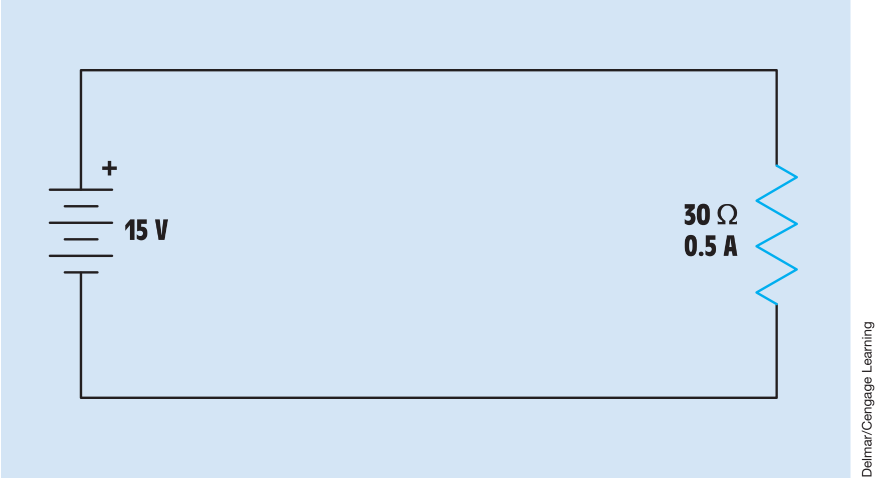


FIGURE 5–1 Resistor used to limit the flow of current.

The second principal function of resistors is to produce a **voltage divider.** The three resistors shown in *Figure 5–2* are connected in series with a 17.5-volt battery. If the leads of a voltmeter were connected between different points in the circuit, it would indicate the following voltages:

A to B, 1.5 V

A to C, 7.5 V

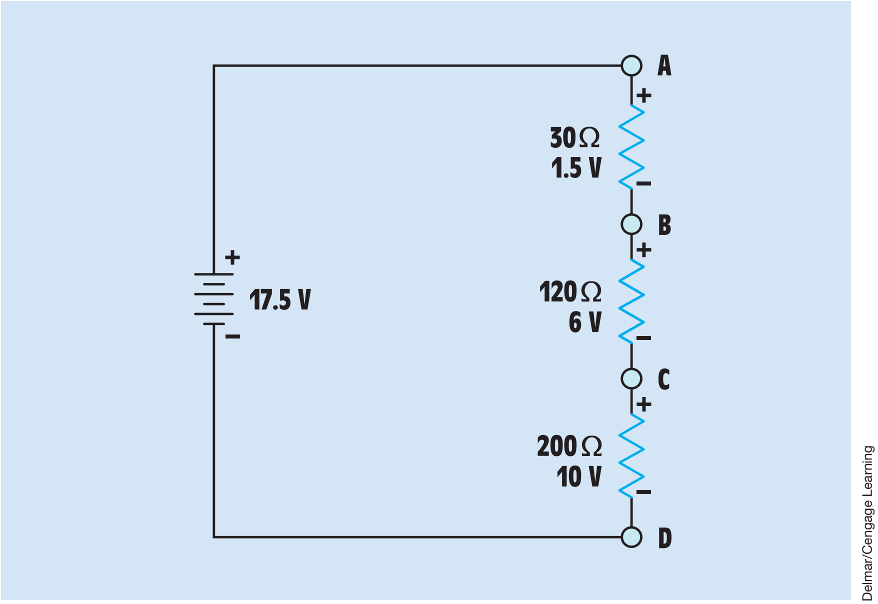


FIGURE 5–2 Resistors used as a voltage divider.

A to D, 17.5 V

B to C, 6 V

B to D, 16 V

C to D, 10 V

By connecting resistors of the proper value, almost any voltage desired can be obtained. Voltage dividers were used to a large extent in vacuum-tube circuits many years ago. Voltage divider circuits are still used today in applications involving field-effect transistors (FETs) and in multirange voltmeter circuits.

5–2 Fixed Resistors

Fixed resistors have only one ohmic value, which cannot be changed or adjusted. There are several different types of fixed resistors. One of the most common types of fixed resistors is the **composition carbon resistor.** Carbon resistors are made from a compound of carbon graphite and a resin bonding material. The proportions of carbon and resin material determine the value of resistance. This compound is enclosed in a case of nonconductive material with connecting leads *(Figure 5–3)*.

Carbon resistors are very popular for most applications because they are inexpensive and readily available. They are made in standard values that range from about 1 ohm to about 22 megohms (MΩ), and they can be obtained in power ratings of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, and 2 watts. The power rating of the resistor is indicated by its size. A $\frac{1}{2}$-watt resistor is approximately $\frac{3}{8}$ inch in length and $\frac{1}{8}$ inch in diameter. A 2-watt resistor has a length of approximately $\frac{11}{16}$ inch

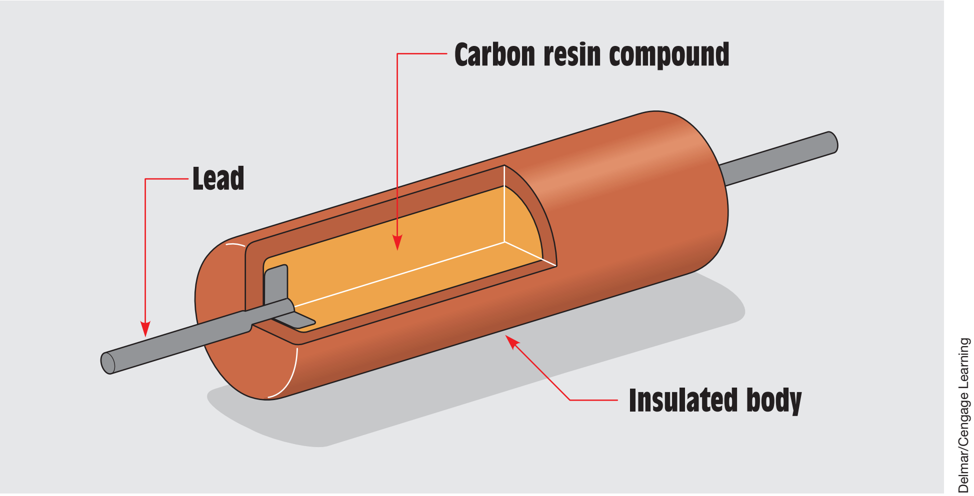


FIGURE 5–3 Composition carbon resistor.

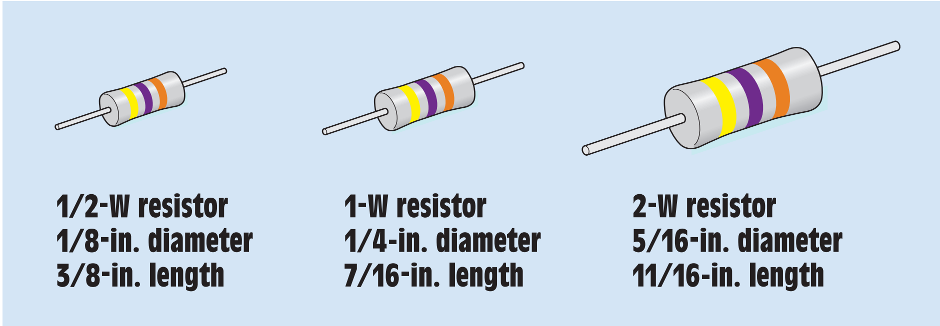


FIGURE 5–4 Power rating is indicated by size.

and a diameter of approximately $\frac{5}{16}$ inch *(Figure 5–4)*. The 2-watt resistor is larger than the ½-watt or 1-watt because it must have a larger surface area to be able to dissipate more heat. Although carbon resistors have a lot of desirable characteristics, they have one characteristic that is not desirable. Carbon resistors will change their value with age or if they are overheated. Carbon resistors generally increase instead of decrease in value.

Metal Film Resistors

Another type of fixed resistor is the **metal film resistor.** Metal film resistors are constructed by applying a film of metal to a ceramic rod in a vacuum *(Figure 5–5)*. The resistance is determined by the type of metal used to form the film and the thickness of the film. Typical thicknesses for the film are

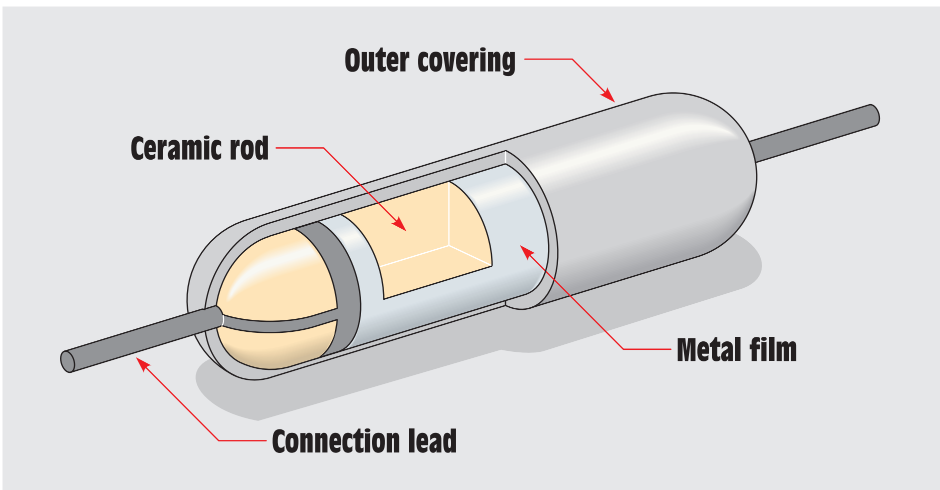


FIGURE 5–5 Metal film resistor.

from 0.00001 to 0.00000001 inch. Leads are then attached to the film coating, and the entire assembly is covered with a coating. These resistors are superior to carbon resistors in several respects. Metal film resistors do not change their value with age, and their **tolerance** is generally better than carbon resistors. Tolerance indicates the plus and minus limits of a resistor's ohmic value. Carbon resistors commonly have a tolerance range of 20%, 10%, or 5%. Metal film resistors generally range in tolerance from 2% to 0.1%. The disadvantage of the metal film resistor is that it costs more.

Carbon Film Resistors

Another type of fixed resistor that is constructed in a similar manner is the **carbon film resistor.** This resistor is made by coating a ceramic rod with a film of carbon instead of metal. Carbon film resistors are less expensive to manufacture than metal film resistors and can have a higher tolerance rating than composition carbon resistors.

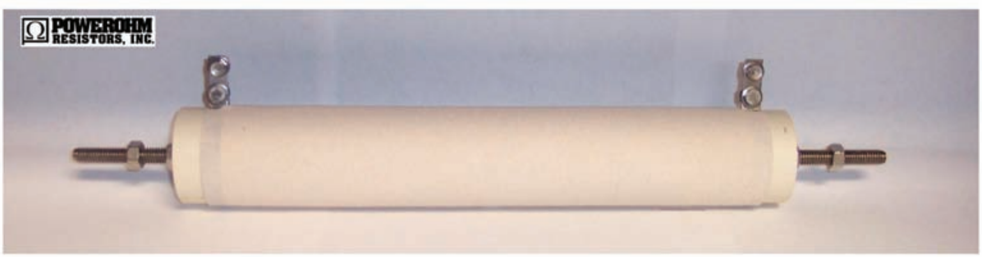
Metal Glaze Resistors

The **metal glaze resistor** is also a fixed resistor, similar to the metal film resistor. This resistor is made by combining metal with glass. The compound is then applied to a ceramic base as a thick film. The resistance is determined by the amount of metal used in the compound. Tolerance ratings of 2% and 1% are common.

Wire-Wound Resistors

Wire-wound resistors are fixed resistors that are made by winding a piece of resistive wire around a ceramic core *(Figure 5–6)*. The resistance of a wire-wound resistor is determined by three factors:

1. the type of material used to make the resistive wire
2. the diameter of the wire
3. the length of the wire



Courtesy of PowerRohm Resistors, Inc.

FIGURE 5–6 Wire-wound resistor.

FIGURE 5–7 Wire-wound resistor with hollow core.

Wire-wound resistors can be found in various case styles and sizes. These resistors are generally used when a high power rating is needed. Wire-wound resistors can operate at higher temperatures than any other type of resistor. A wire-wound resistor that has a hollow center is shown in *Figure 5–7*. This type of resistor should be mounted vertically and not horizontally. The center of the resistor is hollow for a very good reason. When the resistor is mounted vertically, the heat from the resistor produces a chimney effect and causes air to circulate through the center *(Figure 5–8)*. This increase of airflow dissipates heat at a faster rate to help keep the resistor from overheating. The disadvantage of wire-wound resistors is that they are expensive and generally require a large amount of space for mounting. They can also exhibit an amount of inductance in circuits that operate at high frequencies. This added inductance can cause problems to the rest of the circuit. Inductance is covered in later units.

5–3 Color Code

The value of a resistor can often be determined by the **color code.** Many resistors have bands of color that are used to determine the resistance value, tolerance, and in some cases reliability. The color bands represent numbers. Each color represents a different numerical value *(Table 5–1)*. The chart shown in *Figure 5–9* lists the color and the number value assigned to each color. The resistor shown beside the color chart illustrates how to determine the value of a resistor. Resistors can have from three to five bands of color. Resistors that have a tolerance of ±20% have only three color bands. Most resistors contain four bands of color. For resistors with tolerances that range from ±10% to ±2%, the first two color bands represent number values. The third color band is the multiplier. This means to combine the first two numbers and multiply the resulting two-digit number by the power of 10 indicated by the value of the third band. The fourth band indicates the tolerance. For example, assume a resistor has

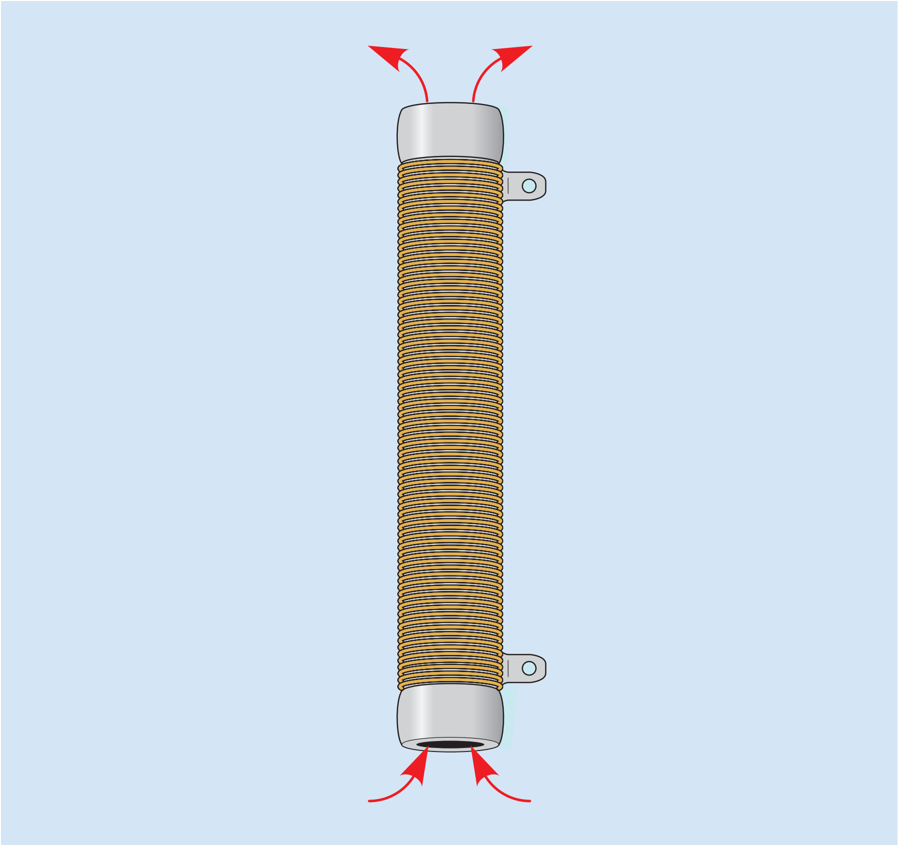


FIGURE 5–8 Airflow helps cool the resistor.

Color	Value	Tolerance
Black	0	No color ± 20%
Brown	1	Silver ± 10%
Red	2	Gold ± 5%
Orange	3	Red ± 2%
Yellow	4	Brown ± 1%
Green	5	
Blue	6	
Violet	7	
Gray	8	
White	9	

TABLE 5–1 Colors and Numeric Values.

First Band	Second Band	Multiplier Band	Resistance Ω
Brown	Black	Black	10
		Brown	100
		Red	1000
		Orange	10000
		Yellow	0.1 Meg.
		Green	1.0 Meg.
		Blue	10.0 Meg.
	Brown	Black	11
		Brown	110
		Red	1100
		Orange	11000
		Yellow	0.11 Meg.
		Green	1.1 Meg.
		Blue	11.0 Meg.
	Red	Black	12
		Brown	120
		Red	1200
		Orange	12000
		Yellow	0.12 Meg.
		Green	1.2 Meg.
		Blue	12.0 Meg.
	Orange	Black	13
		Brown	130
		Red	1300
		Orange	13000
		Yellow	0.13 Meg.
		Green	1.3 Meg.
		Blue	13.0 Meg.
	Green	Black	15
		Brown	150
		Red	1500
		Orange	15000
		Yellow	0.15 Meg.
		Green	1.5 Meg.
		Blue	15.0 Meg.
	Blue	Black	16
		Brown	160
		Red	1600
		Orange	16000
		Yellow	0.16 Meg.
		Green	1.6 Meg.
		Blue	16.0 Meg.
	Gray	Black	18
		Brown	180
		Red	1800
		Orange	18000
		Yellow	0.18 Meg.
		Green	1.8 Meg.
		Blue	18.0 Meg.

First Band	Second Band	Multiplier Band	Resistance Ω
Yellow	Orange	Gold	4.3
		Black	43
		Brown	430
		Red	4300
		Orange	43000
		Yellow	0.43 Meg.
		Green	4.3 Meg.
	Violet	Gold	4.7
		Black	47
		Brown	470
		Red	4700
		Orange	47000
		Yellow	0.47 Meg.
		Green	4.7 Meg.
Green	Brown	Gold	5.1
		Black	51
		Brown	510
		Red	5100
		Orange	51000
		Yellow	0.51 Meg.
		Green	5.1 Meg.
	Blue	Gold	5.6
		Black	56
		Brown	560
		Red	5600
		Orange	56000
		Yellow	0.56 Meg.
		Green	5.6 Meg.
Blue	Red	Gold	6.2
		Black	62
		Brown	620
		Red	6200
		Orange	62000
		Yellow	0.62 Meg.
		Green	6.2 Meg.
	Gray	Gold	6.8
		Black	68
		Brown	680
		Red	6800
		Orange	68000
		Yellow	0.68 Meg.
		Green	6.8 Meg.
Violet	Green	Gold	7.5
		Black	75
		Brown	750
		Red	7500
		Orange	75000
		Yellow	0.75 Meg.
		Green	7.5 Meg.
Gray	Red	Gold	8.2
		Black	82
		Brown	820
		Red	8200
		Orange	82000
		Yellow	0.82 Meg.
		Green	8.2 Meg.
White	Brown	Gold	9.1
		Black	91
		Brown	910
		Red	9100
		Orange	91000
		Yellow	0.91 Meg.
		Green	9.1 Meg.

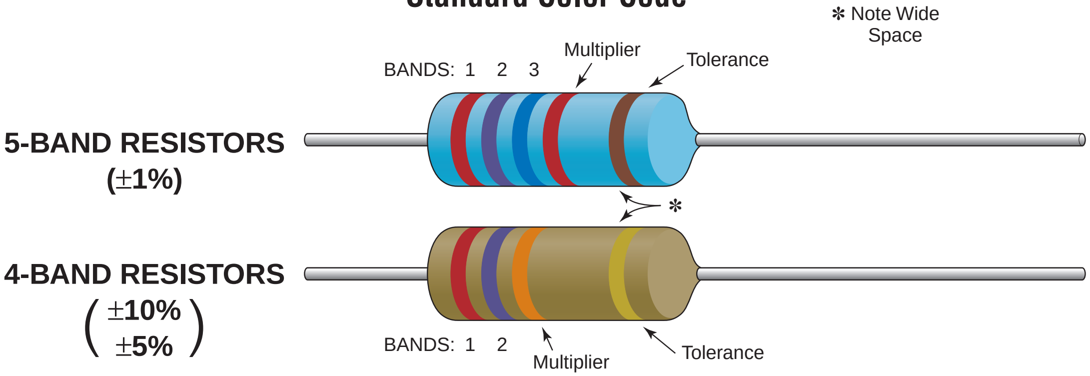
Courtesy of Heathkit Educational Systems

FIGURE 5–9 Resistor color code chart.

First Band	Second Band	Multiplier Band	Resistance Ω
Red	Black	Black	20
		Brown	200
		Red	2000
		Orange	20000
		Yellow	0.2 Meg.
		Green	2.0 Meg.
		Blue	20.0 Meg.
	Red	Black	22
		Brown	220
		Red	2200
		Orange	22000
		Yellow	0.22 Meg.
		Green	2.2 Meg.
		Blue	22.0 Meg.
	Yellow	Black	24
		Brown	240
		Red	2400
		Orange	24000
		Yellow	0.24 Meg.
		Green	2.4 Meg.
	Violet	Gold	2.7
		Black	27
		Brown	270
		Red	2700
		Orange	27000
		Yellow	0.27 Meg.
		Green	2.7 Meg.

First Band	Second Band	Multiplier Band	Resistance Ω
Orange	Black	Gold	3.0
		Black	30
		Brown	300
		Red	3000
		Orange	30000
		Yellow	0.30 Meg.
		Green	3.0 Meg.
	Orange	Gold	3.3
		Black	33
		Brown	330
		Red	3300
		Orange	33000
		Yellow	0.33 Meg.
		Green	3.3 Meg.
	Blue	Gold	3.6
		Black	36
		Brown	360
		Red	3600
		Orange	36000
		Yellow	0.36 Meg.
		Green	3.6 Meg.
	White	Gold	3.9
		Black	39
		Brown	390
		Red	3900
		Orange	39000
		Yellow	0.39 Meg.
		Green	3.9 Meg.

Standard Color Code



Band 1 1st Digit	
Color	Digit
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Band 2 2nd Digit	
Color	Digit
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Band 3 (if used) 3rd Digit	
Color	Digit
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Multiplier	
Color	Multiplier
Black	1
Brown	10
Red	100
Orange	1,000
Yellow	10,000
Green	100,000
Blue	1,000,000
Silver	0.01
Gold	0.1

Resistance Tolerance	
Color	Tolerance
Silver	± 10%
Gold	± 5%
Brown	± 1%

FIGURE 5–9 Continued.

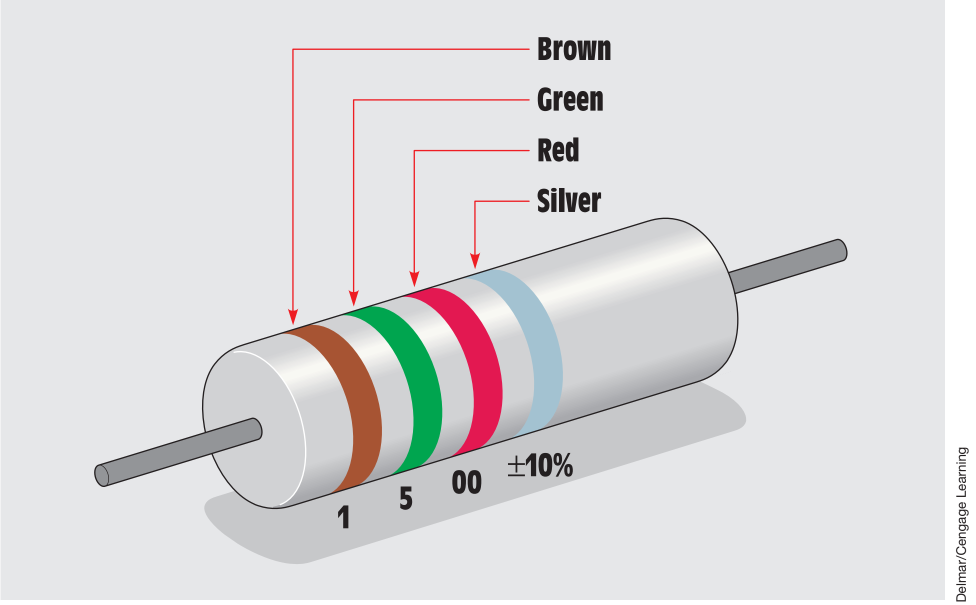


FIGURE 5–10 Determining resistor values using the color code.

color bands of brown, green, red, and silver *(Figure 5–10)*. The first two bands represent the numbers 1 and 5 (brown is 1 and green is 5). The third band is red, which has a number value of 2. The number 15 should be multiplied by 10^2, or 100. The value of the resistor is 1500 ohm. Another method, which is simpler to understand, is to add the number of zeros indicated by the multiplier band to the combined first two numbers. The multiplier band in this example is red, which has a numeric value of 2. Add two zeros to the first two numbers. The number 15 becomes 1500.

The fourth band is the tolerance band. The tolerance band in this example is silver, which means ±10%. This resistor should be 1500 ohm plus or minus 10%. To determine the value limits of this resistor, find 10% of 1500 ohm:

$$1500\ \Omega \times 0.10 = 150\ \Omega$$

The value can range from 1500 Ω + 10%, or 1500 Ω + 150 Ω = 1650 Ω, to 1500 Ω − 10% or 1500 Ω − 150 Ω = 1350 Ω.

Resistors that have a tolerance of ±1%, as well as some military resistors, contain five bands of color.

Gold and Silver as Multipliers

The colors gold and silver are generally found in the fourth band of a resistor, but they can be used in the multiplier band also. When the color gold is used

EXAMPLE 5-1

The resistor shown in *Figure 5–11* contains the following bands of color:

First band = brown

Second band = black

Third band = black

Fourth band = brown

Fifth band = brown

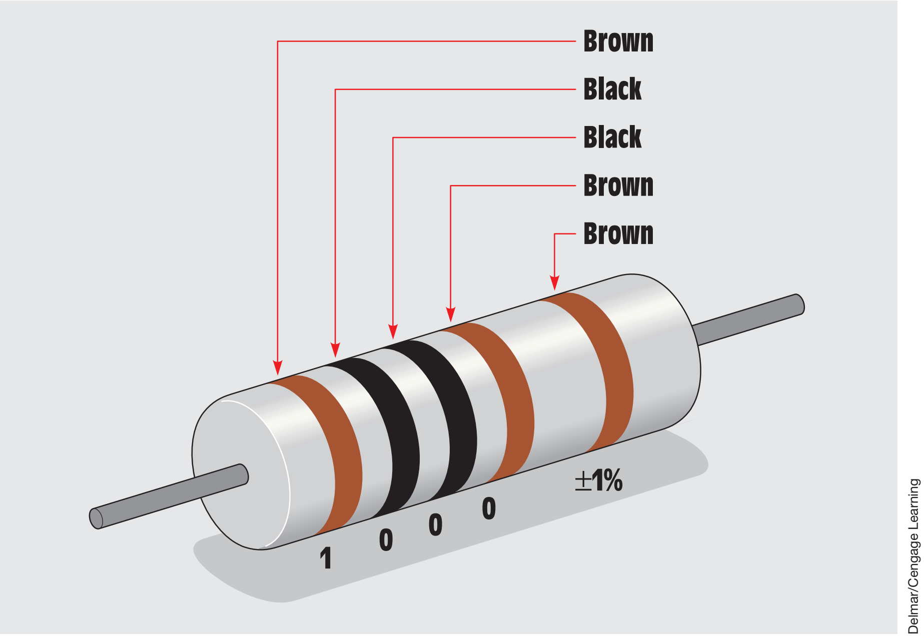


FIGURE 5–11 Determining the value of a ±1% resistor.

Solution

The brown fifth band indicates that this resistor has a tolerance of ±1%. To determine the value of a 1% resistor, the first three bands are numbers, and the fourth band is the multiplier. In this example, the first band is brown, which has a number value of 1. The next two bands are black, which represents a number value of 0. The fourth band is brown, which means add one 0 to the first three numbers. The value of this resistor is 1000 Ω ±1%.

EXAMPLE 5-2

A five-band resistor has the following color bands:

First band = red

Second band = orange

Third band = violet

Fourth band = red

Fifth band = brown

Solution

The first three bands represent number values. Red is 2, orange is 3, and violet is 7. The fourth band is the multiplier; in this case, red represents 2. Add two zeros to the number 237. The value of the resistor is 23,700 Ω. The fifth band is brown, which indicates a tolerance of ±1%.

Military resistors often have five bands of color also. These resistors are read in the same manner as a resistor with four bands of color. The fifth band can represent different things. A fifth band of orange or yellow is used to indicate reliability. Resistors with a fifth band of orange have a reliability good enough to be used in missile systems, and a resistor with a fifth band of yellow can be used in space-flight equipment. A military resistor with a fifth band of white indicates the resistor has solderable leads.

Resistors with tolerance ratings ranging from 0.5% to 0.1% generally have their values printed directly on the resistor.

as the multiplier band, it means to divide the combined first two numbers by 10. If silver is used as the multiplier band, it means to divide the combined first two numbers by 100. For example, assume a resistor has color bands of orange, white, gold, and gold. The value of this resistor is 3.9 ohm with a tolerance of ±5% (orange = 3; white = 9; gold means to divide 39 by 10 = 3.9; and gold in the fourth band means ±5% tolerance).

5–4 Standard Resistance Values of Fixed Resistors

Fixed resistors are generally produced in standard values. The higher the tolerance value, the fewer resistance values available. Standard resistor values are listed in the chart shown in *Figure 5–12*. In the column under 10%, only

STANDARD RESISTANCE VALUES (Ω)									
0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%	0.1% 0.25% 0.5%	1%
10.0	10.0	17.2	–	29.4	29.4	50.5	–	86.6	86.6
10.1	–	17.4	17.4	29.8	–	51.1	51.1	87.6	–
10.2	10.2	17.6	–	30.1	30.1	51.7	–	88.7	88.7
10.4	–	17.8	17.8	30.5	–	52.3	52.3	89.8	–
10.5	10.5	18.0	–	30.9	30.9	53.0	–	90.9	90.9
10.6	–	18.2	18.2	31.2	–	53.6	53.6	92.0	–
10.7	10.7	18.4	–	31.6	31.6	54.2	–	93.1	93.1
10.9	–	18.7	18.7	32.0	–	54.9	54.9	94.2	–
11.0	11.0	18.9	–	32.4	32.4	55.6	–	95.3	95.3
11.1	–	19.1	19.1	32.8	–	56.2	56.2	96.5	–
11.3	11.3	19.3	–	33.2	33.2	56.9	–	97.6	97.6
11.4	–	19.6	19.6	33.6	–	57.6	57.6	98.8	–
11.5	11.5	19.8	–	34.0	34.0	58.3	–		
11.7	–	20.0	20.0	34.4	–	59.0	59.0		
11.8	11.8	20.3	–	34.8	34.8	59.7	–		
12.0	–	20.5	20.5	35.2	–	60.4	60.4		
12.1	12.1	20.8	–	35.7	35.7	61.2	–		
12.3	–	21.0	21.0	36.1	–	61.9	61.9		
12.4	12.4	21.3	–	36.5	36.5	62.6	–		
12.6	–	21.5	21.5	37.0	–	63.4	63.4		
12.7	12.7	21.8	–	37.4	37.4	64.2	–	2%,5%	10%
12.9	–	22.1	22.1	37.9	–	64.9	64.9	10	10
13.0	13.0	22.3	–	38.3	38.3	65.7	–	11	–
13.2	–	22.6	22.6	38.8	–	66.5	66.5	12	12
13.3	13.3	22.9	–	39.2	39.2	67.3	–	13	–
13.5	–	23.2	23.2	39.7	–	68.1	68.1	15	15
13.7	13.7	23.4	–	40.2	40.2	69.0	–	16	–
13.8	–	23.7	23.7	40.7	–	69.8	69.8	18	18
14.0	14.0	24.0	–	41.2	41.2	70.6	–	20	–
14.2	–	24.3	24.3	41.7	–	71.5	71.5	22	22
14.3	14.3	24.6	–	42.2	42.2	72.3	–	24	–
14.5	–	24.9	24.9	42.7	–	73.2	73.2	27	27
14.7	14.7	25.2	–	43.2	43.2	74.1	–	30	–
14.9	–	25.5	25.5	43.7	–	75.0	75.0	33	33
15.0	15.0	25.8	–	44.2	44.2	75.9	–	36	–
15.2	–	26.1	26.1	44.8	–	76.8	76.8	39	39
15.4	15.4	26.4	–	45.3	45.3	77.7	–	43	–
15.6	–	26.7	26.7	45.9	–	78.7	78.7	47	47
15.8	15.8	27.1	–	46.4	46.4	79.6	–	51	–
16.0	–	27.4	27.4	47.0	–	80.6	80.6	56	56
16.2	16.2	27.7	–	47.5	47.5	81.6	–	62	–
16.4	–	28.0	28.0	48.1	–	82.5	82.5	68	68
16.5	16.5	28.4	–	48.7	48.7	83.5	–	75	–
16.7	–	28.7	28.7	49.3	–	84.5	84.5	82	82
16.9	16.9	29.1	–	49.9	49.9	85.6	–	91	–

Delmar/Cengage Learning

FIGURE 5–12 Standard resistance values.

12 values of resistors are listed. These standard values, however, can be multiplied by factors of 10. Notice that one of the standard values listed is 33 ohm. There are also standard values in 10% resistors of 0.33, 3.3, 330, 3300, 33,000, 330,000, and 3,300,000 ohm. The 2% and 5% column shows 24 resistor values, and the 1% column list 96 values. All the values listed in the chart can be multiplied by factors of 10 to obtain other resistance values.

5–5 Power Ratings

Resistors also have a power rating in watts that should not be exceeded or the resistor will be damaged. The amount of heat that must be dissipated by (given off to the surrounding air) the resistor can be determined by the use of one of the following formulas:

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

$$P = EI$$

EXAMPLE 5–3

The resistor shown in *Figure 5–13* has a value of 100 Ω and a power rating of ½ W. If the resistor is connected to a 10-V power supply, will it be damaged?

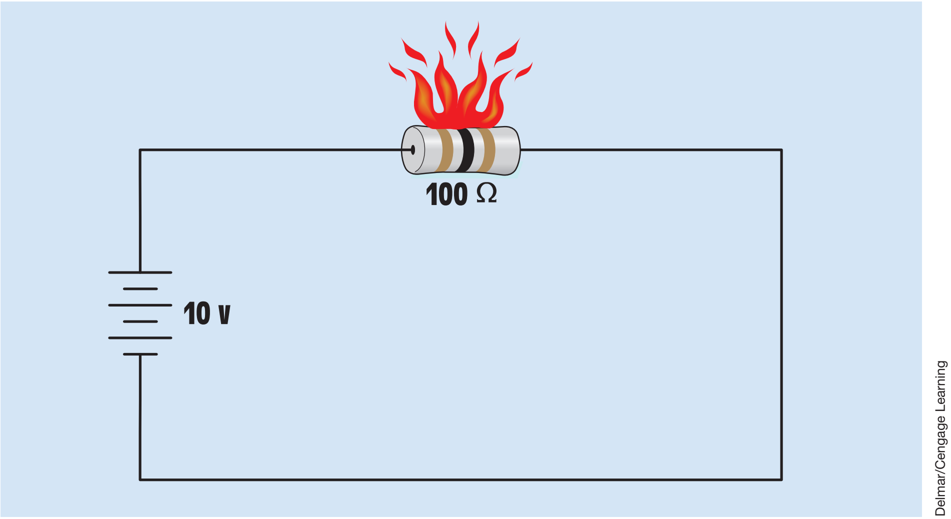


FIGURE 5–13 Exceeding the power rating causes damage to the resistor.

Solution

Using the formula $P = \frac{E^2}{R}$, determine the amount of heat that will be dissipated by the resistor.

$$P = \frac{E^2}{R}$$

$$P = \frac{10\ V \times 10\ V}{100\ \Omega}$$

$$P = \frac{100\ V}{100\ \Omega}$$

$$P = 1\ W$$

Because the resistor has a power rating of ½ W, and the amount of heat that will be dissipated is 1 W, the resistor will be damaged.

5–6 Variable Resistors

A **variable resistor** is a resistor whose values can be changed or varied over a range. Variable resistors can be obtained in different case styles and power ratings. *Figure 5–14* illustrates how a variable resistor is constructed. In this example, a resistive wire is wound in a circular pattern, and a sliding tap makes contact with the wire. The value of resistance can be adjusted between one end of the resistive wire and the sliding tap. If the resistive wire has a total value of 100 ohms, the resistor can be set between the values of 0 and 100 ohms.

A variable resistor with three terminals is shown in *Figure 5–15*. This type of resistor has a wiper arm inside the case that makes contact with the resistive element. The full resistance value is between the two outside terminals, and the wiper arm is connected to the center terminal. The resistance between the center terminal and either of the two outside terminals can be adjusted by turning the shaft and changing the position of the wiper arm. Wire-wound variable resistors of this type can be obtained also *(Figure 5–16)*. The advantage of the wire-wound type is a higher power rating.

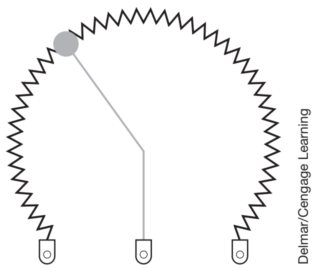
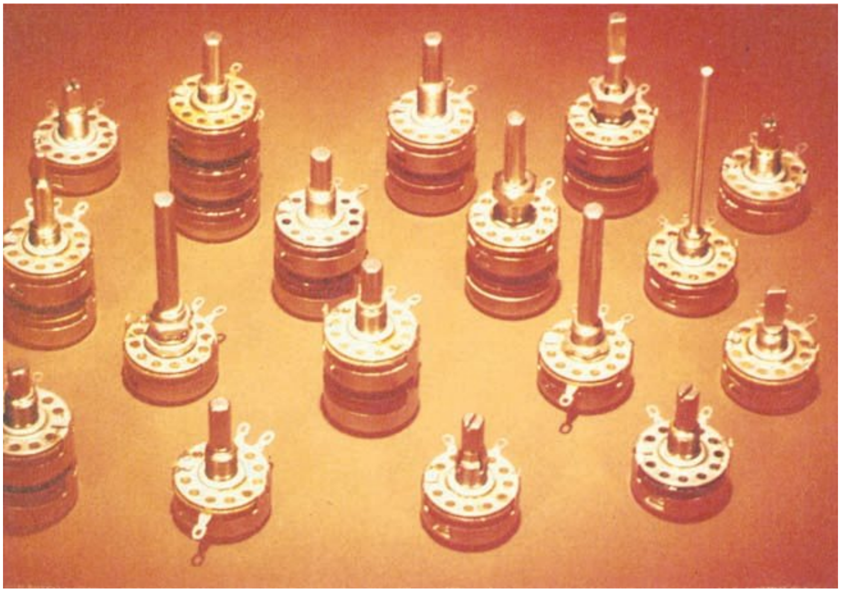


FIGURE 5–14 Variable resistor.



Courtesy of Rockwell Automation

FIGURE 5–15 Variable resistors with three terminals.

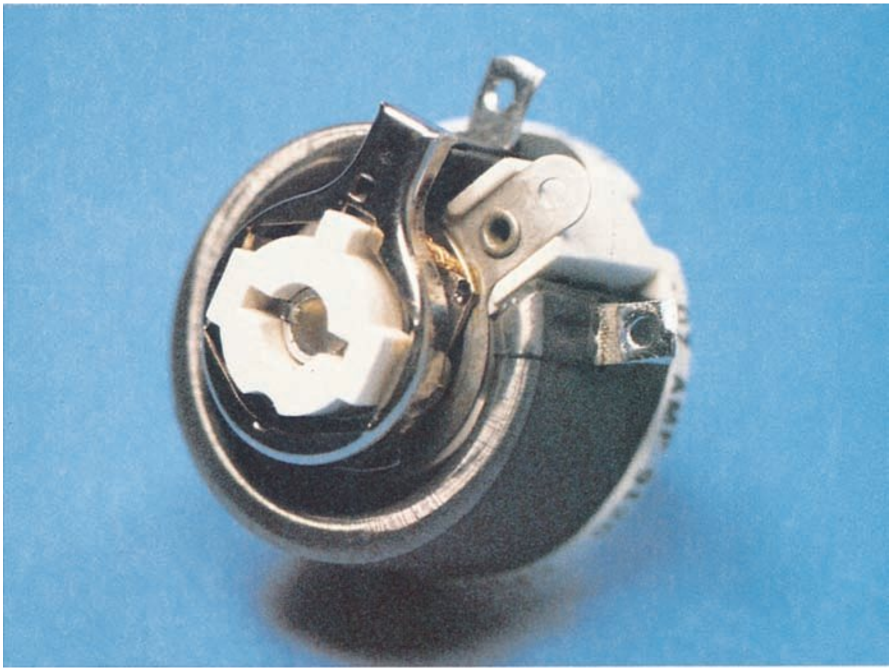


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FIGURE 5–16 Wire-wound variable resistor.

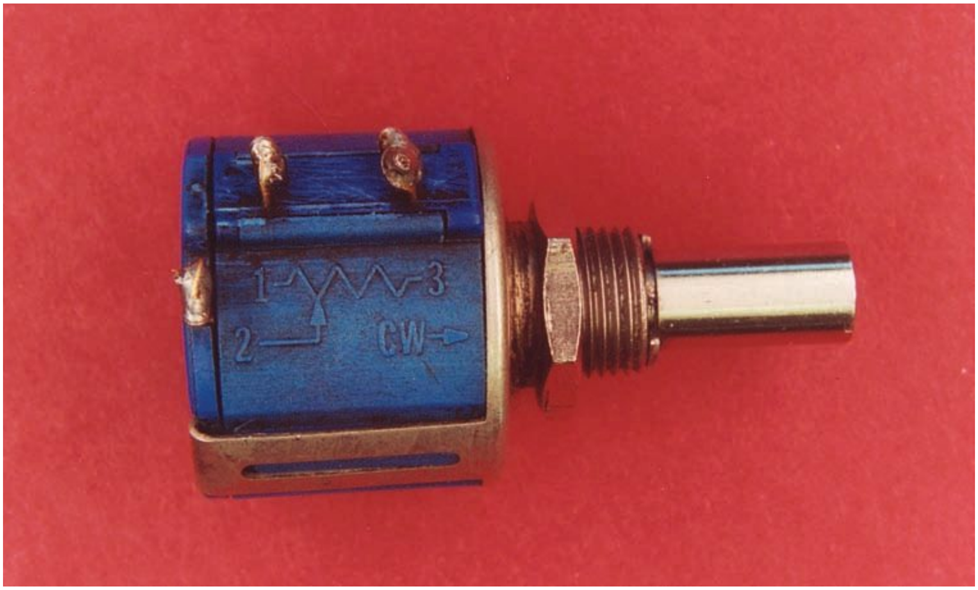

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FIGURE 5–17 Multiturn variable resistor.

The resistor shown in *Figure 5–15* can be adjusted from its minimum to maximum value by turning the control approximately three-quarters of a turn. In some types of electric equipment, this range of adjustment may be too coarse to allow for sensitive adjustments. When this becomes a problem, a multiturn resistor *(Figure 5–17)* can be used. **Multiturn variable resistors** operate by moving the wiper arm with a screw of some number of turns. They generally range from 3 turns to 10 turns. If a 10-turn variable resistor is used, it will require 10 turns of the control knob to move the wiper from one end of the resistor to the other end instead of three-quarters of a turn.

Variable Resistor Terminology

Variable resistors are known by several common names. The most popular name is **pot,** which is shortened from the word **potentiometer.** Another common name is **rheostat.** A rheostat is actually a variable resistor that has two terminals. They are used to adjust the current in a circuit to a certain value. A potentiometer is a variable resistor that has three terminals. Potentiometers can be used as rheostats by only using two of their three terminals. A potentiometer describes how a variable resistor is used rather than some specific type of resistor. The word *potentiometer* comes from the word *potential,* or voltage. A potentiometer is a variable resistor used to provide a variable voltage, as shown in *Figure 5–18*. In this example, one end of a variable resistor is connected to +12 volts and the other end is connected to ground. The middle terminal, or

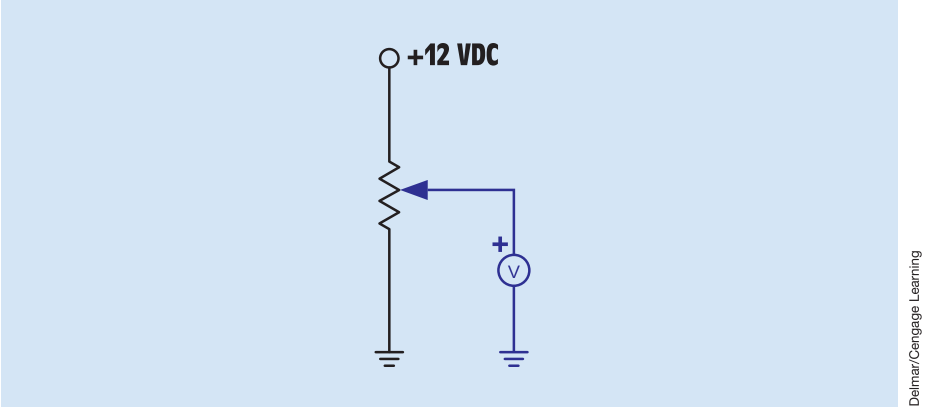

FIGURE 5–18 Variable resistor used as a potentiometer.

wiper, is connected to the positive terminal of a voltmeter and the negative lead is connected to ground. If the wiper is moved to the upper end of the resistor, the voltmeter will indicate a potential of 12 volts. If the wiper is moved to the bottom, the voltmeter will indicate a value of 0 volts. The wiper can be adjusted to provide any value of voltage between 12 and 0 volts.

5–7 Schematic Symbols

Electrical schematics use symbols to represent the use of a resistor. Unfortunately, the symbol used to represent a resistor is not standard. *Figure 5–19* illustrates several schematic symbols used to represent both fixed and variable resistors.

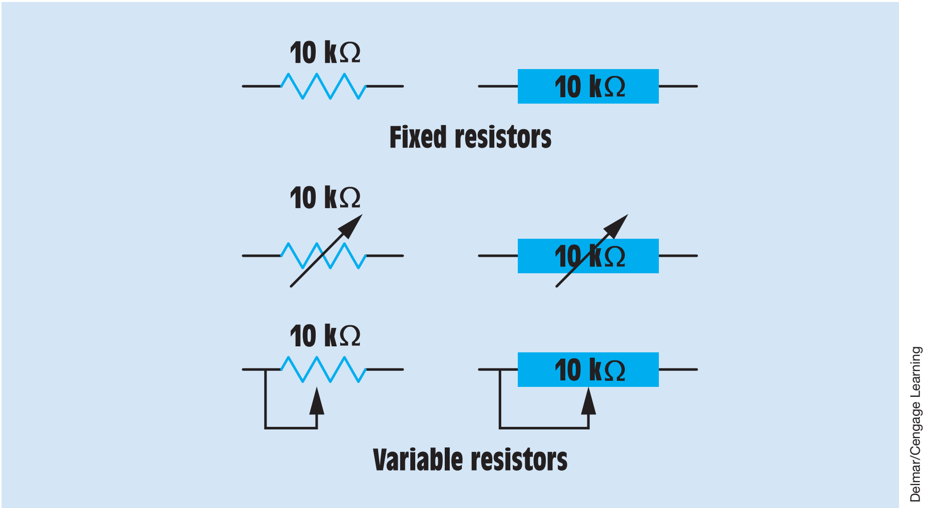

FIGURE 5–19 Schematic symbols used to represent resistors.

Summary

- Resistors are used in two main applications: as voltage dividers and to limit the flow of current in a circuit.
- The value of fixed resistors cannot be changed.
- There are several types of fixed resistors, such as composition carbon, metal film, and wire-wound.
- Carbon resistors change their resistance with age or if overheated.
- Metal film resistors never change their value but are more expensive than carbon resistors.
- The advantage of wire-wound resistors is their high power ratings.
- Resistors often have bands of color to indicate their resistance value and tolerance.
- Resistors are produced in standard values. The number of values between 0 and 100 ohms is determined by the tolerance.
- Variable resistors can change their value within the limit of their full value.
- A potentiometer is a variable resistor used as a voltage divider.

Review Questions

1. Name three types of fixed resistors.
2. What is the advantage of a metal film resistor over a carbon resistor?
3. What is the advantage of a wire-wound resistor?
4. How should tubular wire-wound resistors be mounted and why?
5. A 0.5-W, 2000-Ω resistor has a current flow of 0.01 A through it. Is this resistor operating within its power rating?
6. A 1-W, 350-Ω resistor is connected to 24 V. Is this resistor operating within its power rating?
7. A resistor has color bands of orange, blue, yellow, and gold. What are the resistance and tolerance of this resistor?
8. A 10,000-Ω resistor has a tolerance of 5%. What are the minimum and maximum values of this resistor?
9. Is 51,000 Ω a standard value for a 5% resistor?
10. What is a potentiometer?

Practical Applications

You are an electrician on the job. It is decided that the speed of a large DC motor is to be reduced by connecting a resistor in series with its armature. The DC voltage applied to the motor is 250 V, and the motor has a full-load armature current of 50 A. Your job is to reduce the armature current to 40 A at full load by connecting the resistor in series with the armature. What value of resistance should be used, and what is the power rating of the resistor? ■

Practical Applications

You are working on an electronic circuit. The circuit current is 5 mA. A resistor is marked with the following bands: brown, black, red, gold. A voltmeter measures a voltage drop of 6.5 V across the resistor. Is this resistor within its tolerance rating? ■

Practical Applications

A homeowner uses a 100-watt incandescent lamp as a heater in an outside well pump house to protect the pump from freezing in cold weather. Unfortunately, however, the lamp can burn out and leave the pump unprotected. You have been asked to install a heater that will not burn out and leave the pump unprotected. You have available a 100-watt, 150-ohm wire-wound resistor. Can this resistor be connected to the 120-volt source without damage to the resistor? If so, what would be the power output of the resistor? ■

Practical Applications

You have determined that a 4700-ohm, ½-watt resistor on an electronic circuit board is defective. Assuming room permits, can the resistor be replaced with a 4700-ohm, 1-watt resistor without damage to the rest of the board, or will the higher wattage resistor generate excessive heat that could damage other components? ■

Practice Problems

Resistors

Fill in the missing values.

1st Band	2nd Band	3rd Band	4th Band	Value	%Tolerance
Red	Yellow	Brown	Silver		
				6800 Ω	5
Orange	Orange	Orange	Gold		
				12 Ω	2
Brown	Green	Silver	Silver		
				1.8 MΩ	10
Brown	Black	Yellow	None		
				10 kΩ	5
Violet	Green	Black	Red		
				4.7 kΩ	20
Gray	Red	Green	Red		
				5.6 Ω	2

II

Basic Electric Circuits

Courtesy of Getty Images, Inc.

Unit 6
Series Circuits

OUTLINE

KEY TERMS

Chassis ground
Circuit breakers
Earth ground
Fuses
Ground point
Series circuit
Voltage drop
Voltage polarity

Why You Need to Know

It is important to learn the rules governing the values of resistance, voltage, current, and power in a series circuit. Knowledge of series circuits is essential in understanding more complex circuits that are encountered throughout an electrician's career. There are some series circuits in everyday use, such as many street lighting systems, but knowledge of series circuits is most useful in understanding how components in combination circuits relate to each other. Combination circuits contain components or branches that are connected in both series and parallel. To apply the rules of a series circuit, this unit

- provides a basic understanding of how voltage drop impacts devices that are connected in series.
- explains why each series-connected device increases the total opposition to current flow.
- provides an understanding of how current flows through a series circuit.

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Objectives

After studying this unit, you should be able to

- discuss the properties of series circuits.
- list three rules for solving electrical values of series circuits.
- calculate values of voltage, current, resistance, and power for series circuits.
- calculate the values of voltage drop in a series circuit using the voltage divider formula.

Preview

Electric circuits can be divided into three major types: series, parallel, and combination. Combination circuits are circuits that contain both series and parallel paths. The first type discussed is the series circuit. ■

6–1 Series Circuits

A **series circuit** is a circuit that has only one path for current flow *(Figure 6–1)*. Because there is only one path for current flow, the current is the same at any point in the circuit. Imagine that an electron leaves the negative terminal of the battery. This electron must flow through each resistor before it can complete the circuit to the positive battery terminal.

One of the best examples of a series-connected device is a fuse or circuit breaker *(Figure 6–2)*. Because **fuses** and **circuit breakers** are connected in series with the rest of the circuit, all the circuit current must flow through them. If the current becomes excessive, the fuse or circuit breaker will open and disconnect the rest of the circuit from the power source.

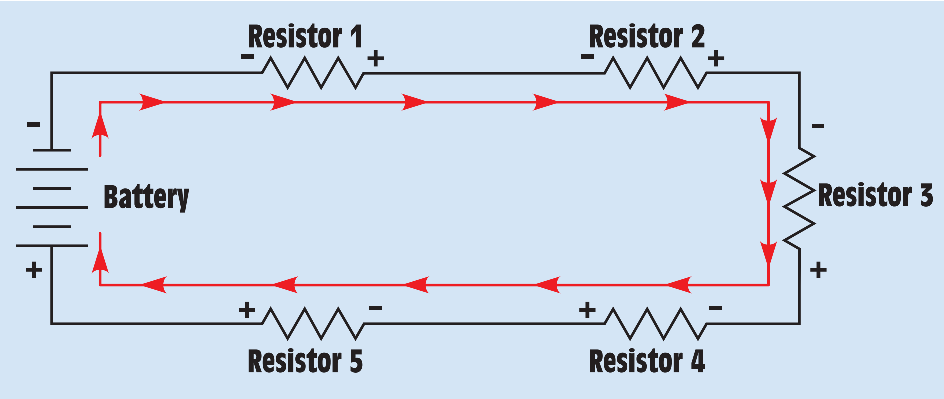

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FIGURE 6–1 A series circuit has only one path for current flow.

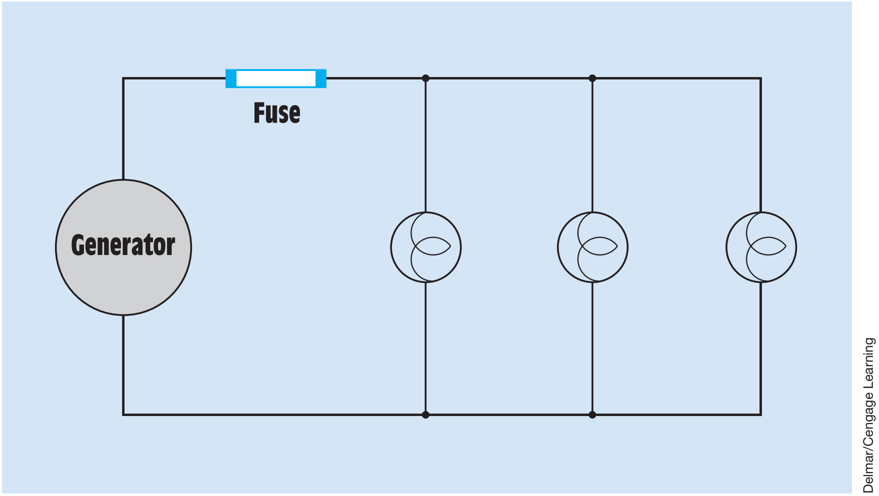

FIGURE 6–2 All the current must flow through the fuse.

6–2 Voltage Drops in a Series Circuit

Voltage is the force that pushes the electrons through a resistance. The amount of voltage required is determined by the amount of current flow and resistance. If a voltmeter is connected across a resistor *(Figure 6–3)*, the amount of voltage necessary to push the current through that resistor is indicated by the meter. This amount is known as **voltage drop.** It is similar to pressure drop in a water system. ***In a series circuit, the sum of all the voltage drops across all the resistors***

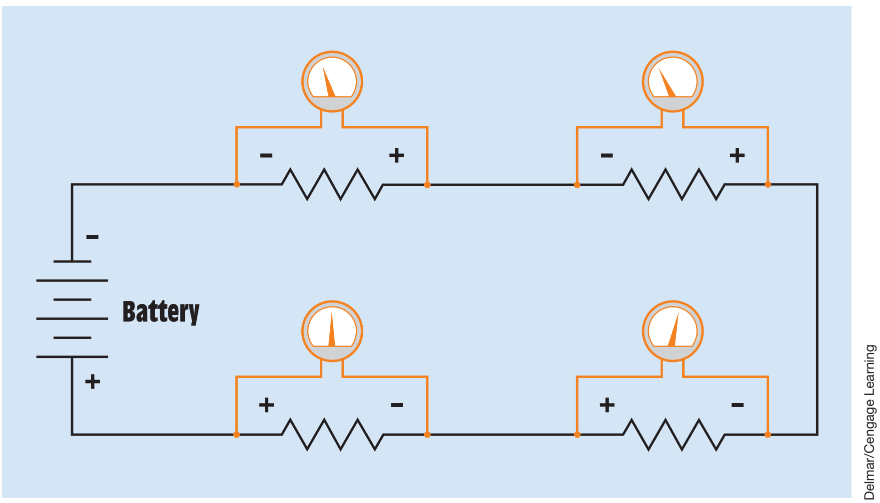

FIGURE 6–3 The voltage drops in a series circuit must equal the applied voltage.

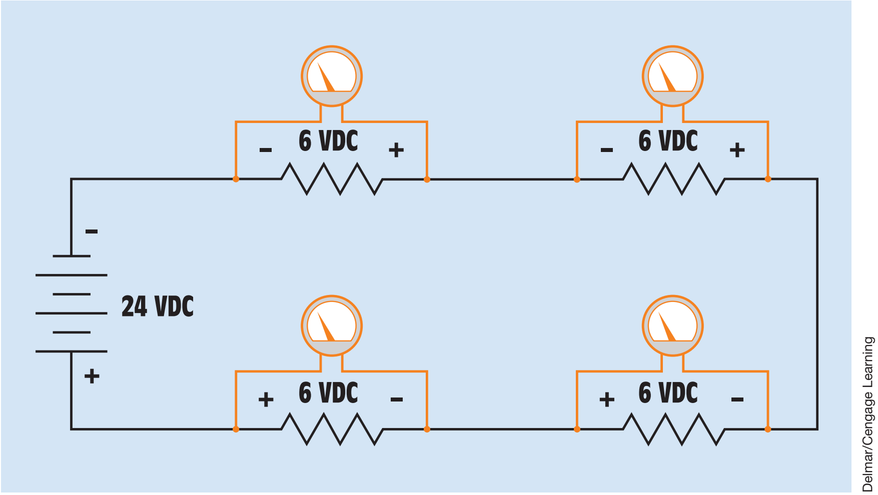

FIGURE 6–4 The voltage drop across each resistor is proportional to its resistance.

must equal the voltage applied to the circuit. The amount of voltage drop across each resistor is proportional to its resistance and the circuit current.

In the circuit shown in *Figure 6–4*, four resistors are connected in series. It is assumed that all four resistors have the same value. The circuit is connected to a 24-volt battery. Because all the resistors have the same value, the voltage drop across each will be 6 volts (24 V/4 resistors = 6 V). Note that all four resistors will have the same voltage drop only if they all have the same value. The circuit shown in *Figure 6–5* illustrates a series circuit comprising resistors

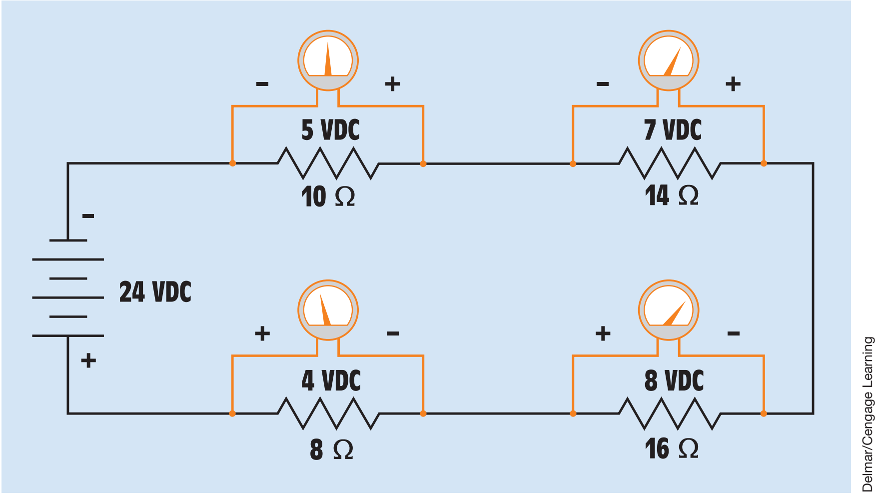

FIGURE 6–5 Series circuit with four resistors having different voltage drops.

of different values. Notice that the voltage drop across each resistor is proportional to its resistance. Also notice that the sum of the voltage drops is equal to the applied voltage of 24 volts.

6–3 Resistance in a Series Circuit

Because only one path exists for the current to flow through a series circuit, it must flow through each resistor in the circuit *(Figure 6–1)*. Each resistor limits or impedes the flow of current in the circuit. Therefore, the total amount of resistance to current flow in a series circuit is equal to the sum of the resistances in that circuit.

6–4 Calculating Series Circuit Values

Three rules can be used with Ohm's law for finding values of voltage, current, resistance, and power in any series circuit:

1. The current is the same at any point in the circuit.
2. The total resistance is the sum of the individual resistors.
3. The applied voltage is equal to the sum of the voltage drops across all the resistors.

The circuit shown in *Figure 6–6* shows the values of current flow, voltage drop, and resistance for each of the resistors. The total resistance (R_T) of

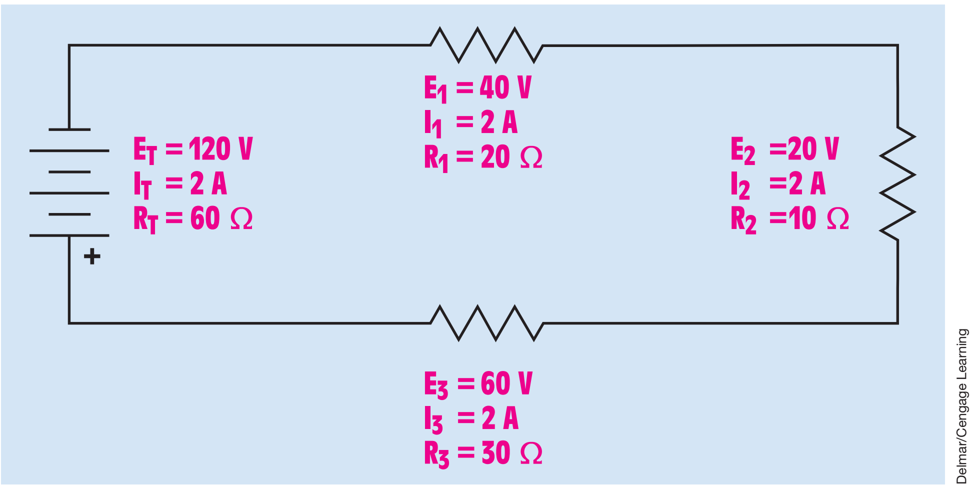

FIGURE 6–6 Series circuit values.

the circuit can be found by adding the values of the three resistors–resistance adds:

$$R_T = R_1 + R_2 + R_3$$
$$R_T = 20\ \Omega + 10\ \Omega + 30\ \Omega$$
$$R_T = 60\ \Omega$$

The amount of current flow in the circuit can be found by using Ohm's law:

$$I = \frac{E}{R}$$
$$I = \frac{120\ V}{60\ \Omega}$$
$$I = 2\ A$$

A current of 2 amperes flows through each resistor in the circuit:

$$I_T = I_1 = I_2 = I_3$$

Because the amount of current flowing through resistor R_1 is known, the voltage drop across the resistor can be found using Ohm's law:

$$E_1 = I_1 \times R_1$$
$$E_1 = 2\ A \times 20\ \Omega$$
$$E_1 = 40\ V$$

In other words, it takes 40 volts to push 2 amperes of current through 20 ohms of resistance. If a voltmeter were connected across resistor R_1, it would indicate a value of 40 volts *(Figure 6–7)*. The voltage drop across resistors R_2 and R_3 can be found in the same way:

$$E_2 = I_2 \times R_2$$
$$E_2 = 2\ A \times 10\ \Omega$$
$$E_2 = 20\ V$$
$$E_3 = I_3 \times R_3$$
$$E_3 = 2\ A \times 30\ \Omega$$
$$E_3 = 60\ V$$

If the voltage drop across all the resistors is added, it equals the total applied voltage (E_T):

$$E_T = E_1 + E_2 + E_3$$
$$E_T = 40\ V + 20\ V + 60\ V$$
$$E_T = 120\ V$$

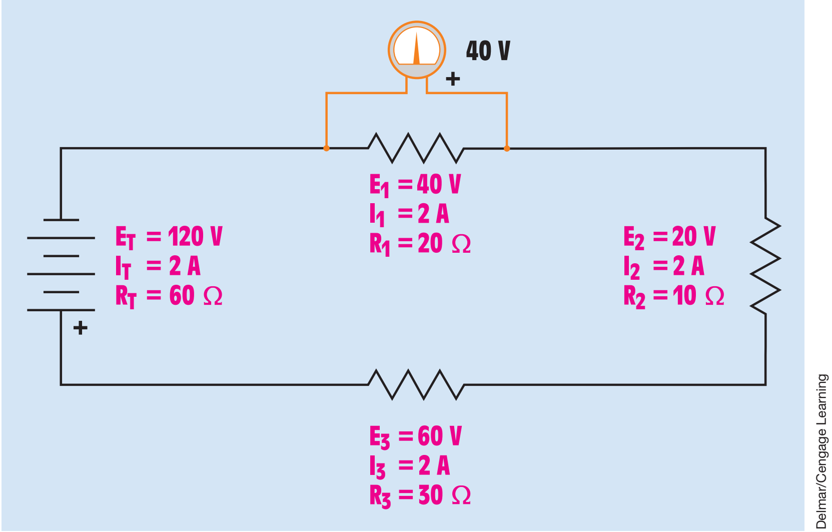

FIGURE 6–7 The voltmeter indicates a voltage drop of 40 volts.

6–5 Solving Circuits

In the following problems, circuits that have missing values are shown. The missing values can be found by using the rules for series circuits and Ohm's law.

EXAMPLE 6-1

The first step in finding the missing values in the circuit shown in *Figure 6–8* is to find the total resistance (R_T). This can be done using the second rule of series circuits, which states that resistances add to equal the total resistance of the circuit:

$$R_T = R_1 + R_2 + R_3 + R_4$$
$$R_T = 100\ \Omega + 250\ \Omega + 150\ \Omega + 300\ \Omega$$
$$R_T = 800\ \Omega$$

Now that the total voltage and the total resistance are known, the current flow through the circuit can be found using Ohm's law:

$$I = \frac{E}{R}$$
$$I = \frac{40\ V}{800\ \Omega}$$
$$I = 0.050\ A$$

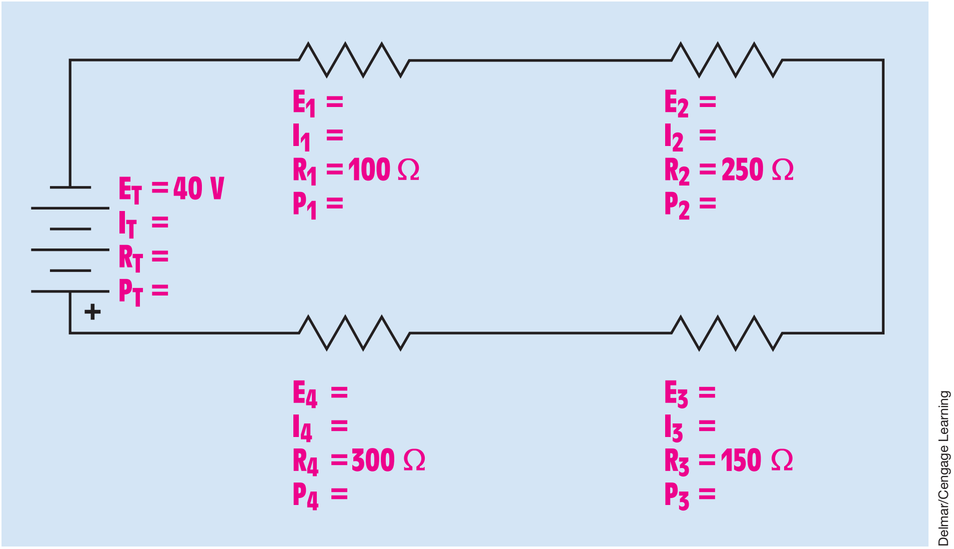

FIGURE 6–8 Series circuit, Example 1.

The first rule of series circuits states that current remains the same at any point in the circuit. Therefore, 0.050 A flows through each resistor in the circuit *(Figure 6–9)*. The voltage drop across each resistor can now be found using Ohm's law *(Figure 6–10)*:

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.050\text{ A} \times 100\ \Omega$$
$$E_1 = 5\text{ V}$$
$$E_2 = I_2 \times R_2$$
$$E_2 = 0.050\text{ A} \times 250\ \Omega$$
$$E_2 = 12.5\text{ V}$$
$$E_3 = I_3 \times R_3$$
$$E_3 = 0.050\text{ A} \times 150\ \Omega$$
$$E_3 = 7.5\text{ V}$$
$$E_4 = I_4 \times R_4$$
$$E_4 = 0.050\text{ A} \times 300\ \Omega$$
$$E_4 = 15\text{ V}$$

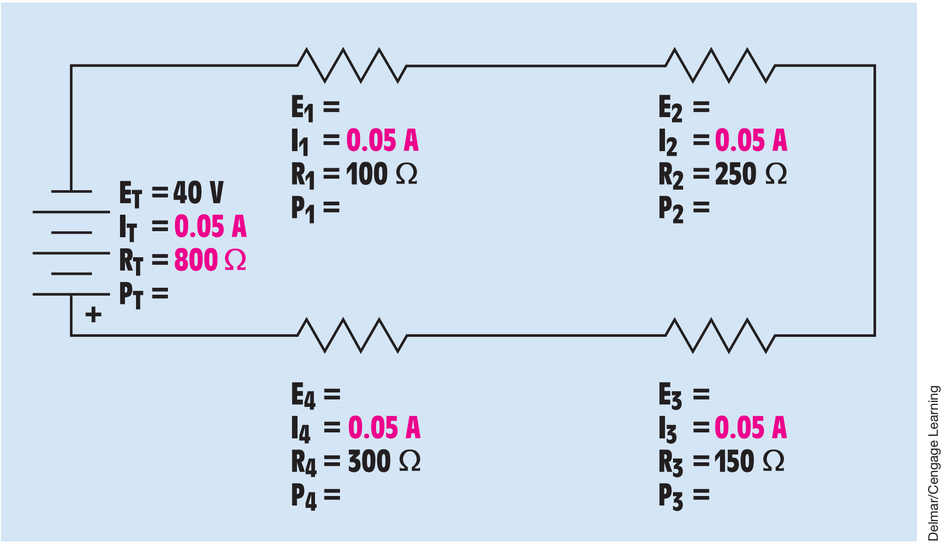

FIGURE 6–9 The current is the same at any point in a series circuit.

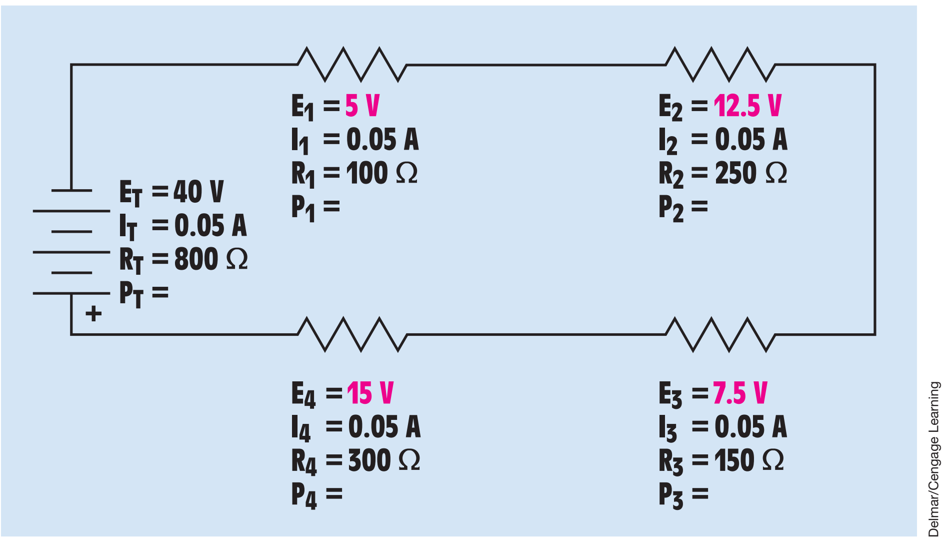

FIGURE 6–10 The voltage drop across each resistor can be found using Ohm's law.

Several formulas can be used to determine the amount of power dissipated (converted into heat) by each resistor. The power dissipation of resistor R_1 will be found using the formula

$$P_1 = E_1 \times I_1$$
$$P_1 = 5\ V \times 0.05\ A$$
$$P_1 = 0.25\ W$$

The amount of power dissipation for resistor R_2 will be calculated using the formula

$$P_2 = \frac{E_2^{\,2}}{R_2}$$
$$P_2 = \frac{156.25\ V^2}{250\ \Omega}$$
$$P_2 = 0.625\ W$$

The amount of power dissipation for resistor R_3 will be calculated using the formula

$$P_3 = I_3^{\,2} \times R_3$$
$$P_3 = 0.0025\ A^2 \times 150\ \Omega$$
$$P_3 = 0.375\ W$$

The amount of power dissipation for resistor R_4 will be found using the formula

$$P_4 = E_4 \times I_4$$
$$P_4 = 15\ V \times 0.05\ A$$
$$P_4 = 0.75\ W$$

A good rule to remember when calculating values of electric circuits is that ***the total power used in a circuit is equal to the sum of the power used by all parts.*** That is, the total power can be found in any kind of a circuit—series, parallel, or combination—by adding the power dissipation of all the parts. The total power for this circuit can be found using the formula

$$P_T = P_1 + P_2 + P_3 + P_4$$
$$P_T = 0.25\ W + 0.625\ W + 0.375\ W + 0.75\ W$$
$$P_T = 2\ W$$

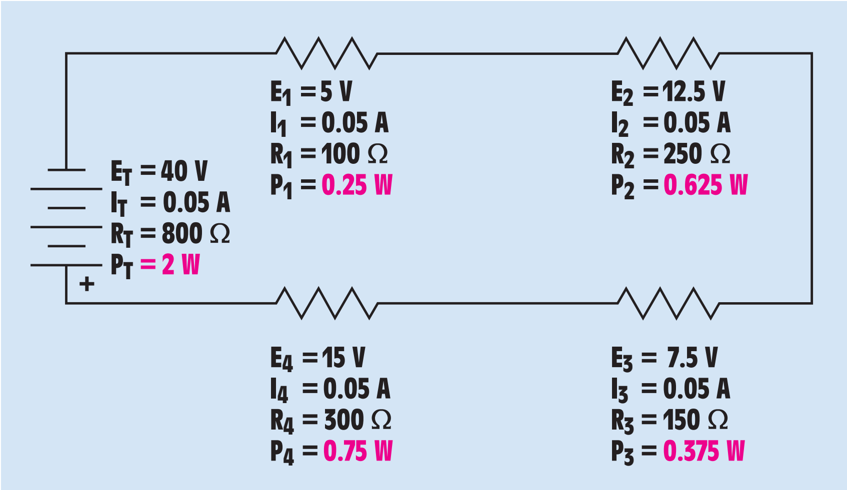

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FIGURE 6–11 The final values for the circuit in Example 1.

Now that all the missing values have been found *(Figure 6–11),* the circuit can be checked by using the third rule of series circuits, which states that voltage drops add to equal the applied voltage:

$$E_T = E_1 + E_2 + E_3 + E_4$$
$$E_T = 5\text{ V} + 12.5\text{ V} + 7.5\text{ V} + 15\text{ V}$$
$$E_T = 40\text{ V}$$

■ EXAMPLE 6-2

The second circuit to be solved is shown in *Figure 6–12*. In this circuit, the total resistance is known, but the value of resistor R_2 is not. The second rule of series circuits states that resistances add to equal the total resistance of the circuit. Because the total resistance is known, the missing resistance of R_2 can be found by adding the values of the other resistors and subtracting their sum from the total resistance of the circuit *(Figure 6–13):*

$$R_2 = R_T - (R_1 + R_3 + R_4)$$
$$R_2 = 6000\ \Omega - (1000\ \Omega + 2000\ \Omega + 1200\ \Omega)$$
$$R_2 = 6000\ \Omega - 4200\ \Omega$$
$$R_2 = 1800\ \Omega$$

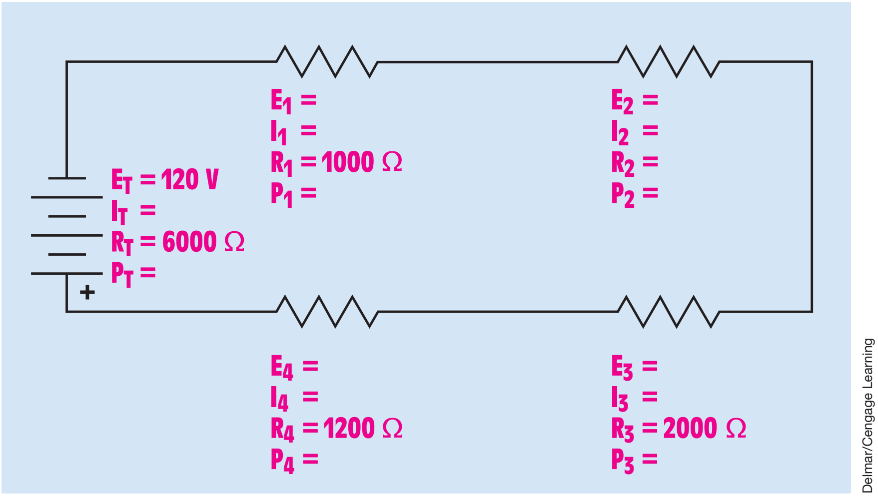

FIGURE 6–12 Series circuit, Example 2.

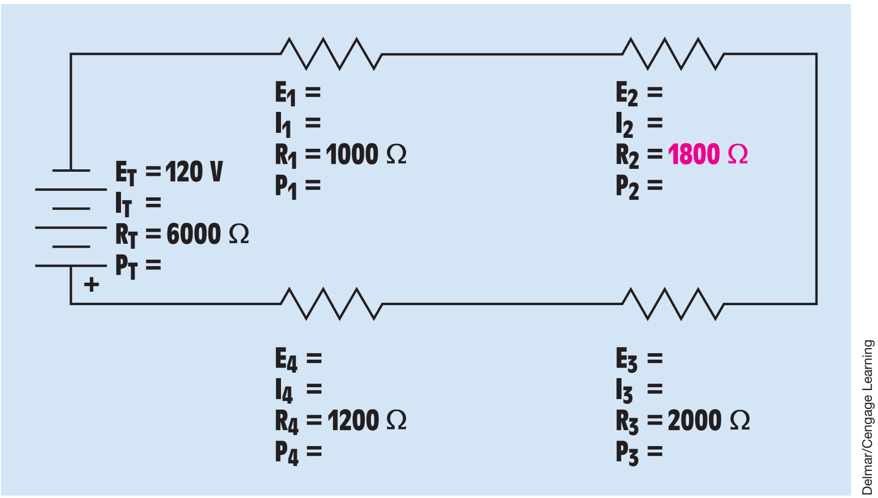

FIGURE 6–13 The missing resistor value.

The amount of current flow in the circuit can be found using Ohm's law:

$$I = \frac{E}{R}$$

$$I = \frac{120\text{ V}}{6000\ \Omega}$$

$$I = 0.020\text{ A}$$

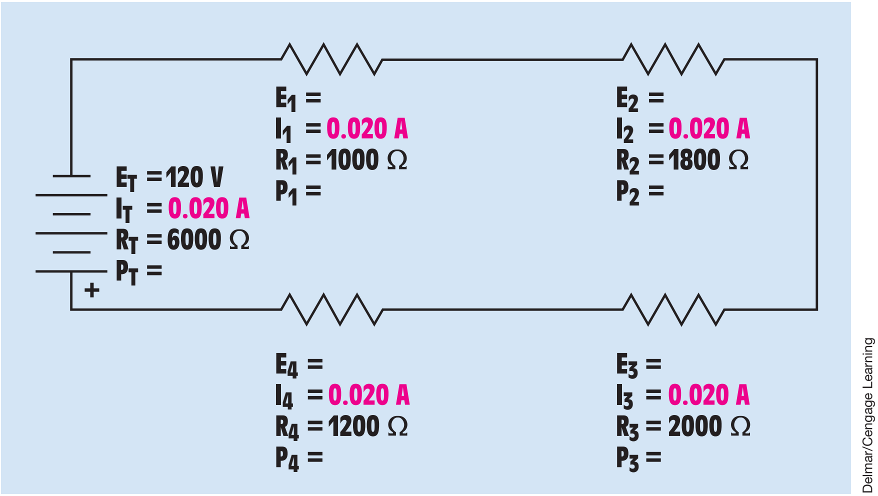

FIGURE 6–14 The current is the same through each circuit element.

Because the amount of current flow is the same through all elements of a series circuit *(Figure 6–14)*, the voltage drop across each resistor can be found using Ohm's law *(Figure 6–15)*:

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.020\ A \times 1000\ \Omega$$
$$E_1 = 20\ V$$
$$E_2 = I_2 \times R_2$$
$$E_2 = 0.020\ A \times 1800\ \Omega$$
$$E_2 = 36\ V$$
$$E_3 = I_3 \times R_3$$
$$E_3 = 0.020\ A \times 2000\ \Omega$$
$$E_3 = 40\ V$$
$$E_4 = I_4 \times R_4$$
$$E_4 = 0.020\ A \times 1200\ \Omega$$
$$E_4 = 24\ V$$

The third rule of series circuits can be used to check the answers:

$$E_T = E_1 + E_2 + E_3 + E_4$$
$$E_T = 20\ V + 36\ V + 40\ V + 24\ V$$
$$E_T = 120\ V$$

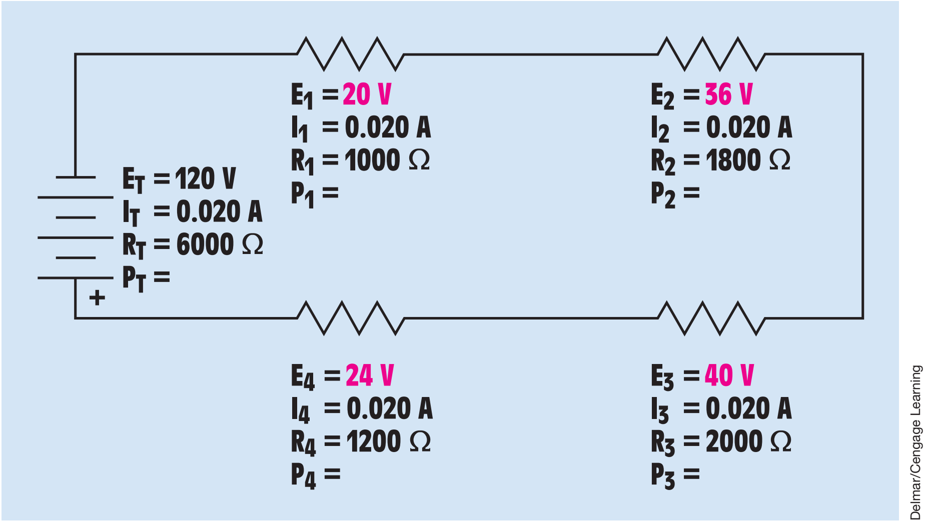

FIGURE 6–15 Voltage drops across each resistor.

The amount of power dissipation for each resistor in the circuit can be calculated using the same method used to solve the circuit in Example 1. The power dissipated by resistor R_1 is calculated using the formula

$$P_1 = E_1 \times I_1$$
$$P_1 = 20 \text{ V} \times 0.02 \text{ A}$$
$$P_1 = 0.4 \text{ W}$$

The amount of power dissipation for resistor R_2 is found by using the formula

$$P_2 = \frac{E_2^2}{R_2}$$
$$P_2 = \frac{1296 \text{ V}^2}{1800\ \Omega}$$
$$P_2 = 0.72 \text{ W}$$

The power dissipation of resistor R_3 is found using the formula

$$P_3 = I_3^2 \times R_3$$
$$P_3 = 0.0004 \text{ A}^2 \times 2000\ \Omega$$
$$P_3 = 0.8 \text{ W}$$

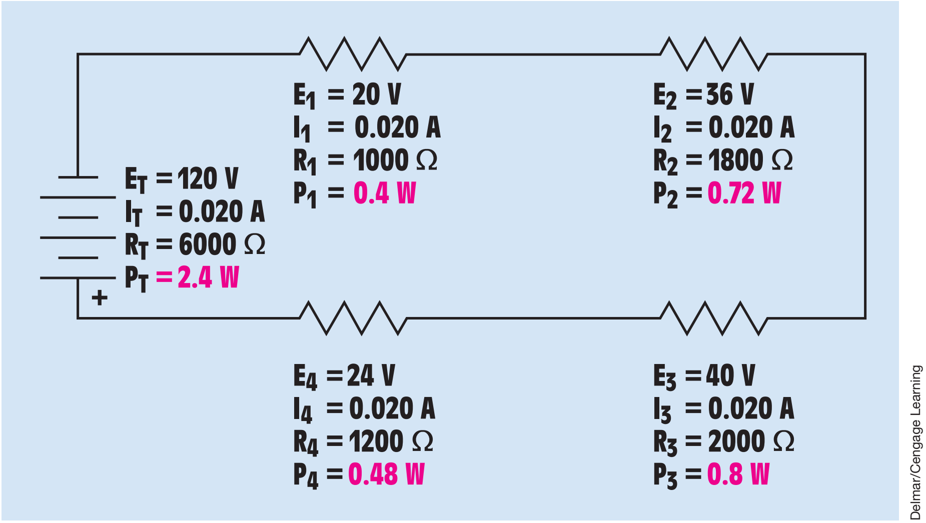

FIGURE 6–16 The remaining unknown values for the circuit in Example 2.

The power dissipation of resistor R_4 is calculated using the formula

$$P_4 = E_4 \times I_4$$
$$P_4 = 24\text{ V} \times 0.02\text{ A}$$
$$P_4 = 0.48\text{ W}$$

The total power is calculated using the formula

$$P_T = E_T \times I_T$$
$$P_T = 120\text{ V} \times 0.02\text{ A}$$
$$P_T = 2.4\text{ W}$$

The circuit with all calculated values is shown in *Figure 6–16.*

EXAMPLE 6-3

In the circuit shown in *Figure 6–17,* resistor R_1 has a voltage drop of 6.4 V, resistor R_2 has a power dissipation of 0.102 W, resistor R_3 has a power dissipation of 0.154 W, resistor R_4 has a power dissipation of 0.307 W, and the total power consumed by the circuit is 0.768 W.

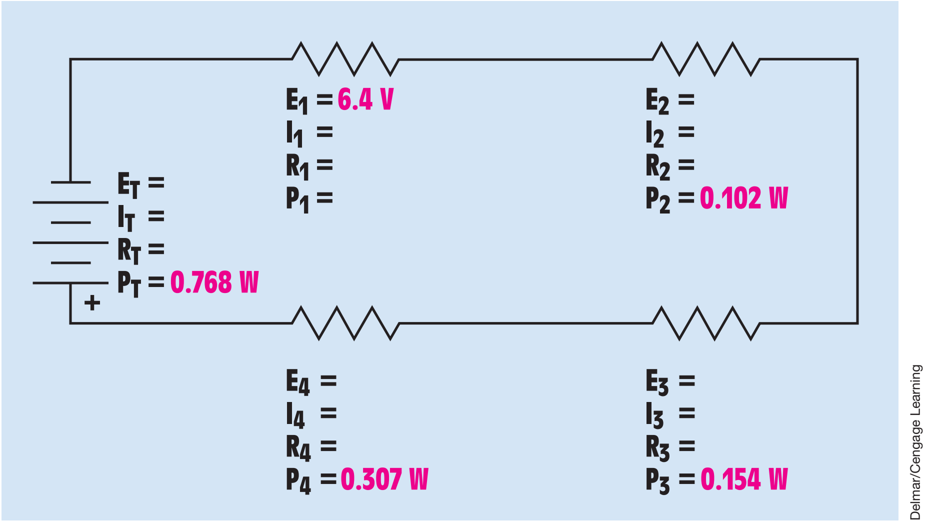

FIGURE 6–17 Series circuit, Example 3.

The only value that can be found with the given quantities is the amount of power dissipated by resistor R_1. Because the total power is known and the power dissipated by the three other resistors is known, the power dissipated by resistor R_1 can be found by subtracting the power dissipated by resistors R_2, R_3, and R_4 from the total power used in the circuit:

$$P_1 = P_T - (P_2 + P_3 + P_4)$$

or

$$P_1 = P_T - P_2 - P_3 - P_4$$
$$P_1 = 0.768 \text{ W} - 0.102 \text{ W} - 0.154 \text{ W} - 0.307 \text{ W}$$
$$P_1 = 0.205 \text{ W}$$

Now that the amount of power dissipated by resistor R_1 and the voltage drop across R_1 are known, the current flow through resistor R_1 can be found using the formula

$$I = \frac{P}{E}$$
$$I = \frac{0.205 \text{ W}}{6.4 \text{ V}}$$
$$I = 0.032 \text{ A}$$

Because the current in a series circuit must be the same at any point in the circuit, it must be the same through all circuit components *(Figure 6–18).*

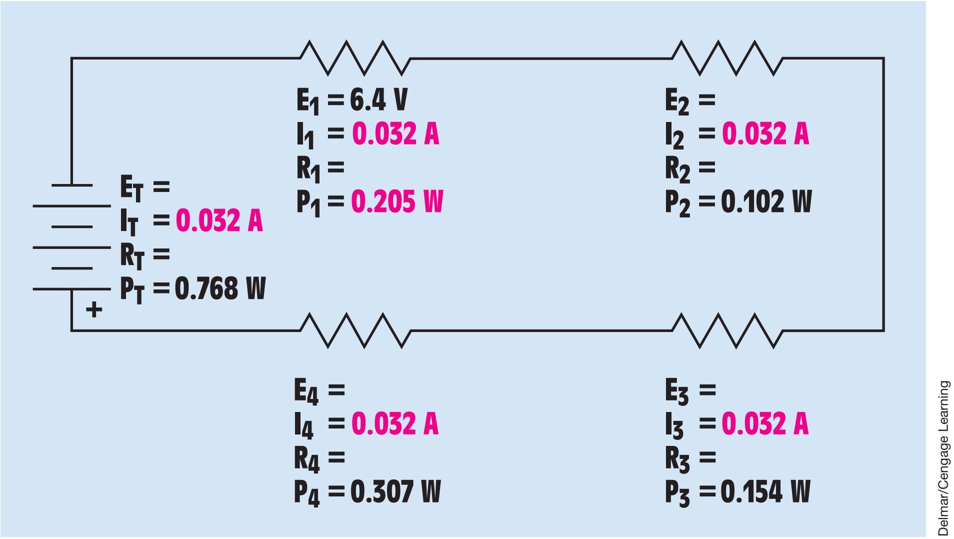

FIGURE 6–18 The current flow in the circuit in Example 3.

Now that the power dissipation of each resistor and the amount of current flowing through each resistor are known, the voltage drop of each resistor can be calculated *(Figure 6–19):*

$$E_2 = \frac{P_2}{I_2}$$

$$E_2 = \frac{0.102\ W}{0.032\ A}$$

$$E_2 = 3.188\ V$$

$$E_3 = \frac{P_3}{I_3}$$

$$E_3 = \frac{0.154\ W}{0.032\ A}$$

$$E_3 = 4.813\ V$$

$$E_4 = \frac{P_4}{I_4}$$

$$E_4 = \frac{0.307\ W}{0.032\ A}$$

$$E_4 = 9.594\ V$$

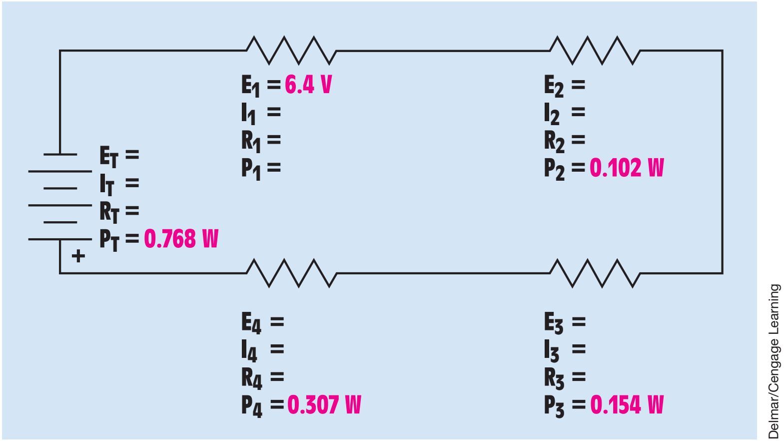

FIGURE 6–19 Voltage drops across each resistor.

Ohm's law can now be used to find the ohmic value of each resistor in the circuit *(Figure 6–20):*

$$R_1 = \frac{E_1}{I_1}$$

$$R_1 = \frac{6.4\ V}{0.032\ A}$$

$$R_1 = 200\ \Omega$$

$$R_2 = \frac{E_2}{I_2}$$

$$R_2 = \frac{3.188\ V}{0.032\ A}$$

$$R_2 = 99.625\ \Omega$$

$$R_3 = \frac{E_3}{I_3}$$

$$R_3 = \frac{4.813\ V}{0.032\ A}$$

$$R_3 = 150.406\ \Omega$$

$$R_4 = \frac{E_4}{I_4}$$

$$R_4 = \frac{9.594\ V}{0.032\ A}$$

$$R_4 = 299.813\ \Omega$$

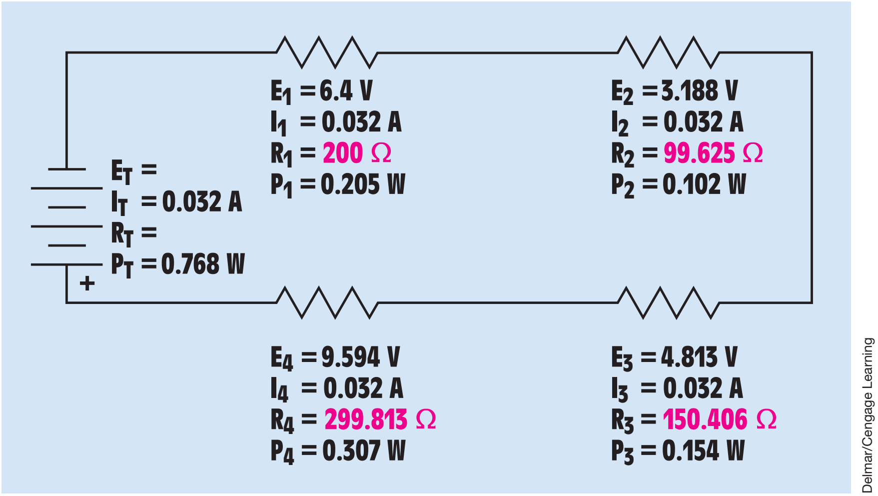

FIGURE 6–20 The ohmic value of each resistor.

The voltage applied to the circuit can be found by adding the voltage drops across the resistor *(Figure 6–21):*

$$E_T = E_1 + E_2 + E_3 + E_4$$
$$E_T = 6.4\text{ V} + 3.188\text{ V} + 4.813\text{ V} + 9.594\text{ V}$$
$$E_T = 23.995\text{ V}$$

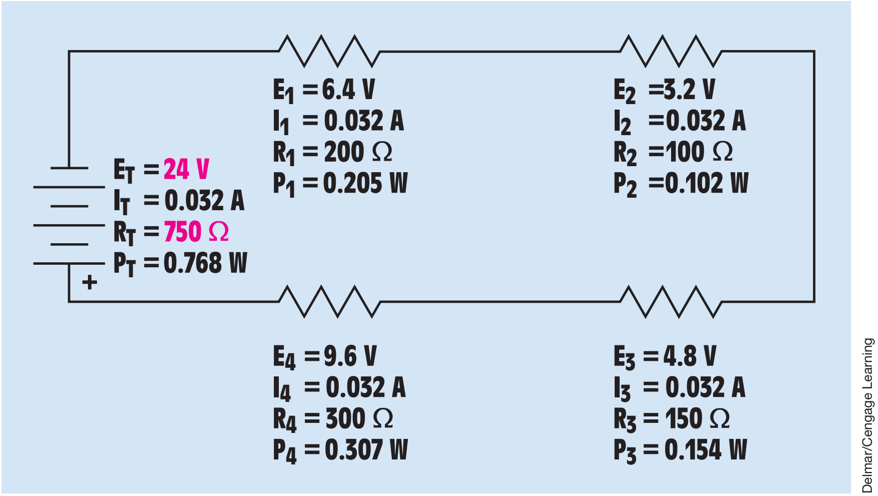

FIGURE 6–21 The applied voltage and the total resistance.

The total resistance of the circuit can be found in a similar manner *(Figure 6–21).* The total resistance is equal to the sum of all the resistive elements in the circuit:

$$R_T = R_1 + R_2 + R_3 + R_4$$
$$R_T = 200\ \Omega + 99.625\ \Omega + 150.406\ \Omega + 299.813\ \Omega$$
$$R_T = 749.844\ \Omega$$

If Ohm's law is used to determine total voltage and total resistance, slightly different answers are produced:

$$E_T = \frac{P_T}{I_T}$$
$$E_T = \frac{0.768\ W}{0.032\ A}$$
$$E_T = 24\ V$$
$$R_T = \frac{E_T}{I_T}$$
$$R_T = \frac{24\ V}{0.032\ A}$$
$$R_T = 750\ \Omega$$

The slight difference in answers is caused by the rounding off of values. Although there is a small difference between the answers, they are within 1% of each other. This small difference has very little effect on the operation of the circuit, and most electric measuring instruments cannot measure values this accurately anyway.

6–6 Voltage Dividers

One common use for series circuits is the construction of voltage dividers. A voltage divider works on the principle that the sum of the voltage drops across a series circuit must equal the applied voltage. Voltage dividers are used to provide different voltages between certain points *(Figure 6–22)*. If a voltmeter is connected between Point A and Point B, a voltage of 20 volts will be seen. If the voltmeter is connected between Point B and Point D, a voltage of 80 volts will be seen.

Voltage dividers can be constructed to produce any voltage desired. For example, assume that a voltage divider is connected to a source of 120 volts

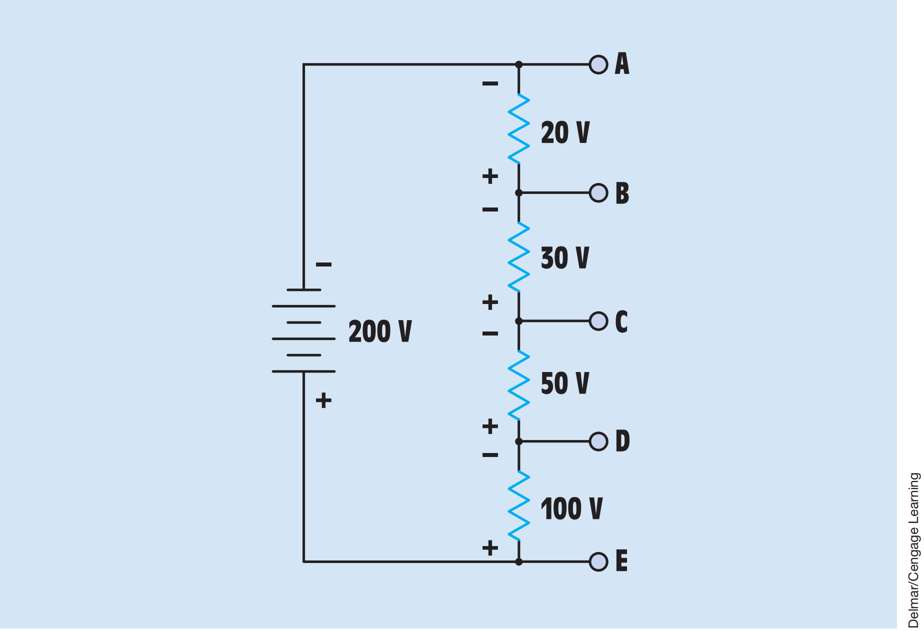

FIGURE 6–22 Series circuit used as a voltage divider.

and is to provide voltage drops of 36 volts, 18 volts, and 66 volts. Notice that the sum of the voltage drops equals the applied voltage. The next step is to decide how much current is to flow through the circuit. Because there is only one path for current flow, the current will be the same through all the resistors. In this circuit, a current flow of 15 milliamperes (0.015 A) will be used. The resistance value of each resistor can now be determined:

$$R = \frac{E}{I}$$

$$R_1 = \frac{36\text{ V}}{0.015\text{ A}}$$

$$R_1 = 2.4\text{ k}\Omega\ (2400\ \Omega)$$

$$R_2 = \frac{18\text{ V}}{0.015\text{ A}}$$

$$R_2 = 1.2\text{ k}\Omega\ (1200\ \Omega)$$

$$R_3 = \frac{66\text{ V}}{0.015\text{ A}}$$

$$R_3 = 4.4\text{ k}\Omega\ (4400\ \Omega)$$

6–7 The General Voltage Divider Formula

Another method of determining the voltage drop across series elements is to use the general voltage divider formula. Because the current flow through a series circuit is the same at all points in the circuit, the voltage drop across any particular resistance is equal to the total circuit current times the value of that resistor:

$$E_X = I_T \times R_X$$

The total circuit current is proportional to the source voltage (E_T) and the total resistance of the circuit:

$$I_T = \frac{E_T}{R_T}$$

If the value of I_T is substituted for E_T/R_T in the previous formula, the expression now becomes:

$$E_X = \left(\frac{E_T}{R_T}\right)R_X$$

If the formula is rearranged, it becomes what is known as the general voltage divider formula:

$$E_X = \left(\frac{R_X}{R_T}\right)E_T$$

The voltage drop across any series component (E_X) can be calculated by substituting the value of R_X for the resistance value of that component when the source voltage and total resistance are known.

EXAMPLE 6-4

Three resistors are connected in series to a 24-V source. Resistor R_1 has a resistance of 200 Ω, resistor R_2 has a value of 300 Ω, and resistor R_3 has a value of 160 Ω. What is the voltage drop across each resistor?

Solution

Find the total resistance of the circuit:

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 200\ \Omega + 300\ \Omega + 160\ \Omega$$

$$R_T = 660\ \Omega$$

Now use the voltage divider formula to calculate the voltage drop across each resistor:

$$E_1 = \left(\frac{R_1}{R_T}\right) E_T$$

$$E_1 = \left(\frac{200\ \Omega}{660\ \Omega}\right) 24\text{ V}$$

$$E_1 = 7.273\text{ V}$$

$$E_2 = \left(\frac{R_2}{R_T}\right) E_T$$

$$E_2 = \left(\frac{300\ \Omega}{660\ \Omega}\right) 24\text{ V}$$

$$E_2 = 10.909\text{ V}$$

$$E_3 = \left(\frac{R_3}{R_T}\right) E_T$$

$$E_3 = \left(\frac{160\ \Omega}{660\ \Omega}\right) 24\text{ V}$$

$$E_3 = 5.818\text{ V}$$

6–8 Voltage Polarity

It is often necessary to know the polarity of the voltage dropped across a resistor. **Voltage polarity** can be determined by observing the direction of current flow through the circuit. In the circuit shown in *Figure 6–22*, it will be assumed that the current flows from the negative terminal of the battery to the positive terminal. Point A is connected to the negative battery terminal, and Point E is connected to the positive terminal. If a voltmeter is connected across Terminals A and B, Terminal B will be positive with respect to A. If a voltmeter is connected across Terminals B and C, however, Terminal B will be negative with respect to Terminal C. Notice that Terminal B is closer to the negative terminal of the battery than Terminal C is. Consequently, electrons flow through the resistor in a direction that makes Terminal B more negative than C. Terminal C would be negative with respect to Terminal D for the same reason.

6–9 Using Ground as a Reference

Two symbols are used to represent ground *(Figure 6–23)*. The symbol shown in *Figure 6–23(A)* is an **earth ground** symbol. It symbolizes a **ground point** that is made by physically driving an object such as a rod or a pipe into the ground. The symbol shown in *Figure 6–23(B)* symbolizes a **chassis ground.** This is a point that is used as a common connection for other parts of a circuit, but it is not actually driven into the ground. Although the symbol shown in *Figure 6–23(B)* is the accepted symbol for a chassis ground, the symbol shown in *Figure 6–23(A)* is often used to represent a chassis ground also.

An excellent example of using a chassis ground as a common connection can be found in the electric system of an automobile. The negative terminal of the battery is grounded to the frame or chassis of the vehicle. The frame of the automobile is not connected directly to earth ground; it is insulated from the ground by rubber tires. In the case of an automobile electric system, the chassis of the vehicle is the negative side of the circuit. An electric circuit using ground as a common connection point is shown in *Figure 6–24*. This circuit is an electronic burglar alarm. Notice the numerous ground points in the schematic. In practice, when the circuit is connected, all the ground points will be connected together.

In voltage divider circuits, ground is often used to provide a common reference point to produce voltages that are above and below ground *(Figure 6–25)*. An above-ground voltage is a voltage that is positive with respect to ground. A below-ground voltage is negative with respect to ground. In *Figure 6–25*, one terminal of a zero-center voltmeter is connected to ground. If the probe is connected to Point A, the pointer of the voltmeter gives a negative indication for voltage. If the probe is connected to Point B, the pointer indicates a positive voltage.

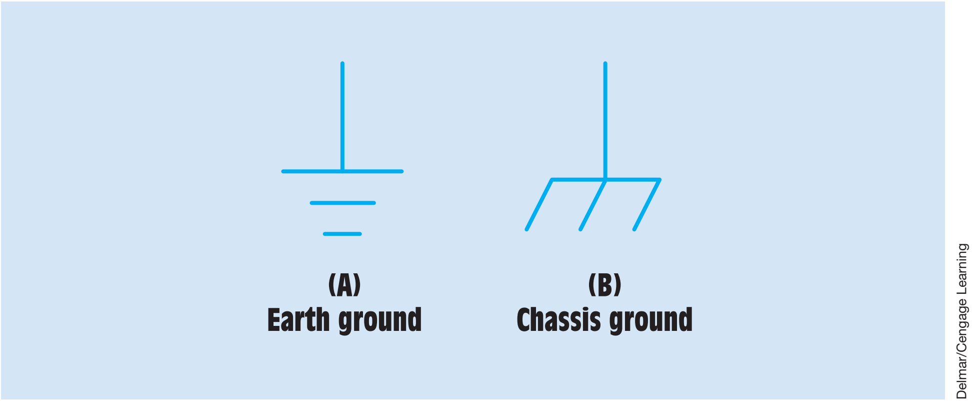

FIGURE 6–23 Ground symbols.

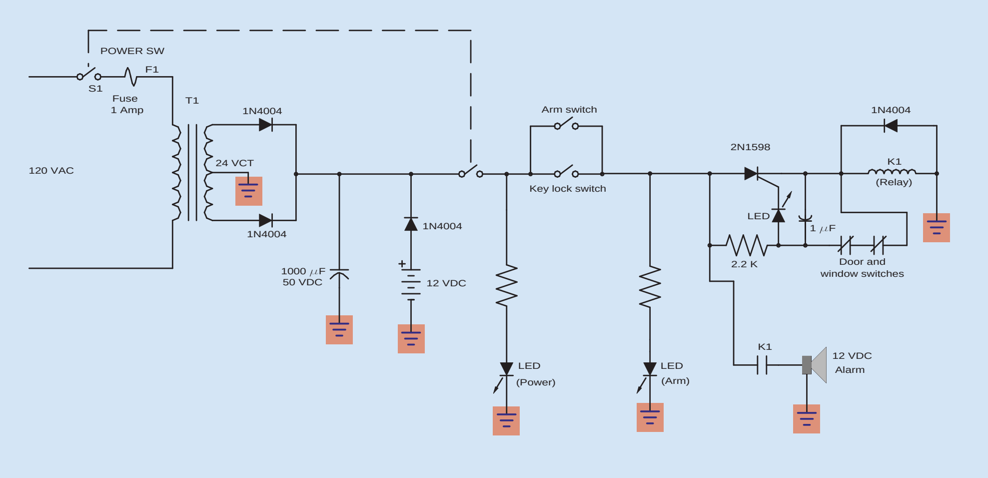

FIGURE 6–24 Burglar alarm with battery backup.

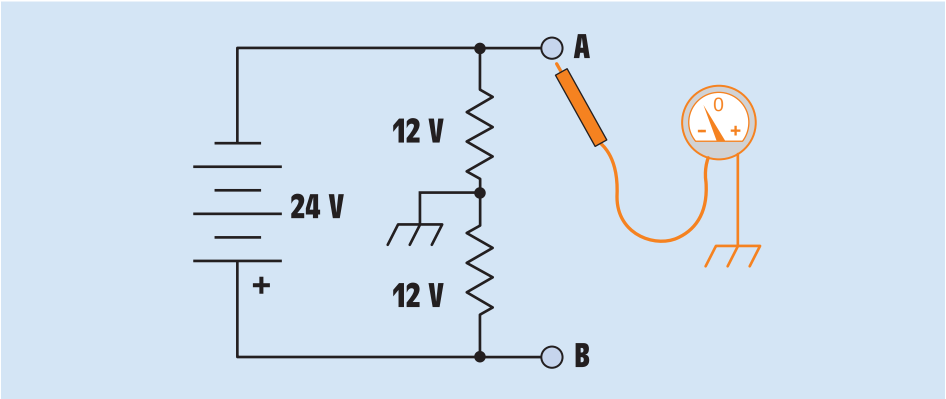

FIGURE 6–25 A common ground used to produce above- and below-ground voltage.

Summary

- Series circuits have only one path for current flow.
- The individual voltage drops in a series circuit can be added to equal the applied voltage.
- The current is the same at any point in a series circuit.
- The individual resistors can be added to equal the total resistance of the circuit.

- Fuses and circuit breakers are connected in series with the devices they are intended to protect.
- The total power in any circuit is equal to the sum of the power dissipated by all parts of the circuit.
- When the source voltage and the total resistance are known, the voltage drop across each element can be calculated using the general voltage divider formula.

Review Questions

1. A series circuit has individual resistor values of 200 Ω, 86 Ω, 91 Ω, 180 Ω, and 150 Ω. What is the total resistance of the circuit?
2. A series circuit contains four resistors. The total resistance of the circuit is 360 Ω. Three of the resistors have values of 56 Ω, 110 Ω, and 75 Ω. What is the value of the fourth resistor?
3. A series circuit contains five resistors. The total voltage applied to the circuit is 120 V. Four resistors have voltage drops of 35 V, 28 V, 22 V, and 15 V. What is the voltage drop of the fifth resistor?
4. A circuit has three resistors connected in series. Resistor R_2 has a resistance of 220 Ω and a voltage drop of 44 V. What is the current flow through resistor R_3?
5. A circuit has four resistors connected in series. If each resistor has a voltage drop of 60 V, what is the voltage applied to the circuit?
6. Define a series circuit.
7. State the three rules for series circuits.
8. A series circuit has resistance values of 160 Ω, 100 Ω, 82 Ω, and 120 Ω. What is the total resistance of this circuit?
9. If a voltage of 24 V is applied to the circuit in Question 8, what will be the total amount of current flow in the circuit?
10. Referring to the circuit described in Questions 8 and 9, determine the voltage drop across each of the resistors.

    160 Ω, ____________ V

    100 Ω, ____________ V

    82 Ω, ____________ V

    120 Ω, ____________ V

11. A series circuit contains the following values of resistors:

$R_1 = 510\ \Omega \quad R_2 = 680\ \Omega \quad R_3 = 390\ \Omega \quad R_4 = 750\ \Omega$

Assume a source voltage of 48 V. Use the general voltage divider formula to calculate the voltage drop across each of the resistors.

$E_1 =$ _______ V $E_2 =$ _______ V $E_3 =$ _______ V $E_4 =$ _______ V

Practical Applications

A 12-V DC automobile head lamp is to be used on a fishing boat with a 24-V power system. The head lamp is rated at 50 W. A resistor is to be connected in series with the lamp to permit it to operate on 24 V. What should be the resistance and power rating of the resistor? ■

Practical Applications

Three wire-wound resistors have the following values: 30 Ω, 80 Ω, and 100 Ω. Each resistor has a voltage rating of 100 V. If these three resistors are connected in series, can they be connected to a 240-V circuit without damage to the resistors? Explain your answer. ■

Practical Applications

You are an electrician working in an industrial plant. A circuit contains eight incandescent lamps connected in series across 480 volts. One lamp has burned out, and you must determine which one is defective. You have available a voltmeter, ammeter, and ohmmeter. Which meter would you use to determine which lamp is defective in the shortest possible time? Explain how you would use this meter and why. ■

Practical Applications

A direct current motor is connected to a 250-volt DC supply. The armature has a current draw of 165 amperes when operating at full load. You have been assigned the task of connecting two resistors in the armature circuit to provide speed control for the motor. When both resistors are connected in the circuit, the armature current is to be limited to 50% of the full-load current draw. When only one resistor is connected in the circuit, the armature current is to be limited to 85% of full-load current. Determine the ohmic value and minimum power rating of each resistor. Refer to *Figure 6–26.* When both switches S_1 and S_2 are open (off), both resistors are connected in the armature circuit, limiting current to 50% of its normal value. When switch S_1 is closed, it causes the current to bypass resistor 1. Resistor 2 now limits the current to 85% of the full-load current. When both switches S_1 and S_2 are closed, all resistance is bypassed, and the armature is connected to full power. ■

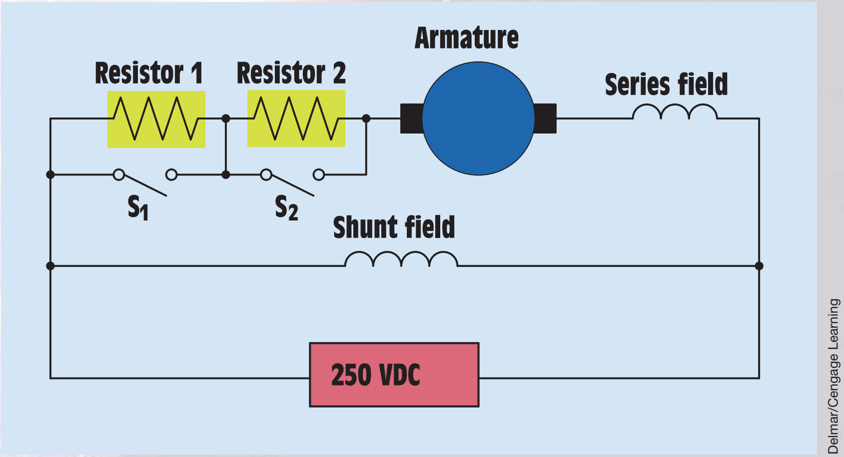

FIGURE 6–26 Determine the resistance and power rating of the two series resistors.

Practice Problems

Series Circuits

1. Using the three rules for series circuits and Ohm's law, solve for the missing values.

E_T 120 V	E_1	E_2	E_3	E_4	E_5
I_T	I_1	I_2	I_3	I_4	I_5
R_T	R_1 430 Ω	R_2 360 Ω	R_3 750 Ω	R_4 1000 Ω	R_5 620 Ω
P_T	P_1	P_2	P_3	P_4	P_5

E_T	E_1	E_2	E_3 11 V	E_4	E_5
I_T	I_1	I_2	I_3	I_4	I_5
R_T	R_1	R_2	R_3	R_4	R_5
P_T 0.25 W	P_1 0.03 W	P_2 0.0825 W	P_3	P_4 0.045 W	P_5 0.0375 W

E_T 340 V	E_1 44 V	E_2 94 V	E_3 60 V	E_4 40 V	E_5
I_T	I_1	I_2	I_3	I_4	I_5
R_T	R_1	R_2	R_3	R_4	R_5
P_T	P_1	P_2	P_3	P_4	P_5 0.204 W

2. Use the general voltage divider formula to calculate the values of voltage drop for the following series-connected resistors. Assume a source voltage of 120 V.

R^1 = 1K Ω　　R_2 = 2.2K Ω　　R_3 = 1.8K Ω　　R_4 = 1.5K Ω

E_1 = _____ V　　E_2 = _____ V　　E_3 = _____ V　　E_4 = _____ V

Unit 7

Parallel Circuits

Why You Need to Know

There are probably more devices connected in parallel than any other way. Learning the rules concerning voltage, current, resistance, and power in parallel circuits is paramount to understanding all electric circuits. Without this knowledge, it is impossible for an electrician to ever know how or why things work the way they do. In this unit, you will

- use Ohm's law and three rules governing parallel circuits to determine different electrical values.
- use Ohm's law to understand how voltage remains constant while current changes in a parallel circuit.
- learn why total resistance decreases when resistors are connected in parallel.

Although working Ohm's law problems often becomes tedious, it is the only way to gain an understanding of the relationship of voltage, current, resistance, and power in a parallel circuit.

OUTLINE

KEY TERMS

Circuit branch

Current dividers

Load

Parallel circuits

Objectives

After studying this unit, you should be able to

- discuss the characteristics of parallel circuits.
- state three rules for solving electrical values of parallel circuits.
- solve the missing values in a parallel circuit using the three rules and Ohm's law.
- discuss the operation of a current divider circuit.
- calculate current values using the current divider formula.

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Preview

Parallel circuits are probably the type of circuit with which most people are familiar. Most devices such as lights and receptacles in homes and office buildings are connected in parallel. Imagine if the lights in your home were wired in series. All the lights in the home would have to be turned on in order for any light to operate, and, if one were to burn out, all the lights would go out. The same is true for receptacles. If receptacles were connected in series, some device would have to be connected into each receptacle before power could be supplied to any other device. ■

7–1 Parallel Circuit Values

Total Current

Parallel circuits are circuits that have more than one path for current flow *(Figure 7–1)*. If it is assumed that current leaves Terminal A and returns to Terminal B, it can be seen that the electrons can take three separate paths. In *Figure 7–1, 3* amperes of current leave Terminal A. One ampere flows through Resistor R_1, and 2 amperes flow to Resistors R_2 and R_3. At the junction of Resistors R_2 and R_3, 1 ampere flows through Resistor R_2, and 1 ampere flows to Resistor R_3. Notice that the power supply, Terminals A and B, must furnish all the current that flows through each individual resistor, or **circuit branch.** One of the rules for parallel circuits states that ***the total current flow in the circuit is equal to the sum of the currents through all the branches.*** This rule is known as current adds. Notice that the amount of current leaving the source *must* return to the source.

Voltage Drop

Figure 7–2 shows another parallel circuit and gives the values of voltage, current, and resistance for each individual resistor or branch. Notice that the voltage drop across all three resistors is the same. If the circuit is traced, it can be

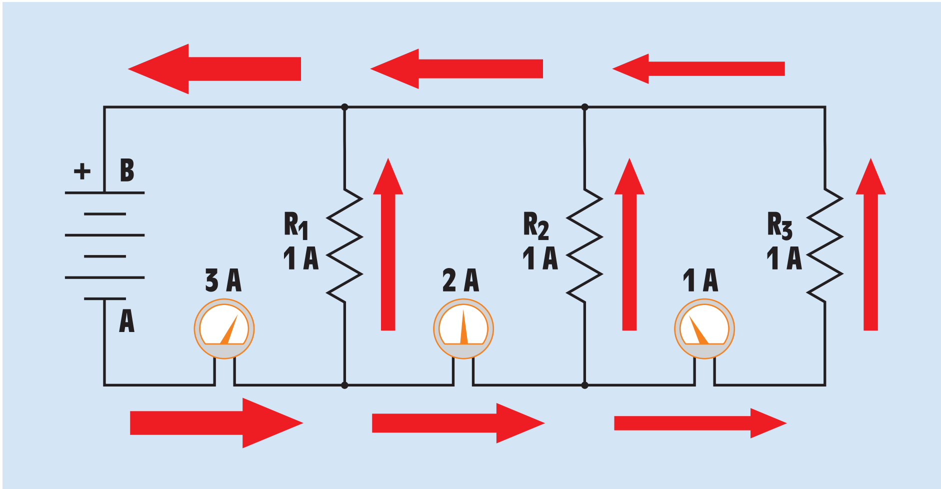


FIGURE 7–1 Parallel circuits provide more than one path for current flow.

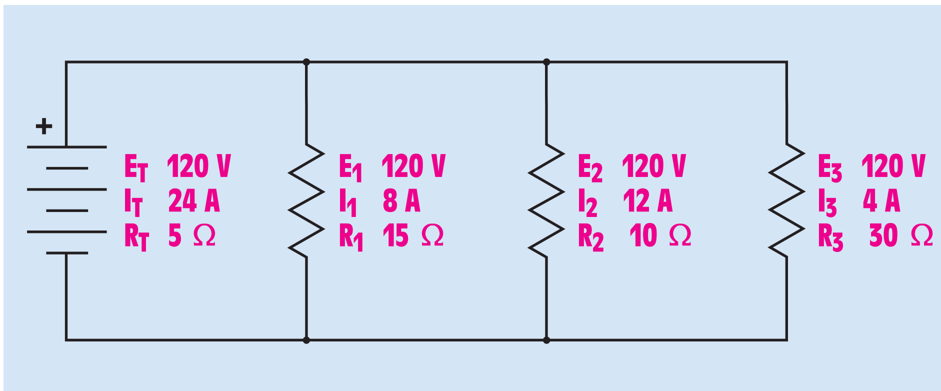


FIGURE 7–2 Parallel circuit values.

seen that each resistor is connected directly to the power source. A second rule for parallel circuits states that ***the voltage drop across any branch of a parallel circuit is the same as the applied voltage.*** For this reason, most electric circuits in homes are connected in parallel. Each lamp and receptacle is supplied with 120 volts *(Figure 7–3)*.

Total Resistance

In the circuit shown in *Figure 7–4,* three separate resistors have values of 15 ohms, 10 ohms, and 30 ohms. The total resistance of the circuit, however, is 5 ohms. ***The total resistance of a parallel circuit is always less than the resistance of the lowest value resistor, or branch, in the circuit.*** Each

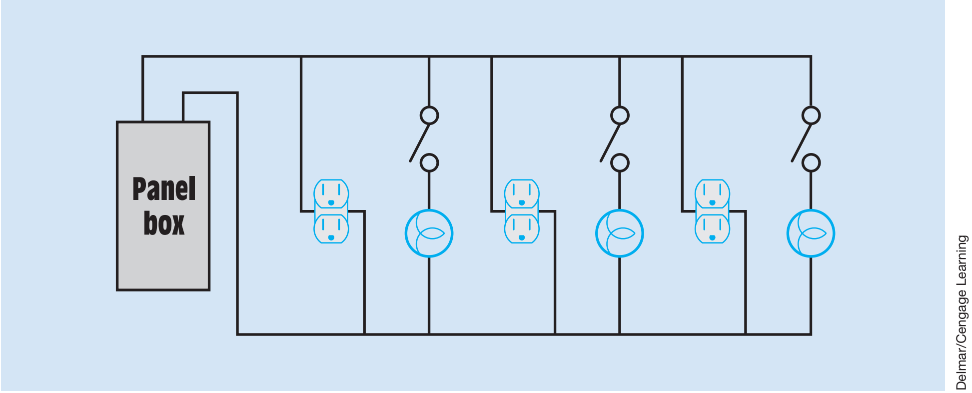


FIGURE 7–3 Lights and receptacles are connected in parallel.

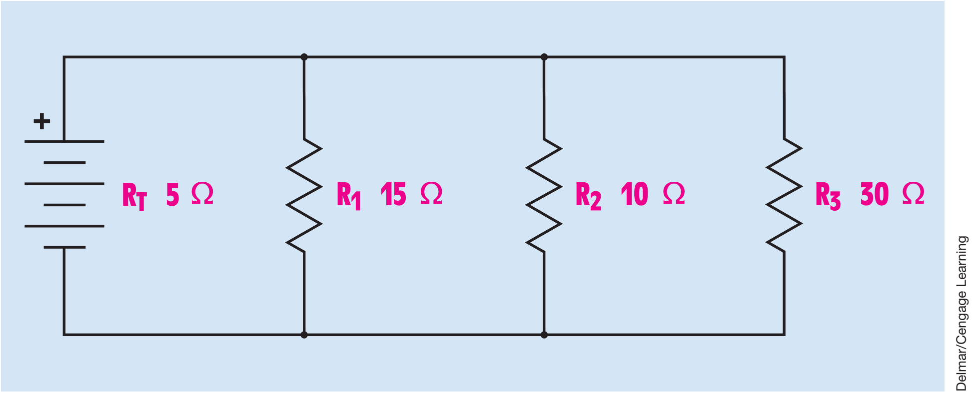


FIGURE 7–4 Total resistance is always less than the resistance of any single branch.

time another element is connected in parallel, there is less opposition to the flow of current through the entire circuit. Imagine a water system consisting of a holding tank, a pump, and return lines to the tank *(Figure 7–5)*. Although large return pipes have less resistance to the flow of water than small pipes, the small pipes do provide a return path to the holding tank. Each time another return path is added, regardless of size, there is less overall resistance to flow and the rate of flow increases.

That concept often causes confusion concerning the definition of **load** among students of electricity. Students often think that an increase of resistance constitutes an increase of load. An increase of current, not resistance, results in an increase of load. In laboratory exercises, students often see the circuit current increase each time a resistive element is connected to the circuit, and they conclude that an increase of resistance must therefore cause an increase of current. That conclusion is, of course, completely contrary to Ohm's law,

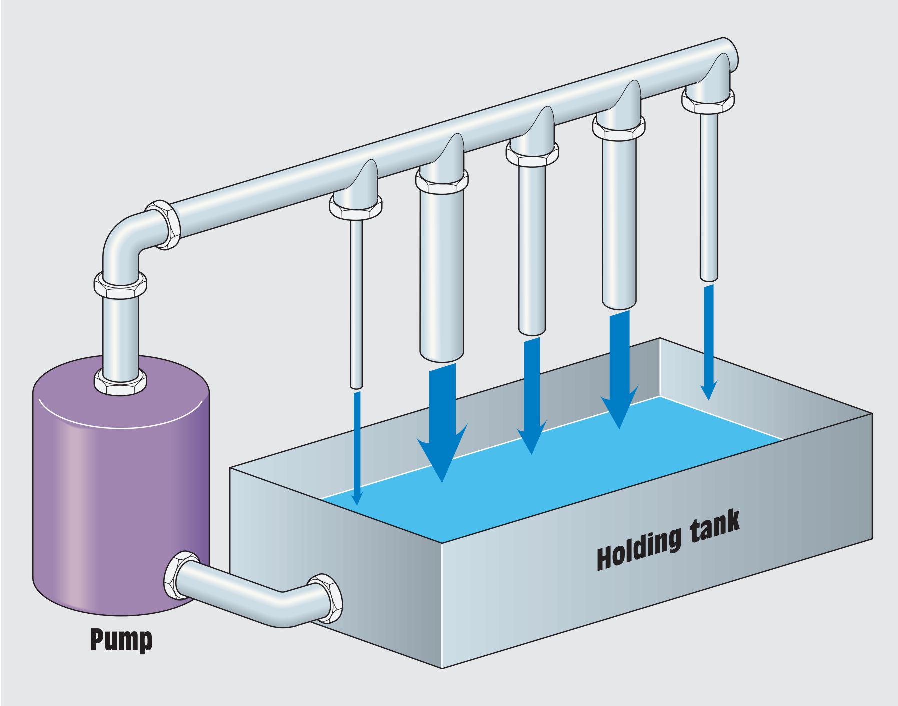


FIGURE 7–5 Each new path reduces the total resistance to the flow of water.

which states that an increase of resistance must cause a proportional decrease of current. The false concept that an increase of resistance causes an increase of current can be overcome once the student understands that if the resistive elements are being connected in parallel, the circuit resistance is actually being decreased and not increased.

7–2 Parallel Resistance Formulas

Resistors of Equal Value

Three formulas can be used to determine the total resistance of a parallel circuit. The first formula can be used only when all the resistors in the circuit are of equal value. This formula states that ***when all resistors are of equal value, the total resistance is equal to the value of one individual resistor, or branch, divided by the number (N) of resistors or branches.***

$$R_T = \frac{R}{N}$$

For example, assume that three resistors, each having a value of 24 ohms, are connected in parallel *(Figure 7–6)*. The total resistance of this circuit can

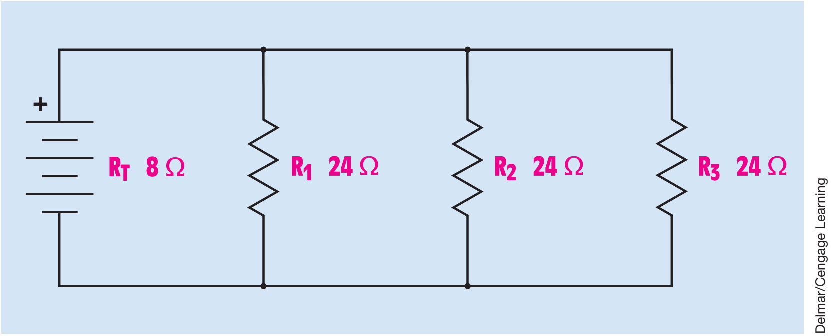


FIGURE 7–6 Finding the total resistance when all resistors have the same value.

be found by dividing the resistance of one single resistor by the total number of resistors:

$$R_T = \frac{R}{N}$$

$$R_T = \frac{24\ \Omega}{3}$$

$$R_T = 8\ \Omega$$

Product over Sum

The second formula used to determine the total resistance in a parallel circuit divides the product of pairs of resistors by their sum sequentially until only one pair is left. This is commonly referred to as the product-over-sum method for finding total resistance.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

In the circuit shown in *Figure 7–7,* three branches having resistors with values of 20 ohms, 30 ohms, and 60 ohms are connected in parallel. To find the total resistance of the circuit using the product-over-sum method, find the total resistance of any two branches in the circuit *(Figure 7–8):*

$$R_T = \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_T = \frac{30\ \Omega \times 60\ \Omega}{30\ \Omega + 60\ \Omega}$$

$$R_T = \frac{1800\ \Omega}{90\ \Omega}$$

$$R_T = 20\ \Omega$$

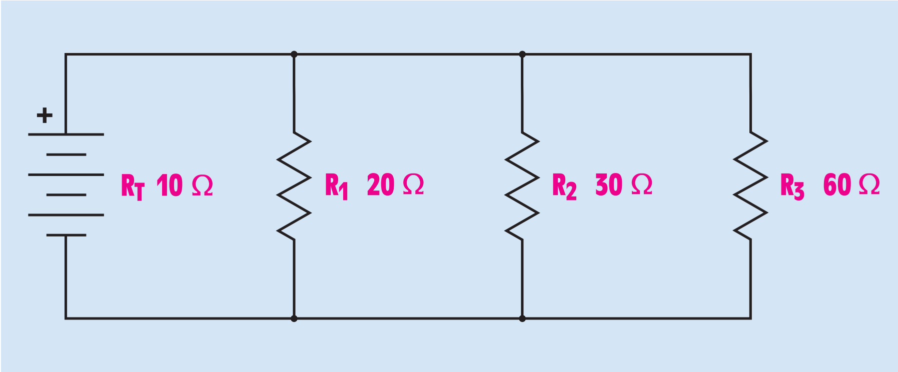


FIGURE 7–7 Finding the total resistance of a parallel circuit by dividing the product of two resistors by their sum.

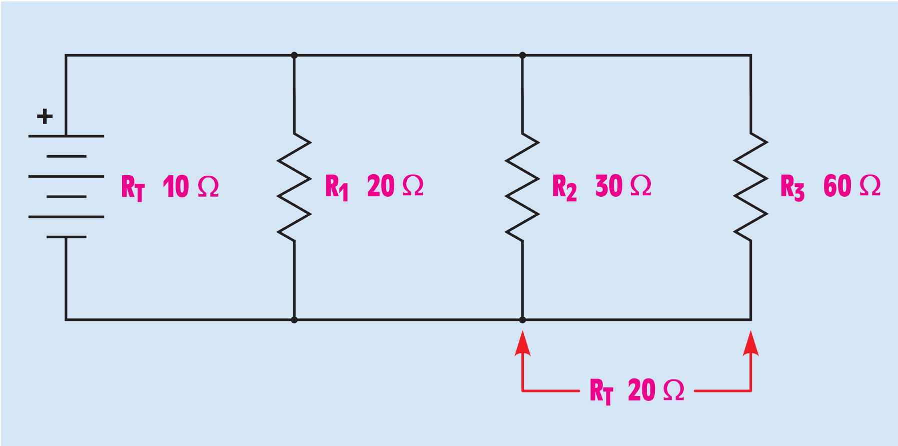


FIGURE 7–8 The total resistance of the last two branches.

The total resistance of the last two resistors in the circuit is 20 ohms. This 20 ohms, however, is connected in parallel with a 20-ohms resistor. The total resistance of the last two resistors is now substituted for the value of R_1 in the formula, and the value of the first resistor is substituted for the value of R_2 *(Figure 7–9):*

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{20\ \Omega \times 20\ \Omega}{20\ \Omega + 20\ \Omega}$$

$$R_T = \frac{400\ \Omega}{40\ \Omega}$$

$$R_T = 10\ \Omega$$

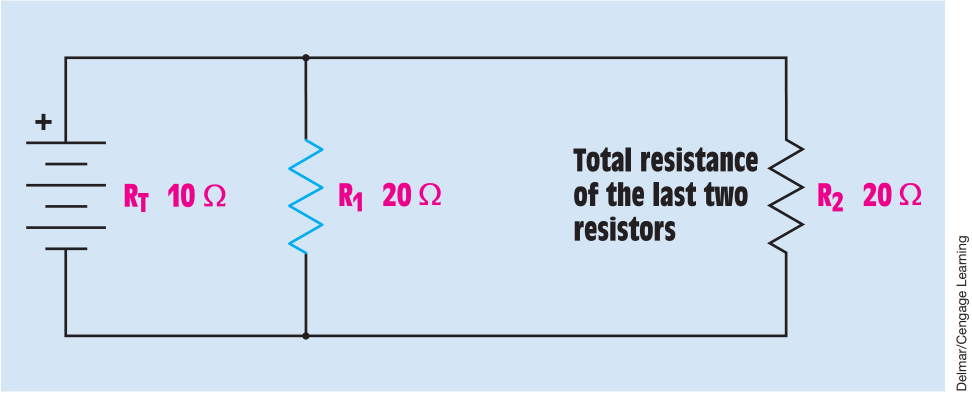


FIGURE 7–9 The total value of the first two resistors is used as Resistor 2.

Reciprocal Formula

The third formula used to find the total resistance of a parallel circuit is

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}$$

Notice that this formula actually finds the reciprocal of the total resistance, instead of the total resistance. To make the formula equal to the total resistance, it can be rewritten as follows:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}}$$

The value R_N stands for the number of resistors in the circuit. If the circuit has 25 resistors connected in parallel, for example, the last resistor in the formula would be R_{25}.

This formula is known as the reciprocal formula. The reciprocal of any number is that number divided into 1. The reciprocal of 4, for example, is 0.25 because $\frac{1}{4} = 0.25$. Another rule of parallel circuits is that ***the total resistance of a parallel circuit is the reciprocal of the sum of the reciprocals of the individual branches.*** A modified version of this formula is used in several different applications to find values other than resistance. Some of those other formulas are covered later.

Before the invention of handheld calculators, the slide rule was often employed to help with the mathematical calculations in electrical work. At that time, the product-over-sum method of finding total resistance was the most popular. Since the invention of calculators, however, the reciprocal formula has become the most popular because scientific calculators have a reciprocal key (1/X), which makes calculating total resistance using the reciprocal method very easy.

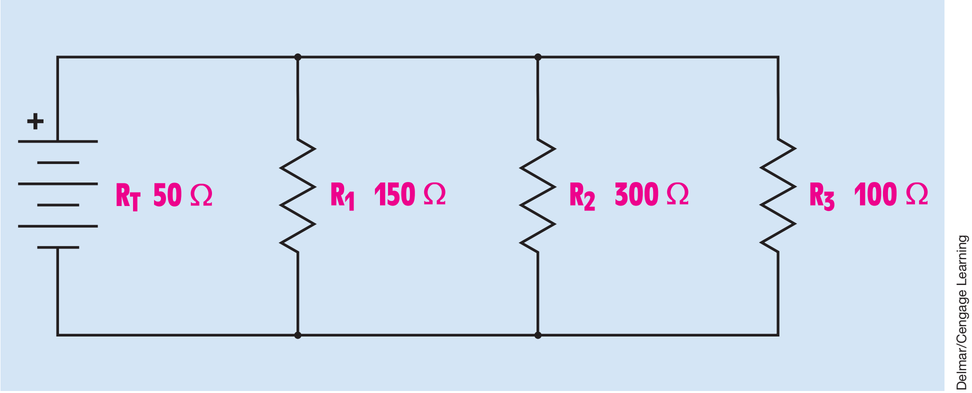


FIGURE 7–10 Finding the total resistance using the reciprocal method.

In *Figure 7–10,* three resistors having values of 150 ohms, 300 ohms, and 100 ohms are connected in parallel. The total resistance can be found using the reciprocal formula:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{\frac{1}{150\ \Omega} + \frac{1}{300\ \Omega} + \frac{1}{100\ \Omega}}$$

$$R_T = \frac{1}{(0.006667 + 0.003333 + 0.01)\frac{1}{\Omega}}$$

$$R_T = \frac{1}{(0.02)\frac{1}{\Omega}}$$

$$R_T = 50\ \Omega$$

To find the total resistance of the previous example using a scientific calculator, press the following keys. Note that the calculator automatically carries each answer to the maximum number of decimal places. This increases the accuracy of the answer.

[1] [5] [0] [1/x] [+] [3] [0] [0] [1/x] [+] [1] [0] [0] [1/x] [=] [1/x]

Note that this is intended to illustrate how total parallel resistance can be determined using many scientific calculators. Some calculators may require a different key entry or pressing the equal key at the end.

■ EXAMPLE 7–1

In the circuit shown in *Figure 7–11,* three resistors having values of 300 Ω, 200 Ω, and 600 Ω are connected in parallel. The total current flow through the circuit is 0.6 A. Find all the missing values in the circuit.

Solution

The first step is to find the total resistance of the circuit. The reciprocal formula is used:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{\frac{1}{300\ \Omega} + \frac{1}{200\ \Omega} + \frac{1}{600\ \Omega}}$$

$$R_T = \frac{1}{(0.00333 + 0.0050 + 0.00167)\frac{1}{\Omega}}$$

$$R_T = \frac{1}{(0.01)\frac{1}{\Omega}}$$

$$R_T = 100\ \Omega$$

Now that the total resistance of the circuit is known, the voltage applied to the circuit can be found by using the total current value and Ohm's law:

$$E_T = I_T \times R_T$$

$$E_T = 0.6\ \text{A} \times 100\ \Omega$$

$$E_T = 60\ \text{V}$$

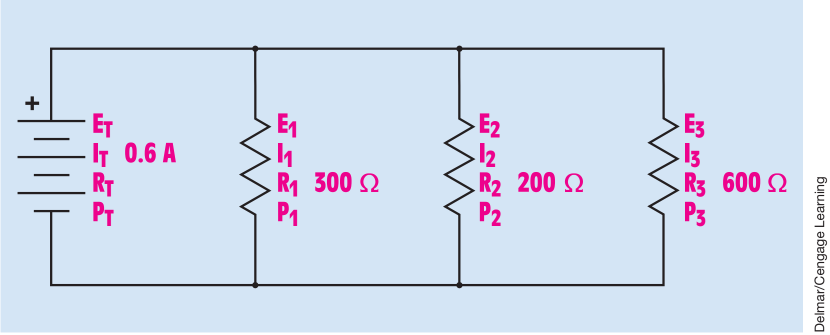


FIGURE 7–11 Parallel circuit, Example 1.

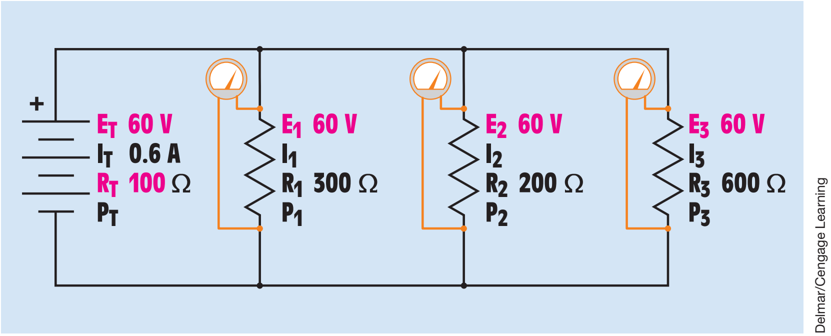


FIGURE 7–12 The voltage is the same across all branches of a parallel circuit.

One of the rules for parallel circuits states that the voltage drops across all the parts of a parallel circuit are the same as the total voltage. Therefore, the voltage drop across each resistor is 60 V *(Figure 7–12):*

$$E_T = E_1 = E_2 = E_3$$

Because the voltage drop and the resistance of each resistor are known, Ohm's law can be used to determine the amount of current flow through each resistor *(Figure 7–13):*

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{60\ V}{300\ \Omega}$$

$$I_1 = 0.2\ A$$

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{60\ V}{200\ \Omega}$$

$$I_2 = 0.3\ A$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{60\ V}{600\ \Omega}$$

$$I_3 = 0.1\ A$$

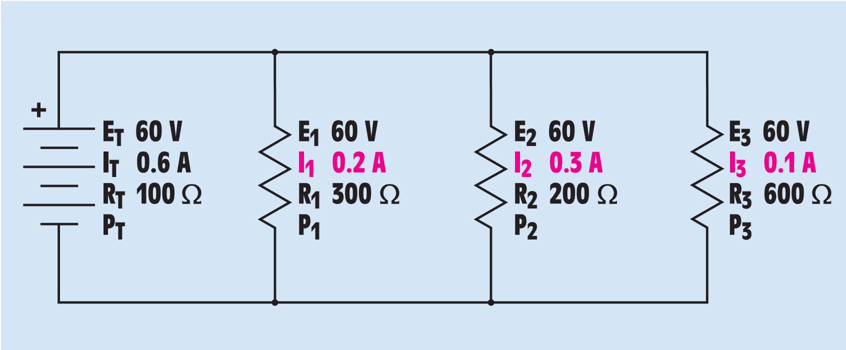


FIGURE 7–13 Ohm's law is used to calculate the amount of current through each branch.

The amount of power (W) used by each resistor can be found by using Ohm's law. A different formula is used to find the amount of electrical energy converted into heat by each of the resistors:

$$P_1 = \frac{E_1^2}{R_1}$$

$$P_1 = \frac{60\text{ V} \times 60\text{ V}}{300\ \Omega}$$

$$P_1 = \frac{3600\text{ V}^2}{300\ \Omega}$$

$$P_1 = 12\text{ W}$$

$$P_2 = I_2^2 \times R_2$$

$$P_2 = 0.3\text{ A} \times 0.3\text{ A} \times 200\ \Omega$$

$$P_2 = 0.09\text{ A}^2 \times 200\ \Omega$$

$$P_2 = 18\text{ W}$$

$$P_3 = E_3 \times I_3$$

$$P_3 = 60\text{ V} \times 0.1\text{ A}$$

$$P_3 = 6\text{ W}$$

In Unit 6, it was stated that the total amount of power in a circuit is equal to the sum of the power used by all the parts. This is true for any type of circuit. Therefore, the total amount of power used by this circuit can be found by taking the sum of the power used by all the resistors *(Figure 7–14):*

$$P_T = P_1 + P_2 + P_3$$

$$P_T = 12\text{ W} + 18\text{ W} + 6\text{ W}$$

$$P_T = 36\text{ W}$$

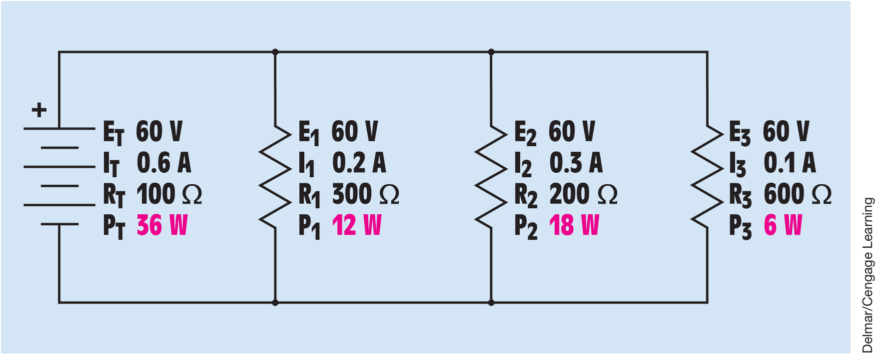


FIGURE 7–14 The amount of power used by the circuit.

EXAMPLE 7-2

In the circuit shown in *Figure 7–15,* three resistors are connected in parallel. Two of the resistors have a value of 900 Ω and 1800 Ω. The value of Resistor R_2 is unknown. The total resistance of the circuit is 300 Ω. Resistor R_2 has a current flow of 0.2 A. Find the missing circuit values.

Solution

The first step in solving this problem is to find the missing resistor value. This can be done by changing the reciprocal formula as shown:

$$\frac{1}{R_2} = \frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}$$

or

$$R_2 = \frac{1}{\frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}}$$

One of the rules for parallel circuits states that the total resistance is equal to the reciprocal of the sum of the reciprocals of the individual resistors. Therefore, the reciprocal of any individual resistor is equal to the reciprocal of the difference

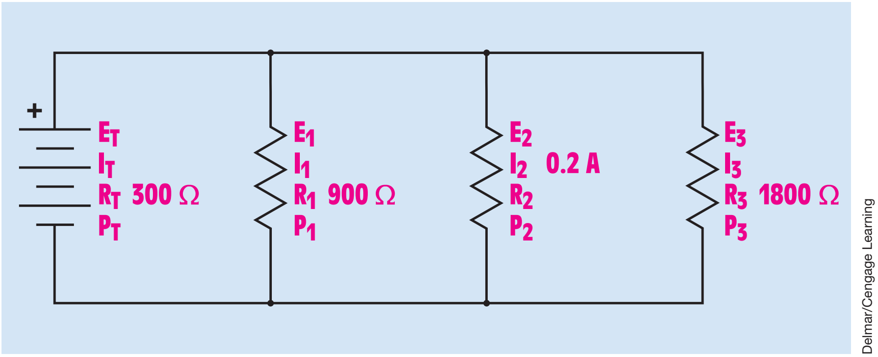


FIGURE 7–15 Parallel circuit, Example 2.

between the reciprocal of the total resistance and the sum of the reciprocals of the other resistors in the circuit:

$$R_2 = \frac{1}{\frac{1}{R_T} - \frac{1}{R_1} - \frac{1}{R_3}}$$

$$R_2 = \frac{1}{\frac{1}{300\ \Omega} - \frac{1}{900\ \Omega} - \frac{1}{1800\ \Omega}}$$

$$R_2 = \frac{1}{(0.003333 - 0.001111 - 0.0005556)\frac{1}{\Omega}}$$

$$R_2 = \frac{1}{(0.001666)\frac{1}{\Omega}}$$

$$R_2 = 600\ \Omega$$

Now that the resistance of Resistor R_2 has been found, the voltage drop across Resistor R_2 can be determined using the current flow through the resistor and Ohm's law *(Figure 7–16):*

$$E_2 = I_2 \times R_2$$

$$E_2 = 0.2\ \text{A} \times 600\ \Omega$$

$$E_2 = 120\ \text{V}$$

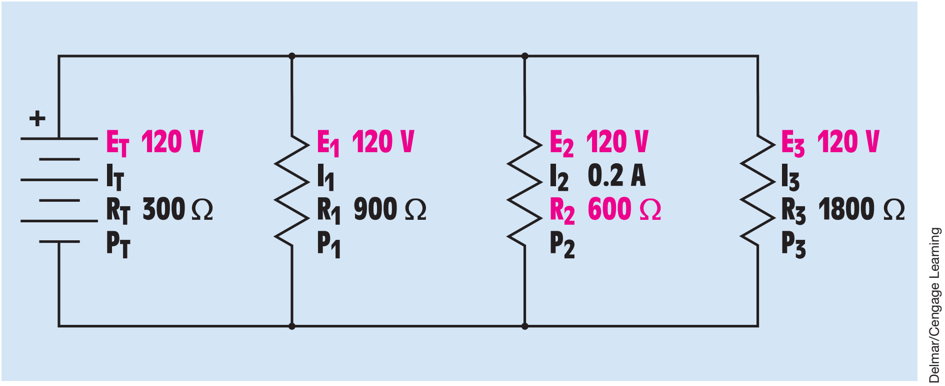


FIGURE 7–16 The missing resistor and voltage values.

If 120 V is dropped across Resistor R_2, the same voltage is dropped across each component of the circuit:

$$E_2 = E_T = E_1 = E_3$$

Now that the voltage drop across each part of the circuit is known and the resistance is known, the current flow through each branch can be determined using Ohm's law *(Figure 7–17):*

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{120\text{ V}}{300\ \Omega}$$

$$I_T = 0.4\text{ A}$$

$$I_1 = \frac{E_1}{R_1}$$

$$I_1 = \frac{120\text{ V}}{1800\ \Omega}$$

$$I_1 = 0.1333\text{ A}$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{120\text{ V}}{1800\ \Omega}$$

$$I_3 = 0.0667\text{ A}$$

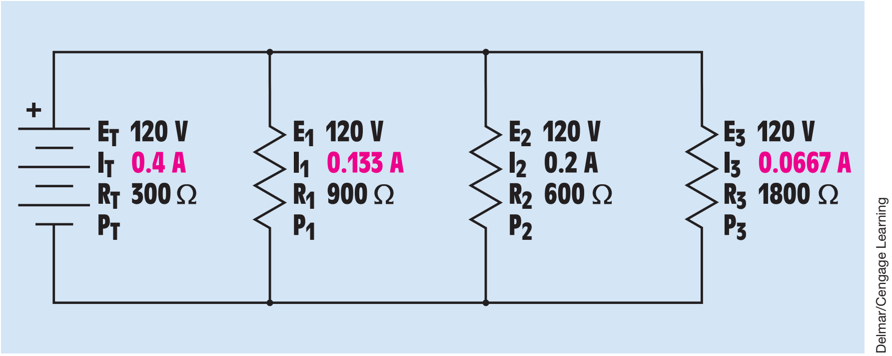


FIGURE 7–17 Determining the current using Ohm's law.

The amount of power used by each resistor can be found using Ohm's law *(Figure 7–18)*:

$$P_1 = \frac{E_1^2}{R_1}$$

$$P_1 = \frac{120\text{ V} \times 120\text{ V}}{900\ \Omega}$$

$$P_1 = \frac{14{,}400\text{ V}^2}{900\ \Omega}$$

$$P_1 = 16\text{ W}$$

$$P_2 = I_2^2 \times R_2$$

$$P_2 = 0.2\text{ A} \times 0.2\text{ A} \times 600\ \Omega$$

$$P_2 = 0.04\text{ A}^2 \times 600\ \Omega$$

$$P_2 = 24\text{ W}$$

$$P_3 = E_3 \times I_3$$

$$P_3 = 120\text{ V} \times 0.0667\text{ A}$$

$$P_3 = 8.004\text{ W}$$

$$P_T = E_T \times I_T$$

$$P_T = 120\text{ V} \times 0.4\text{ A}$$

$$P_T = 48\text{ W}$$

If the wattage values of the three resistors are added to calculate total power for the circuit, it will be seen that their total is 48.004 W instead of the calculated 48 W. The small difference in answers is caused by the rounding off of other values. In this instance, the current of Resistor R_3 was rounded from 0.066666666 to 0.0667.

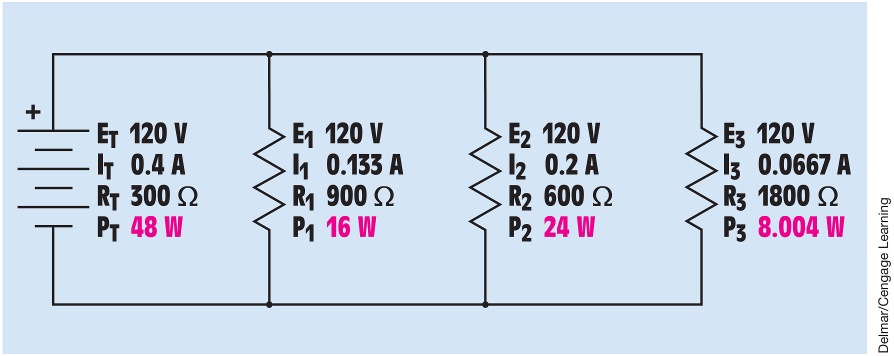


FIGURE 7–18 The values of power for the circuit in Example 2.

EXAMPLE 7-3

In the circuit shown in *Figure 7–19,* three resistors are connected in parallel. Resistor R_1 is producing 0.075 W of heat, R_2 is producing 0.45 W of heat, and R_3 is producing 0.225 W of heat. The circuit has a total current of 0.05 A.

Solution

Because the amount of power dissipated by each resistor is known, the total power for the circuit can be found by finding the sum of the power used by the components:

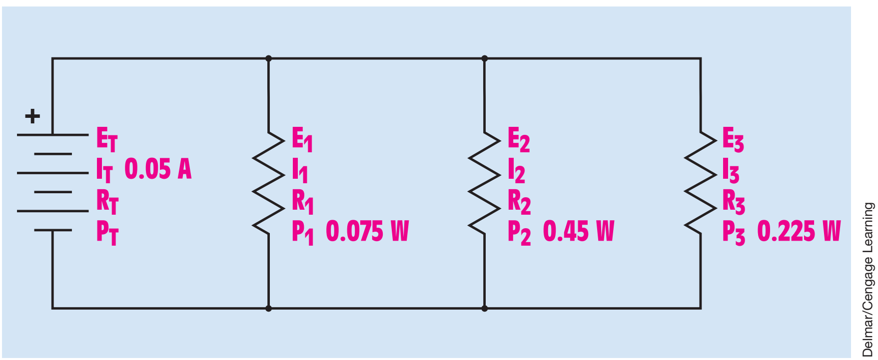


FIGURE 7–19 Parallel circuit, Example 3.

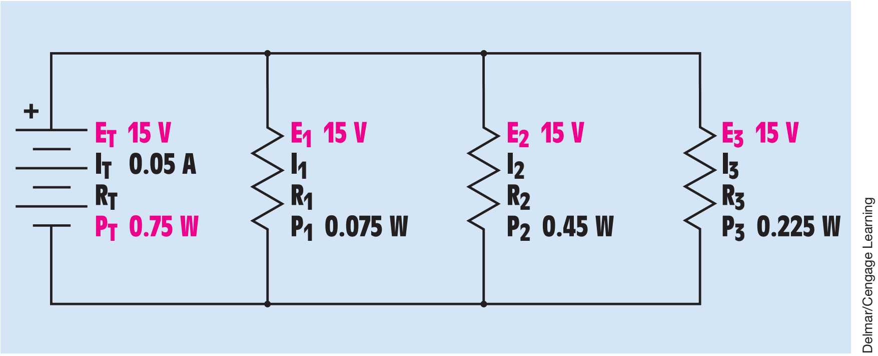


FIGURE 7–20 The applied voltage for the circuit.

$$P_T = P_1 + P_2 + P_3$$
$$P_T = 0.075\ W + 0.45\ W + 0.225\ W$$
$$P_T = 0.75\ W$$

Now that the amount of total current and total power for the circuit are known, the applied voltage can be found using Ohm's law *(Figure 7–20):*

$$E_T = \frac{P_T}{I_T}$$
$$E_T = \frac{0.75\ W}{0.05\ A}$$
$$E_T = 15\ V$$

The amount of current flow through each resistor can now be found using Ohm's law *(Figure 7–21):*

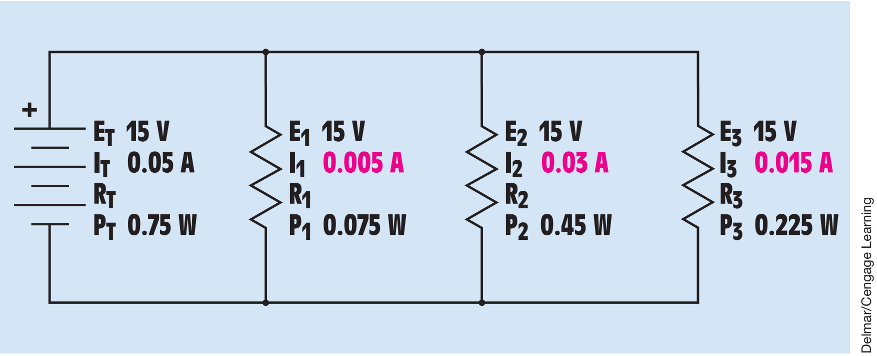


FIGURE 7–21 The current through each branch.

$$I_1 = \frac{P_1}{E_1}$$

$$I_1 = \frac{0.075\ \text{W}}{15\ \text{V}}$$

$$I_1 = 0.005\ \text{A}$$

$$I_2 = \frac{P_2}{E_2}$$

$$I_2 = \frac{0.45\ \text{W}}{15\ \text{V}}$$

$$I_2 = 0.03\ \text{A}$$

$$I_3 = \frac{P_3}{E_3}$$

$$I_3 = \frac{0.225\ \text{W}}{15\ \text{V}}$$

$$I_3 = 0.015\ \text{A}$$

All resistance values for the circuit can now be found using Ohm's law *(Figure 7–22):*

$$R_1 = \frac{E_1}{I_1}$$

$$R_1 = \frac{15\ \text{V}}{0.005\ \text{A}}$$

$$R_1 = 3000\ \Omega$$

$$R_2 = \frac{E_2}{I_2}$$

$$R_2 = \frac{15\ \text{V}}{0.03\ \text{A}}$$

$$R_2 = 500\ \Omega$$

$$R_3 = \frac{E_3}{I_3}$$

$$R_3 = \frac{15\ \text{V}}{0.015\ \text{A}}$$

$$R_3 = 1000\ \Omega$$

$$R_T = \frac{E_T}{I_T}$$

$$R_T = \frac{15\ \text{V}}{0.05\ \text{A}}$$

$$R_T = 300\ \Omega$$

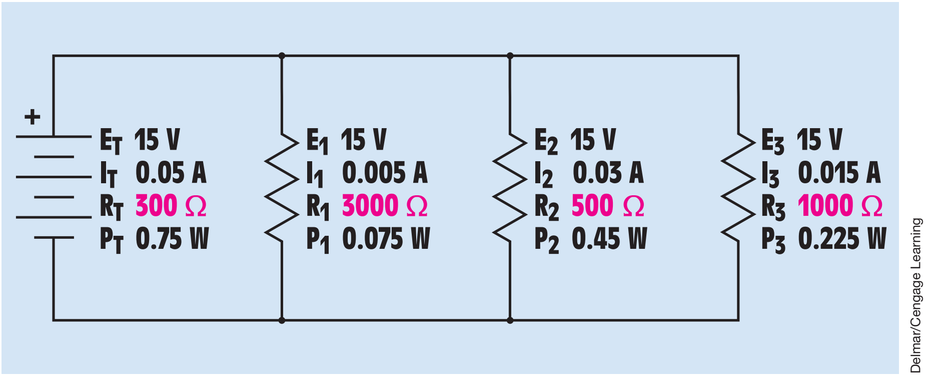


FIGURE 7–22 The remaining values for the circuit.

Current Dividers

All parallel circuits are **current dividers** *(Figure 7–23)*. As previously discussed in this unit, the sum of the currents in a parallel circuit must equal the total current. Assume that a current of 1 ampere enters the circuit at Point A. This 1 ampere of current will divide between Resistors R_1 and R_2, and then recombine at Point B. The amount of current that flows through each resistor is inversely proportional to the resistance value. A greater amount of current will

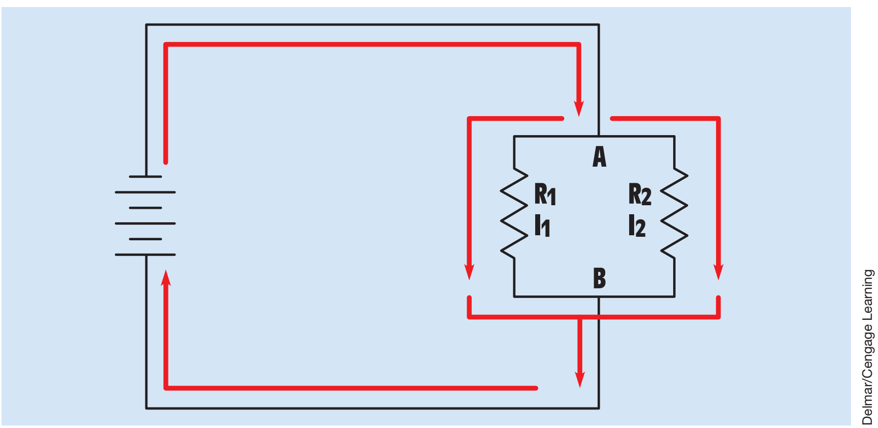


FIGURE 7–23 Parallel circuits are current dividers.

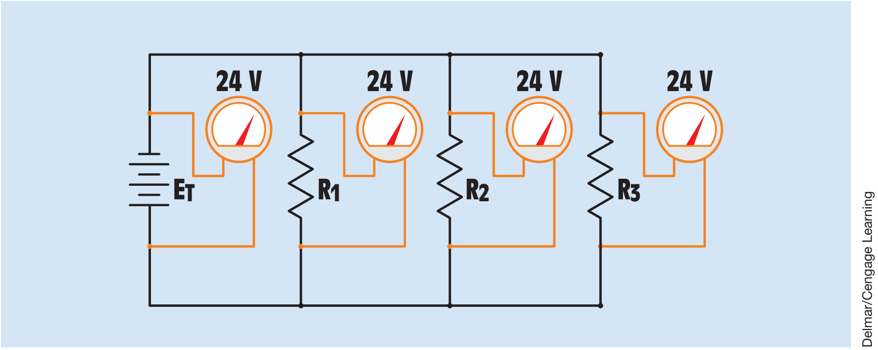


FIGURE 7–24 The voltage is the same across all branches of a parallel circuit.

flow through a low-value resistor, and less current will flow through a high-value resistor. In other words, the amount of current flowing through each resistor is inversely proportional to its resistance.

In a parallel circuit, the voltage across each branch must be equal *(Figure 7–24)*. Therefore, the current flow through any branch can be calculated by dividing the source voltage (E_T) by the resistance of that branch. The current flow through Branch 1 can be calculated using the formula

$$I_1 = \frac{E_T}{R_1}$$

It is also true that the total circuit voltage is equal to the product of the total circuit current and the total circuit resistance:

$$E_T = I_T \times R_T$$

If the value of ET is substituted for ($I_T \times R_T$) in the previous formula, it becomes

$$I_1 = \frac{I_T \times R_T}{R_1}$$

If the formula is rearranged and the values of I_1 and R_1 are substituted for I_X and R_X, it becomes what is generally known as the *current divider formula:*

$$I_X = \left(\frac{R_T}{R_X}\right) I_T$$

This formula can be used to calculate the current flow through any branch by substituting the values of I_X and R_X for the branch values when the total circuit current and the resistance are known. In the circuit shown in *Figure 7–25,*

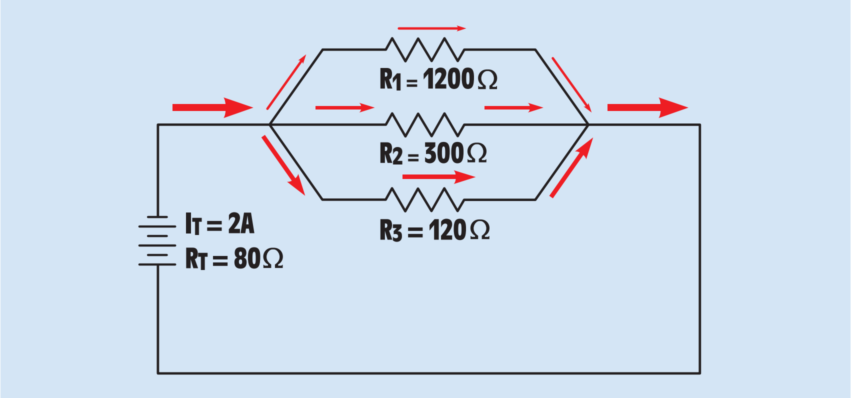


FIGURE 7–25 The current divides through each branch of a parallel circuit.

Resistor R_1 has a value of 1200 ohms, Resistor R_2 has a value of 300 ohms, and Resistor R_3 has a value of 120 ohms, producing a total resistance of 80 ohms for the circuit. It is assumed that a total current of 2 amperes flows in the circuit. The amount of current flow through Resistor R_1 can be found using the formula

$$I_1 = \left(\frac{R_T}{R_1}\right) I_T$$

$$I_1 = \left(\frac{80\ \Omega}{1200\ \Omega}\right) 2\ A$$

$$I_1 = 0.133\ A$$

The current flow through each of the other resistors can be found by substituting in the same formula:

$$I_2 = \left(\frac{R_T}{R_2}\right) I_T$$

$$I_2 = \left(\frac{80\ \Omega}{300\ \Omega}\right) 2\ A$$

$$I_2 = 0.533\ A$$

$$I_3 = \left(\frac{R_T}{R_3}\right) I_T$$

$$I_3 = \left(\frac{80\ \Omega}{120\ \Omega}\right) 2\ A$$

$$I_3 = 1.333\ A$$

Summary

- A Parallel circuit is characterized by the fact that it has more than one path for current flow.
- Three rules for solving parallel circuits are as follows:
  a. The total current is the sum of the currents through all of the branches of the circuit.
  b. The voltage across any part of the circuit is the same as the total voltage.
  c. The total resistance is the reciprocal of the sum of the reciprocals of each individual branch.
- Circuits in homes are connected in parallel.
- The total power in a parallel circuit is equal to the sum of the power dissipation of all the components.
- Parallel circuits are current dividers.
- The current flowing through each branch of a parallel circuit can be calculated when the total resistance and the total current are known.
- The amount of current flow through each branch of a parallel circuit is inversely proportional to its resistance.

Review Questions

1. What characterizes a parallel circuit?
2. Why are circuits in homes connected in parallel?
3. State three rules concerning parallel circuits.
4. A parallel circuit contains four branches. One branch has a current flow of 0.8 A, another has a current flow of 1.2 A, the third has a current flow of 0.25 A, and the fourth has a current flow of 1.5 A. What is the total current flow in the circuit?
5. Four resistors having a value of 100 Ω each are connected in parallel. What is the total resistance of the circuit?
6. A parallel circuit has three branches. An ammeter is connected in series with the output of the power supply and indicates a total current flow of 2.8 A. If Branch 1 has a current flow of 0.9 A and Branch 2 has a current flow of 1.05 A, what is the current flow through Branch 3?

7. Four resistors having values of 270 Ω, 330 Ω, 510 Ω, and 430 Ω are connected in parallel. What is the total resistance in the circuit?

8. A parallel circuit contains four resistors. The total resistance of the circuit is 120 Ω. Three of the resistors have values of 820 Ω, 750 Ω, and 470 Ω. What is the value of the fourth resistor?

9. A circuit contains a 1200-Ω, a 2200-Ω, and a 3300-Ω resistor connected in parallel. The circuit has a total current flow of 0.25 A. How much current flows through each of the resistors?

Practical Applications

You have been hired by a homeowner to install a ceiling fan and light kit in a living room. The living room luminaire (light fixture) being used at the present time contains two 60-W lamps. After locating the circuit in the panel box, you find that the circuit is protected by a 15-A circuit breaker and is run with 14 AWG copper wire. After turning on all lights connected to this circuit, you have a current draw of 8.6 A and a voltage of 120 V. The ceiling fan light kit contains four 60-W lamps, and the fan has a maximum current draw of 1.6 A. Can this fan be connected to the existing living room circuit? Recall that a continuous-use circuit should not be loaded to more than 80% of its rated capacity. ■

Practical Applications

You are employed in a large industrial plant. A 480-V, 5000-W heater is used to melt lead in a large tank. It has been decided that the heater is not sufficient to raise the temperature of the lead to the desired level. A second 5000-W heater is to be installed on the same circuit. What will be the circuit current after installation of the second heater, and what is the minimum size circuit breaker that can be used if this is a continuous-duty circuit? ■

Practical Applications

You are an electrician. You have been asked by a homeowner to install a lighted mirror in a bathroom. The mirror contains eight 40-watt lamps. Upon checking the service panel you discover that the bathroom circuit is connected to a single 120-volt, 20-ampere circuit breaker. At the present time, the circuit supplies power to an electric wall heater rated at 1000 watts, a ceiling fan with a light kit, and a light fixture over the mirror. The fan motor has a full-load current draw of 3.2 amperes and the light kit contains three 60-watt lamps. The light fixture presently installed over the mirror contains four 60-watt lamps. The homeowner asked whether the present light fixture over the mirror can be replaced by the lighted mirror. Assuming all loads are continuous, can the present circuit supply the power needed to operate all the loads without overloading the circuit? ■

Practical Applications

A car lot uses incandescent lamps to supply outside lighting during the night. There are three strings of lamps connected to a single 20-ampere circuit. Each string contains eight lamps. What is the largest standard lamp that can be used without overloading the circuit? Standard size lamps are 25 watt, 40 watt, 60 watt, 75 watt, and 100 watt. ■

Practice Problems

Parallel Circuits

Using the rules for parallel circuits and Ohm's law, solve for the missing values.

1.

E_T	E_1	E_2	E_3	E_4
I_T 0.942 A	I_1	I_2	I_3	I_4
R_T	R_1 680 Ω	R_2 820 Ω	R_3 470 Ω	R_4 330 Ω
P_T	P_1	P_2	P_3	P_4

2.

E_T	E_1	E_2	E_3	E_4
I_T 0.00639 A	I_1	I_2 0.00139 A	I_3 0.00154 A	I_4 0.00115 A
R_T	R_1	R_2	R_3	R_4
P_T	P_1 0.640 W	P_2	P_3	P_4

3.

E_T	E_1	E_2	E_3	E_4
I_T	I_1	I_2	I_3 3.2 A	I_4
R_T 3.582 Ω	R_1 16 Ω	R_2 10 Ω	R_3	R_4 20 Ω
P_T	P_1	P_2	P_3	P_4

4.

E_T	E_1	E_2	E_3	E_4
I_T	I_1	I_2	I_3	I_4
R_T	R_1 82 kΩ	R_2 75 kΩ	R_3 56 kΩ	R_4 62 kΩ
P_T 3.436 W	P_1	P_2	P_3	P_4

5. A parallel circuit contains the following resistor values:

$R_1 = 360\ \Omega$ $R_2 = 470\ \Omega$ $R_3 = 300\ \Omega$

$R_4 = 270\ \Omega$ $I_T = 0.05$ A

Find the following missing values:

R_T = ____________ Ω I_1 = ____________ A I_2 = ____________ A

I_3 = ____________ A I_4 = ____________ A

6. A parallel circuit contains the following resistor values:

$R_1 = 270\text{K}\ \Omega$ $R_2 = 360\text{K}\ \Omega$ $R_3 = 430\text{K}\ \Omega$

$R_4 = 100\text{K}\ \Omega$ $I_T = 0.006$ A

Find the following missing values:

R_T = ____________ Ω I_1 = ____________ A I_2 = ____________ A

I_3 = ____________ A I_4 = ____________ A

Unit 8

DVD VIDEO

Combination Circuits

Why You Need to Know

Understanding how values of voltage, current, and resistance relate to each other in combination circuits is essential to understanding how all electric circuits work. Although it is not a common practice for electricians on the job to use a calculator to calculate values of voltage and current, they must have an understanding of how these electrical values relate to each other in different kinds of circuits. An understanding of Ohm's law and basic circuits is also essential in being able to troubleshoot problems that occur in an electric circuit. In this unit

- the rules for series circuits are employed for those components connected in series, and parallel rules are used for components connected in parallel.
- you are shown how to reduce a complex combination circuit to a simple series or parallel circuit and then apply circuit rules and Ohm's law to determine the values of voltage, current, and power for the different components.

OUTLINE

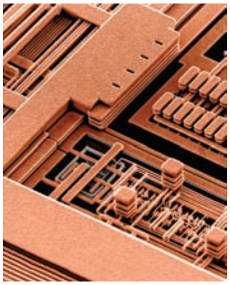
KEY TERMS

Combination circuit
Node
Parallel block
Redraw
Reduce
Simple parallel circuit
Trace the current path

Objectives

After studying this unit, you should be able to

- define a combination circuit.
- list the rules for parallel circuits.
- list the rules for series circuits.
- solve combination circuits using the rules for parallel circuits, the rules for series circuits, and Ohm's law.



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Preview

Combination circuits contain a combination of both series and parallel elements. To determine which components are in parallel and which are in series, trace the flow of current through the circuit. Remember that a series circuit has only one path for current flow and a parallel circuit has more than one path for current flow. ■

8–1 Combination Circuits

A simple combination circuit is shown in *Figure 8–1*. It is assumed that the current in *Figure 8–1* flows from Point A to Point B. To identify the series and parallel elements, **trace the current path.** All the current in the circuit must flow through the first resistor, R_1. R_1 is therefore in series with the rest of the circuit. When the current reaches the junction point of R_2 and R_3, however, it splits. A junction point such as this is often referred to as a **node.** Part of the current flows through R_2, and part flows through R_3. These two resistors are in parallel. Because this circuit contains both series and parallel elements, it is a **combination circuit.**

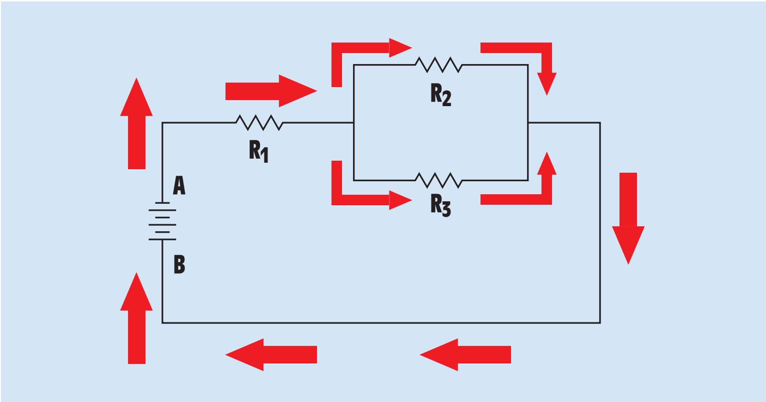

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FIGURE 8–1 A simple combination circuit.

8–2 Solving Combination Circuits

The circuit shown in *Figure 8–2* contains four resistors with values of 325 ohms, 275 ohms, 150 ohms, and 250 ohms. The circuit has a total current flow of 1 ampere. In order to determine which resistors are in series and which are in parallel, trace the path for current flow through the circuit. When the path of current flow is traced, it can be seen that current can flow by two separate paths from the negative terminal to the positive terminal. One path is through R_1 and R_2, and the other path is through R_3 and R_4. These two paths are therefore in parallel. However, the same current must flow through R_1 and R_2. So these two resistors are in series. The same is true for R_3 and R_4.

To solve the unknown values in a combination circuit, use series circuit rules for those sections of the circuit that are connected in series and parallel circuit rules for those sections connected in parallel. The circuit rules are as follows:

Series Circuits

1. The current is the same at any point in the circuit.
2. The total resistance is the sum of the individual resistances.
3. The applied voltage is equal to the sum of the voltage drops across all the resistors.

Parallel Circuits

1. The voltage drop across any branch of a parallel circuit is the same as the applied voltage.
2. The total current flow is equal to the sum of the currents through all of the circuit branches.

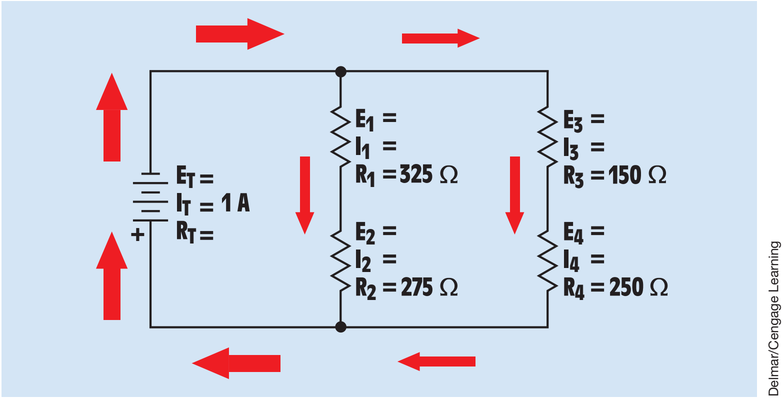


FIGURE 8–2 Tracing the current paths through a combination circuit.

3. The total resistance is equal to the reciprocal of the sum of the reciprocals of the branch resistances.

8–3 Simplifying the Circuit

The circuit shown in *Figure 8–2* can be reduced or simplified to a **simple parallel circuit** *(Figure 8–3)*. Because R_1 and R_2 are connected in series, their values can be added to form one equivalent resistor, $R_{c(1\&2)}$, which stands for a combination of Resistors 1 and 2. The same is true for R_3 and R_4. Their values are added to form $R_{c(3\&4)}$. Now that the circuit has been reduced to a simple parallel circuit, the total resistance can be found:

$$R_T = \frac{1}{\frac{1}{R_{c(1\&2)}} + \frac{1}{R_{c(3\&4)}}}$$

$$R_T = \frac{1}{\frac{1}{600\ \Omega} + \frac{1}{400\ \Omega}}$$

$$R_T = \frac{1}{(0.0016667 + 0.0025)\frac{1}{\Omega}}$$

$$R_T = \frac{1}{(0.0041667)\frac{1}{\Omega}}$$

$$R_T = 240\ \Omega$$

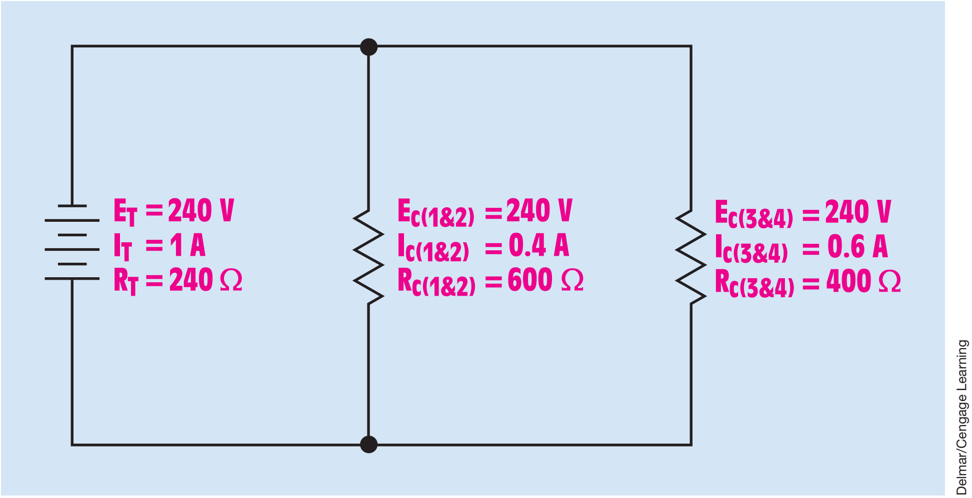


FIGURE 8–3 Simplifying the combination circuit.

Now that the total resistance has been found, the other circuit values can be calculated. The applied voltage can be found using Ohm's law:

$$E_T = I_T \times R_T$$
$$E_T = 1\ A \times 240\ \Omega$$
$$E_T = 240\ V$$

One of the rules for parallel circuits states that the voltage is the same across each branch of the circuit. For this reason, the voltage drops across $R_{c(1\&2)}$ and $R_{c(3\&4)}$ are the same. Because the voltage drop and the resistance are known, Ohm's law can be used to find the current flow through each branch:

$$I_{c(1\&2)} = \frac{E_{c(1\&2)}}{R_{c(1\&2)}}$$
$$I_{c(1\&2)} = \frac{240\ V}{600\ \Omega}$$
$$I_{c(1\&2)} = 0.4\ A$$
$$I_{c(3\&4)} = \frac{E_{c(3\&4)}}{R_{c(3\&4)}}$$
$$I_{c(3\&4)} = \frac{240\ V}{400\ \Omega}$$
$$I_{c(3\&4)} = 0.6\ A$$

These values can now be used to solve the missing values in the original circuit. $R_{c(1\&2)}$ is actually a combination of R_1 and R_2. The values of voltage and current that apply to $R_{c(1\&2)}$ therefore apply to R_1 and R_2. R_1 and R_2 are connected in series. One of the rules for a series circuit states that the current is the same at any point in the circuit. Because 0.4 ampere of current flows through $R_{c(1\&2)}$, the same amount of current flows through R_1 and R_2. Now that the current flow through these two resistors is known, the voltage drop across each can be calculated using Ohm's law:

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.4\ A \times 325\ \Omega$$
$$E_1 = 130\ V$$

$$E_2 = I_2 \times R_2$$
$$E_2 = 0.4\ A \times 275\ \Omega$$
$$E_2 = 110\ V$$

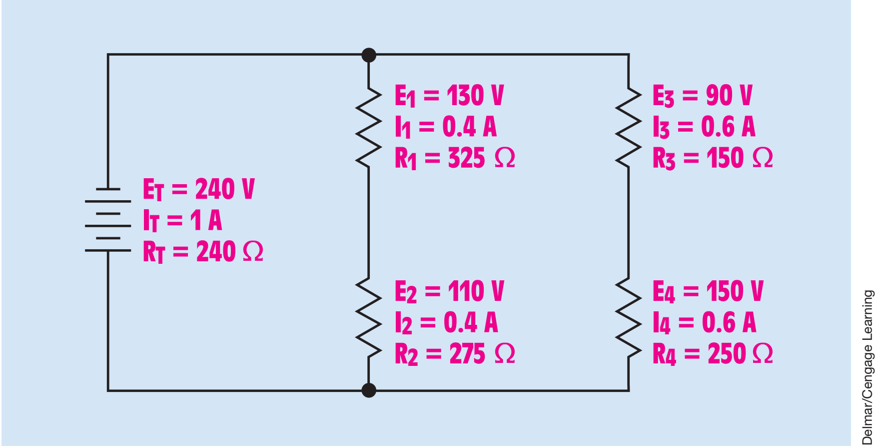


FIGURE 8–4 All the missing values for the combination circuit.

These values of voltage and current can now be added to the circuit in *Figure 8–2* to produce the circuit shown in *Figure 8–4*.

The values of voltage and current for $R_{c(3\&4)}$ apply to R_3 and R_4. The same amount of current that flows through $R_{c(3\&4)}$ flows through R_3 and R_4. The voltage across these two resistors can now be calculated using Ohm's law:

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.6\text{ A} \times 150\ \Omega$$
$$E_3 = 90\text{ V}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.6\text{ A} \times 250\ \Omega$$
$$E_4 = 150\text{ V}$$

EXAMPLE 8–1

Solve the combination circuit shown in *Figure 8–5*.

Solution

The first step in finding the missing values is to trace the current path through the circuit to determine which resistors are in series and which are in parallel. All the current must flow through R_1. R_1 is therefore in series with the rest of the

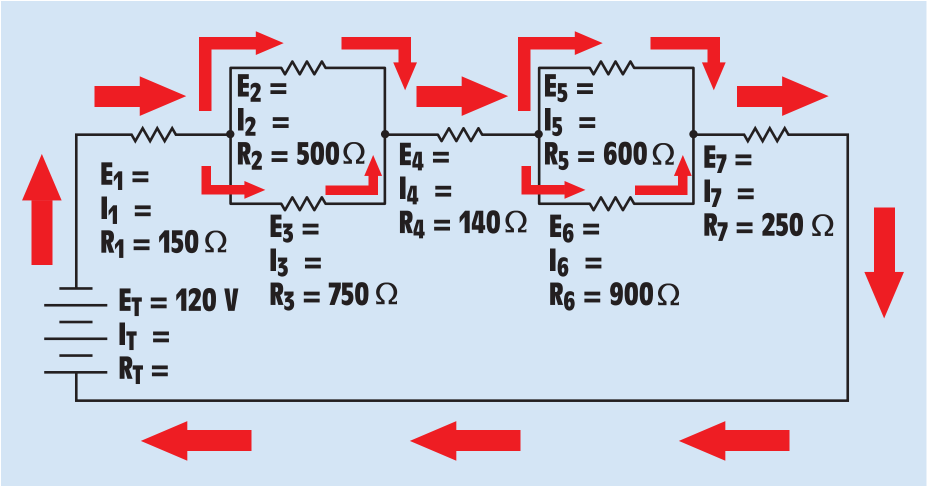


FIGURE 8–5 Tracing the flow of current through the combination circuit.

circuit. When the current reaches the junction of R_2 and R_3, it divides, and part flows through each resistor. R_2 and R_3 are in parallel. All the current must then flow through R_4, which is connected in series, to the junction of R_5 and R_6. The current path is divided between these two resistors. R_5 and R_6 are connected in parallel. All the circuit current must then flow through R_7.

The next step in solving this circuit is to **reduce** it to a simpler circuit. If the total resistance of the first **parallel block** formed by R_2 and R_3 is found, this block can be replaced by a single resistor:

$$R_{(2,\,3)} = \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_{(2,\,3)} = \frac{1}{\frac{1}{500\ \Omega} + \frac{1}{750\ \Omega}}$$

$$R_{(2,\,3)} = \frac{1}{(0.002 + 0.0013333)\ \frac{1}{\Omega}}$$

$$R_{(2,\,3)} = \frac{1}{(0.0033333)\ \frac{1}{\Omega}}$$

$$R_{(2,\,3)} = 300\ \Omega$$

The equivalent resistance of the second parallel block can be calculated in the same way:

$$R_{(5,\,6)} = \frac{1}{\frac{1}{R_5} + \frac{1}{R_6}}$$

$$R_{(5,\,6)} = \frac{1}{\frac{1}{600\ \Omega} + \frac{1}{900\ \Omega}}$$

$$R_{(5,\,6)} = \frac{1}{(0.0016667 + 0.0011111)\ \frac{1}{\Omega}}$$

$$R_{(5,\,6)} = \frac{1}{(0.00277778)\ \frac{1}{\Omega}}$$

$$R_{(5,\,6)} = 360\ \Omega$$

Now that the total resistance of the second parallel block is known, you can **redraw** the circuit as a simple series circuit as shown in *Figure 8–6*. The first parallel block has been replaced with a single resistor of 300 Ω labeled $R_{c(2\&3)}$, and the second parallel block has been replaced with a single 360-Ω resistor labeled $R_{c(5\&6)}$. Ohm's law can be used to find the missing values in this series circuit.

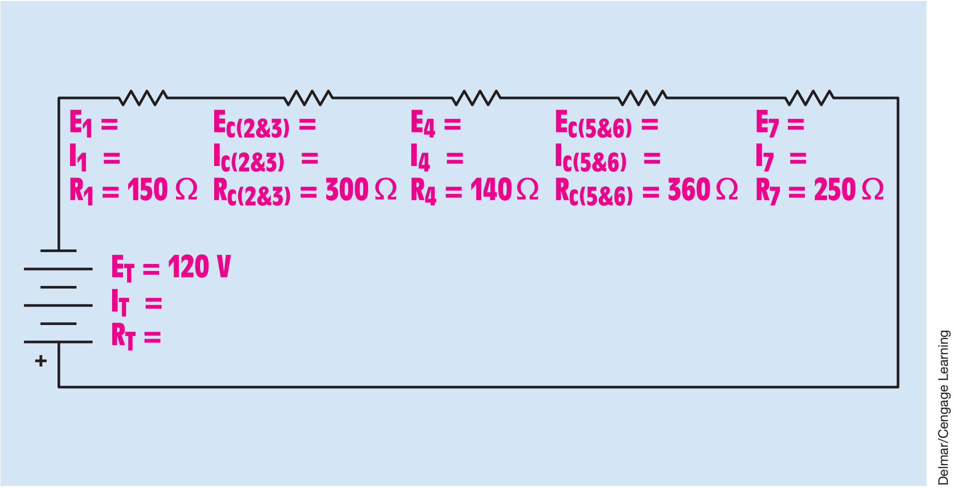


FIGURE 8–6 Simplifying the combination circuit.

One of the rules for series circuits states that the total resistance of a series circuit is equal to the sum of the individual resistances. R_T can be calculated by adding the resistances of all the resistors:

$$R_T = R_1 + R_{c(2\&3)} + R_4 + R_{c(5\&6)} + R_7$$
$$R_T = 150\ \Omega + 300\ \Omega + 140\ \Omega + 360\ \Omega + 250\ \Omega$$
$$R_T = 1200\ \Omega$$

Because the total voltage and total resistance are known, the total current flow through the circuit can be calculated:

$$I_T = \frac{E_T}{R_T}$$
$$I_T = \frac{120\ V}{1200\ \Omega}$$
$$I_T = 0.1\ A$$

The first rule of series circuits states that the current is the same at any point in the circuit. The current flow through each resistor is therefore 0.1 A. The voltage drop across each resistor can now be calculated using Ohm's law:

$$E_1 = I_1 \times R_1$$
$$E_1 = 0.1\ A \times 150\ \Omega$$
$$E_1 = 15\ \Omega$$
$$E_{c(2\&3)} = I_{c(2\&3)} \times R_{c(2\&3)}$$
$$E_{c(2\&3)} = 0.1\ A \times 300\ \Omega$$
$$E_{c(2\&3)} = 30\ V$$
$$E_4 = I_4 \times R_4$$
$$E_4 = 0.1\ A \times 140\ \Omega$$
$$E_4 = 14\ V$$
$$E_{c(5\&6)} = I_{c(5\&6)} \times R_{c(5\&6)}$$
$$E_{c(5\&6)} = 0.1\ A \times 360\ \Omega$$
$$E_{c(5\&6)} = 36\ V$$
$$E_7 = I_7 \times R_7$$
$$E_7 = 0.1\ A \times 250\ \Omega$$
$$E_7 = 25\ V$$

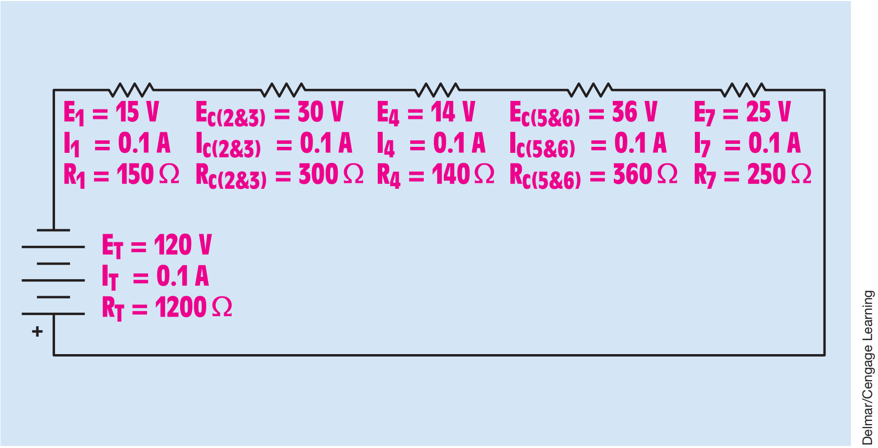


FIGURE 8–7 The simplified circuit with all values solved.

The series circuit with all solved values is shown in *Figure 8–7*. These values can now be used to solve missing parts in the original circuit.

$R_{c(2\&3)}$ is actually the parallel block containing R_2 and R_3. The values for $R_{c(2\&3)}$ therefore apply to this parallel block. One of the rules for a parallel circuit states that the voltage drop of a parallel circuit is the same at any point in the circuit. Because 30 V are dropped across $R_{c(2\&3)}$, the same 30 V are dropped across R_2 and R_3 *(Figure 8–8)*. The current flow through these resistors can now be

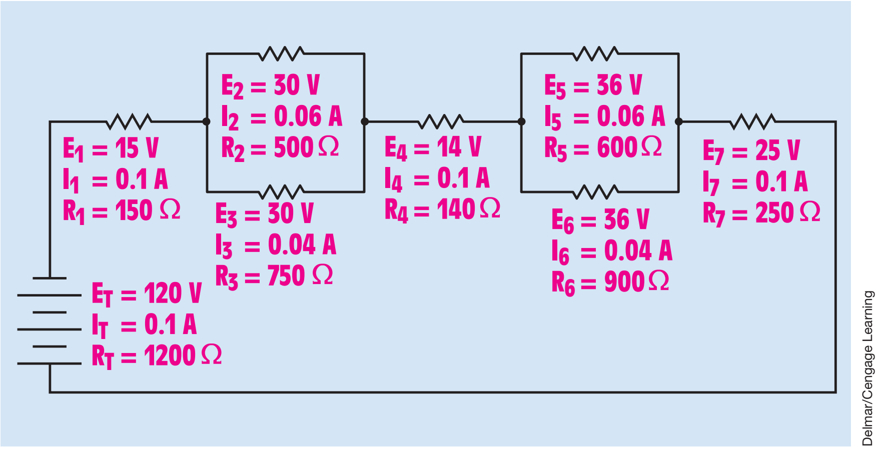


FIGURE 8–8 All values solved for the combination circuit.

calculated using Ohm's law:

$$I_2 = \frac{E_2}{R_2}$$

$$I_2 = \frac{30\ V}{500\ \Omega}$$

$$I_2 = 0.06\ A$$

$$I_3 = \frac{E_3}{R_3}$$

$$I_3 = \frac{30\ V}{750\ \Omega}$$

$$I_3 = 0.04\ A$$

The values of $R_{c(5\&6)}$ can be applied to the parallel block composed of R_5 and R_6. $E_{c(5\&6)}$ is 36 volts. This is the voltage drop across R_5 and R_6. The current flow through these two resistors can be calculated using Ohm's law:

$$I_5 = \frac{E_5}{R_5}$$

$$I_5 = \frac{36\ V}{600\ \Omega}$$

$$I_5 = 0.06\ A$$

$$I_6 = \frac{E_6}{R_6}$$

$$I_6 = \frac{36\ V}{900\ \Omega}$$

$$I_6 = 0.04\ A$$

EXAMPLE 8-2

Both of the preceding circuits were solved by first determining which parts of the circuit were in series and which were in parallel. The circuits were then reduced to a simple series or parallel circuit. This same procedure can be used for

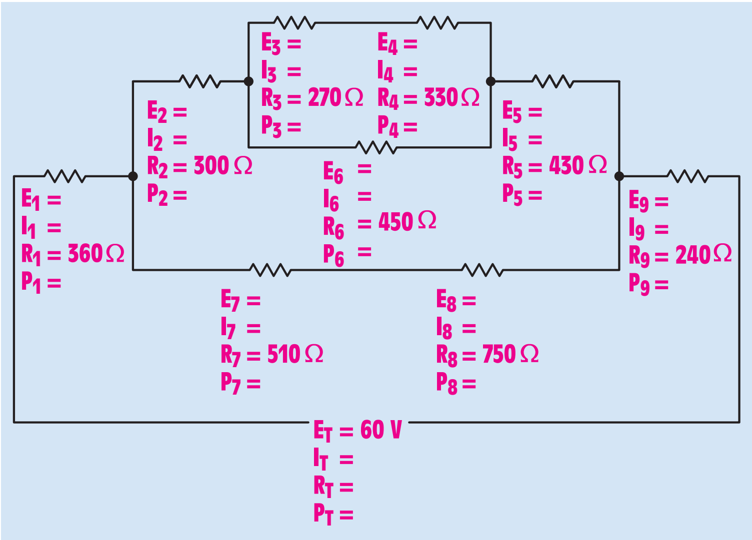


FIGURE 8–9 A complex combination circuit.

any combination circuit. The circuit shown in *Figure 8–9* is reduced to a simpler circuit first. Once the values of the simple circuit are found, they can be placed back in the original circuit to find other values.

Solution

The first step is to reduce the top part of the circuit to a single resistor. This part consists of R_3 and R_4. Because these two resistors are connected in series with each other, their values can be added to form one single resistor. This combination will form R_{c1} *(Figure 8–10):*

$$R_{c1} = R_3 + R_4$$
$$R_{c1} = 270\ \Omega + 330\ \Omega$$
$$R_{c1} = 600\ \Omega$$

The top part of the circuit is now formed by R_{c1} and R_6. These two resistors are in parallel with each other. If their total resistance is calculated, they can be changed into one single resistor with a value of 257.143 Ω. This combination becomes R_{c2} *(Figure 8–11):*

$$R_T = \frac{1}{\frac{1}{600\ \Omega} + \frac{1}{450\ \Omega}}$$
$$R_T = 257.143\ \Omega$$

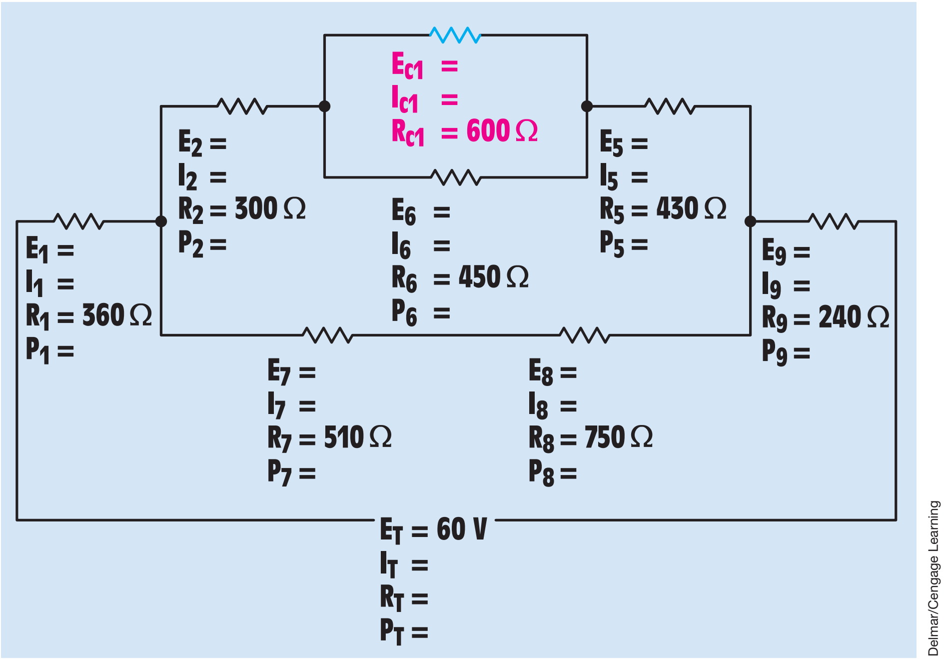


FIGURE 8–10 R_1 and R_2 are combined to form R_{c1}.

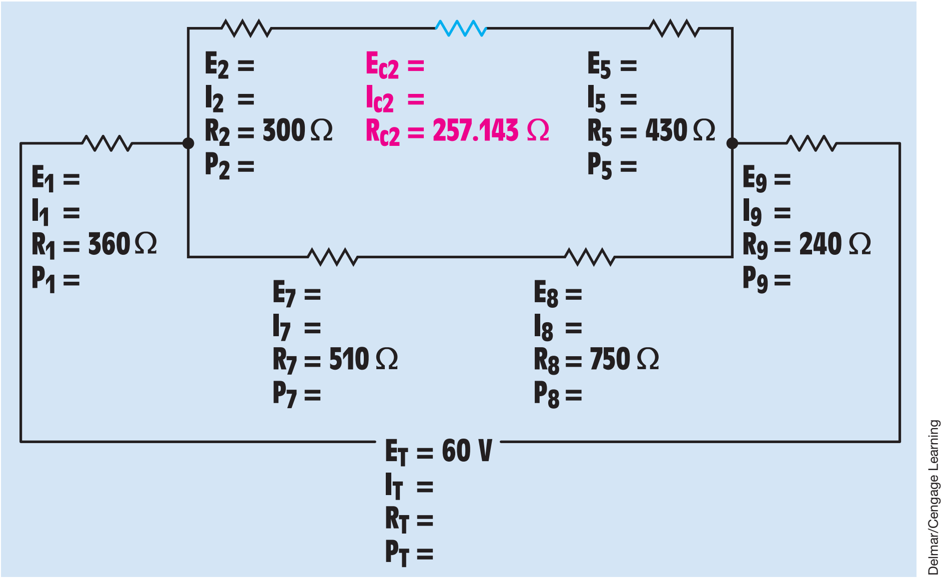


FIGURE 8–11 R_{c1} and R_6 are combined to form R_{c2}.

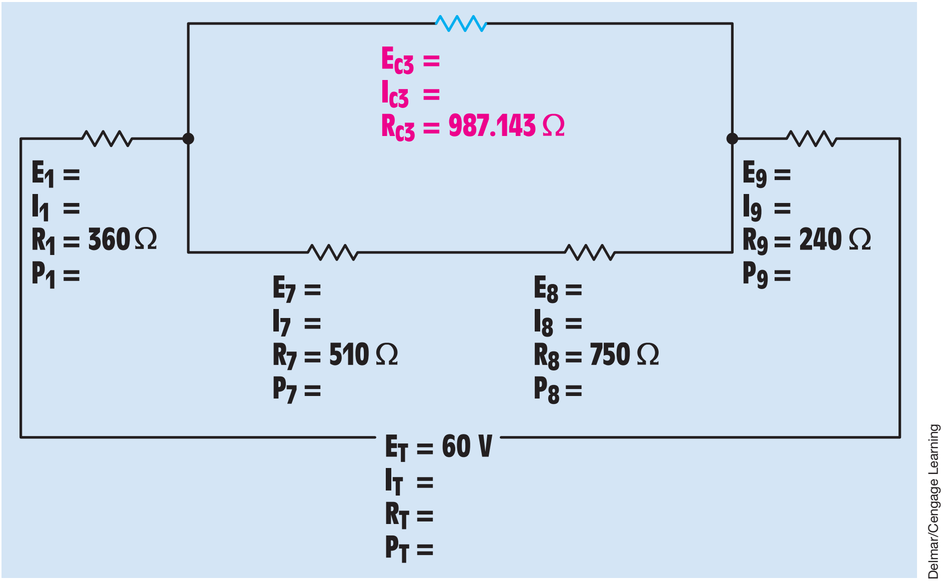


FIGURE 8–12 R_2, R_{c2}, and R_5 are combined to form R_{c3}.

The top of the circuit now consists of R_2, R_{c2}, and R_5. These three resistors are connected in series with each other. They can be combined to form R_{c3} by adding their resistances together *(Figure 8–12):*

$$R_{c3} = R_2 + R_{c2} + R_5$$
$$R_{c3} = 300\ \Omega + 257.143\ \Omega + 430\ \Omega$$
$$R_{c3} = 987.143\ \Omega$$

R_7 and R_8 are connected in series with each other also. These two resistors are added to form R_{c4} *(Figure 8–13):*

$$R_{c4} = R_7 + R_8$$
$$R_{c4} = 510\ \Omega + 750\ \Omega$$
$$R_{c4} = 1260\ \Omega$$

R_{c3} and R_{c4} are connected in parallel with each other. Their total resistance can be calculated to form R_{c5} *(Figure 8–14):*

$$R_{c5} = \frac{1}{\dfrac{1}{987.143\ \Omega} + \dfrac{1}{1260\ \Omega}}$$
$$R_{c5} = 553.503\ \Omega$$

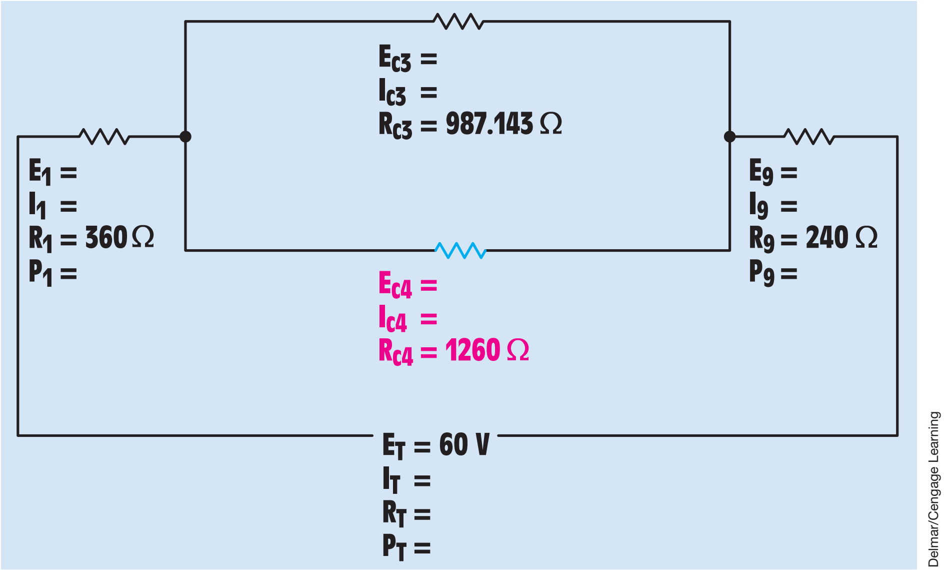


FIGURE 8–13 R_7 and R_8 are combined to form R_{c4}.

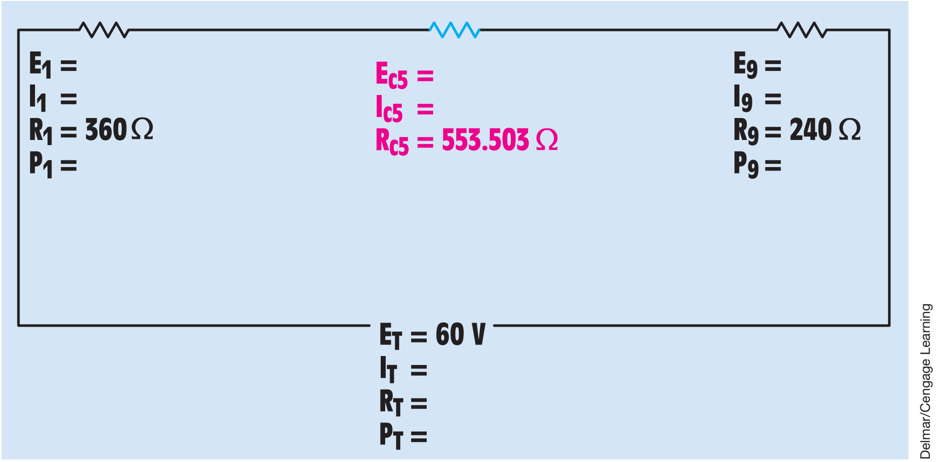


FIGURE 8–14 R_{c3} and R_{c4} are combined to form R_{c5}.

The circuit has now been reduced to a simple series circuit containing three resistors. The total resistance of the circuit can be calculated by adding R_1, R_{c5}, and R_9:

$$R_T = R_1 + R_{c5} + R_9$$
$$R_T = 360\ \Omega + 553.503\ \Omega + 240\ \Omega$$
$$R_T = 1153.503\ \Omega$$

Now that the total resistance and total voltage are known, the total circuit current and total circuit power can be calculated using Ohm's law:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{60\ V}{1153.503\ \Omega}$$

$$I_T = 0.052\ A$$

$$P_T = E_T \times I_T$$

$$P_T = 60\ V \times 0.052\ A$$

$$P_T = 3.12\ W$$

Ohm's law can now be used to find the missing values for R_1, R_{c5}, and R_9 *(Figure 8–15)*:

$$E_1 = I_1 \times R_1$$

$$E_1 = 0.052\ A \times 360\ \Omega$$

$$E_1 = 18.72\ V$$

$$P_1 = E_1 \times I_1$$

$$P_1 = 18.72\ V \times 0.052\ A$$

$$P_1 = 0.973\ W$$

$$E_{c5} = I_{c5} \times R_{c5}$$

$$E_{c5} = 0.052\ A \times 553.503\ \Omega$$

$$E_{c5} = 28.782\ V$$

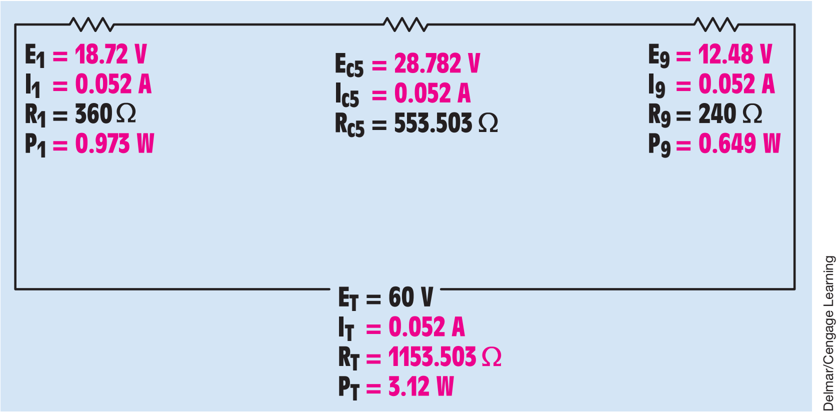


FIGURE 8–15 Missing values are found for the first part of the circuit.

$$E_9 = I_9 \times R_9$$
$$E_9 = 0.052\ A \times 240\ \Omega$$
$$E_9 = 12.48\ V$$

$$P_9 = E_9 \times I_9$$
$$P_9 = 12.48\ V \times 0.052\ A$$
$$P_9 = 0.649\ W$$

R_{c5} is actually the combination of R_{c3} and R_{c4}. The values of R_{c5} therefore apply to R_{c3} and R_{c4}. Since these two resistors are connected in parallel with each other, the voltage drop across them will be the same. Each will have the same voltage drop as R_{c5} *(Figure 8–16)*. Ohm's law can now be used to find the remaining values of R_{c3} and R_{c4}:

$$I_{c4} = \frac{E_{c4}}{R_{c4}}$$
$$I_{c4} = \frac{28.782\ V}{1260\ \Omega}$$
$$I_{c4} = 0.0228\ A$$

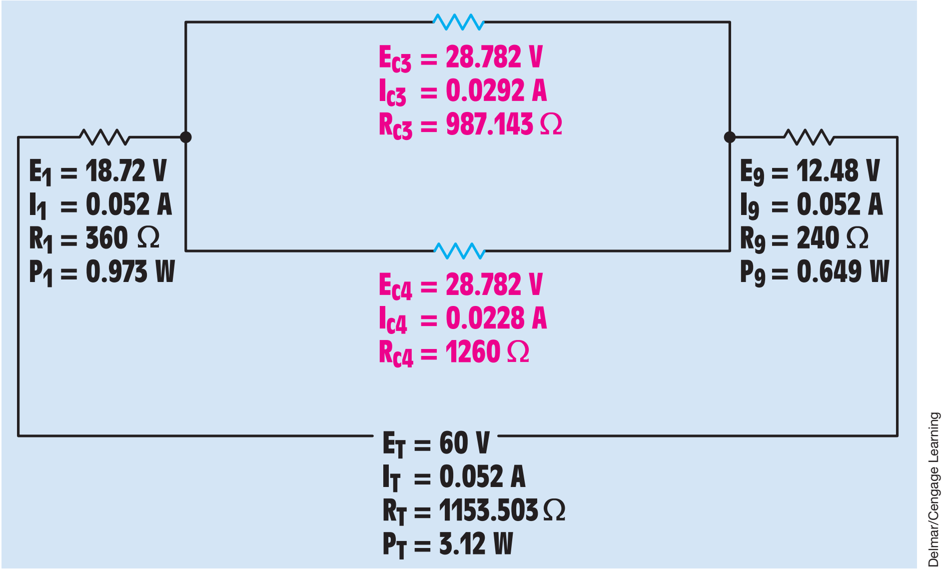


FIGURE 8–16 The values for R_{c3} and R_{c4}.

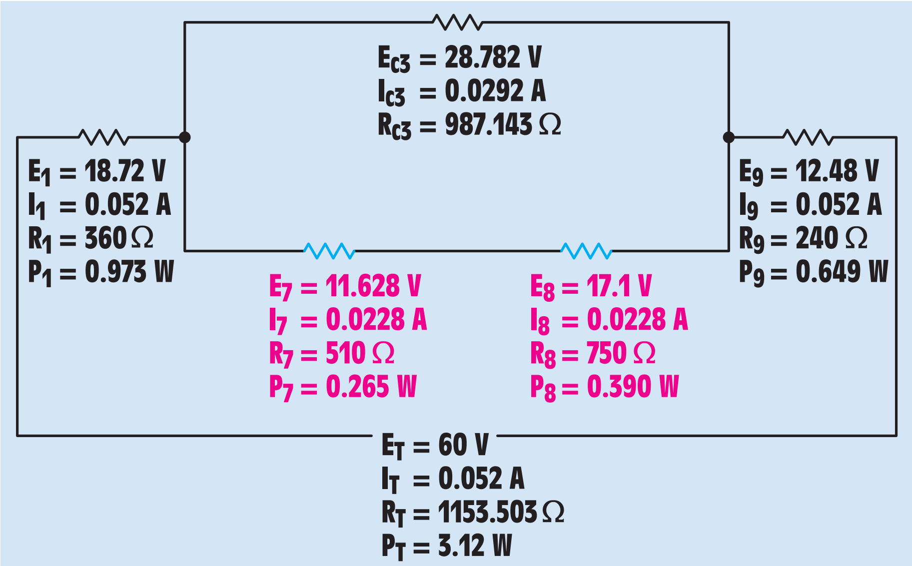


FIGURE 8–17 The values for R_7 and R_8.

$$I_{c3} = \frac{E_{c3}}{R_{c3}}$$

$$I_{c3} = \frac{28.782\ \text{V}}{987.143\ \Omega}$$

$$I_{c3} = 0.0292\ \text{A}$$

R_{c4} is the combination of R_7 and R_8. The values of R_{c4} apply to R_7 and R_8. Because R_7 and R_8 are connected in series with each other, the current flow will be the same through both *(Figure 8–17)*. Ohm's law can now be used to calculate the remaining values for these two resistors:

$$E_7 = I_7 \times R_7$$

$$E_7 = 0.0228\ \text{A} \times 510\ \Omega$$

$$E_7 = 11.628\ \text{V}$$

$$P_7 = E_7 \times I_7$$

$$P_7 = 11.628\ \text{V} \times 0.0228\ \text{A}$$

$$P_7 = 0.265\ \text{W}$$

$$E_8 = I_8 \times R_8$$

$$E_8 = 0.0228\ \text{A} \times 750\ \Omega$$

$$E_8 = 17.1\ \text{V}$$

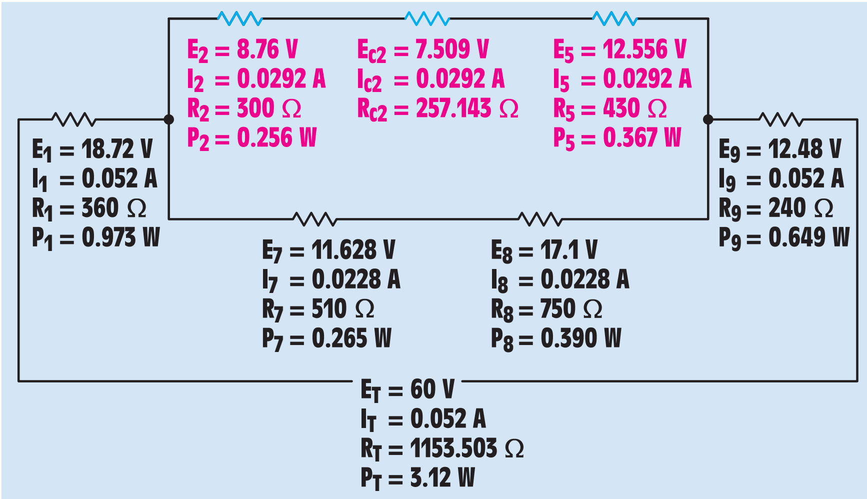


FIGURE 8–18 Determining values for R_1, R_{c2}, and R_5.

$$P_8 = E_8 \times I_8$$
$$P_8 = 17.1\ \text{V} \times 0.0228\ \text{A}$$
$$P_8 = 0.390\ \text{W}$$

R_{c3} is the combination of R_2, R_{c2}, and R_5. Because these resistors are connected in series with each other, the current flow through each will be the same as the current flow through R_{c3}. The remaining values can now be calculated using Ohm's law *(Figure 8–18)*:

$$E_{c2} = I_{c2} \times R_{c2}$$
$$E_{c2} = 0.0292\ \text{A} \times 257.143\ \Omega$$
$$E_{c2} = 7.509\ \text{V}$$

$$E_2 = I_2 \times R_2$$
$$E_2 = 0.0292\ \text{A} \times 300\ \Omega$$
$$E_2 = 8.76\ \text{V}$$

$$P_2 = E_2 \times I_2$$
$$P_2 = 8.76\ \text{A} \times 0.292\ \text{A}$$
$$P_2 = 0.256\ \text{W}$$

$$E_5 = I_5 \times R_5$$
$$E_5 = 0.0292\ \text{A} \times 430\ \Omega$$
$$E_5 = 12.556\ \text{V}$$

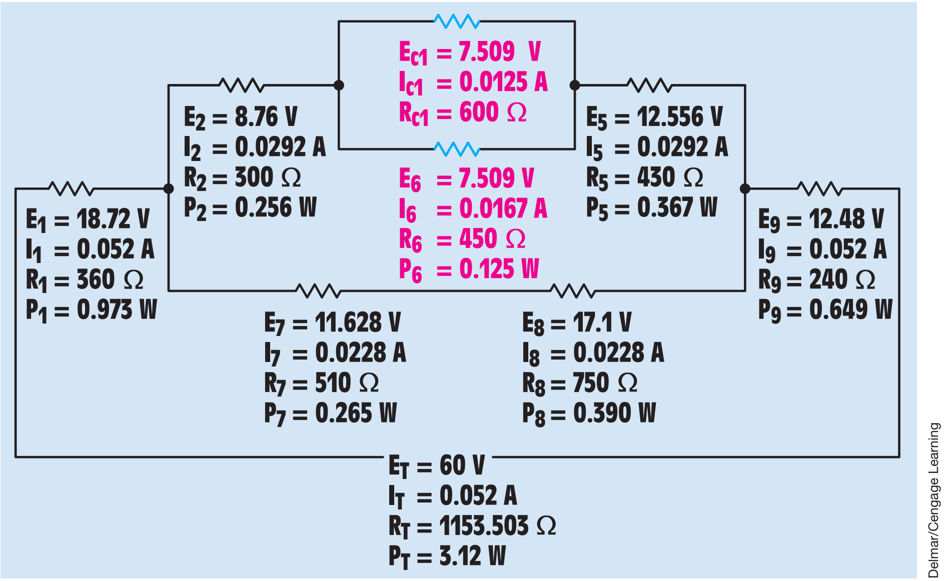


FIGURE 8–19 The values of R_{c1} and R_6.

$$P_5 = E_5 \times I_5$$
$$P_5 = 12.556 \text{ V} \times 0.0292 \text{ A}$$
$$P_5 = 0.367 \text{ W}$$

R_{c2} is the combination of R_{c1} and R_6. R_{c1} and R_6 are connected in parallel and will therefore have the same voltage drop as R_{c2}. Ohm's law can be used to calculate the remaining values for R_{c2} and R_6 *(Figure 8–19):*

$$I_{c1} = \frac{E_{c1}}{R_{c1}}$$
$$I_{c1} = \frac{7.509 \text{ V}}{600 \ \Omega}$$
$$I_{c1} = 0.0125 \text{ A}$$
$$I_6 = \frac{E_6}{R_6}$$
$$I_6 = \frac{7.509 \text{ V}}{450 \ \Omega}$$
$$I_6 = 0.0167 \text{ A}$$

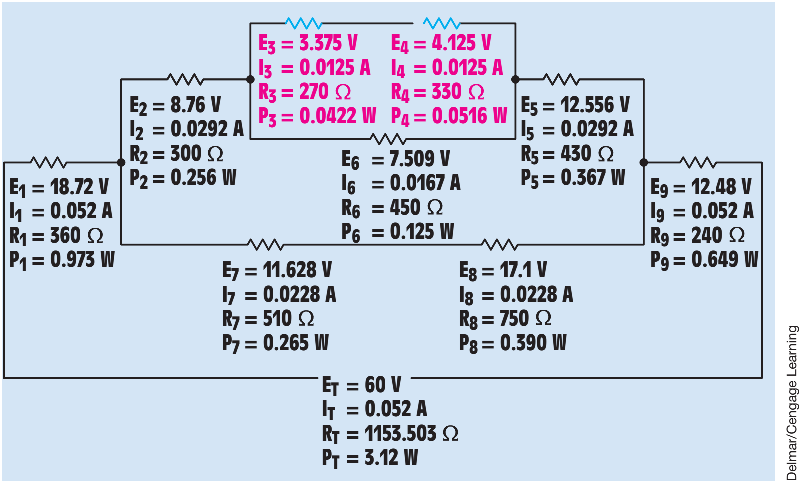


FIGURE 8–20 The values for R_3 and R_4.

$$P_6 = E_6 \times I_6$$
$$P_6 = 7.509 \text{ V} \times 0.0167 \text{ A}$$
$$P_6 = 0.125 \text{ W}$$

R_{c1} is the combination of R_3 and R_4. Because these two resistors are connected in series, the amount of current flow through R_{c1} will be the same as the flow through R_3 and R_4. The remaining values of the circuit can now be found using Ohm's law *(Figure 8–20):*

$$E_3 = I_3 \times R_3$$
$$E_3 = 0.0125 \text{ A} \times 270 \ \Omega$$
$$E_3 = 3.375 \text{ V}$$

$$P_3 = E_3 \times I_3$$
$$P_3 = 3.375 \text{ V} \times 0.0125 \text{ A}$$
$$P_3 = 0.0422 \text{ W}$$

$$E_4 = I_4 \times R_4$$
$$E_4 = 0.0125 \text{ A} \times 330 \ \Omega$$
$$E_4 = 4.125 \text{ V}$$

$$P_4 = E_4 \times I_4$$
$$P_4 = 4.125 \text{ V} \times 0.0125 \text{ A}$$
$$P_4 = 0.0516 \text{ W}$$

Summary

- Combination circuits are circuits that contain both series and parallel branches.
- The three rules for series circuits are as follows:
  a. The current is the same at any point in the circuit.
  b. The total resistance is the sum of the individual resistances.
  c. The applied voltage is equal to the sum of the voltage drops across all the resistors.
- The three rules for parallel circuits are as follows:
  a. The voltage drop across any branch of a parallel circuit is the same as the applied voltage.
  b. The total current is the sum of the individual currents through each path in the circuit (current adds).
  c. The total resistance is the reciprocal of the sum of the reciprocals of the branch resistances.
- When solving combination circuits, it is generally easier if the circuit is reduced to simpler circuits.

Review Questions

1. Refer to *Figure 8–2*. Replace the values shown with the following. Solve for all the unknown values.

   $I_T = 0.6$ A
   $R_1 = 470\ \Omega$
   $R_2 = 360\ \Omega$
   $R_3 = 510\ \Omega$
   $R_4 = 430\ \Omega$

2. Refer to *Figure 8–5*. Replace the values shown with the following. Solve for all the unknown values.

   $E_T = 63$ V
   $R_1 = 1000\ \Omega$
   $R_2 = 2200\ \Omega$
   $R_3 = 1800\ \Omega$
   $R_4 = 910\ \Omega$
   $R_5 = 3300\ \Omega$
   $R_6 = 4300\ \Omega$
   $R_7 = 860\ \Omega$

3. Refer to the circuit shown in *Figure 8–2*. Redraw the circuit and use the following values:

   E_T = 12 V
   R_1 = 270 Ω
   R_2 = 510 Ω
   R_3 = 470 Ω
   R_4 = 330 Ω

   Assume that an ammeter indicates a total circuit current of 15 mA.
   A voltmeter indicates the following voltage drops across each resistor:

   E_1 = 12 V
   E_2 = 0 V
   E_3 = 7 V
   E_4 = 5 V

   What is the most likely problem with this circuit?

4. Refer to the circuit shown in *Figure 8–22*. The circuit has an applied voltage of 24 V and the resistors have values as follows:

   R_1 = 1 kΩ
   R_2 = 300 Ω
   R_3 = 750 Ω
   R_4 = 1 kΩ

   An ammeter and a voltmeter indicate the following values:

   I_T = 42.5 mA
   I_1 = 24 mA
   E_1 = 24 V
   I_2 = 18.5 mA
   E_2 = 5.5 V
   I_3 = 0 A
   E_3 = 18.5 V
   I_4 = 18.5 mA
   E_4 = 18.5 V

   What is the most likely problem with this circuit?

5. Refer to *Figure 8–21*. Assume that the resistors have the following values:

   R_1 = 150 Ω
   R_2 = 120 Ω
   R_3 = 47 Ω
   R_4 = 220 Ω

Assume that an ohmmeter connected across the entire circuit indicates a value of 245 Ω. Does this reading indicate that there is a problem with the circuit and, if so, what is the most likely problem?

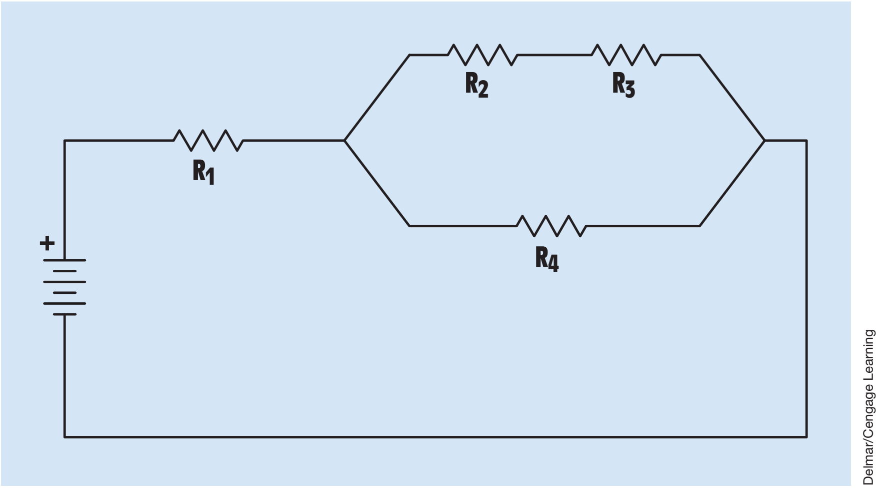


FIGURE 8–21 Series-parallel circuit.

Practical Applications

A circuit contains a 1000-Ω and a 300-Ω resistor connected in series with each other. The total circuit resistance must be reduced to a value of 1150 Ω. Using standard resistance values for 5% resistors discussed in Unit 5, explain how to change the present resistance value to the value desired. ■

Practical Applications

Two resistors are connected in series. One resistor has a resistance of 1000 Ω, and the other resistor value is not known. The circuit is connected to a 50-V power supply, and there is a current of 25 mA flowing in the circuit. If a 1500-Ω resistor is connected in parallel with the unknown resistor, how much current will flow in this circuit? ■

Practical Applications

A single-phase electric motor is connected to a 240-volt, 30-ampere circuit. The motor nameplate indicates that the full-load current draw of the motor is 21 amperes. The motor is connected to an inertia load (a large flywheel) that requires several seconds for the motor to accelerate full speed. Due to the long starting time, the motor causes the circuit breaker to trip before the load has reached full speed. Your job is to connect a resistor in series with the motor during the starting period that will limit the starting current to 90% of the circuit-breaker rating. An ammeter indicates that the motor has a current draw of 64 amperes when power is first applied to the motor. Determine the ohmic value and wattage rating of the resistor that should be connected in series with the motor during the starting period. ■

Practical Applications

The hot water for the heating system for a small factory is supplied by a single boiler. The boiler is located in a small building separate from the factory. The power supplied to the boiler is 240-volt single-phase without a neutral conductor. At the present time, the small building housing the boiler has no inside lighting. The business owner desires that four 100-watt lamps be installed inside the building. All lamps are to be connected to a single switch. The lamps are to be connected to the present 240-volt service inside the building. How would you accomplish this task? Explain your answer. ■

Practice Problems

Series-Parallel Circuits

Refer to the circuit shown in *Figure 8–21* to solve the following problems.

1. Find the unknown values in the circuit if the applied voltage is 75 V and the resistors have the following values:

$R_1 = 1.5\ k\Omega$ $R_2 = 910\ \Omega$ $R_3 = 2\ k\Omega$ $R_4 = 3.6\ k\Omega$

I_T ______ E_1 ______ E_2 ______ E_3 ______ E_4 ______

R_T ______ I_1 ______ I_2 ______ I_3 ______ I_4 ______

2. Find the unknown values in the circuit if the applied voltage is 350 V and the resistors have the following values:

   R_1 = 22 kΩ R_2 = 18 kΩ R_3 = 12 kΩ R_4 = 30 kΩ

   I_T ________ E_1 ________ E_2 ________ E_3 ________ E_4 ________

   R_T ________ I_1 ________ I_2 ________ I_3 ________ I_4 ________

3. Find the unknown values in the circuit if the applied voltage is 18 V and the resistors have the following values:

   R_1 = 82 Ω R_2 = 160 Ω R_3 = 220 Ω R_4 = 470 Ω

   I_T ________ E_1 ________ E_2 ________ E_3 ________ E_4 ________

   R_T ________ I_1 ________ I_2 ________ I_3 ________ I_4 ________

Parallel-Series Circuits

Refer to the circuit shown in *Figure 8–22* to solve the following problems.

4. Find the unknown values in the circuit if the total current is 0.8 A and the resistors have the following values:

   R_1 = 1.5 kΩ R_2 = 910 Ω R_3 = 2 kΩ R_4 = 3.6 kΩ

   E_T ________ E_1 ________ E_2 ________ E_3 ________ E_4 ________

   R_T ________ I_1 ________ I_2 ________ I_3 ________ I_4 ________

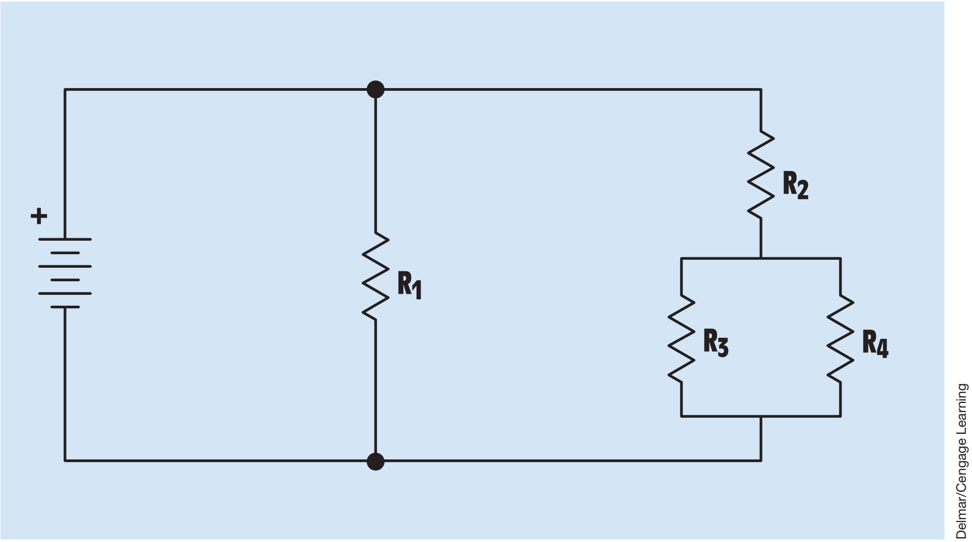


FIGURE 8–22 A parallel-series circuit.

5. Find the unknown values in the circuit if the total current is 0.65 A and the resistors have the following values:

$R_1 = 22\ k\Omega$ $R_2 = 15\ k\Omega$ $R_3 = 22\ k\Omega$ $R_4 = 33\ k\Omega$

E_T ________ E_1 ________ E_2 ________ E_3 ________ E_4 ________

R_T ________ I_1 ________ I_2 ________ I_3 ________ I_4 ________

6. Find the unknown values in the circuit if the total current is 1.2 A and the resistors have the following values:

$R_1 = 75\ \Omega$ $R_2 = 47\ \Omega$ $R_3 = 220\ \Omega$ $R_4 = 160\ \Omega$

E_T ________ E_1 ________ E_2 ________ E_3 ________ E_4 ________

R_T ________ I_1 ________ I_2 ________ I_3 ________ I_4 ________

Combination Circuits

Refer to the circuit shown in *Figure 8–23* to solve the following problems.

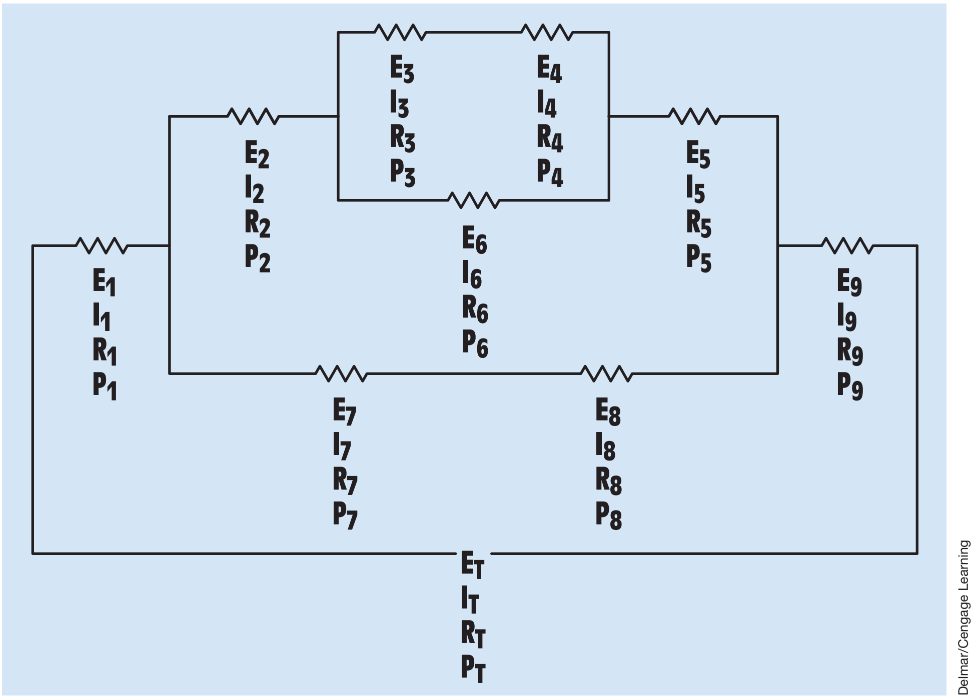


FIGURE 8–23 A combination circuit.

7.

E_T 250 V	E_1	E_2	E_3	E_4
I_T	I_1	I_2	I_3	I_4
R_T	R_1 220 Ω	R_2 500 Ω	R_3 470 Ω	R_4 280 Ω
P_T	P_1	P_2	P_3	P_4

E_5	E_6	E_7	E_8	E_9
I_5	I_6	I_7	I_8	I_9
R_5 400 Ω	R_6 500 Ω	R_7 350 Ω	R_8 450 Ω	R_9 300 Ω
P_5	P_6	P_7	P_8	P_9

8.

E_T	E_1	E_2	E_3	E_4 1.248 V
I_T	I_1	I_2	I_3	I_4
R_T	R_1	R_2	R_3	R_4
P_T 0.576 W	P_1 0.0806 W	P_2 0.0461 W	P_3 0.00184 W	P_4

E_5	E_6	E_7	E_8	E_9
I_5	I_6	I_7	I_8	I_9
R_5	R_6	R_7	R_8	R_9
P_5 0.0203 W	P_6 0.00995 W	P_7 0.0518 W	P_8 0.0726 W	P_9 0.288 W

Unit 9

Kirchhoff's Laws, Thevenin's, Norton's, and Superposition Theorems

Why You Need to Know

There are some circuits that are difficult to solve using Ohm's Law. Circuits that contain more than one power source, for example, can be solved using Kirchhoff's voltage and current laws. Thevenin's and Norton's theorems can be employed to simplify the calculations needed to solve electrical values in certain types of circuits. The superposition theorem combines the principles of Thevenin's and Norton's theorems to simplify circuit calculations. In this unit

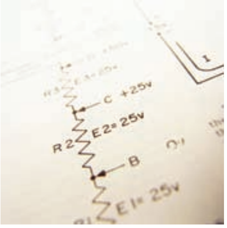
- Kirchhoff's voltage and current laws are presented.
- you are shown how to reduce a circuit to a simple Thevenin equivalent circuit that contains a single voltage source and resistor.
- you are shown how to reduce a circuit to a simple Norton equivalent circuit that contains a single current source and resistor.
- you will be shown how to solve a complex circuit using the superposition theorem.

OUTLINE

KEY TERMS

Kirchhoff's current law
Kirchhoff's voltage law
Norton's theorem
Superposition theorem
Thevenin's theorem

Objectives



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After studying this unit, you should be able to

- state Kirchhoff's voltage and current laws.
- solve problems using Kirchhoff's laws.
- discuss Thevenin's theorem.
- find the Thevenin equivalent voltage and resistance values for a circuit network.
- discuss Norton's theorem.
- find the Norton equivalent current and resistance values for a circuit network.
- solve circuits using the superposition theorem.

Preview

Thus far in this text, electrical values for series, parallel, and combination circuits have been calculated using Ohm's law. There are some circuits, however, where Ohm's law either cannot be used or it would be very difficult to use to find unknown values. Some circuits do not have clearly defined series or parallel connections. When this is the case, Kirchhoff's laws are often employed because they can be used to solve any type of circuit. This is especially true for circuits that contain more than one source of power.

Also discussed in this unit are Thevenin's and Norton's theorems. These theorems are used to simplify circuit networks, making it easier to find electrical quantities for different values of load resistances. ■

9–1 Kirchhoff's Laws

Kirchhoff's laws were developed by a German physicist named Gustav R. Kirchhoff. In 1847, Kirchhoff stated two laws for dealing with voltage and current relationships in an electric circuit:

1. ***The algebraic sum of the voltage sources and voltage drops in a closed circuit must equal zero.***
2. ***The algebraic sum of the currents entering and leaving a point must equal zero.***

These two laws are actually two of the rules used for series and parallel circuits discussed earlier in this text. The first law is actually the series circuit rule that states the sum of the voltage drops in a series circuit must equal the applied voltage. The second law is the parallel circuit rule that states that the total current will be the sum of the currents through all the circuit branches.

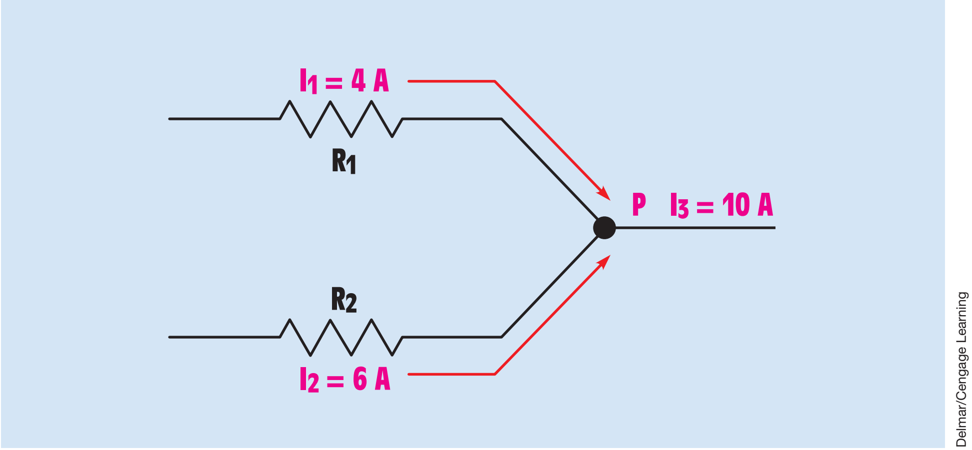

FIGURE 9–1 The algebraic sum of the currents entering and leaving a point must equal zero.

Kirchhoff's Current Law

Kirchhoff's current law states that the algebraic sum of the currents entering and leaving any particular point must equal zero. The proof of this law lies in the fact that if more current entered a particular point than left, some type of charge would have to develop at that point. Consider the circuit shown in *Figure 9–1*. Four amperes of current flow through R_1 to point P, and 6 amperes of current flow through R_2 to point P. The current leaving point P is the sum of the two currents or 10 amperes. Kirchhoff's current law, however, states that the algebraic sum of the currents must equal zero. When using Kirchhoff's law, current entering a point is considered to be positive and current leaving a point is considered to be negative.

$$4\text{ A} + 6\text{ A} - 10\text{ A} = 0\text{ A}$$

Currents I_1 and I_2 are considered to be positive because they enter point P. Current I_3 is negative because it leaves point P.

A second circuit that illustrates Kirchhoff's current law can be seen in *Figure 9–2*. Consider what happens to the current at point B. Two amperes of current flow into point B from R_1. The current splits at point B, part flowing to R_2 and part to R_4 through R_6. The current entering point B is positive, and the two currents leaving point B are negative.

$$I_1 - I_2 - I_4 = 0$$
$$2\text{ A} - 0.8\text{ A} - 1.2\text{ A} = 0\text{ A}$$

Now consider the currents at point E. There is 0.8 ampere of current entering point E from R_2, and 1.2 amperes of current enter point E from R_4 through R_6. Two amperes of current leave point E and flow through R_3.

$$0.8\text{ A} + 1.2\text{ A} - 2\text{ A} = 0\text{ A}$$

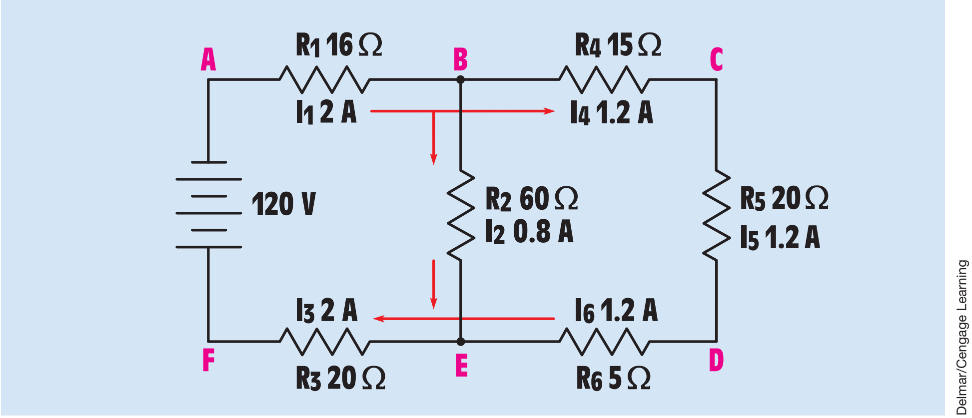

FIGURE 9–2 The current splits to separate branches.

Kirchhoff's Voltage Law

Kirchhoff's voltage law is very similar to the current law in that the algebraic sum of the voltages around any closed loop must equal zero. Before determining the algebraic sum of the voltages, it is necessary to first determine which end of the resistive element is positive and which is negative. To make this determination, assume a direction of current flow and mark the end of the resistive element where current enters and where current leaves. It will be assumed that current flows from negative to positive. Therefore, the point at which current enters a resistor will be marked negative, and the point where current leaves the resistor will be marked positive. The voltage drops and the polarity markings have been added to each of the resistors in the example circuit shown in *Figure 9–2*. The amended circuit is shown in *Figure 9–3*.

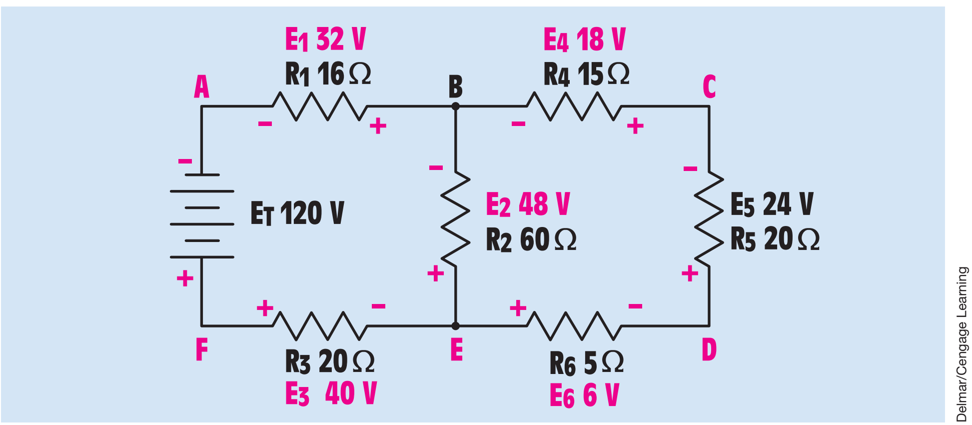

FIGURE 9–3 Marking resistor elements.

To use Kirchhoff's voltage law, start at some point and add the voltage drops around any closed loop. Be certain to return to the starting point. In the circuit shown in *Figure 9–3*, there are actually three separate closed loops to be considered. Loop ACDF contains the voltage drops E_1, E_4, E_5, E_6, E_3, and E_T (120-volt source). Loop ABEF contains voltage drops E_1, E_2, E_3, and E_T. Loop BCDE contains voltage drops E_4, E_5, E_6, and E_2.

The voltage drops for the first loop are as follows:

$$-E_1 - E_4 - E_5 - E_6 - E_3 + E_T = 0$$
$$-32\text{ V} - 18\text{ V} - 24\text{ V} - 6\text{ V} - 40\text{ V} + 120\text{ V} = 0\text{ V}$$

The positive or negative sign for each number is determined by the assumed direction of current flow. In this example, it is assumed that current leaves point A and returns to point A. Current leaving point A enters R_1 at the negative end. Therefore, the voltage is considered to be negative (−32 V). The same is true for R_4, R_5, R_6, and R_3. The current enters the voltage source at the positive end, however. Therefore, E_T is assumed to be positive.

For the second loop, it is assumed that current will leave point A and return to point A through R_1, R_2, R_3, and the voltage source. The voltage drops are as follows:

$$-E_1 - E_2 - E_3 + E_T = 0$$
$$-32\text{ V} - 48\text{ V} - 40\text{ V} + 120\text{ V} = 0\text{ V}$$

The current path for the third loop assumes that current leaves point B and returns to point B. The current will flow through R_4, R_5, R_6, and R_2.

$$-E_4 - E_5 - E_6 + E_2 = 0$$
$$-18\text{ V} - 24\text{ V} - 6\text{ V} + 48\text{ V} = 0\text{ V}$$

Solving Problems with Kirchhoff's Laws

Up to this point, the values of voltage and current have been given to illustrate how Kirchhoff's laws are applied to a circuit. If the values of voltage and current had to be known before Kirchhoff's laws could be used, however, there would be little need for them. In the circuit shown in *Figure 9–4*, the voltage drops and currents are not shown. This circuit contains three resistors and two voltage sources. Although there are three separate loops in this circuit, only two are needed to find the missing values. The two loops used are ABEF and CBED as shown in *Figure 9–4*. The resistors have been marked positive and negative to correspond with the assumed direction of current flow. For the first loop, it is assumed that current leaves point A and returns to point A. The equation for this loop is

$$-E_1 - E_3 + E_{S1} = 0$$
$$-E_1 - E_3 + 60\text{ V} = 0\text{ V}$$

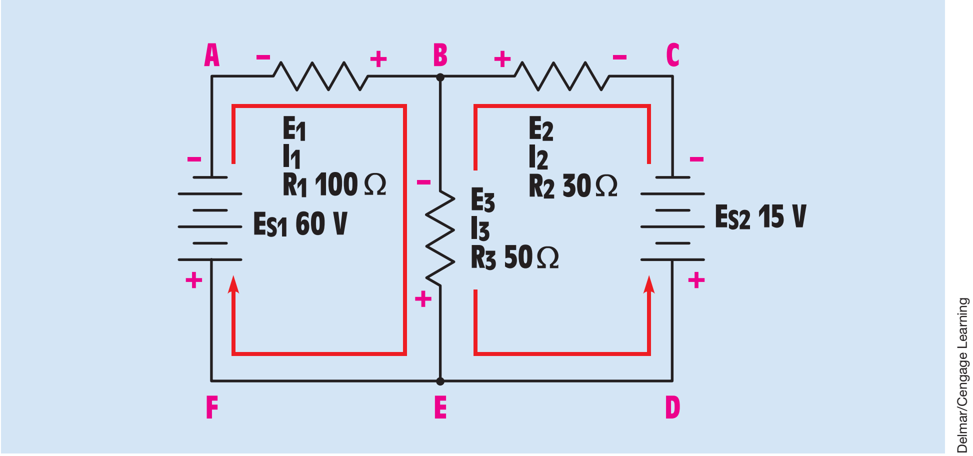

FIGURE 9–4 Finding circuit values with Kirchhoff's voltage law.

For the second loop, it is assumed that current leaves point C and returns to point C. The equation for the second loop is

$$-E_2 - E_3 + E_{S2} = 0$$
$$-E_2 - E_3 + 15\text{ V} = 0\text{ V}$$

To simplify these two equations, the whole numbers are moved to the other side of the equal sign. This is done in the first equation by subtracting 60 volts from both sides. The equation now becomes

$$-E_1 - E_3 = -60\text{ V}$$

In the second equation, 15 volts is subtracted from both sides. The equation becomes

$$-E_2 - E_3 = -15\text{ V}$$

The equations can be further simplified by removing the negative signs. To do this, both equations are multiplied by negative one (-1). The two equations now become

$$E_1 + E_3 = 60\text{ V}$$
$$E_2 + E_3 = 15\text{ V}$$

According to Ohm's law, the voltage drop across any resistive element is equal to the amount of current flowing through the element times its resistance ($E = I \times R$). In order to solve the equations presented, it is necessary to change the values of E_1, E_2, and E_3 to their Ohm's law equivalents:

$$E_1 = I_1 \times R_1 = I_1 \times 100\ \Omega = 100\ \Omega\ I_1$$
$$E_2 = I_2 \times R_2 = I_2 \times 30\ \Omega = 30\ \Omega\ I_2$$

Although it is true that $E_3 = I_3 \times R_3$, this would produce three unknown currents in the equation. Because Kirchhoff's current law states that the currents entering a point must equal the current leaving a point, I_3 is actually the sum of currents I_1 and I_2. Therefore, the third voltage equation will be written

$$E_3 = (I_1 + I_2) \times R_3 = (I_1 + I_2) \times 50\ \Omega = 50\ \Omega\ (I_1 + I_2)$$

The two equations can now be written as

$$100\ \Omega\ I_1 + 50\ \Omega\ (I_1 + I_2) = 60\ V$$
$$30\ \Omega\ I_2 + 50\ \Omega\ (I_1 + I_2) = 15\ V$$

The parentheses can be removed by multiplying I_1 and I_2 by 50. The equations now become

$$100\ \Omega\ I_1 + 50\ \Omega\ I_1 + 50\ \Omega\ I_2 = 60\ V$$
$$30\ \Omega\ I_2 + 50\ \Omega\ I_1 + 50\ \Omega\ I_2 = 15\ V$$

After gathering terms, the equations become

$$150\ \Omega\ I_1 + 50\ \Omega\ I_2 = 60\ V$$
$$50\ \Omega\ I_1 + 80\ \Omega\ I_2 = 15\ V$$

In order to solve these equations, it is necessary to solve them as simultaneous equations. To solve simultaneous equations, it is necessary to eliminate unknowns until there is only one unknown left. An equation cannot be solved if there is more than one unknown. Multiplying the bottom equation by negative 3 (−3) will result in 50 Ω I_1 becoming −150 Ω I_1. The positive 150 Ω I_1 in the top equation and the negative 150 Ω I_1 now cancel each other, eliminating one unknown.

$$-3(50\ \Omega\ I_1 + 80\ \Omega\ I_2 = 15\ V)$$
$$-150\ \Omega\ I_1 - 240\ \Omega\ I_2 = -45\ V$$

The two equations can now be added:

$$150\ \Omega\ I_1 + 50\ \Omega\ I_2 = 60\ V$$
$$-150\ \Omega\ I_1 - 240\ \Omega\ I_2 = -45\ V$$

The positive 150 ohms I_1 and the negative 150 ohms I_1 cancel each other, leaving −190 ohms I_2.

$$-190\ \Omega\ I_2 = 15\ V$$

Dividing both sides of the equation by −190 produces the answer for I_2:

$$I_2 = -0.0789\ A$$

The negative answer for I_2 indicates that the assumed direction of current flow was incorrect. Current actually flows through the circuit as shown in *Figure 9–5*.

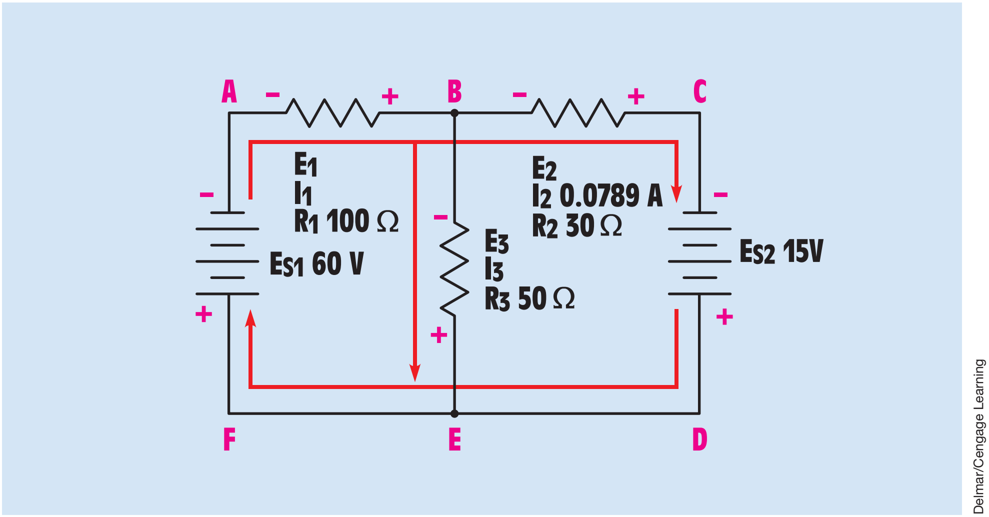

FIGURE 9–5 Actual direction of current flow.

Now that the value of I_2 is known, that answer can be substituted in either of the equations to find I_1.

$$150\ \Omega\ I_1 + 50\ \Omega\ (-0.0789\ A) = 60\ V$$
$$150\ \Omega\ I_1 - 3.945\ A = 60\ V$$

Now add +3.945 to both sides of the equation:

$$150\ \Omega\ I_1 = 63.945\ V$$
$$I_1 = 0.426\ A$$

There is 0.426 ampere leaving point A, flowing through R_1, and entering point B. At point B, 0.0789 ampere branches to point C through R_2 and the remainder of the current branches to point E through R_3. The value for I_3, therefore, can be found by subtracting 0.0789 ampere from 0.426 ampere:

$$I_3 = I_1 - I_2$$
$$I_3 = 0.426\ A - 0.0789\ A$$
$$I_3 = 0.347\ A$$

The voltage drops across each resistor can now be determined using Ohm's law:

$$E_1 = 0.426\ A \times 100\ \Omega$$
$$E_1 = 42.6\ V$$

$$E_2 = 0.0789\ A \times 30\ \Omega$$
$$E_2 = 2.367\ V$$

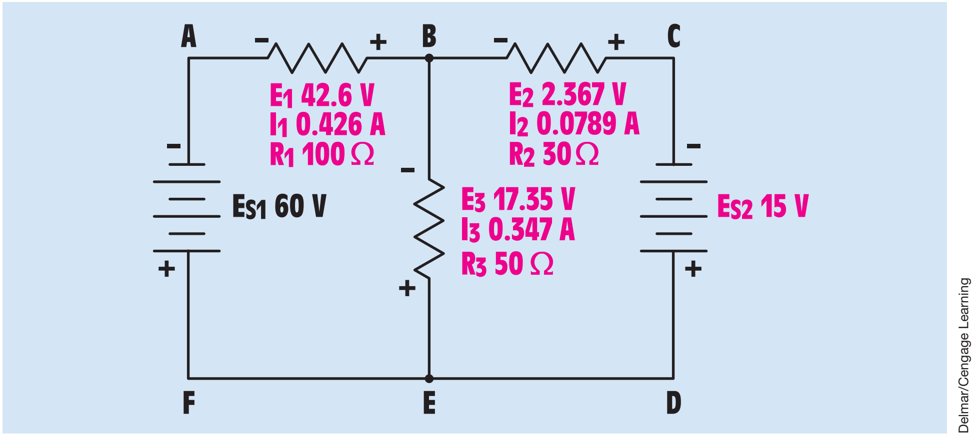

FIGURE 9–6 All circuit values have been calculated.

$$E_3 = 0.347\ \text{A} \times 50\ \Omega$$
$$E_3 = 17.35\ \text{V}$$

The values for the entire circuit are shown in *Figure 9–6*. To check the answers, add the voltages around the loops. The answers should total zero. Loop BCDE is added first.

$$-E_2 - E_{S2} + E_3 = 0$$
$$-2.367\ \text{V} - 15\ \text{V} + 17.35\ \text{V} = -0.017\ \text{V}$$

(The slight negative voltage in the answer is caused by rounding off values.)

The second loop checked is ABEF:

$$-E_1 - E_3 + E_{S1} = 0$$
$$-42.6\ \text{V} - 17.35\ \text{V} + 60\ \text{V} = 0.05\ \text{V}$$

The third loop checked is ACDF:

$$-E_1 - E_2 - E_{S2} + E_{S1} = 0$$
$$-42.6\ \text{V} - 2.367\ \text{V} - 15\ \text{V} + 60 = 0.033\ \text{V}$$

9–2 Thevenin's Theorem

Thevenin's theorem was developed by a French engineer named M. L. Thevenin. It is ***used to simplify a circuit network into an equivalent circuit, which contains a single voltage source and series resistor*** *(Figure 9–7)*. Imagine a black box that contains an unknown circuit and two

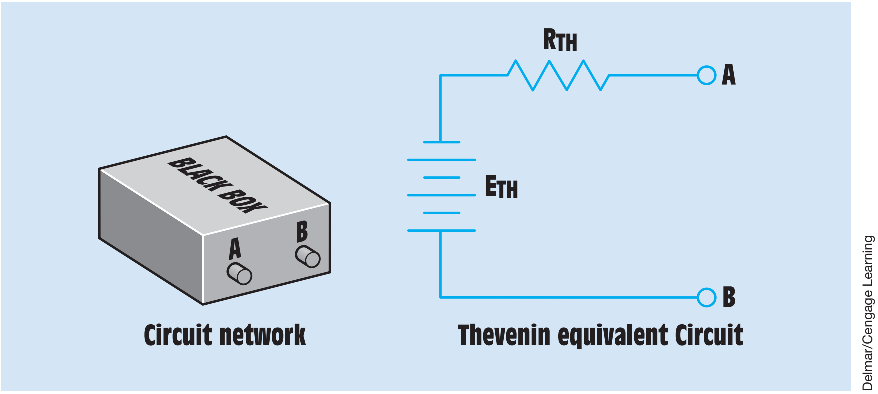

FIGURE 9–7 Thevenin's theorem reduces a circuit network to a single power source and a single series resistor.

output terminals labeled A and B. The output terminals exhibit some amount of voltage and some amount of internal impedance.

Thevenin's theorem reduces the circuit inside the black box to a single source of power and a series resistor equivalent to the internal impedance. The equivalent Thevenin circuit assumes the output voltage to be the open circuit voltage with no load connected. The equivalent Thevenin resistance is the open circuit resistance with no power source connected. Imagine the Thevenin circuit shown in *Figure 9–7* with the power source removed and a single conductor between Terminal B and the equivalent resistor *(Figure 9–8)*. If an ohmmeter were to be connected across Terminals A and B, the equivalent Thevenin resistance would be measured.

Calculating the Thevenin Values

The circuit shown in *Figure 9–9* has a single power source of 24 volts and two resistors connected in series. R_1 has a value of 2 ohms, and R_2 has

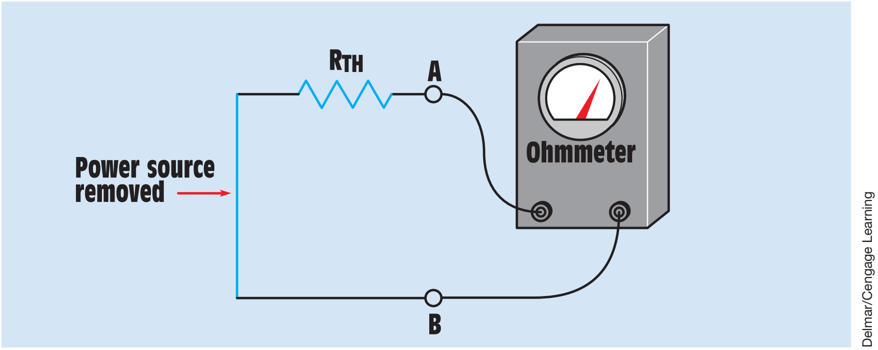

FIGURE 9–8 Equivalent Thevenin resistance.

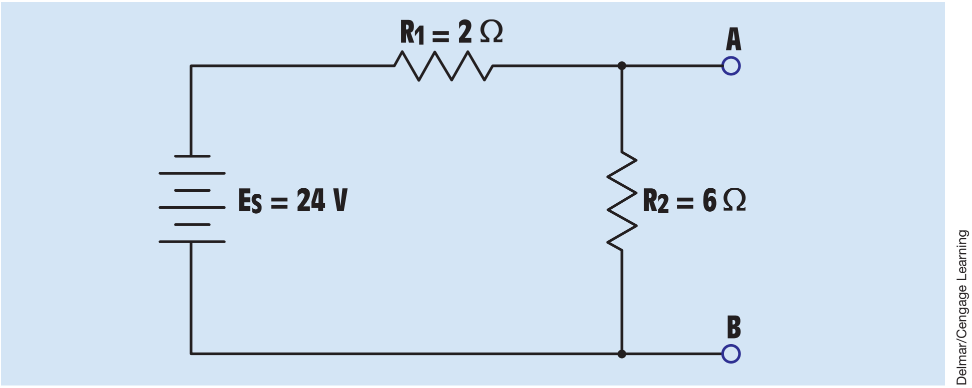

FIGURE 9–9 Determining the Thevenin equivalent circuit.

a value of 6 ohms. The Thevenin equivalent circuit is calculated across Terminals A and B. To do this, determine the voltage drop across R_2 because it is connected directly across Terminals A and B. The voltage drop across R_2 is the open circuit voltage of the equivalent Thevenin circuit when no load is connected across Terminals A and B. Because R_1 and R_2 form a series circuit, a total of 8 ohms are connected to the 24-volt power source. This produces a current flow of 3 amperes through R_1 and R_2 (24 V/8 Ω = 3 A). Because 3 amperes of current flow through R_2, a voltage drop of 18 volts will appear across it (3 A × 6 Ω = 18 V). The equivalent Thevenin voltage for this circuit is 18 volts.

To determine the equivalent Thevenin resistance, disconnect the power source and replace it with a conductor *(Figure 9–10)*. In this circuit, R_1 and

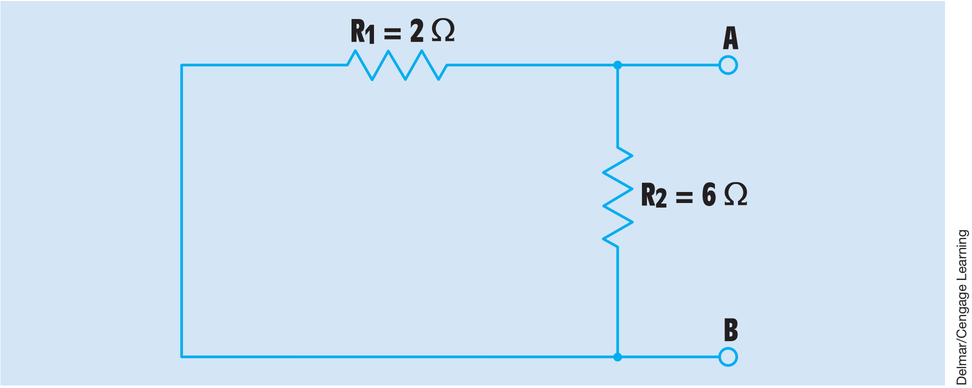

FIGURE 9–10 Determining the Thevenin equivalent resistance.

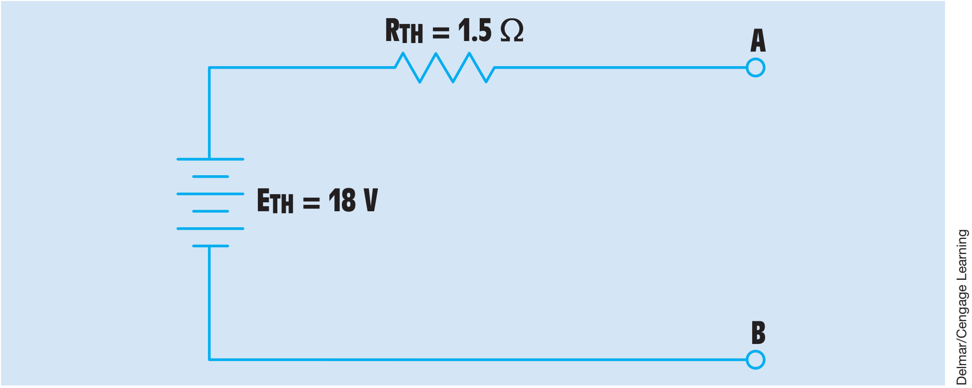

FIGURE 9–11 The Thevenin equivalent circuit.

R_2 are connected in parallel with each other. The total resistance can now be determined using one of the formulas for finding parallel resistance:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{2\ \Omega \times 6\ \Omega}{2\ \Omega + 6\ \Omega}$$

$$R_T = 1.5\ \Omega$$

The Thevenin equivalent circuit is shown in *Figure 9–11*.

Now that the Thevenin equivalent of the circuit is known, the voltage and current values for different load resistances can be quickly calculated. Assume, for example, that a load resistance of 10 ohms is connected across Terminals A and B *(Figure 9–12)*. The voltage and current values for the circuit can now easily

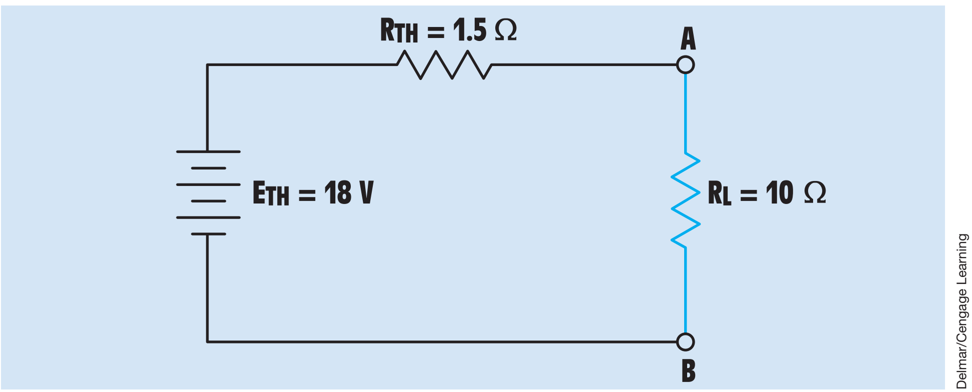

FIGURE 9–12 A 10-ohm load resistor is connected across Terminals A and B.

be calculated. The total resistance of the circuit is 11.5 ohms (1.5 Ω + 10 Ω). This produces a current flow of 1.565 amperes (18 V/11.5 Ω), and a voltage drop of 15.65 volts (1.565 A × 10 Ω) across the 10-ohm load resistor.

9–3 Norton's Theorem

Norton's theorem was developed by an American scientist named E. L. Norton. ***Norton's theorem is used to reduce a circuit network into a simple current source and a single parallel resistance.*** This is the opposite of Thevenin's theorem, which reduces a circuit network into a simple voltage source and a single series resistor *(Figure 9–13)*. Norton's theorem assumes a source of current that is divided among parallel branches. A source of current is often easier to work with, especially when calculating values for parallel circuits, than a voltage source, which drops voltages across series elements.

Current Sources

Power sources can be represented in one of two ways, as a voltage source or as a current source. Voltage sources are generally shown as a battery with a resistance connected in series with the circuit to represent the internal resistance of the source. This is the case when using Thevenin's theorem. Voltage sources are rated with some amount of voltage such as 12 volts, 24 volts, and so on.

Power sources can also be represented by a current source connected to a parallel resistance that delivers a certain amount of current such as 1 ampere, 2 amperes, 3 amperes, and so on. Assume that a current source is rated at

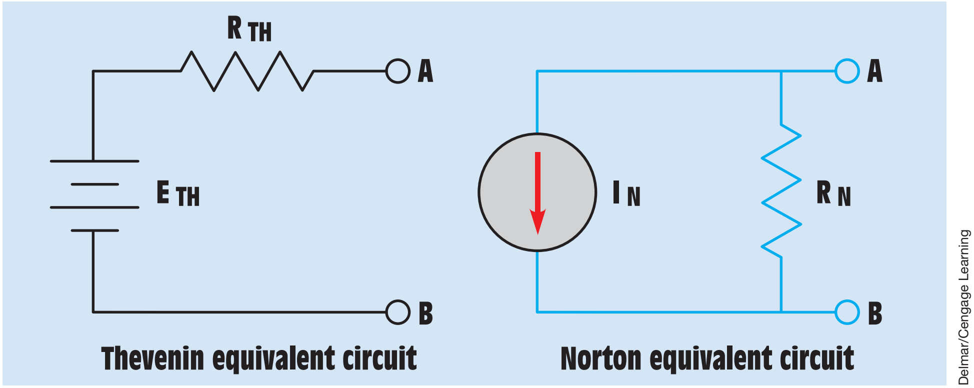

FIGURE 9–13 The Thevenin equivalent circuit contains a voltage source and series resistance. The Norton equivalent circuit contains a current source and parallel resistance.

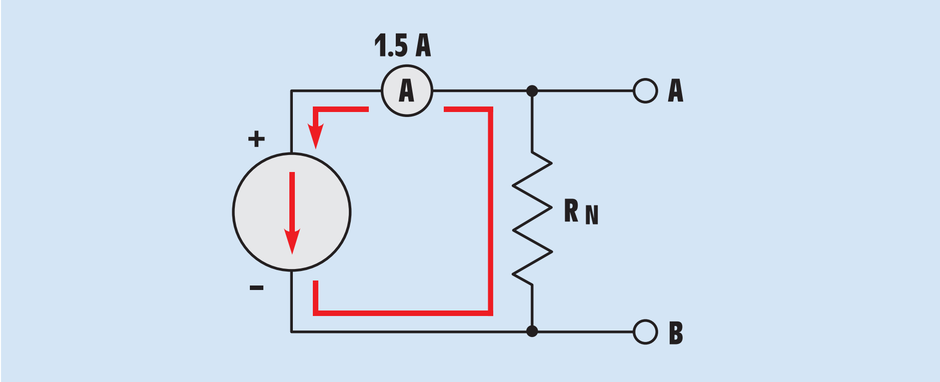

FIGURE 9–14 The current source supplies a continuous 1.5 amperes.

1.5 amperes *(Figure 9–14)*. This means that 1.5 amperes will flow from the power source regardless of the circuit connected. In the circuit shown in *Figure 9–14,* 1.5 amperes flow through R_N.

Determining the Norton Equivalent Circuit

The same circuit used previously to illustrate Thevenin's theorem is used to illustrate Norton's theorem. Refer to the circuit shown in *Figure 9–15*. In this basic circuit, a 2-ohm and a 6-ohm resistor are connected in series with a 24-volt power source. To determine the Norton equivalent of this circuit, imagine a short circuit placed across Terminals A and B *(Figure 9–16)*. Because this places the short circuit directly across R_2, that resistance is eliminated from the circuit and a resistance of 2 ohms is left connected in series with the voltage

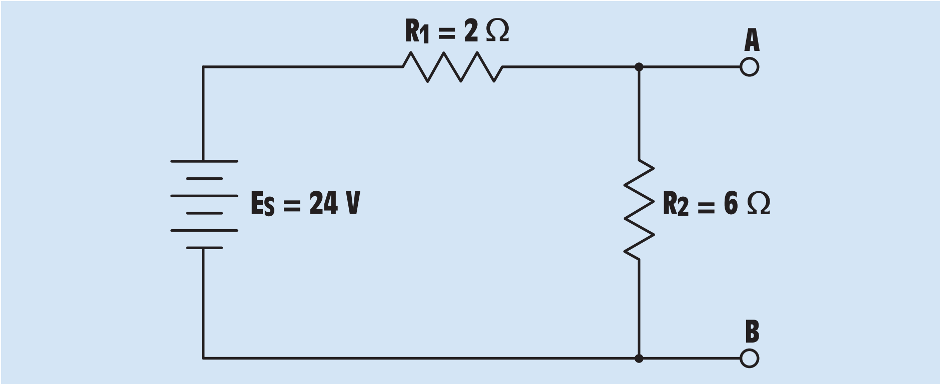

FIGURE 9–15 Determining the Norton equivalent circuit.

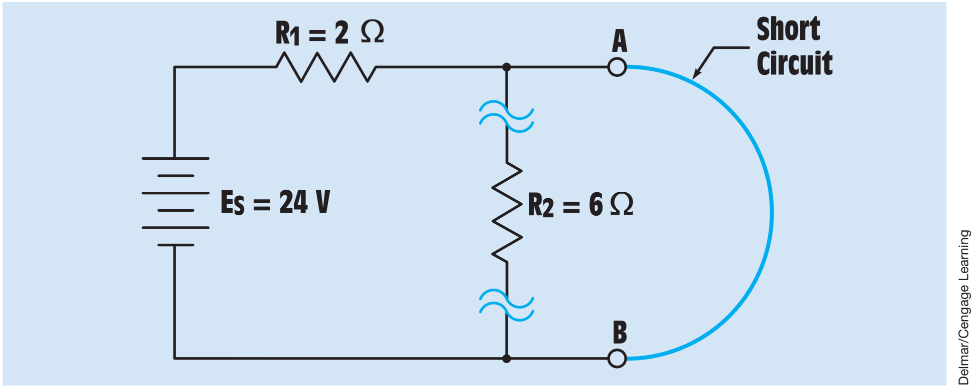

FIGURE 9–16 Shorting Terminals A and B eliminates the 6-ohm resistor.

source. The next step is to determine the amount of current that can flow through this circuit. This current value is known as I_N:

$$I_N = \frac{E_s}{R_1}$$

$$I_N = \frac{24\text{ V}}{2\ \Omega}$$

$$I_N = 12\text{ A}$$

I_N, or 12 amperes, is the amount of current available in the Norton equivalent circuit.

The next step is to find the equivalent parallel resistance, R_N, connected across the current source. To do this, remove the short circuit across Terminals A and B. Now replace the power source with a short circuit just as was done in determining the Thevenin equivalent circuit *(Figure 9–17)*. The circuit

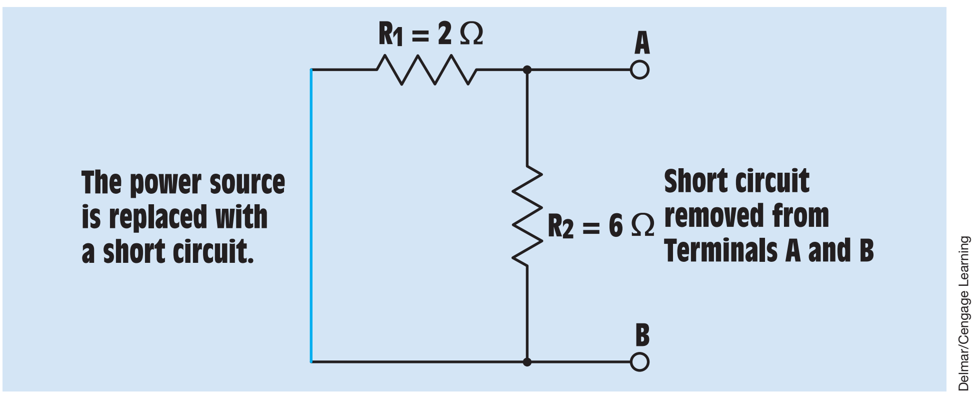

FIGURE 9–17 Determining the Norton equivalent resistance.

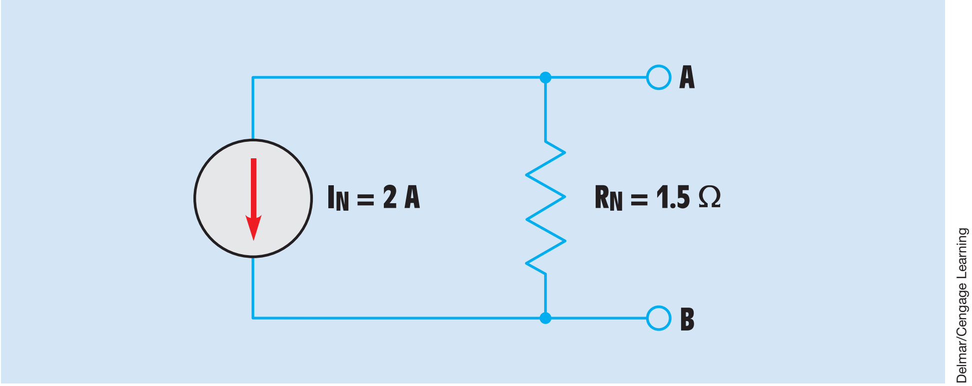

FIGURE 9–18 Equivalent Norton circuit.

now has a 2-ohm and a 6-ohm resistor connected in parallel. This produces an equivalent resistance of 1.5 ohms. The Norton equivalent circuit, shown in *Figure 9–18,* is a 1.5-ohm resistor connected in parallel with a 12-ampere current source.

Now that the Norton equivalent for the circuit has been calculated, any value of resistance can be connected across Terminals A and B and the electrical values calculated quickly. Assume that a 6-ohm load resistor, R_L, is connected across Terminals A and B *(Figure 9–19)*. The 6-ohm load resistor is connected in parallel with the Norton equivalent resistance of 1.5 ohms. This produces a total resistance of 1.2 ohms for the circuit. In a Norton equivalent circuit, it is assumed that the Norton equivalent current, I_N, flows at all times. In this circuit, the Norton equivalent current is 12 amperes. Therefore, a current of 12 amperes flows through the 1.2-ohm resistance. This produces a voltage drop of 14.4 volts across the resistance ($E = 12\text{ A} \times 1.2\ \Omega$). Because the resistors shown in *Figure 9–19* are connected in parallel, 14.4 volts are dropped across

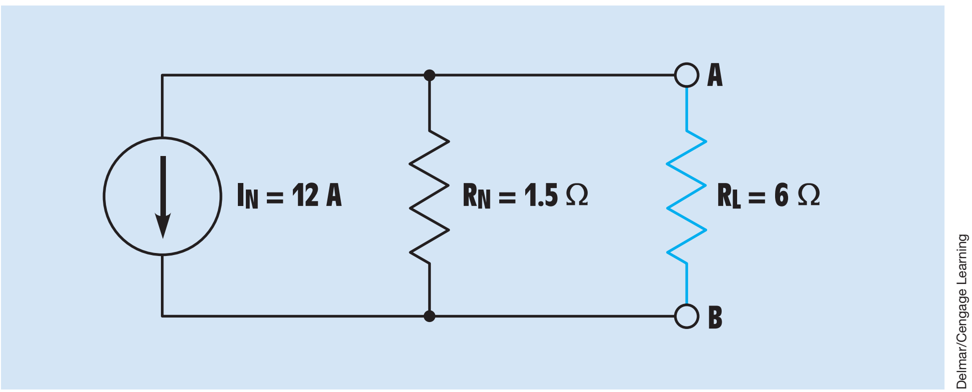

FIGURE 9–19 A 6-ohm load resistor is connected to the equivalent Norton circuit.

each. This produces a current flow of 9.6 amperes through R_N (14.4 V/1.5 Ω = 9.6 A) and a current flow of 2.4 amperes through R_L (14.4 V/6 Ω = 2.4 A).

9–4 The Superposition Theorem

The **superposition theorem** is used to find the current flow through any branch of a circuit containing more than one power source. ***The superposition theorem works on the principle that the current in any branch of a circuit supplied by a multipower source can be determined by finding the current produced in that particular branch by each of the individual power sources acting alone. All other power sources must be replaced by a resistance equivalent to their internal resistances. The total current flow through the branch is the algebraic sum of the individual currents produced by each of the power sources.***

EXAMPLE 9–1

An example circuit is shown in *Figure 9–20*. In this example, the circuit contains two voltage sources. The amount of current flowing through R_2 is determined using the superposition theorem. The circuit can be solved by following a procedure through several distinct steps.

Solution

STEP 1

Reduce all but one of the voltage sources to zero by replacing it with a short circuit, leaving any internal series resistance. Reduce the current source to zero

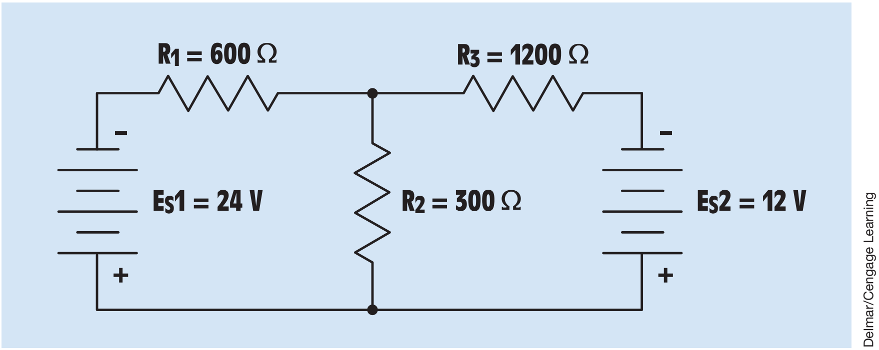

FIGURE 9–20 A circuit with two power sources.

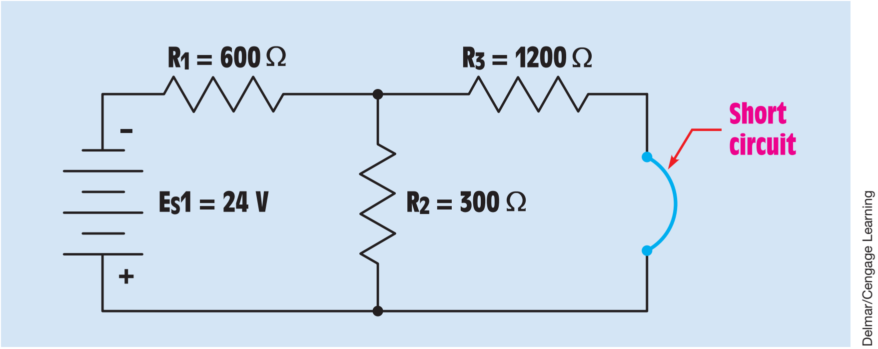

FIGURE 9–21 Voltage source E_S2 is replaced with a short circuit.

by replacing it with an open circuit, leaving any internal parallel resistance. Voltage source E_S2 will be shorted *(Figure 9–21)*. The circuit now exists as a simple combination circuit with R_1 connected in series with R_2 and R_3, which are in parallel with each other *(Figure 9–22)*. The total resistance of this circuit can now be found by finding the total resistance of the two resistors connected in parallel, R_2 and R_3, and adding them to R_1:

$$R_T = R_1 + \left(\frac{1}{\frac{1}{R_2} + \frac{1}{R_3}}\right)$$

$$R_T = 600\ \Omega + \left(\frac{1}{\frac{1}{300\ \Omega} + \frac{1}{1200\ \Omega}}\right)$$

$$R_T = 840\ \Omega$$

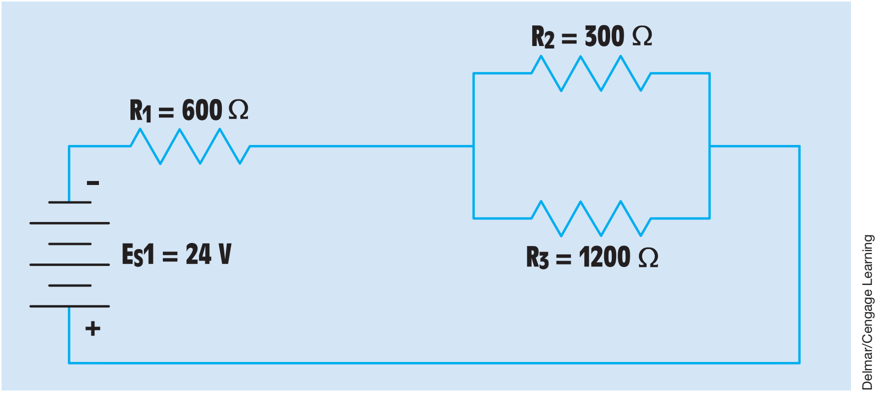

FIGURE 9–22 The circuit is reduced to a simple combination circuit.

Now that the total resistance is known, the total current flow can be calculated:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{24\ V}{840\ \Omega}$$

$$I_T = 0.0286\ A$$

The voltage drop across the parallel block can be calculated using the total current and the combined resistance of R_2 and R_3:

$$E_{COMBINATION} = 0.0286\ A \times 240\ \Omega$$

$$E_{COMBINATION} = 6.864\ V$$

The current flowing through R_2 can now be calculated:

$$I_2 = \frac{6.864\ V}{300\ \Omega}$$

$$I_2 = 0.0229\ A$$

Notice that the current is flowing through R_2 in the direction of the arrow in *Figure 9–23*.

■ STEP 2

Find the current flow through R_2 by shorting voltage source E_S1. Power is now supplied by voltage source E_S2 *(Figure 9–24)*. In this circuit, R_1 and R_2 are in parallel with each other. R_3 is in series with R_1 and R_2.

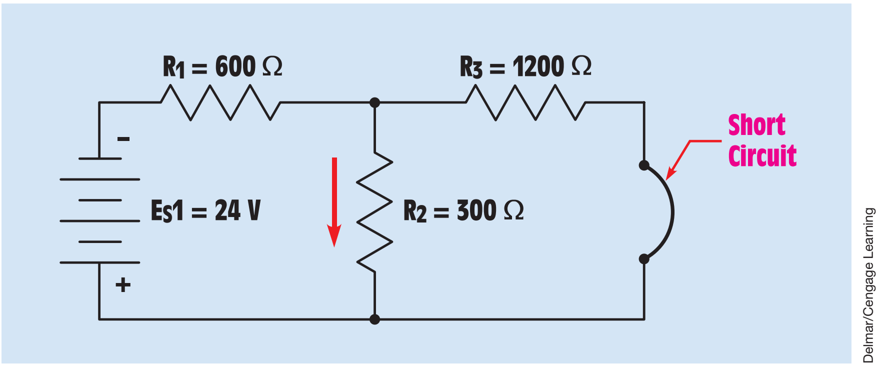

FIGURE 9–23 Current flows through the resistor in the direction shown.

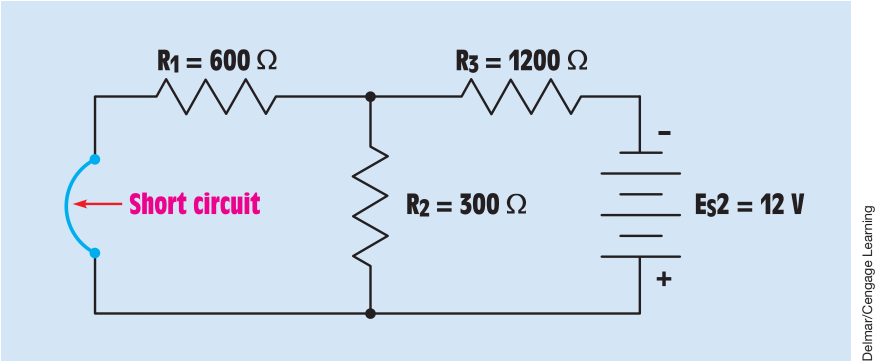

FIGURE 9–24 Voltage source E_S2 is shorted.

$$R_T = R_3 + \left(\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}\right)$$

$$R_T = 1200\ \Omega + 200\ \Omega$$

$$R_T = 1400\ \Omega$$

The total current flow in the circuit can now be determined:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{12\ V}{1400\ \Omega}$$

$$I_T = 0.00857\ A$$

The amount of voltage drop across the parallel combination can now be calculated:

$$E_C = 0.00857\ A \times 200\ \Omega$$

$$E_C = 1.714\ V$$

The amount of current flow through R_2 can now be calculated using Ohm's law:

$$I_2 = \frac{1.714\ V}{300\ \Omega}$$

$$I_2 = 0.00571\ A$$

Notice that the current flowing through R_2 is in the same direction as in the previous circuit *(Figure 9–25)*.

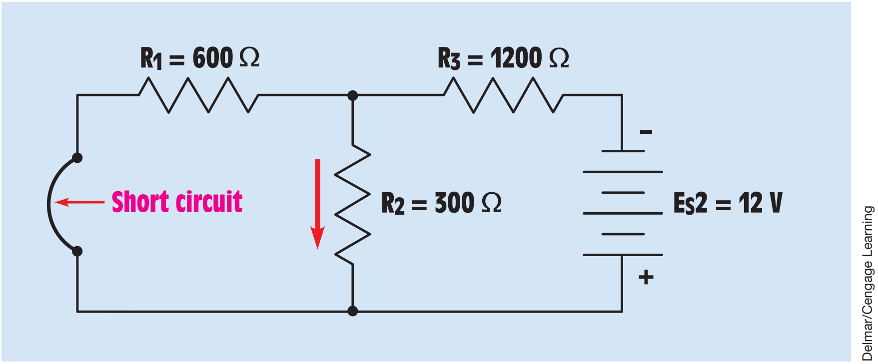

FIGURE 9–25 Current flows in the same direction.

STEP 3

The next step is to find the algebraic sum of the two currents. Because both currents flow through R_2 in the same direction, the two currents are added:

$$I_{2(TOTAL)} = 0.0229\ A + 0.00571\ A$$
$$I_{2(TOTAL)} = 0.0286\ A$$

EXAMPLE 9–2

Example circuit 2 is shown in *Figure 9–26*. This circuit contains a voltage source of 30 V and a current source of 0.2 A. The amount of current flowing through R_2 will be calculated.

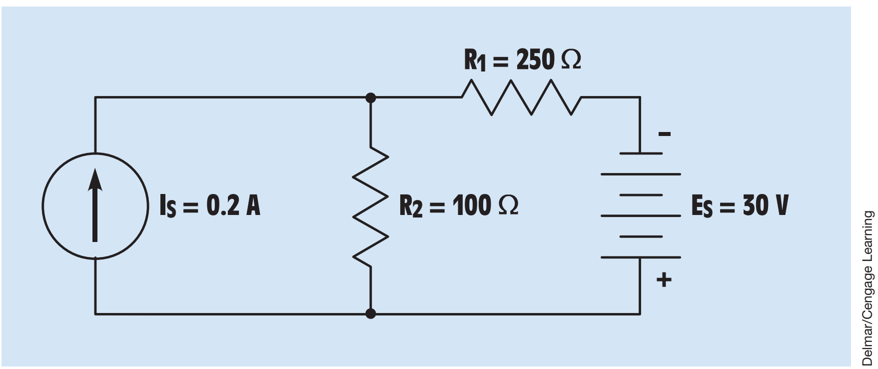

FIGURE 9–26 Example circuit 2 contains a current source and a voltage source.

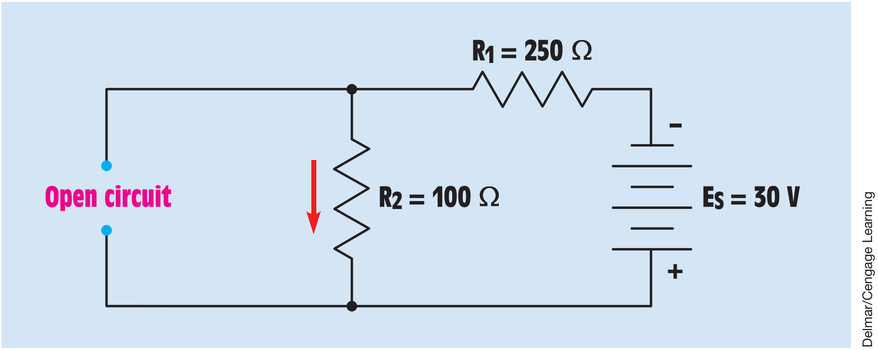

FIGURE 9–27 The current source is replaced with an open circuit.

Solution

■ **STEP 1**

The first step is to find the current flow through R_2 using the voltage source only. This is done by replacing the current source with an open circuit *(Figure 9–27)*. Notice the direction of current flow through R_2.

When the current source is replaced with an open circuit, R_1 and R_2 become connected in series with each other. The total resistance is the sum of the two resistances:

$$R_T = R_1 + R_2$$
$$R_T = 250\ \Omega + 100\ \Omega$$
$$R_T = 350\ \Omega$$

Now that the total resistance is known, the total current flow in the circuit can be found using Ohm's law:

$$I_T = \frac{30\text{ V}}{350\ \Omega}$$
$$I_T = 0.0857\text{ A}$$

Because the current flow must be the same in all points of a series circuit, the same amount of current flows through resistor R_2:

$$I_T = I_2$$
$$I_2 = 0.0857\text{ A}$$

■ **STEP 2**

The next step is to find the amount of current flow through R_2 that would be supplied by the current source only. This can be done by replacing the voltage

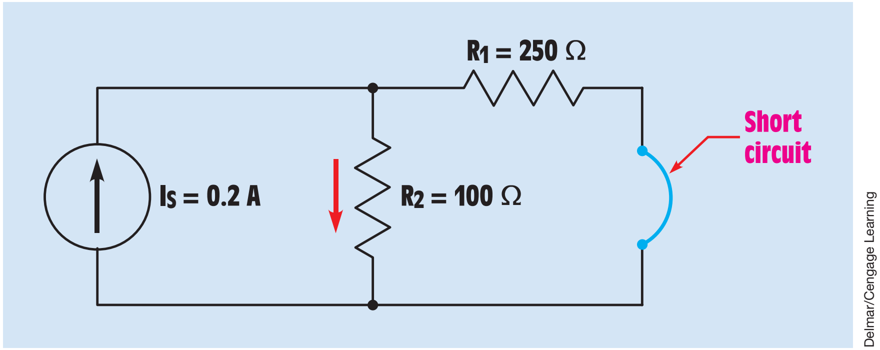

FIGURE 9–28 The voltage source is replaced with a short circuit.

source with a short circuit *(Figure 9–28)*. Notice the direction of current flow through R_2.

When the voltage source is removed and replaced with a short circuit, R_1 and R_2 become connected in parallel with each other. The current flow through R_2 will be calculated using the current divider formula:

$$I_2 = \left(\frac{R_1}{R_1 + R_2}\right) \times I_S$$

$$I_2 = \frac{250\ \Omega}{350\ \Omega} \times 0.2\text{ A}$$

$$I_2 = 0.143\text{ A}$$

■ **STEP 3**

The total amount of current flow through R_2 can now be determined by finding the algebraic sum of both currents:

$$I_{2(TOTAL)} = 0.0857\text{ A} + 0.143\text{ A}$$

$$I_{2(TOTAL)} = 0.229\text{ A}$$

■ EXAMPLE 9-3

In the third example, a circuit contains two resistors and two current sources *(Figure 9–29)*. The amount of current flowing through R_2 will be determined.

■ **STEP 1**

Remove one of the current sources from the circuit and replace it with an open circuit. In this example, current source I_S2 is removed first *(Figure 9–30)*. R_1 is

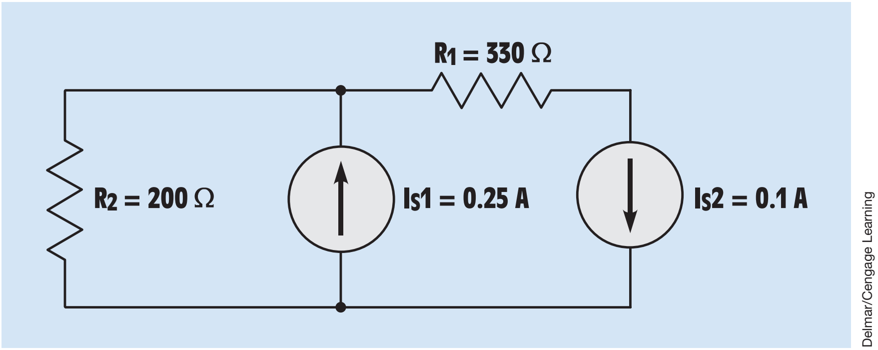

FIGURE 9–29 The circuit contains two current sources.

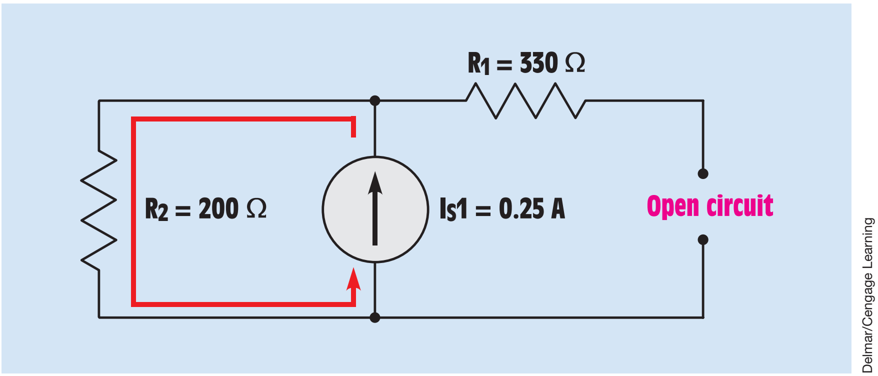

FIGURE 9–30 Current source I_S2 is replaced with an open circuit.

now removed from the circuit and the entire 0.25 A of current flows through R_2. Notice the direction of current flow through the resistor.

■ **STEP 2**

The next step is to replace current source I_S1 with an open circuit and determine the amount and direction of current flow through resistor R_2 produced by current source I_S2 *(Figure 9–31)*.

When I_S1 is replaced with an open circuit, R_1 and R_2 become connected in series with each other. Because the current is the same in a series circuit, both resistors have a current flow of 0.1 A through them.

■ **STEP 3**

Now that the amount and the direction of current flow through R_2 for both current sources are known, the total current flow can be determined by adding the two currents together. Because the currents flow in opposite directions, the

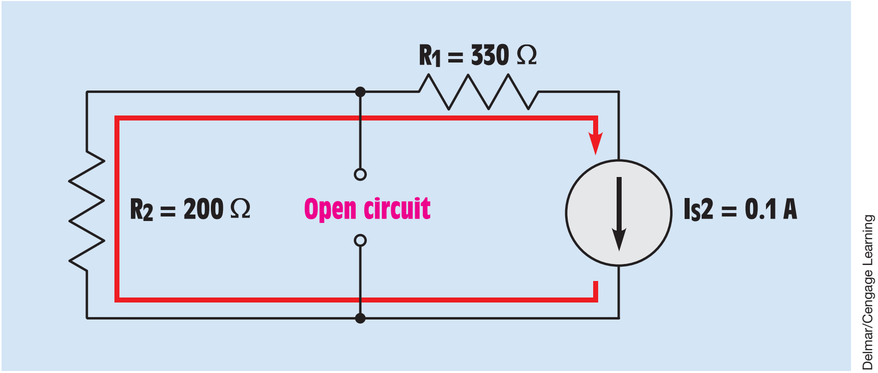

FIGURE 9–31 Current source I_S1 is replaced with an open circuit.

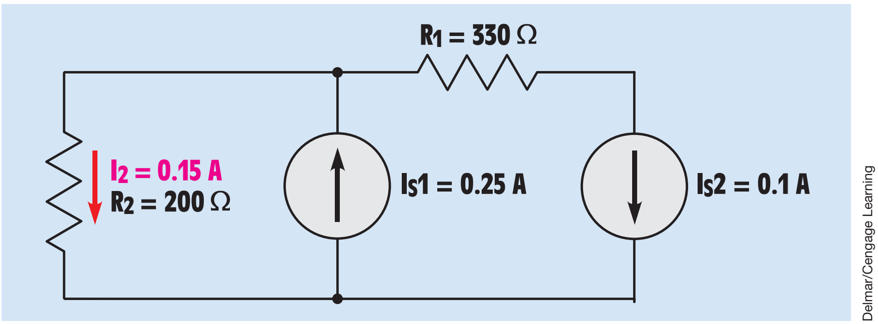

FIGURE 9–32 The amount and the direction of current flow through R_2 have been determined.

algebraic sum will be the difference of the two currents and the direction will be determined by the greater *(Figure 9–32)*.

$$I_{2(TOTAL)} = 0.25\text{ A} - 0.1\text{ A}$$
$$I_{2(TOTAL)} = 0.15\text{ A}$$

Summary

- Kirchhoff's laws can be used to solve any type of circuit.
- Kirchhoff's voltage law states that the algebraic sum of the voltage drops and voltage sources around any closed path must equal zero.
- Kirchhoff's current law states that the algebraic sum of the currents entering and leaving any point must equal zero.

- Kirchhoff's laws can be used to solve unknown values for circuits that contain more than one power source.
- When using Kirchhoff's laws it is generally necessary to solve simultaneous equations.
- Thevenin's theorem involves reducing a circuit network to a simple voltage source and series resistance.
- The Thevenin equivalent voltage is the open circuit voltage across two points.
- To determine the Thevenin equivalent resistance, replace the voltage source with a short circuit.
- Norton's theorem involves reducing a circuit network to a current source and parallel resistance.
- The Norton equivalent current is determined by shorting the output terminals.
- The Norton equivalent resistance is determined by replacing the current source with a short circuit.
- The superposition theorem is used to find the current flow through any branch of a circuit containing more than one power source.

Review Questions

1. State Kirchhoff's voltage law.
2. State Kirchhoff's current law.
3. What is the purpose of Thevenin's and Norton's theorems?
4. When using Kirchhoff's current law, do the currents entering a point carry a positive or negative sign?
5. When using Kirchhoff's current law, if a negative answer is found for current flow, what does this indicate?

To answer Questions 6 through 10, refer to the circuit shown in *Figure 9–33*.

6. How much current flows through R_1?

   I_1 = ___________

7. How much current flows through R_2?

   I_2 = ___________

8. How much voltage is dropped across R_1?

   E_1 = ___________

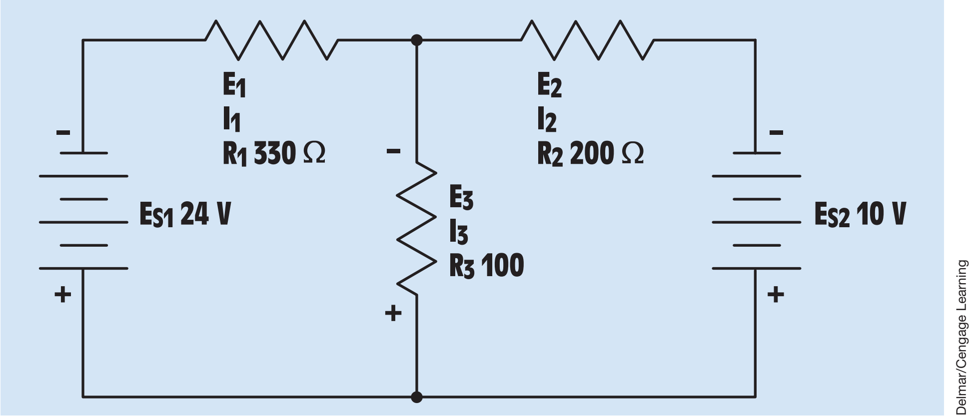

FIGURE 9–33 Review Questions 6 through 10.

9. How much voltage is dropped across R_2?

   E_2 = ___________

10. How much voltage is dropped across R_3?

    E_3 = ___________

To answer Questions 11 through 15, refer to the circuit shown in *Figure 9–34*.

11. In the circuit shown in *Figure 9–34*, assume that R_1 has a resistance of 4 Ω and R_2 has a resistance of 20 Ω. Battery E_S has a voltage of 48 V. What is the Thevenin equivalent voltage for this circuit across Terminals A and B?

    E_{THEV} = ___________

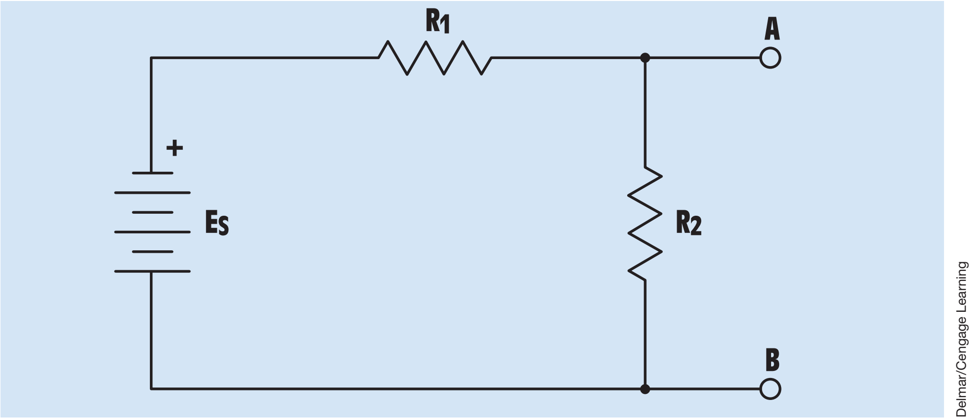

FIGURE 9–34 Review Questions 11 through 15.

12. What is the equivalent Thevenin resistance for the circuit described in Question 11?

 R_{THEV} __________ Ω

13. In the circuit shown in *Figure 9–34*, assume that R_1 has a resistance of 2.5 Ω and R_2 has a resistance of 16 Ω. Power source E_S has a voltage of 20 V. As measured across Terminals A and B, what would be the equivalent Norton current for this circuit?

 I_{NORTON} = __________

14. What is the equivalent Norton resistance for the circuit described in Question 13?

 R_{NORTON} = __________ Ω

15. Assume that an 8-Ω load resistance is connected across Terminals A and B for the circuit described in Question 13. How much current will flow through the load resistance?

 I_{LOAD} = __________

Practice Problems

To solve the following Kirchhoff's laws problems, refer to the circuit shown in *Figure 9–35*.

1. E_{S1} = 12 V	E_1 = ________	E_2 = ________	E_3 = ________
E_{S2} = 32 V	I_1 = ________	I_2 = ________	I_3 = ________
	R_1 = 680 Ω	R_2 = 1000 Ω	R_3 = 500 Ω
2. E_{S1} = 3 V	E_1 = ________	E_2 = ________	E_3 = ________
E_{S2} = 1.5 V	I_1 = ________	I_2 = ________	I_3 = ________
	R_1 = 200 Ω	R_2 = 120 Ω	R_3 = 100 Ω
3. E_{S1} = 6 V	E_1 = ________	E_2 = ________	E_3 = ________
E_{S2} = 60 V	I_1 = ________	I_2 = ________	I_3 = ________
	R_1 = 1.6 kΩ	R_2 = 1.2 kΩ	R_3 = 2.4 kΩ

To answer the following questions, refer to the circuit shown in *Figure 9–34*.

4. Find the Thevenin equivalent voltage and resistance across Terminals A and B.

 E_S = 32 V R_1 = 4 Ω R_2 = 6 Ω E_{TH} = ______ R_{TH} = ______

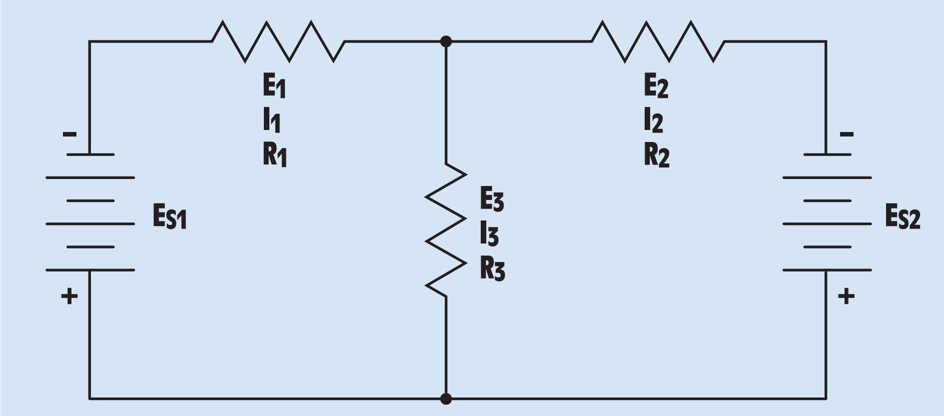

FIGURE 9–35 Kirchhoff's law practice problem circuit.

5. $E_S = 18$ V $R_1 = 2.5\ \Omega$ $R_2 = 12\ \Omega$ E_{TH} = _____ R_{TH} = _____

6. Find the Norton equivalent current and resistance across Terminals A and B.

   $E_S = 10$ V $R_1 = 3\ \Omega$ $R_2 = 7\ \Omega$ I_N = _____ R_N = _____

7. $E_S = 48$ V $R_1 = 12\ \Omega$ $R_2 = 64\ \Omega$ I_N = _____ R_N = _____

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III Meters and Wire Sizes

Courtesy of Getty Images, Inc.

Unit 10
Measuring Instruments

OUTLINE

KEY TERMS

Ammeter
Ammeter shunt
Analog meters
Ayrton shunt
Bridge circuit
Clamp-on ammeter
Current transformer
D'Arsonval movement
Galvanometers
Moving-coil meter
Multirange ammeters
Multirange voltmeters
Ohmmeter
Oscilloscope
Voltmeter
Wattmeter
Wheatstone bridge

Why You Need to Know

Measuring instruments are the eyes of the electrician. An understanding of how measuring instruments operate is very important to anyone working in the electrical field. They provide the electrician with the ability to evaluate problems on the job through the use of technical tools. They also enable an electrician to correctly determine electrical values of voltage, current, resistance, power, and many others. In this unit you will learn

- how different types of meters are constructed. This knowledge will aid you in knowing how the meters are to be connected in a circuit and how to interpret their readings.
- the differences between analog and digital meters, as well as how to interpret the waveforms shown on an oscilloscope. Oscilloscopes must be used to observe specific voltage patterns that would render a conventional voltmeter useless.


Courtesy of DeVry University

Objectives

After studying this unit, you should be able to

- discuss the operation of a d'Arsonval meter movement.
- discuss the operation of a moving-iron type of movement.
- connect a voltmeter to a circuit.
- connect and read an analog multimeter.
- connect an ammeter to a circuit.
- measure resistance using an ohmmeter.
- interpret waveforms shown on the display of an oscilloscope.
- connect a wattmeter into a circuit.

Preview

Anyone desiring to work in the electrical and electronics field must become proficient with the common instruments used to measure electrical quantities. These instruments are the voltmeter, the ammeter, and the ohmmeter. Without meters, it would be impossible to make meaningful interpretations of what is happening in a circuit. Meters can be divided into two general types: analog and digital. ■

10–1 Analog Meters

Analog meters are characterized by the fact that they use a pointer and scale to indicate their value *(Figure 10–1)*. There are different types of analog meter movements. One of the most common is the **d'Arsonval movement** shown in *Figure 10–2*. This type of movement is often referred to as a **moving-coil meter.** A coil of wire is suspended between the poles of a permanent magnet. The coil is suspended either by jeweled movements similar to those used in watches or by taut bands. The taut-band type offers less turning friction than the jeweled movement. These meters can be made to operate on very small amounts of current and often are referred to as **galvanometers.**

Principle of Operation

Analog meters operate on the principle that like magnetic poles repel each other. As current passes through the coil, a magnetic field is created around the coil. The direction of current flow through the meter is such that the same polarity of magnetic pole is created around the coil as that of the permanent magnet. This like polarity causes the coil to be deflected away from the pole

Courtesy of Simpson Electric

FIGURE 10–1 An analog meter.

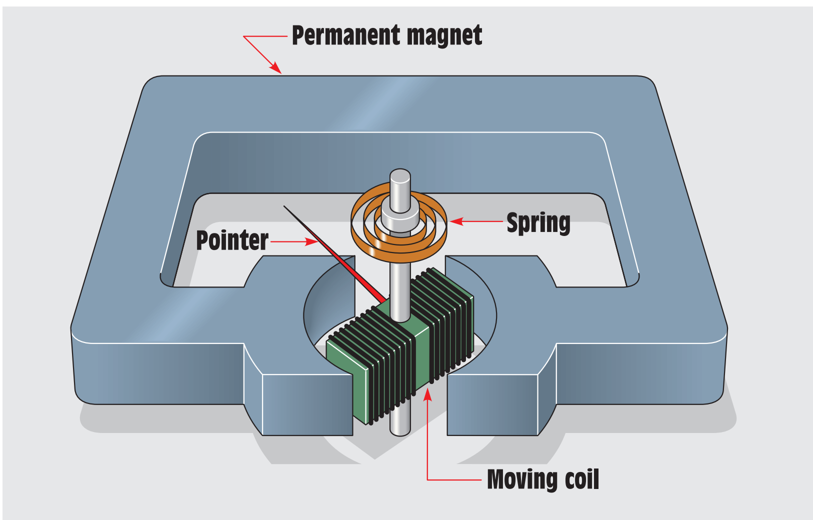

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FIGURE 10–2 Basic d'Arsonval meter movement.

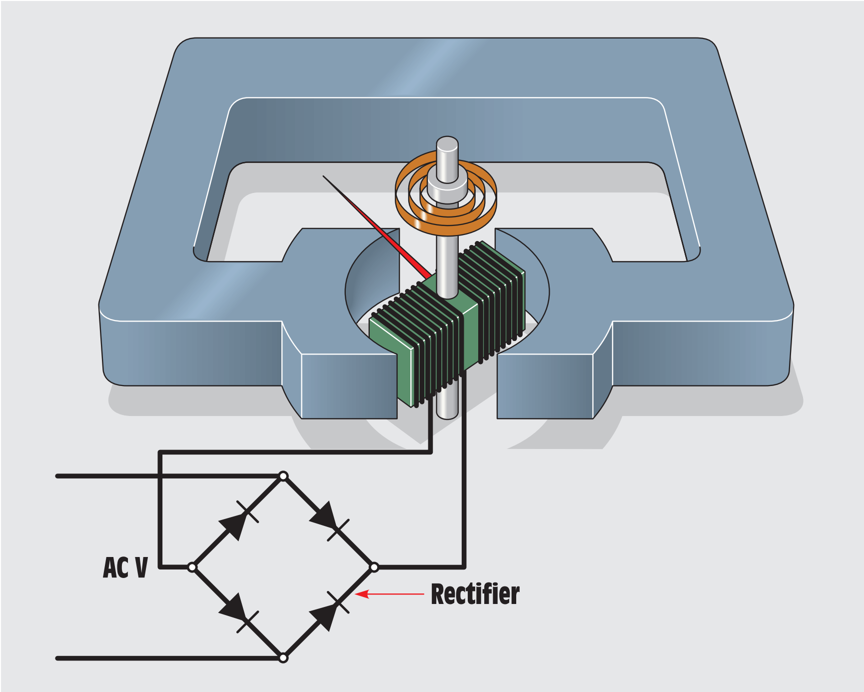

FIGURE 10–3 Rectifier changes AC voltage into DC voltage.

of the magnet. A spring is used to retard the turning of the coil. The distance the coil turns against the spring is proportional to the strength of the magnetic field developed in the coil. If a pointer is added to the coil and a scale is placed behind the pointer, a meter movement is created.

Because the turning force of this meter depends on the repulsion of magnetic fields, it will operate on DC only. If AC is connected to the moving coil, the magnetic polarity will change 60 times per second and the net turning force will be zero. For this reason, a DC voltmeter will indicate zero if connected to an AC line. When this type of movement is to be used to measure AC values, the current must be rectified, or changed into DC, before it is applied to the meter *(Figure 10–3)*.

10–2 The Voltmeter

The **voltmeter** is designed to be connected directly across the source of power. *Figure 10–4* shows a voltmeter being used to test the voltage of a battery. Notice that the leads of the meter are connected directly across the source of voltage. A voltmeter can be connected directly across the power

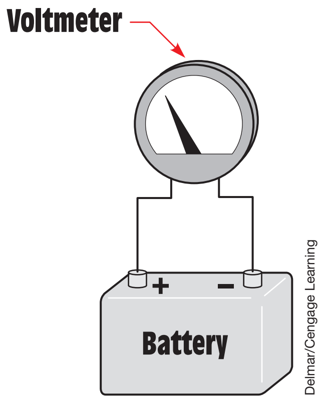

FIGURE 10–4 A voltmeter connects directly across the power source.

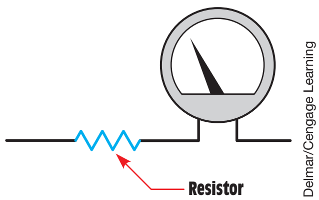

FIGURE 10–5 A resistor connects in series with the meter.

source because it has a very high resistance connected in series with the meter movement *(Figure 10–5)*. The industrial standard for a voltmeter is 20,000 ohms per volt for DC and 5000 ohms per volt for AC. Assume the voltmeter shown in *Figure 10–5* is an AC meter and has a full-scale range of 300 volts. The meter circuit (meter plus resistor) would therefore have a resistance of 1,500,000 ohms (300 V × 5000 Ω per volt = 1,500,000 Ω).

Calculating the Resistor Value

Before the resistor value can be calculated, the operating characteristics of the meter must be known. It will be assumed that the meter requires a current of 50 microamperes and a voltage of 1 volt to deflect the pointer full scale. These are known as the *full-scale values* of the meter.

When the meter and resistor are connected to a source of voltage, their combined voltage drop must be 300 volts. Because the meter has a voltage drop of 1 volt, the resistor must have a drop of 299 volts. The resistor and meter are connected in series with each other. In a series circuit, the current flow must be the same in all parts of the circuit. If 50 microamperes of current flow are required to deflect the meter full scale, then the resistor must have a current of 50 microamperes flowing through it when it has a voltage drop of 299 volts. The value of resistance can now be calculated using Ohm's law:

$$R = \frac{E}{I}$$

$$R = \frac{299\text{ V}}{0.000050\text{ A}}$$

$$R = 5.98\text{ M}\Omega\ (5,980,000\ \Omega)$$

10–3 Multirange Voltmeters

Most voltmeters are **multirange voltmeters,** which means that they are designed to use one meter movement to measure several ranges of voltage. For example, one meter may have a selector switch that permits full-scale ranges to be selected. These ranges may be 3 volts full scale, 12 volts full scale, 30 volts full scale, 60 volts full scale, 120 volts full scale, 300 volts full scale, and 600 volts full scale. Meters are made with that many scales so that they will be as versatile as possible. If it is necessary to check for a voltage of 480 volts, the meter can be set on the 600-volt range. It would be very difficult, however, to check a 24-volt system on the 600-volt range. If the meter is set on the 30-volt range, it is simple to test for a voltage of 24 volts. The meter shown in *Figure 10–6* has multirange selection for voltage.

Courtesy of Triplett Corp.

FIGURE 10–6 Volt-ohm-milliampere meter with multirange selection.

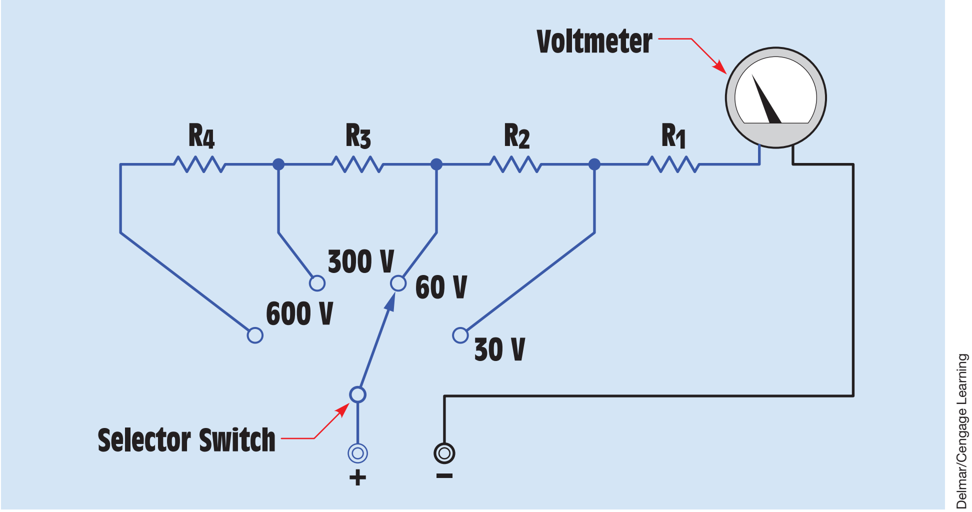

FIGURE 10–7 A rotary selector switch is used to change the full-range setting.

When the selector switch of this meter is turned, steps of resistance are inserted in the circuit to increase the range or are removed from the circuit to decrease the range. The meter shown in *Figure 10–7* has four range settings for full-scale voltage: 30 volts, 60 volts, 300 volts, and 600 volts. Notice that when the higher voltage settings are selected, more resistance is inserted in the circuit.

Calculating the Resistor Values

The values of the four resistors shown in *Figure 10–7* can be determined using Ohm's law. Assume that the full-scale values of the meter are 50 microamperes and 1 volt. The first step is to determine the value for R_1, which is used to provide a full-scale value of 30 volts. R_1, therefore, must have a voltage drop of 29 volts when a current of 50 microamperes is flowing through it.

$$R = \frac{E}{I}$$

$$R = \frac{29\ V}{0.000050\ A}$$

$$R = 5.80\ k\Omega\ (580{,}000\ \Omega)$$

When the selector switch is moved to the second position, the meter circuit should have a total voltage drop of 60 volts. The meter movement and R_1 have a total voltage drop of 30 volts, so R_2 must have a voltage drop of 30 volts when

50 microamperes of current flow through it. This will provide a total voltage drop of 60 volts for the entire circuit:

$$R = \frac{E}{I}$$

$$R = \frac{30\ V}{50\ \mu A\ (0.000050\ A)}$$

$$R = 600\ k\Omega\ (600{,}000\ \Omega)$$

When the selector switch is moved to the third position, the circuit must have a total voltage drop of 300 volts. R_1 and R_2, plus the meter movement, have a combined voltage drop of 60 volts at rated current. R_3, therefore, must have a voltage drop of 240 volts at 50 microamperes.

$$R = \frac{E}{I}$$

$$R = \frac{240\ V}{50\ \mu A}$$

$$R = 4.8\ M\Omega\ (4{,}800{,}000\ \Omega)$$

When the selector switch is moved to the fourth position, the circuit must have a total voltage drop of 600 volts at rated current. Because R_1, R_2, and R_3, plus the meter movement produce a voltage drop of 300 volts at rated current, R_4 must have a voltage drop of 300 volts when 50 microamperes of current flow through it.

$$R = \frac{E}{I}$$

$$R = \frac{300\ V}{50\ \mu A}$$

$$R = 6\ M\Omega\ (6{,}000{,}000\ \Omega)$$

10–4 Reading a Meter

Learning to read the scale of a multimeter takes time and practice. Most people use meters every day without thinking about it. A common type of meter used daily by most people is shown in *Figure 10–8*. The meter illustrated is a speedometer similar to those seen in automobiles. This meter is designed to measure speed. It is calibrated in miles per hour (mph). The speedometer shown has a full-scale value of 80 miles per hour. If the pointer is positioned as shown in *Figure 10–8,* most people would know instantly that the speed of the automobile is 55 miles per hour.

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FIGURE 10–8 A speedometer.

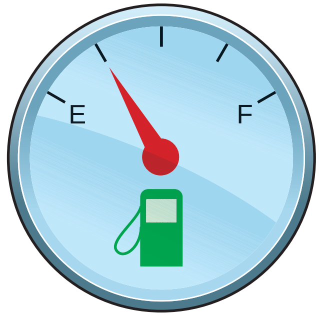

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FIGURE 10–9 A fuel gauge.

Figure 10–9 illustrates another common meter used by most people. This meter is used to measure the amount of fuel in the tank of the automobile. Most people can glance at the pointer of the meter and know that the meter is indicating that there is one quarter of a tank of fuel remaining. Now assume that the tank has a capacity of 20 gallons. The meter is indicating that 5 gallons of fuel remain in the tank.

Learning to read the scale of a multimeter is similar to learning to read a speedometer or fuel gauge. The meter scale shown in *Figure 10–10* has several scales used to measure different quantities and values. The top of the scale is used to measure resistance, or ohms. Notice that the scale begins on the left at

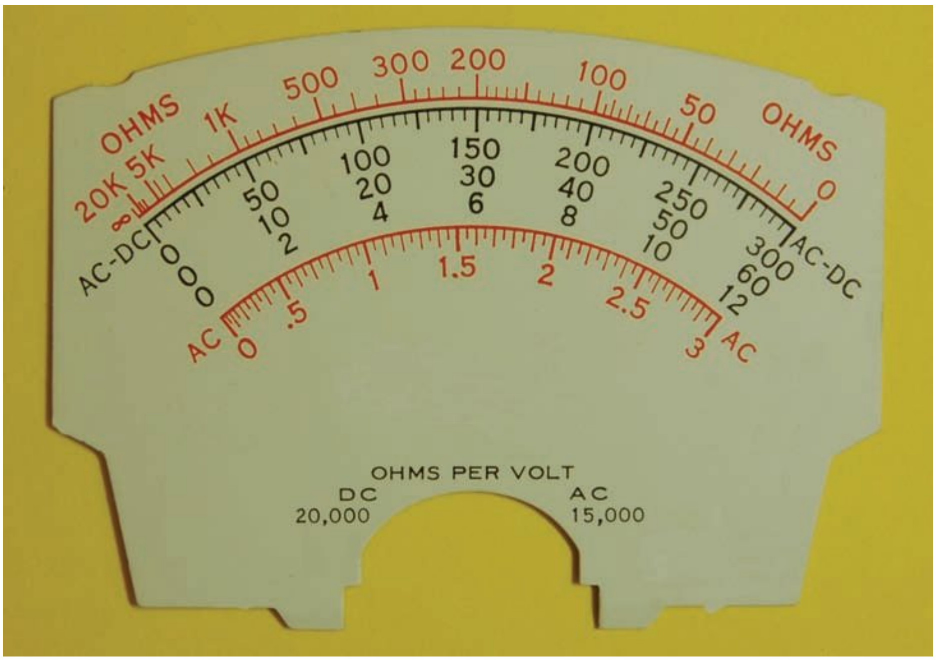

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FIGURE 10–10 Typical multimeter scale.

infinity and ends at zero on the right. Ohmmeters are covered later in this unit. The second scale is labeled AC–DC and is used to measure voltage. Notice that this scale has three different full-scale values. The top scale is 0–300, the second scale is 0–60, and the third scale is 0–12. The scale used is determined by the setting of the range control switch. The third set of scales is labeled "AC amperes." This scale is used with a clamp-on ammeter attachment that can be used with some meters. The last scale is labeled "dBm," which is used to measure decibels.

Reading a Voltmeter

Notice that the three voltmeter scales use the primary numbers 3, 6, and 12 and are in multiples of 10 of these numbers. Because the numbers are in multiples of 10, it is easy to multiply or divide the readings in your head by moving a decimal point. Remember that any number can be multiplied by 10 by moving the decimal point one place to the right, and any number can be divided by 10 by moving the decimal point one place to the left. For example, if the selector switch were set to permit the meter to indicate a voltage of 3 volts full scale, the 300-volt scale would be used, and the reading would be divided by 100. The reading can be divided by 100 by moving the decimal point two places to the left. In *Figure 10–11,* the pointer is indicating a value of 250. If the selector switch is set for 3 volts full scale, moving the decimal point two places to the left will give a reading of 2.5 volts. If the selector switch were set for a full-scale

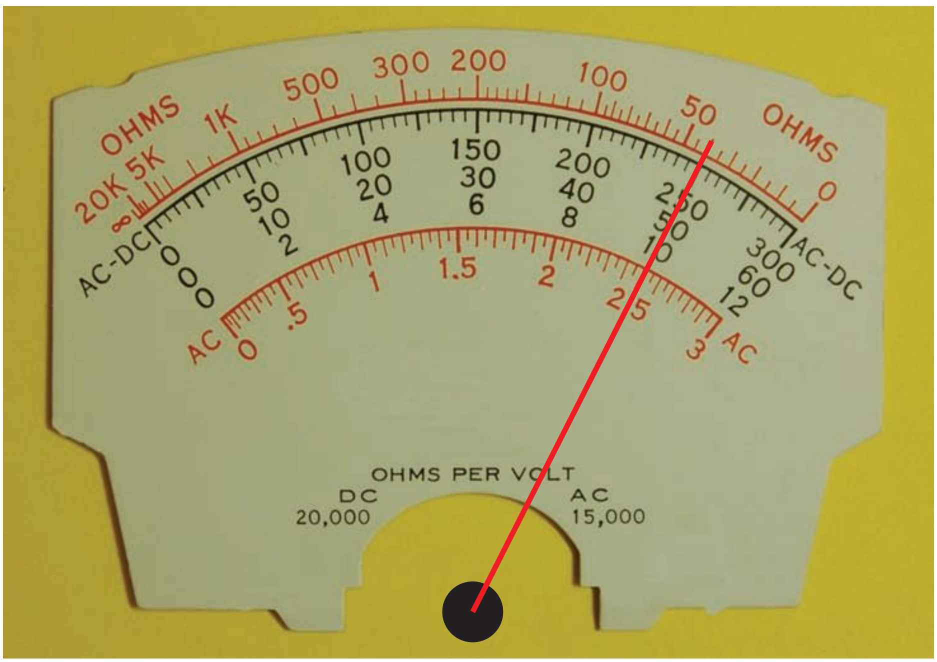

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FIGURE 10–11 The meter indicates a value of 250.

value of 30 volts, the meter shown in *Figure 10–11* would be indicating a value of 25 volts. That reading is obtained by dividing the scale by 10 and moving the decimal point one place to the left.

Now assume that the meter has been set to have a full-scale value of 600 volts. The pointer in *Figure 10–12* is indicating a value of 44. Because the full-scale value of the meter is set for 600 volts, use the 60-volt range and multiply the reading on the meter by 10 by moving the decimal point one place to the right. The correct reading becomes 440 volts.

Three distinct steps should be followed when reading a meter. These steps are especially helpful for someone who has not had a great deal of experience reading a multimeter. The steps are as follows:

1. *Determine what the meter indicates*. Is the meter set to read a value of DC voltage, DC current, AC voltage, AC current, or ohms? It is impossible to read a meter if you do not know what the meter is used to measure.

2. *Determine the full-scale value of the meter*. The advantage of a multimeter is that it can measure a wide range of values and quantities. After it has been determined what quantity the meter is set to measure, it must then be determined what the range of the meter is.

   There is a great deal of difference in reading when the meter is set to indicate a value of 600 volts full scale and when it is set for 30 volts full scale.

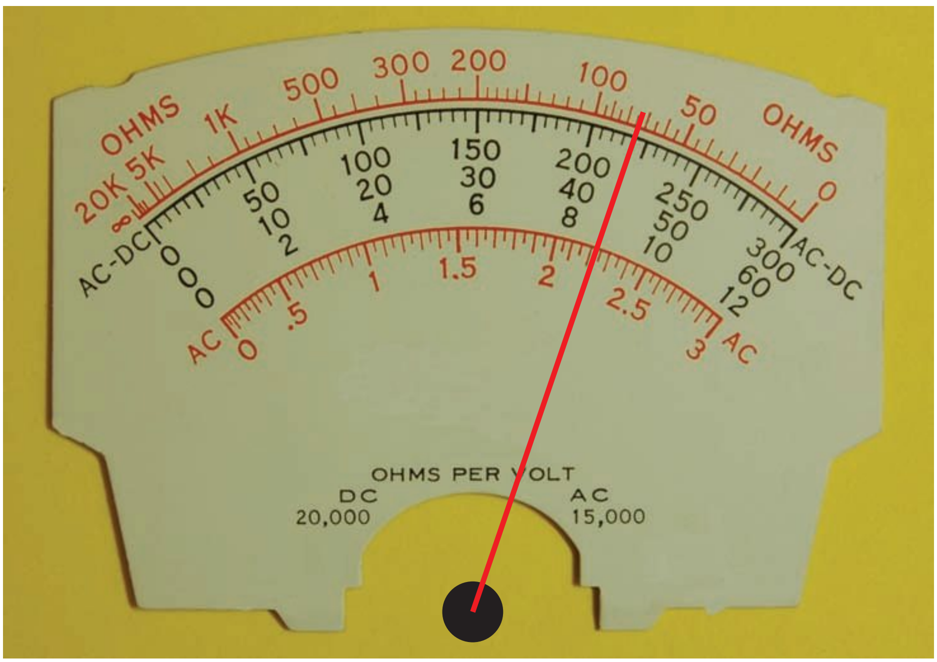

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FIGURE 10–12 The meter indicates a value of 440.

3. *Read the meter.* The last step is to determine what the meter is indicating. It may be necessary to determine the value of the hash marks on the meter face for the range for which the selector switch is set. If the meter in *Figure 10–10* is set for 300 volts full scale, each hash mark has a value of 5 volts. If the full-scale value of the meter is 60 volts, however, each hash mark has a value of 1 volt.

10–5 The Ammeter

CAUTION: The **ammeter**, unlike the voltmeter, is a very low-impedance device. The ammeter is used to measure current and must be connected in series with the load to permit the load to limit the current flow *(Figure 10–13).*

An ammeter has a typical impedance of less than 0.1 ohm. If this meter is connected in parallel with the power supply, the impedance of the ammeter is the only thing to limit the amount of current flow in the circuit. Assume that an ammeter with a resistance of 0.1 ohm is connected across a 240-volt AC line. The current flow in this circuit would be 2400 amperes (240 V/0.1 Ω = 2400 A). A blinding flash of light would be followed by the destruction of the ammeter.

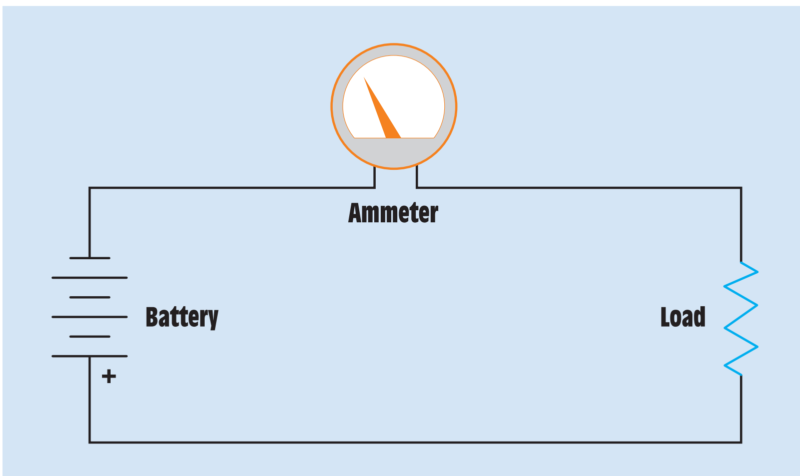

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FIGURE 10–13 An ammeter connects in series with the load.

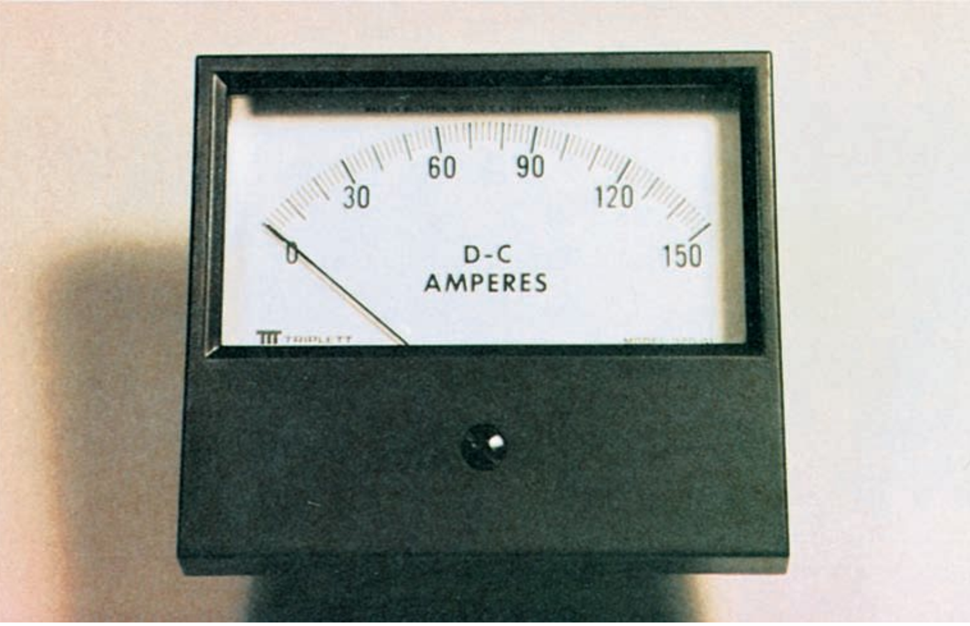

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FIGURE 10–14 In-line ammeter.

Ammeters connected directly into the circuit as shown in *Figure 10–13* are referred to as in-line ammeters. *Figure 10–14* shows an ammeter of this type.

10–6 Ammeter Shunts

DC ammeters are constructed by connecting a common moving-coil type of meter across a shunt. An **ammeter shunt** is a low-resistance device used to conduct most of the circuit current away from the meter movement. Because the meter movement is connected in parallel with the shunt, the voltage drop across the shunt is the voltage applied to the meter. Most ammeter shunts are manufactured to have a voltage drop of 50 millivolts (mv). If a 50-millivolt meter movement is connected across the shunt as shown in *Figure 10–15,* the pointer will move to the full-scale value when the rated current of the shunt is flowing. In the example shown, the ammeter shunt is rated to have a 50-millivolt drop when a 10-ampere current is flowing in the circuit. Because the meter movement has a full-scale voltage of 50 millivolts, it will indicate the full-scale value when 10 amperes of current are flowing through the shunt. An ammeter shunt is shown in *Figure 10–16.*

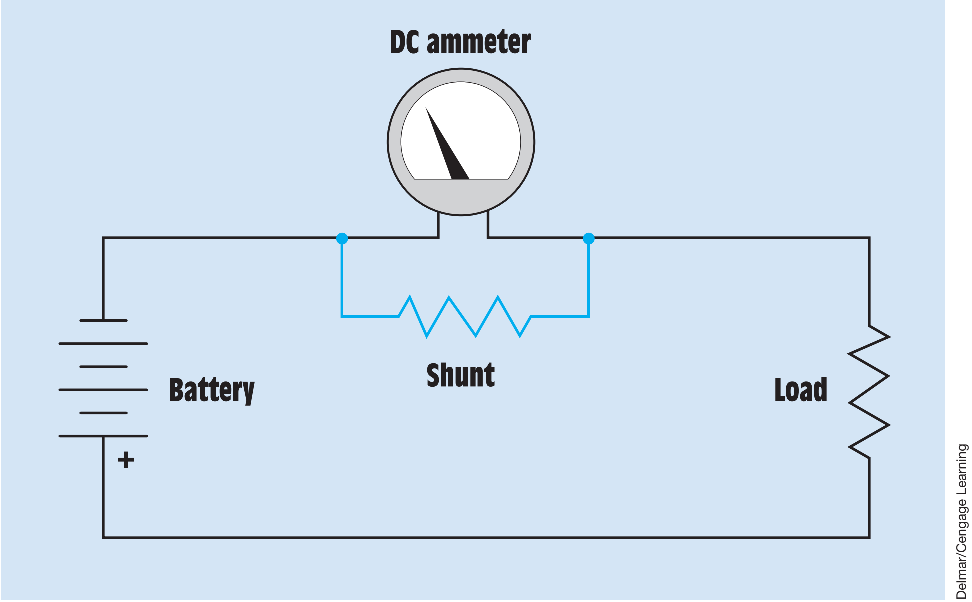

FIGURE 10–15 A shunt is used to set the value of the ammeter.

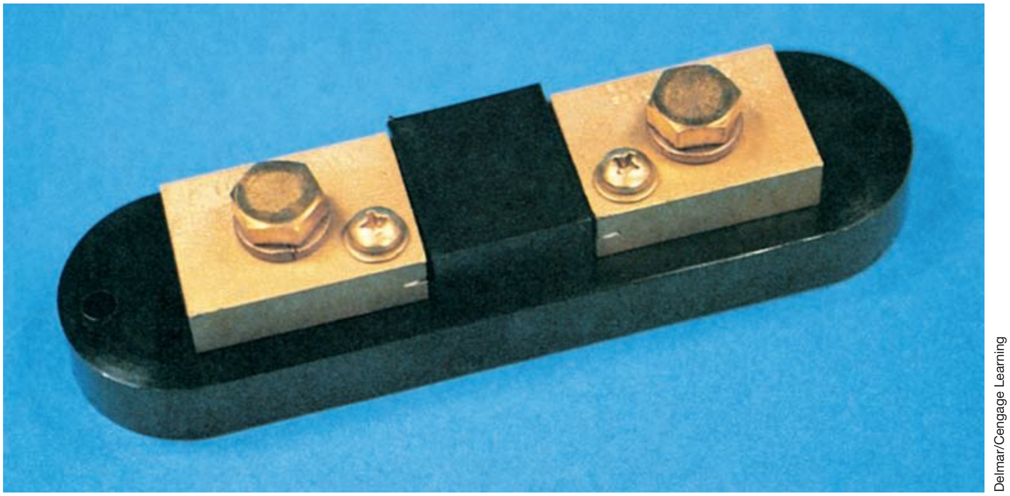

FIGURE 10–16 Ammeter shunt.

Ammeter shunts can be purchased to indicate different values. If the same 50-millivolt movement is connected across a shunt designed to drop 50 millivolts when 100 amperes of current flow through it, the meter will have a full-scale value of 100 amperes.

The resistance of an ammeter shunt can be calculated using Ohm's law. The resistance of a shunt designed to have a voltage drop of 50 millivolts when 100 amperes of current flow through it is

$$R = \frac{E}{I}$$

$$R = \frac{0.050\ V}{100\ A}$$

$$R = 0.0005\ \Omega,\ \text{or}\ 0.5\ m\Omega$$

In the preceding problem, no consideration was given to the electrical values of the meter movement. The reason is that the amount of current needed to operate the meter movement is so small compared with the 100-ampere circuit current it could have no meaningful effect on the resistance value of the shunt. When calculating the value for a low-current shunt, however, the meter values must be taken into consideration. For example, assume the meter has a voltage drop of 50 millivolts (0.050 V) and requires a current of 1 milliampere (0.001 A) to deflect the meter full scale. Using Ohm's law, it can be found that the meter has an internal resistance of 50 ohms (0.050 V/0.001 A = 50 Ω). Now assume that a shunt is to be constructed that will permit the meter to have a full-scale value of 10 milliamperes. If a total of 10 milliamperes is to flow through the circuit and 1 milliampere must flow through the meter, then 9 milliamperes must flow through the shunt *(Figure 10–17)*. Because the shunt must have a voltage drop of 50 millivolts when 9 milliamperes of current are flowing through it, its resistance must be 5.555 ohms (0.050 V/0.009 A = 5.555 Ω).

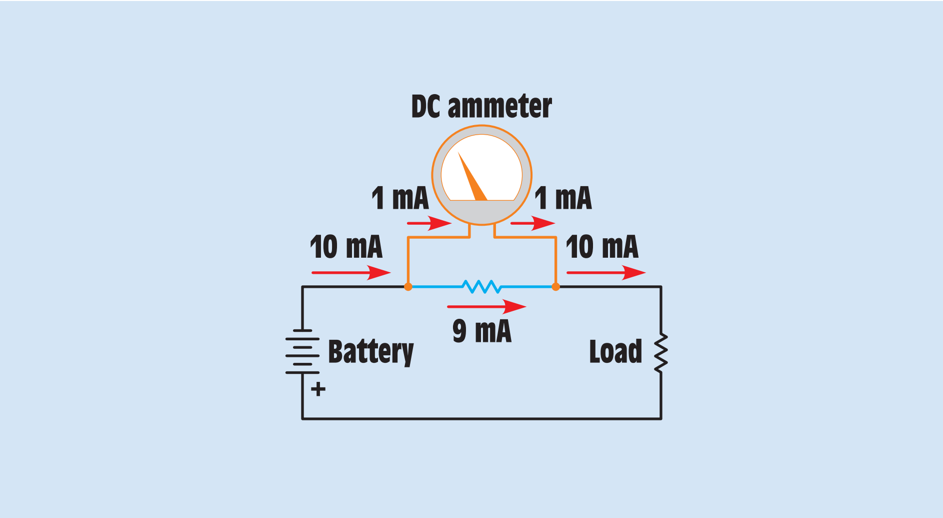

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FIGURE 10–17 The total current is divided between the meter and the shunt.

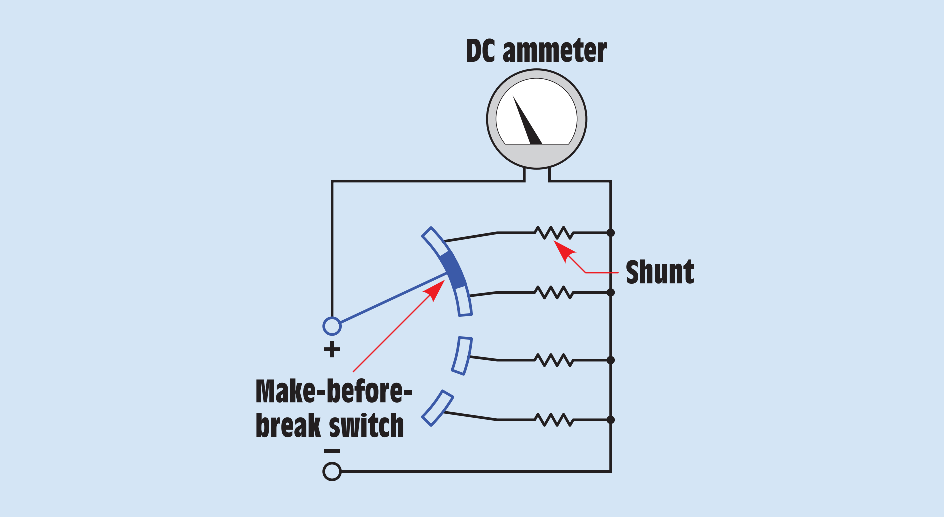

FIGURE 10–18 A make-before-break switch is used to change meter shunts.

10–7 Multirange Ammeters

Many ammeters, called **multirange ammeters,** are designed to operate on more than one range. This is done by connecting the meter movement to different shunts. ***When a multirange meter is used, care must be taken that the shunt is never disconnected from the meter.*** Disconnection would cause the meter movement to be inserted in series with the circuit, and full-circuit current would flow through the meter. Two basic methods are used for connecting shunts to a meter movement. One method is to use a make-before-break switch. This type of switch is designed so that it will make contact with the next shunt before it breaks connection with the shunt to which it is connected *(Figure 10–18)*. This method does, however, present a problem—contact resistance. Notice in *Figure 10–18* that the rotary switch is in series with the shunt resistors. This arrangement causes the contact resistance to be added to the shunt resistance and can cause inaccuracy in the meter reading.

10–8 The Ayrton Shunt

The second method of connecting a shunt to a meter movement is to use an **Ayrton shunt** *(Figure 10–19)*. In this type of circuit, connection is made to different parts of the shunt, and the meter movement is never disconnected from the shunt. Also notice that the switch connections are made external to the shunt and meter. This arrangement prevents contact resistance from affecting the accuracy of the meter.

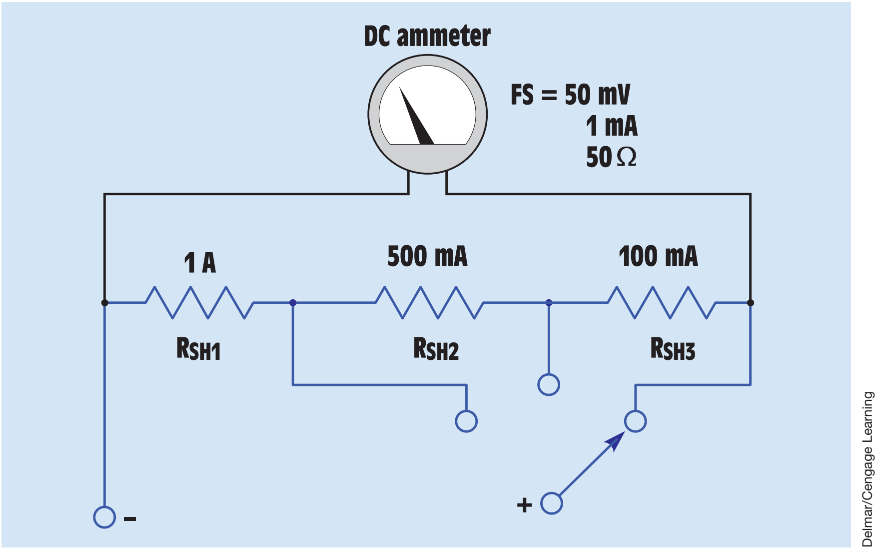

FIGURE 10–19 An Ayrton shunt.

Calculating the Resistor Values for an Ayrton Shunt

When an Ayrton shunt is used, the resistors are connected in parallel with the meter on some ranges and in series with the meter for other ranges. In this example, the meter movement has full-scale values of 50 millivolts, 1 milliampere, and 50 ohms of resistance. The shunt will permit the meter to have full-scale current values of 100 milliamperes, 500 milliamperes, and 1 ampere.

To find the resistor values, first calculate the resistance of the shunt when the range switch is set to permit a full-scale current of 100 milliampere *(Figure 10–20)*. When the range switch is set in this position, all three shunt resistors are connected in series across the meter movement. The formula for finding this resistance is

$$R_s = \frac{I_m \times R_m}{I_T}$$

where

R_s = resistance of the shunt

I_m = current of the meter movement

R_m = resistance of the meter movement

I_T = total circuit current

$$R_s = \frac{0.001\ \text{A} \times 50\ \Omega}{0.100\ \text{A}}$$

$$R_s = 0.5\ \Omega$$

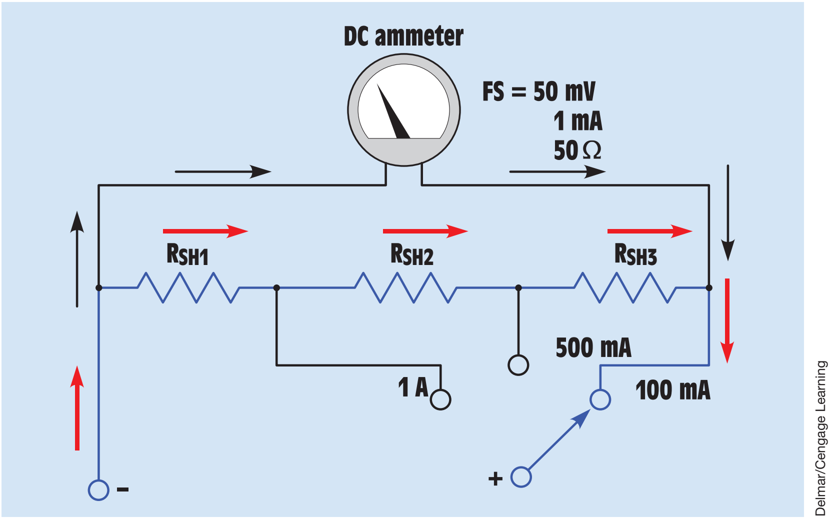

FIGURE 10–20 The meter is in parallel with all shunt resistors.

Next, find the resistance of R_{SH1}, which is the shunt resistor used to produce a full-scale current of 1 ampere. When the selector switch is set in this position, R_{SH1} is connected in parallel with the meter and with R_{SH2} and R_{SH3}. R_{SH2} and R_{SH3}, however, are connected in series with the meter movement *(Figure 10–21)*. To calculate the value of this resistor, a variation of the previous formula is used. The new formula is

$$R_{SH1} = \frac{I_m \times R_{SUM}}{I_T}$$

where

R_{SH1} = the resistance of shunt 1

I_m = current of the meter movement

R_{SUM} = the sum of all the resistance in the circuit. Note that this is not the sum of the series-parallel combination. It is the sum of all the resistance. In this instance it will be 50.5 Ω (50 Ω [meter] + 0.5 Ω [shunt]).

I_T = total circuit current

$$R_{SH1} = \frac{0.001\ \text{A} \times 50.5\ \Omega}{1\ \text{A}}$$

$$R_{SH1} = 0.0505\ \Omega$$

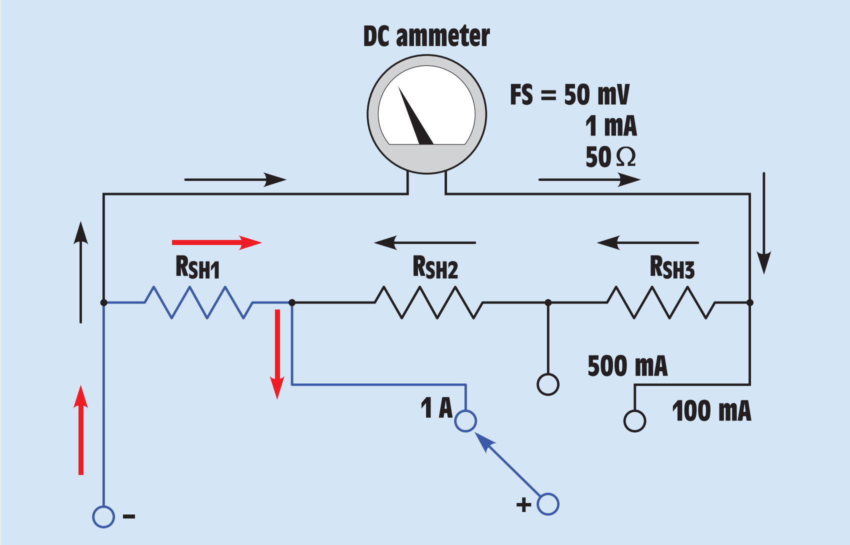

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FIGURE 10–21 Current path through shunt and meter for a full-scale value of 1 ampere.

When the selector switch is changed to the 500-milliampere position, R_{SH1} and R_{SH2} are connected in series with each other and in parallel with the meter movement and R_{SH3} *(Figure 10–22)*. The combined resistance value for R_{SH1} and R_{SH2} can be found using the formula

$$R_{SH1} \text{ and } R_{SH2} = \frac{I_m \times R_{SUM}}{I_T}$$

$$R_{SH1} \text{ and } R_{SH2} = \frac{0.001 \text{ A} \times 50.5\ \Omega}{0.5 \text{ A}}$$

$$R_{SH1} \text{ and } R_{SH2} = 0.101\ \Omega$$

Now that the total resistance for the sum of R_{SH1} and R_{SH2} is known, the value of R_{SH2} can be found by subtracting it from the value of R_{SH1}.

$$R_{SH2} = 0.101\ \Omega - 0.0505\ \Omega$$

$$R_{SH2} = 0.0505\ \Omega$$

The value of R_{SH3} can be found by subtracting the total shunt resistance from the values of R_{SH1} and R_{SH2}.

$$R_{SH3} = 0.5\ \Omega - 0.0505\ \Omega - 0.0505\ \Omega$$

$$R_{SH3} = 0.399\ \Omega$$

The preceding procedure can be used to find the value of any number of shunt resistors for any value of current desired. Note, however, that this type of

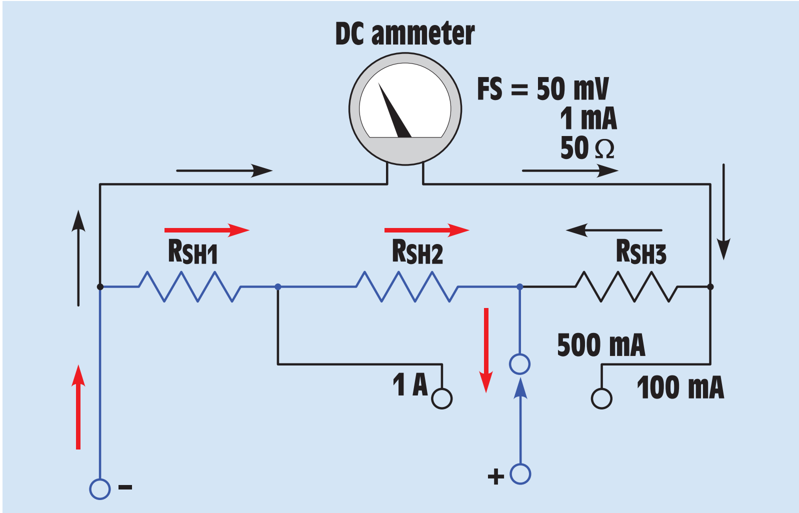

FIGURE 10–22 Current path through the meter and shunt for a full-scale value of 0.5 ampere.

FIGURE 10–23 DC ammeter with an Ayrton shunt.

shunt is not used for large current values because of the problem of switching contacts and contact size. The Ayrton shunt is seldom used for currents above 10 amperes. An ammeter with an Ayrton shunt is shown in *Figure 10–23*. The Ayrton shunt with all resistor values is shown in *Figure 10–24*.

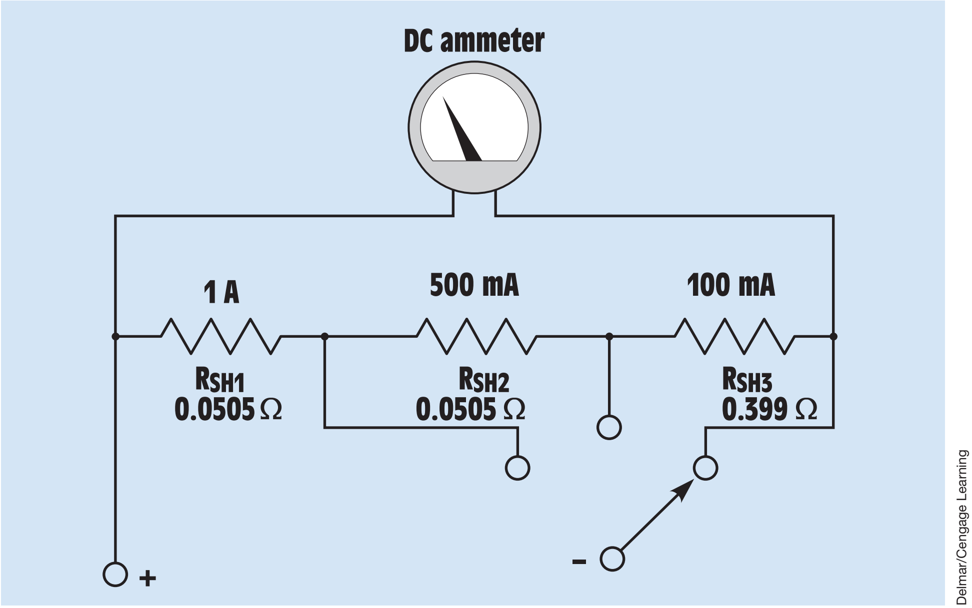

FIGURE 10–24 The Ayrton shunt with resistor values.

10–9 AC Ammeters

Shunts can be used with AC ammeters to increase their range but cannot be used to decrease their range. Most AC ammeters use a **current transformer** instead of shunts to change scale values. This type of ammeter is shown in *Figure 10–25*. The primary of the transformer is connected in series with the load, and the ammeter is connected to the secondary of the transformer. Notice that the range of the meter is changed by selecting different taps on the secondary of the current transformer. The different taps on the transformer provide different turns ratios between the primary and secondary of the transformer. The turns ratio is the ratio of the number of turns of wire in the primary as compared to the number of turns of wire in the secondary.

Calculating the Turns Ratio

In this example, it is assumed that an AC meter movement requires a current flow of 100 milliamperes to deflect the meter full scale. It is also assumed that the primary of the current transformer contains five turns of wire. A transformer will be designed to provide full-scale current readings of 1 ampere, 5 amperes,

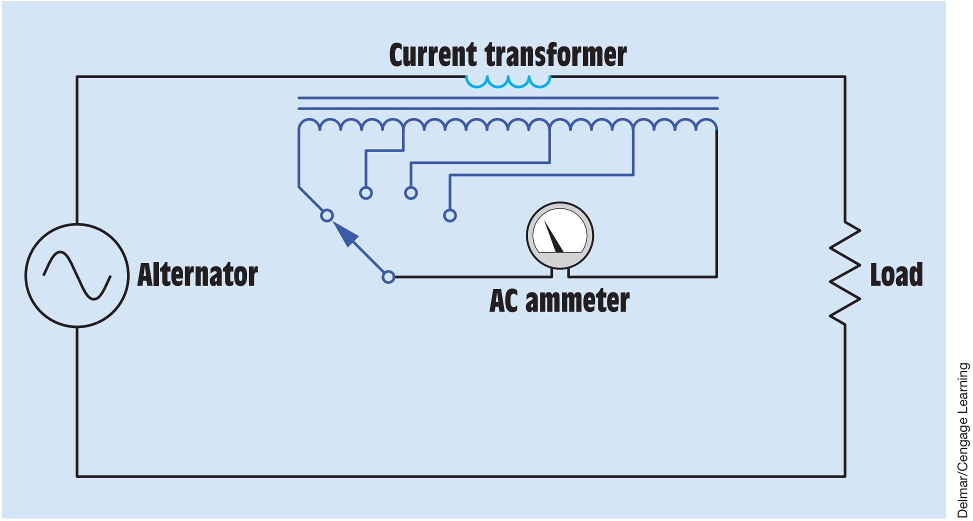

FIGURE 10–25 A current transformer is used to change the range of an AC ammeter.

and 10 amperes. To find the number of turns required in the secondary winding, the following formula can be used:

$$\frac{N_p}{N_s} = \frac{I_s}{I_p}$$

where

N_p = number of turns of wire in the primary

N_s = number of turns of wire in the secondary

I_p = current of the primary

I_s = current of the secondary

The number of turns of wire in the secondary to produce a full-scale current reading of 1 ampere can be calculated as follows:

$$\frac{5}{N_s} = \frac{0.1\ \text{A}}{1\ \text{A}}$$

Cross-multiplication is used to solve the problem. Cross-multiplication is accomplished by multiplying the bottom half of the equation on one side of the equal sign by the top half of the equation on the other side of the equal sign.

$$0.1\ \text{A}\ N_s = 5\text{A –turns}$$

$$N_s = 50\ \text{turns}$$

The transformer secondary must contain 50 turns of wire if the ammeter is to indicate a full-scale reading when 1 ampere of current flows through the primary winding.

The number of secondary turns can be found for the other values of primary current in the same way:

$$\frac{5}{N_s} = \frac{0.1\ \text{A}}{5\ \text{A}}$$

$$0.1\ \text{A}\ N_s = 25\ \text{A}$$

$$N_s = 250\ \text{turns}$$

$$\frac{5}{N_s} = \frac{0.1\ \text{A}}{10\ \text{A}}$$

$$0.1\ \text{A}\ N_s = 50\ \text{A}$$

$$N_s = 500\ \text{turns}$$

Current Transformers (CTs)

When a large amount of AC must be measured, a different type of current transformer is connected in the power line. These transformers have ratios that start at 200:5 and can have ratios of several thousand to five. These current transformers, generally referred to in industry as CTs, have a standard secondary current rating of 5 ampere AC. They are designed to be operated with a 5-ampere AC ammeter connected directly to their secondary winding, which produces a short circuit. CTs are designed to operate with the secondary winding shorted.

CAUTION: The secondary winding of a CT should never be opened when there is power applied to the primary. This will cause the transformer to produce a step-up in voltage that could be high enough to kill anyone who comes in contact with it. ■

A current transformer is basically a toroid transformer. A toroid transformer is constructed with a hollow core similar to a doughnut *(Figure 10–26)*. When current transformers are used, the main power line is inserted through the opening in the transformer *(Figure 10–27)*. The power line acts as the primary of the transformer and is considered to be one turn.

Courtesy of Square D Company

FIGURE 10–26 A toroid current transformer.

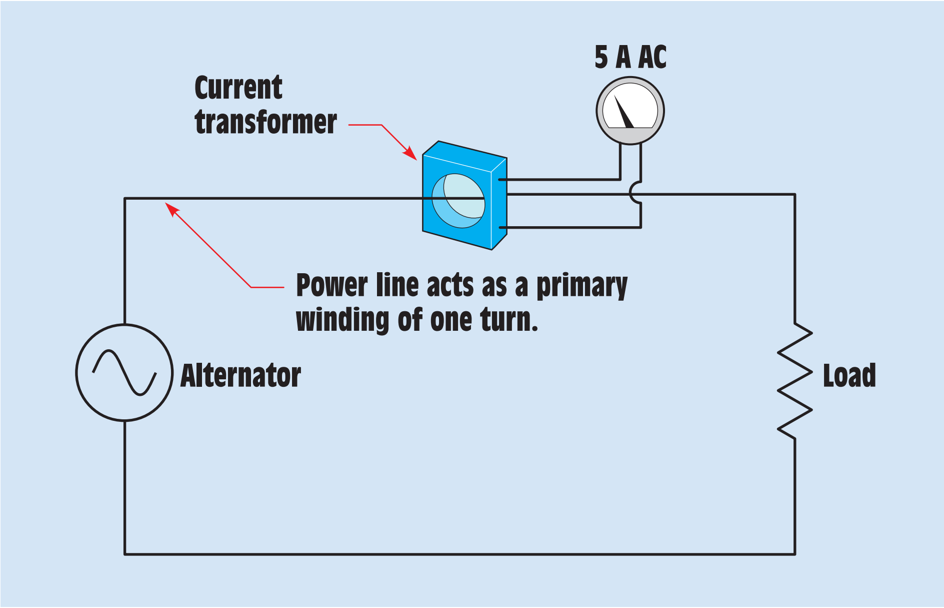

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FIGURE 10–27 Toroid transformer used to change the scale factor of an AC ammeter.

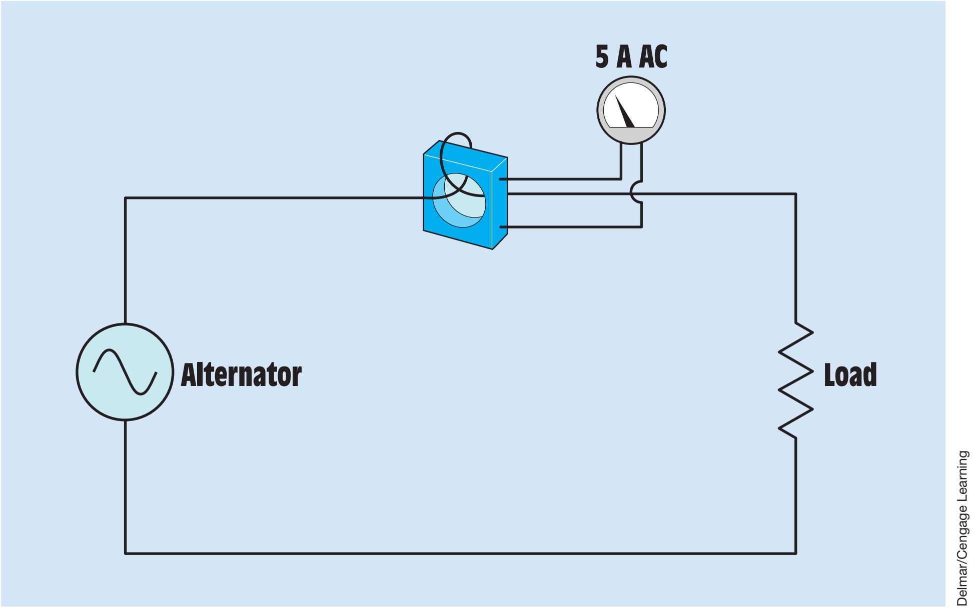


FIGURE 10–28 The primary conductor loops through the CT to produce a second turn, which changes the ratio.

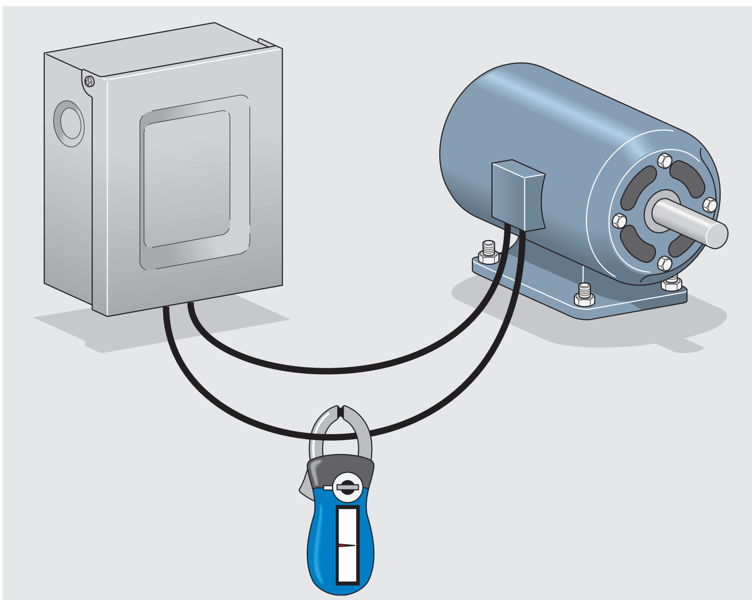
The turns ratio of the transformer can be changed by looping the power wire through the opening in the transformer to produce a primary winding of more than one turn. For example, assume a current transformer has a ratio of 600:5. If the primary power wire is inserted through the opening, it will require a current of 600 amperes to deflect the meter full scale. If the primary power conductor is looped around and inserted through the window a second time, the primary now contains two turns of wire instead of one *(Figure 10–28)*. It now requires 300 amperes of current flow in the primary to deflect the meter full scale. If the primary conductor is looped through the opening a third time, it will require only 200 amperes of current flow to deflect the meter full scale.

10–10 Clamp-On Ammeters

Many electricians use the **clamp-on ammeter** *(Figure 10–29)*. The jaw of this type of meter is clamped around one of the conductors supplying power to the load *(Figure 10–30)*. The meter is clamped around only one of the lines. If the meter is clamped around more than one line, the magnetic fields of the wires cancel each other and the meter indicates zero.

Courtesy of Advanced Test Products

FIGURE 10–29 **(A)** Analog type clamp-on ammeter with vertical scale. **(B)** Analog type clamp-on ammeter with flat scale. **(C)** Clamp-on ammeter with digital scale.



Delmar/Cengage Learning

FIGURE 10–30 The clamp-on ammeter connects around only one conductor.

The clamp-on meter also uses a current transformer to operate. The jaw of the meter is part of the core material of the transformer. When the meter is connected around the current-carrying wire, the changing magnetic field produced by the AC induces a voltage into the current transformer. The strength and frequency of the magnetic field determine the amount of voltage induced in the current transformer. Because 60 hertz is a standard frequency throughout the country, the amount of induced voltage is proportional to the strength of the magnetic field.

The clamp-on type ammeter can be given different range settings by changing the turns ratio of the secondary of the transformer just as is done on the in-line ammeter. The primary of the transformer is the conductor around which the movable jaw is connected. If the ammeter is connected around one wire, the primary has one turn of wire compared with the turns of the secondary. The turns ratio can be changed in the same manner that the ratio of the CT is changed. If two turns of wire are wrapped around the jaw of the ammeter *(Figure 10–31),* the primary winding now contains two turns instead of one, and the turns ratio of the transformer is changed. The ammeter will now indicate double the amount of current in the circuit. The reading on the scale of the meter would have to be divided by 2 to get the correct reading. The ability to change the turns ratio of a clamp-on ammeter can be useful for measuring low currents. Changing the turns ratio is not limited to wrapping two turns of wire around the jaw of the ammeter. Any number of turns can be wrapped around the jaw of the ammeter, and the reading will be divided by that number.

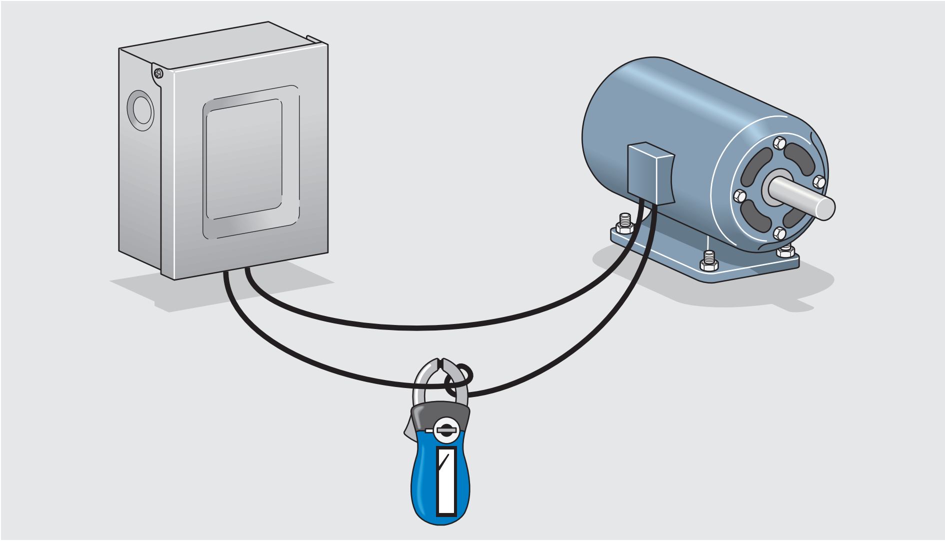


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FIGURE 10–31 Looping the conductor around the jaw of the ammeter changes the ratio.

10–11 DC–AC Clamp-On Ammeters

Most clamp-on ammeters that have the ability to measure both DC and AC do not operate on the principle of the current transformer. Current transformers depend on induction, which means that the current in the line must change direction periodically to provide a change of magnetic field polarity. It is the continuous change of field strength and direction that permits the current transformer to operate. The current in a DC circuit is unidirectional and does not change polarity, which would not permit the current transformer to operate.

DC–AC clamp-on ammeters *(Figure 10–32)* use the *Hall effect* as the basic principle of operation. The Hall effect was discovered by Edward H. Hall at

Courtesy of Advanced Test Products

FIGURE 10–32 DC–AC clamp-on ammeter.

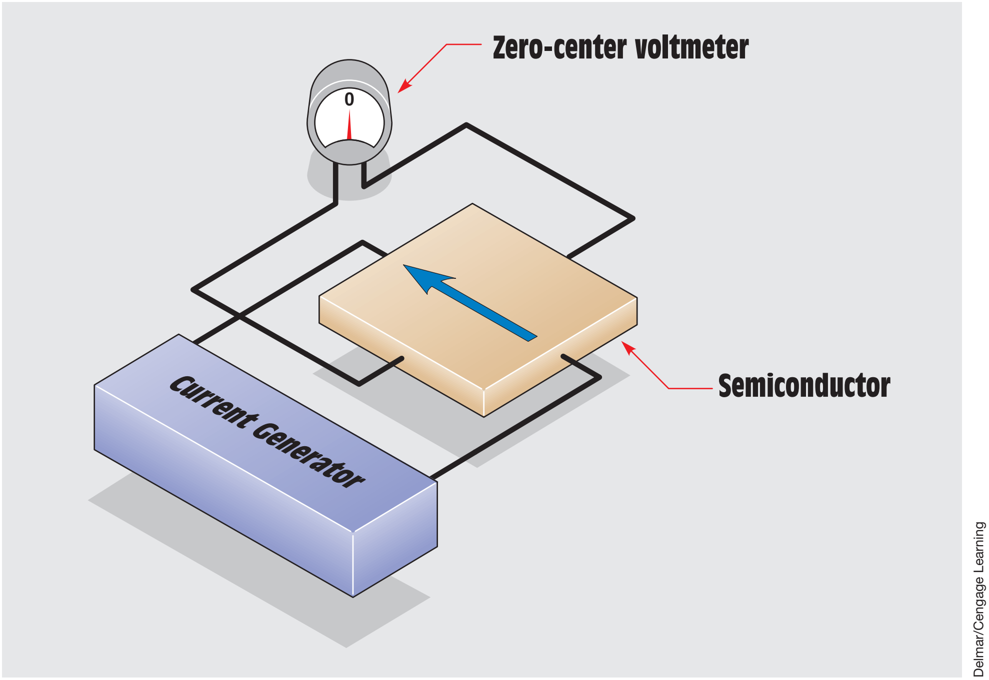

FIGURE 10–33 Basic Hall generator.

Johns Hopkins University in 1879. Hall originally used a piece of pure gold to produce the Hall effect, but today a semiconductor material is used because it has better operating characteristics and is less expensive. The device is often referred to as a *Hall generator. Figure 10–33* illustrates the operating principle of the Hall generator. A constant-current generator is used to supply a continuous current to the semiconductor chip. The leads of a zero-center voltmeter are connected across the opposite sides of the chip. As long as the current flows through the center of the semiconductor chip, no potential difference or voltage develops across the chip.

If a magnetic field comes near the chip *(Figure 10–34),* the electron path is distorted and the current no longer flows through the center of the chip. A voltage across the sides of the chip is produced. The voltage is proportional to the amount of current flow and the amount of current distortion. Because the current remains constant and the amount of distortion is proportional to the strength of the magnetic field, the voltage produced across the chip is proportional to the strength of the magnetic field.

If the polarity of the magnetic field were reversed *(Figure 10–35),* the current path would be distorted in the opposite direction, producing a voltage of the opposite polarity. Notice that the Hall generator produces a voltage

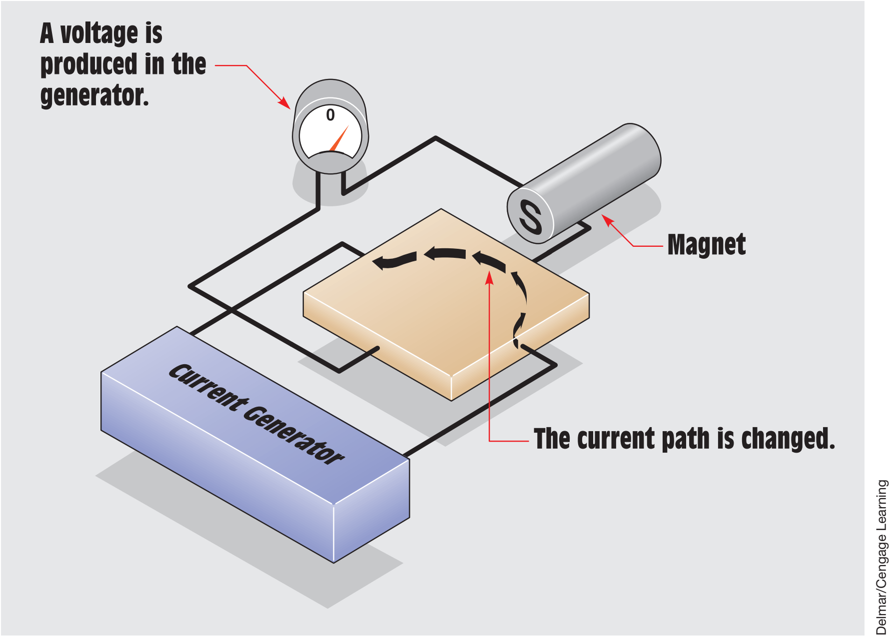

FIGURE 10–34 The presence of a magnetic field causes the Hall generator to produce a voltage.

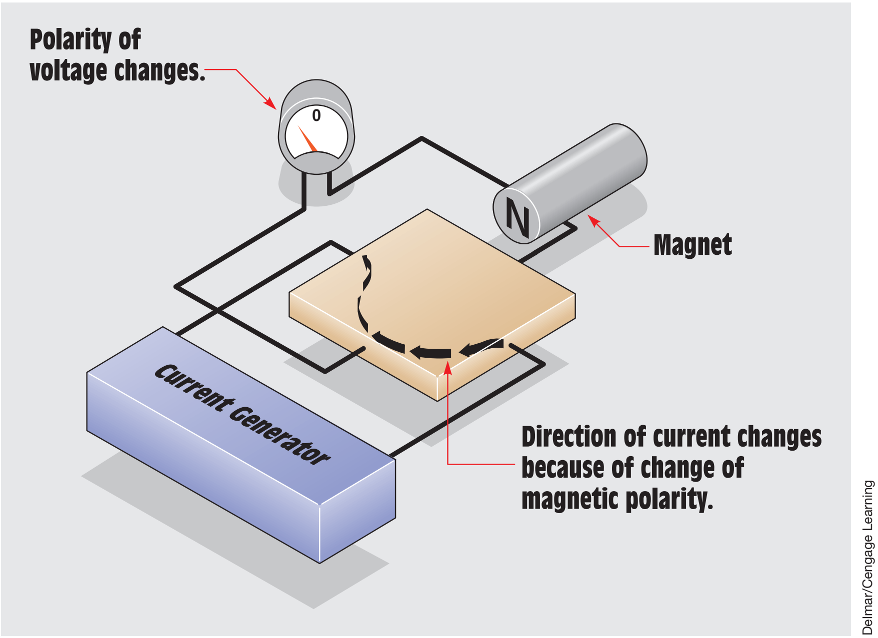

FIGURE 10–35 If the magnetic field polarity changes, the polarity of the voltage changes.

in the presence of a magnetic field. It makes no difference whether the field is moving or stationary. The Hall effect can therefore be used to measure DC or AC.

10–12 The Ohmmeter

The **ohmmeter** is used to measure resistance. The common volt-ohm-milliammeter (VOM) contains an ohmmeter. The ohmmeter has the only scale on a VOM that is nonlinear. The scale numbers increase in value as they progress from right to left. There are two basic types of analog ohmmeters—the series and the shunt. The series ohmmeter is used to measure high values of resistance, and the shunt type is used to measure low values of resistance. Regardless of the type used, the meter must provide its own power source to measure resistance. The power is provided by batteries located inside the instrument.

The Series Ohmmeter

A schematic for a basic series ohmmeter is shown in *Figure 10–36*. It is assumed that the meter movement has a resistance of 1000 ohms and requires a current of 50 microamperes to deflect the meter full scale. The power source will be a 3-volt battery. R_1, a fixed resistor with a value of 54 kilohms, is connected in series with the meter movement, and R_2, a variable resistor with a value of 10 kilohms, is connected in series with the meter and R_1.

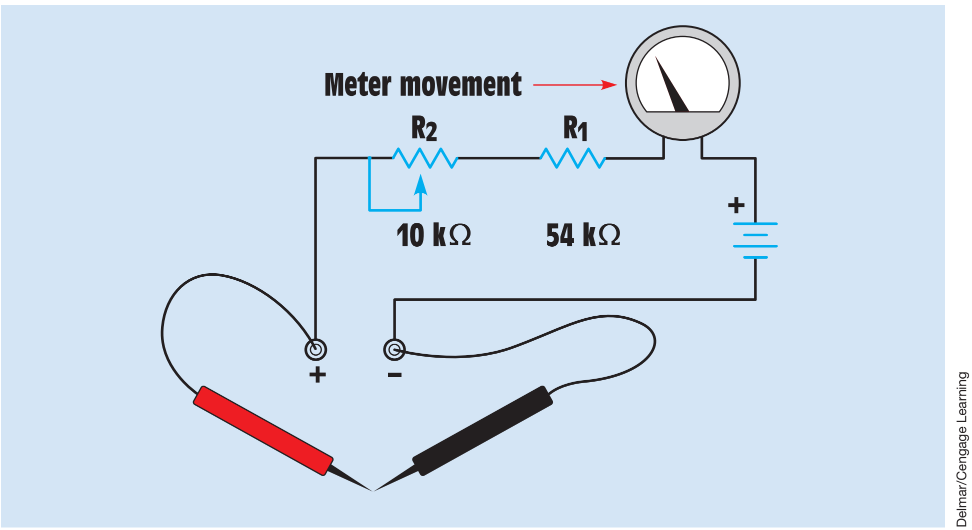

FIGURE 10–36 Basic series ohmmeter.

These resistance values were chosen to ensure there would be enough resistance in the circuit to limit the current flow through the meter movement to 50 microamperes. If Ohm's law is used to calculate the resistance needed ($3\text{ V}/0.000050\text{ A} = 60{,}000\ \Omega$), it will be seen that a value of 60 kilohms is needed. This circuit contains a total of 65,000 ohms ($1000\ \Omega$ [meter] $+\ 54{,}000\ \Omega\ +\ 10{,}000\ \Omega$). The circuit resistance can be changed by adjusting the variable resistor to a value as low as 55,000 ohms, however, to compensate for the battery as it ages and becomes weaker.

When resistance is to be measured, the meter must first be zeroed. This is done with the ohms-adjust control, the variable resistor located on the front of the meter. To zero the meter, connect the leads *(Figure 10–36)* and turn the ohms-adjust knob until the meter indicates zero at the far right end of the scale *(Figure 10–37)*. When the leads are separated, the meter will again indicate infinity resistance at the left side of the scale. When the leads are connected across a resistance, the meter will again go up the scale. Because resistance has been added to the circuit, less than 50 microamperes of current will flow and the meter will indicate some value other than zero. *Figure 10–38* shows a meter indicating a resistance of 150 ohms, assuming the range setting is R×1.

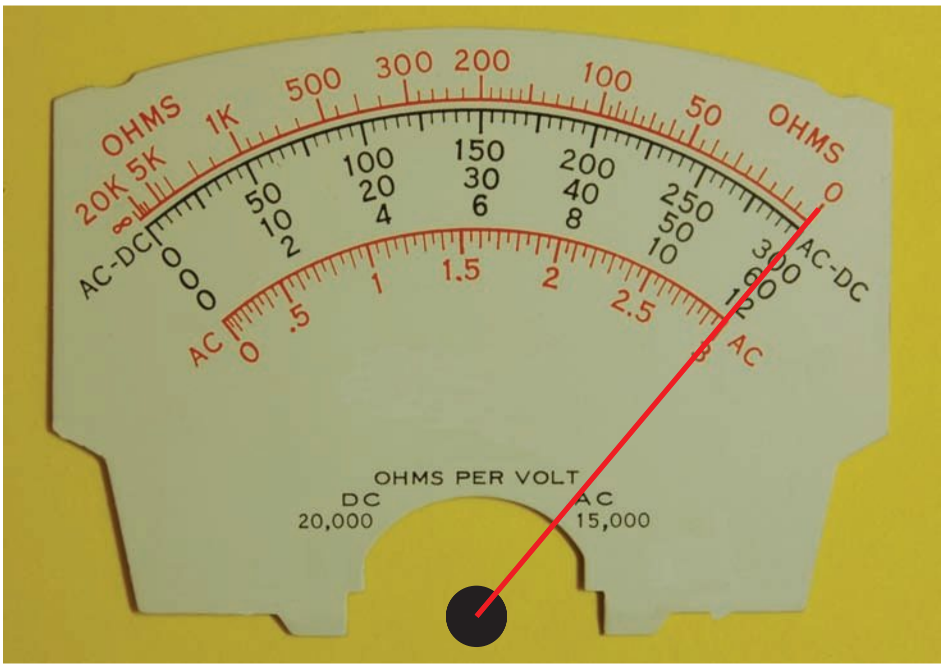

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FIGURE 10–37 Adjusting the ohmmeter to zero.

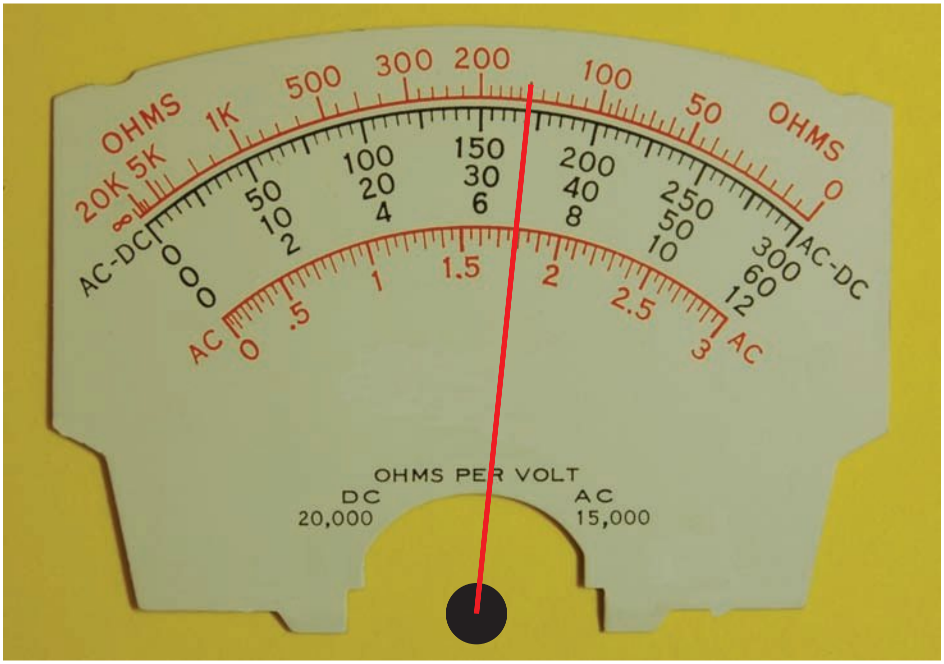

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FIGURE 10–38 Reading the ohmmeter.

Ohmmeters can have different range settings such as R×1, R×100, R×1000, or R×10,000. These different scales can be obtained by adding different values of resistance in the meter circuit and resetting the meter to zero. ***An ohmmeter should always be readjusted to zero when the scale is changed.*** On the R×1 setting, the resistance is measured straight off the resistance scale located at the top of the meter. If the range is set for R×1000, however, the reading must be multiplied by 1000. The ohmmeter reading shown in *Figure 10–38* would be indicating a resistance of 150,000 ohms if the range had been set for R×1000. Notice that the ohmmeter scale is read backward from the other scales. Zero ohms is located on the far right side of the scale, and maximum ohms is located at the far left side. It generally takes a little time and practice to read the ohmmeter properly.

10–13 Shunt-Type Ohmmeters

The shunt-type ohmmeter is used for measuring low values of resistance. It operates on the same basic principle as an ammeter shunt. When using a shunt-type ohmmeter, place the unknown value of resistance in parallel with the meter movement. This placement causes part of the circuit current to bypass the meter *(Figure 10–39)*.

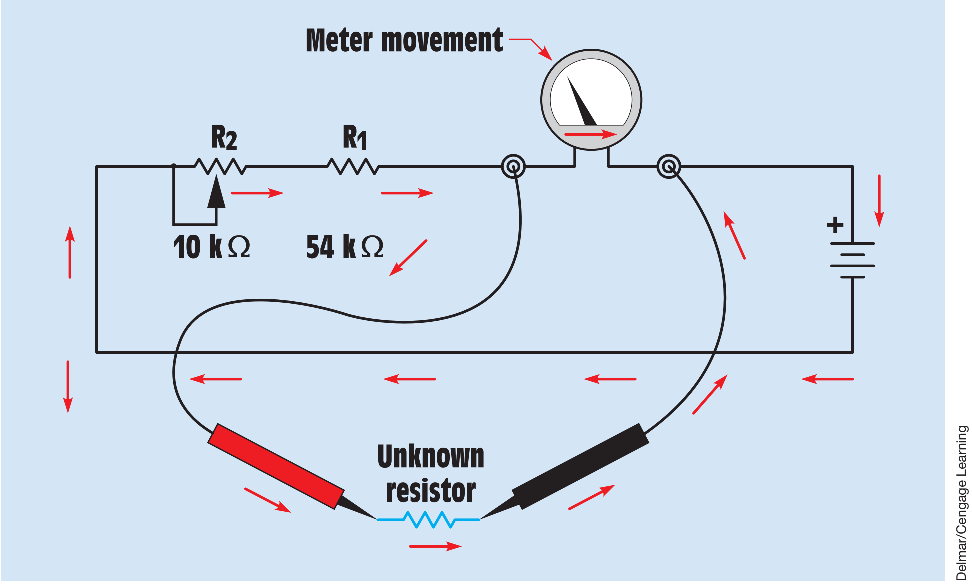


FIGURE 10–39 Shunt-type ohmmeter.

10–14 Digital Meters

Digital Ohmmeters

Digital ohmmeters display the resistance in figures instead of using a meter movement. When using a digital ohmmeter, care must be taken to notice the scale indication on the meter. For example, most digital meters will display a *K* on the scale to indicate kilohms or an M to indicate megohms (kilo means 1000 and mega means 1,000,000). If the meter is showing a resistance of 0.200 kilohms, it means 0.200 × 1000, or 200 ohms. If the meter indicates 1.65 megohms, it means 1.65 × 1,000,000, or 1,650,000 ohms.

Appearance is not the only difference between analog and digital ohmmeters. Their operating principle is different also. Analog meters operate by measuring the amount of current change in the circuit when an unknown value of resistance is added. Digital ohmmeters measure resistance by measuring the amount of voltage drop across an unknown resistance. In the circuit shown in *Figure 10–40,* a constant-current generator is used to supply a known amount of current to a resistor, R_X. It will be assumed that the amount of current supplied is 1 milliampere. The voltage dropped across the resistor is proportional to the resistance of the resistor and the amount of current flow. For example, assume the value of the unknown resistor is 4700 ohms. The voltmeter would indicate a drop of 4.7 volts when 1 milliampere of current flowed through

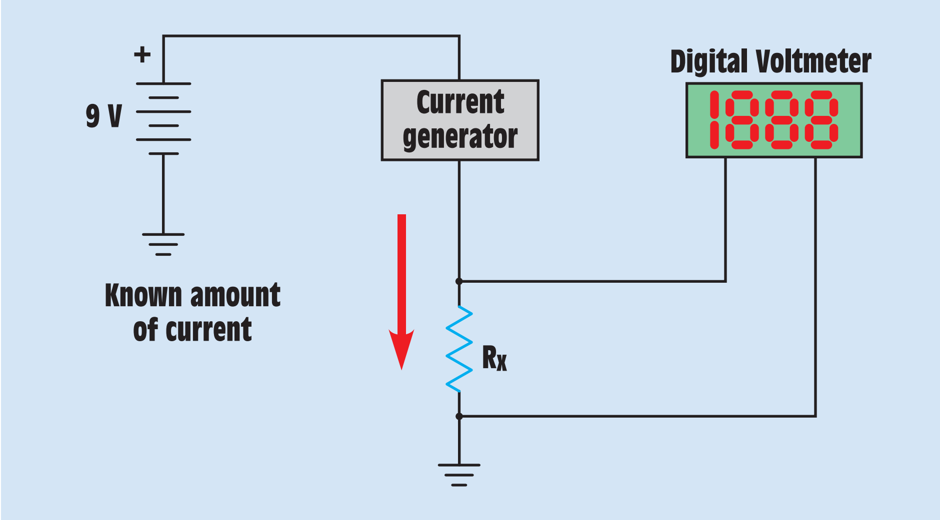


FIGURE 10–40 Digital ohmmeters operate by measuring the voltage drop across a resistor when a known amount of current flows through it.

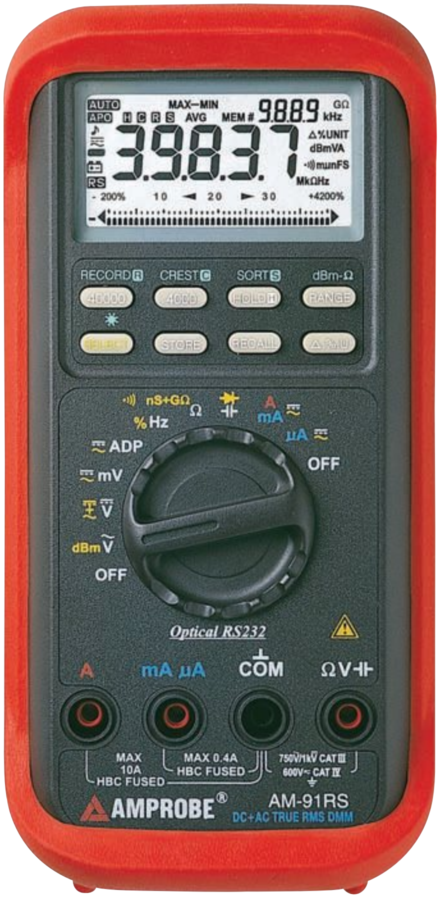
the resistor. The scale factor of the ohmmeter can be changed by changing the amount of current flow through the resistor. Digital ohmmeters generally exhibit an accuracy of about 1%.

The ohmmeter, whether digital or analog, must never be connected to a circuit when the power is turned on. Because the ohmmeter uses its own internal power supply, it has a very low operating voltage. Connecting a meter to power when it is set in the ohms position will probably damage or destroy the meter.

Digital Multimeters

Digital multimeters have become increasingly popular in the past few years. The most apparent difference between digital meters and analog meters is that digital meters display their reading in discrete digits instead of with a pointer and scale. A digital multimeter is shown in *Figure 10–41*. Some digital meters have a range switch similar to the range switch used with analog meters. This switch sets the full-range value of the meter. Many digital meters have voltage range settings from 200 millivolts to 2000 volts. The lower ranges are used for accuracy. For example, assume it is necessary to measure a voltage of 16 volts. The meter will be able to make a more accurate measurement when set on the 20-volt range than when set on the 2000-volt range.

Some digital meters do not contain a range setting control. These meters are known as autoranging meters. They contain a function control switch that permits selection of the electrical quantity to be measured, such as AC volts,



Courtesy of Advanced Test Products

FIGURE 10–41 Digital multimeter.

DC volts, ohms, and so on. When the meter probes are connected to the object to be tested, the meter automatically selects the proper range and displays the value.

Analog meters change scale value by inserting or removing resistance from the meter circuit *(Figure 10–7)*. The typical resistance of an analog meter is 20,000 ohms per volt for DC and 5000 ohms per volt for AC. If the meter is set for a full-scale value of 60 volts, there will be 1.2 megohms of resistance connected in series with the meter if it is being used to measure DC ($60\ V \times 20{,}000\ \Omega/V = 1{,}200{,}000\ \Omega$) and 300 kilohms if it is being used to measure AC ($60\ V \times 5000\ \Omega/V = 300{,}000\ \Omega$). The impedance of the meter is of little concern if it is used to measure circuits that are connected to a high-current source. For example, assume the voltage of a 480-volt panel is to be measured with a multimeter that has a resistance of 5000 ohms per volt. If the meter is set on the 600-volt range, the resistance connected in series with the meter is 3 megohms (600 V × 5000 Ω/V = 3,000,000 Ω). This resistance will permit a current of 160 microamperes to flow in the meter circuit (480 V/3,000,000 Ω = 0.000160 A). This 160 microamperes of current is not enough to affect the circuit being tested.

Now assume that this meter is to be used to test a 24-volt circuit that has a current flow of 100 microamperes. If the 60-volt range is used, the meter circuit contains a resistance of 300 kilohms (60 V × 5000 Ω/V = 300,000 Ω). Therefore, a current of 80 microamperes will flow when the meter is connected to the circuit (24 V/300,000 Ω = 0.000080 A). The connection of the meter to the circuit has changed the entire circuit operation. This phenomenon is known as the *loading effect*.

Digital meters do not have a loading effect. Most digital meters have an input impedance of about 10 megohms on all ranges. The input impedance is the ohmic value used to limit the flow of current through the meter. This impedance is accomplished by using field-effect transistors (FETs) and a voltage divider circuit. A simple schematic for such a circuit is shown in *Figure 10–42*. Notice that the meter input is connected across 10 megohms of resistance regardless of the range setting of the meter. If this meter is used to measure the voltage of the 24-volt circuit, a current of 2.4 microamperes will flow through the meter. This is not enough current to upset the rest of the circuit, and voltage measurements can be made accurately.

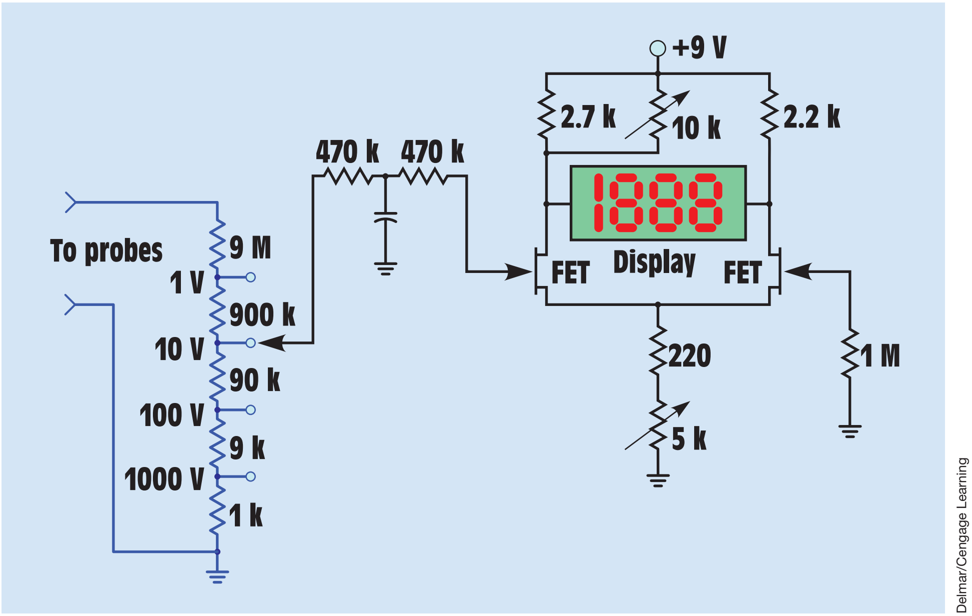


FIGURE 10–42 Digital voltmeter.

10–15 The Low-Impedance Voltage Tester

Another device used to test voltage is often referred to as a voltage tester. This device does measure voltage, but it does not contain a meter movement or digital display. It contains a coil and a plunger. The coil produces a magnetic field that is proportional to the amount of voltage to which the coil of the tester is connected. The higher the voltage to which the tester is connected, the stronger the magnetic field becomes. The plunger must overcome the force of a spring as it is drawn into the coil *(Figure 10–43)*. The plunger acts as a pointer to indicate the amount of voltage to which the tester is connected. The tester has an impedance of approximately 5000 ohms and can generally be used to measure voltages as high as 600 volts. ***The low-impedance voltage tester has a very large current draw compared with other types of voltmeters and should never be used to test low-power circuits.***

The relatively high current draw of the voltage tester can be an advantage when testing certain types of circuits, however, because it is not susceptible to giving the misleading voltage readings caused by high-impedance ground paths or feedback voltages that affect other types of voltmeters. An example of this advantage is shown in *Figure 10–44*. A transformer is used to supply power to a load. Notice that neither the output side of the transformer nor the load is connected to ground. If a high-impedance voltmeter is used to measure between one side of the transformer and a grounded point, it will most likely indicate some amount of voltage. That is because ground can act as a large capacitor and can permit a small amount of current to flow through the circuit created by the meter. This high-impedance ground path can support only a few

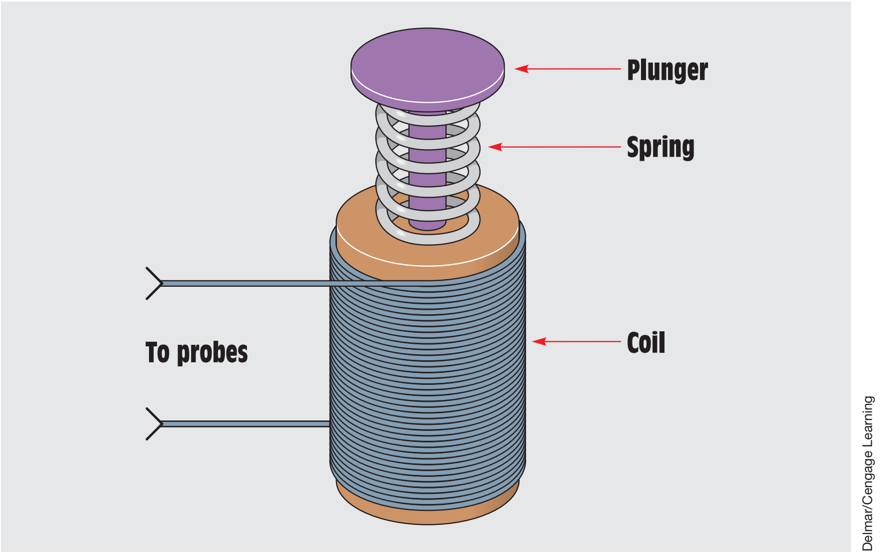
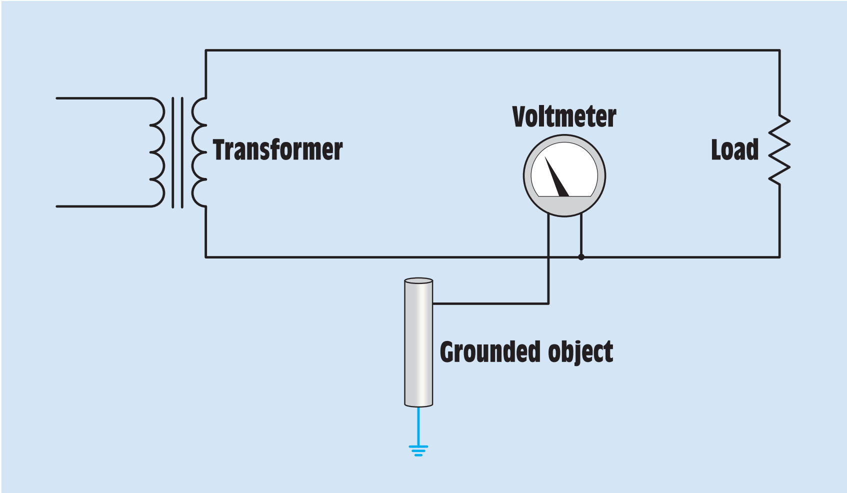


FIGURE 10–43 Low-impedance voltage tester.



Delmar/Cengage Learning

FIGURE 10–44 High-impedance ground paths can produce misleading voltage readings.

microamperes of current flow, but it is enough to operate the meter movement. If a voltage tester is used to make the same measurement, it will not show a voltage because there cannot be enough current flow to attract the plunger. A voltage tester is shown in *Figure 10–45*.

Photo courtesy of Square D Company

FIGURE 10–45 Wiggy voltage tester.

10–16 The Oscilloscope

Many of the electronic control systems in today's industry produce voltage pulses that are meaningless to a VOM. In many instances, it is necessary to know not only the amount of voltage present at a particular point, but also the length or duration of the pulse and its frequency. Some pulses may be less than 1 volt and last for only a millisecond. A VOM would be useless for measuring such a pulse. It is therefore necessary to use an **oscilloscope** to learn what is actually happening in the circuit.

The oscilloscope is a powerful tool in the hands of a trained technician. The first thing to understand is that an *oscilloscope* is a voltmeter. It does not measure current, resistance, or watts. The oscilloscope measures an amount of voltage during a period of time and produces a two-dimensional image.

Voltage Range Selection

The oscilloscope is divided into two main sections. One section is the voltage section, and the other is the time base. The display of the oscilloscope is divided by vertical and horizontal lines *(Figure 10–46)*. Voltage is measured on the vertical, or *Y*, axis of the display, and time is measured on the horizontal, or *X*, axis. When using a VOM, a range-selection switch is used to determine the full-scale value of the meter. Ranges of 600 volts, 300 volts, 60 volts, and 12 volts are common. The ability to change ranges permits more-accurate measurements to be made.

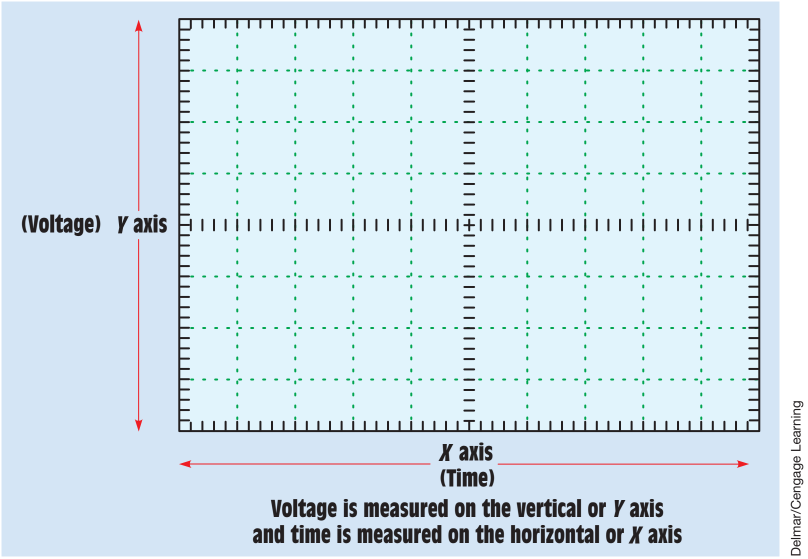
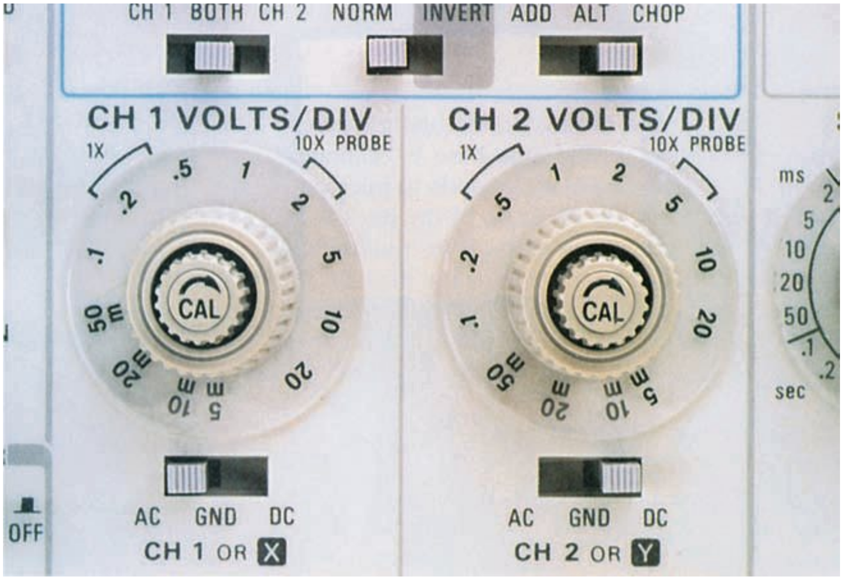


FIGURE 10–46 Voltage is measured on the vertical or *Y* axis and time is measured on the horizontal or *X* axis.



Courtesy of Tektronix, Inc.

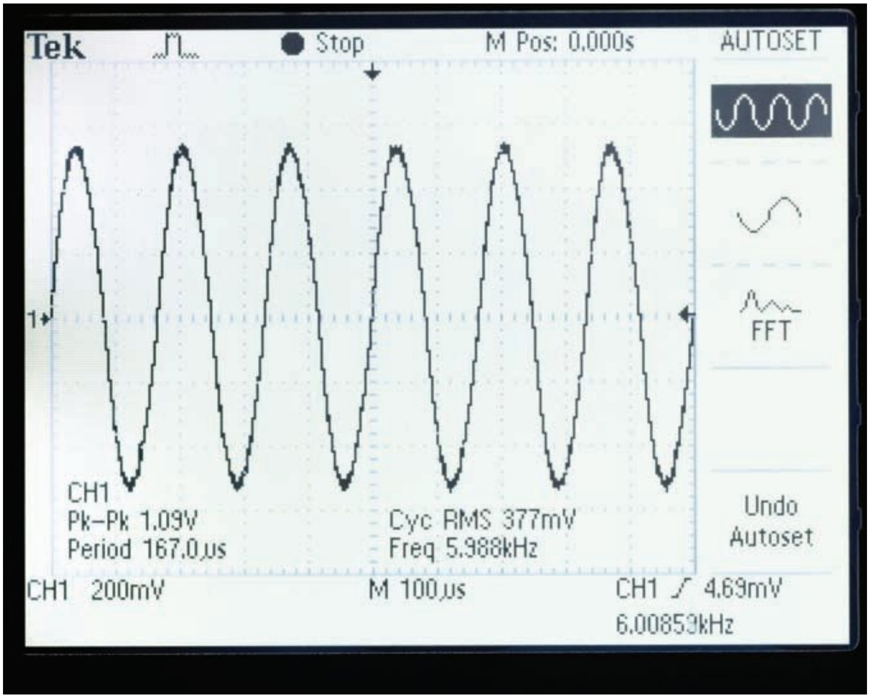
FIGURE 10–47 Voltage control of an analog oscilloscope.

Oscilloscopes can be divided into two main types: analog and digital. Analog oscilloscopes have been used for years and many are still in use; however, digital oscilloscopes are rapidly taking their place. Analog scopes generally employ some type of control knob to change their range of operation, *Figure 10–47*. The setting indicates the volts per division instead of volts full scale. The settings in *Figure 10–47* indicate that Channel 1 is set for 0.2 volts per division and Channel 2 is set for 0.5 volts per division.

Digital oscilloscopes often indicate their setting on the display instead of marking them on the face of the oscilloscope. Voltage control knobs for a four-channel digital oscilloscope are shown in *Figure 10–48*. The display of

Courtesy of Tektronix, Inc.

FIGURE 10–48 Voltage control knobs of a four channel digital oscilloscope.



Courtesy of Tektronix, Inc.

FIGURE 10–49 Display of a digital oscilloscope.

a typical digital oscilloscope is shown in *Figure 10–49*. In the lower left-hand corner of the display the notation CH1 200mV can be seen. This indicates that the voltage range has been set for 200 millivolts per division.

Oscilloscopes can display both positive and negative voltages. In the display shown in *Figure 10–50,* assume that a value of 0 volts has been set at the center line. The voltage shown at position A is positive with respect to 0 and the voltage at position B is negative with respect to 0. If the oscilloscope were set for a value of 2 volts per division, the value at point A would be 6 volts positive with respect to 0 and the value at point B would be 6 volts negative with respect to 0.

Another example of the oscilloscope's ability to display both positive and negative voltage values is in *Figure 10–51*. The waveform is basically an AC square wave. Notice that the voltage peaks at the leading edge of both the negative and positive waves. This could never be detected with a common voltmeter.

Many oscilloscopes have the ability to display more than one voltage at a time. Each voltage is generally referred to as a trace or channel. The oscilloscope shown in *Figure 10–52* has the ability to display four voltages or four traces. Many digital-type oscilloscopes have the ability to display a different color for each trace.

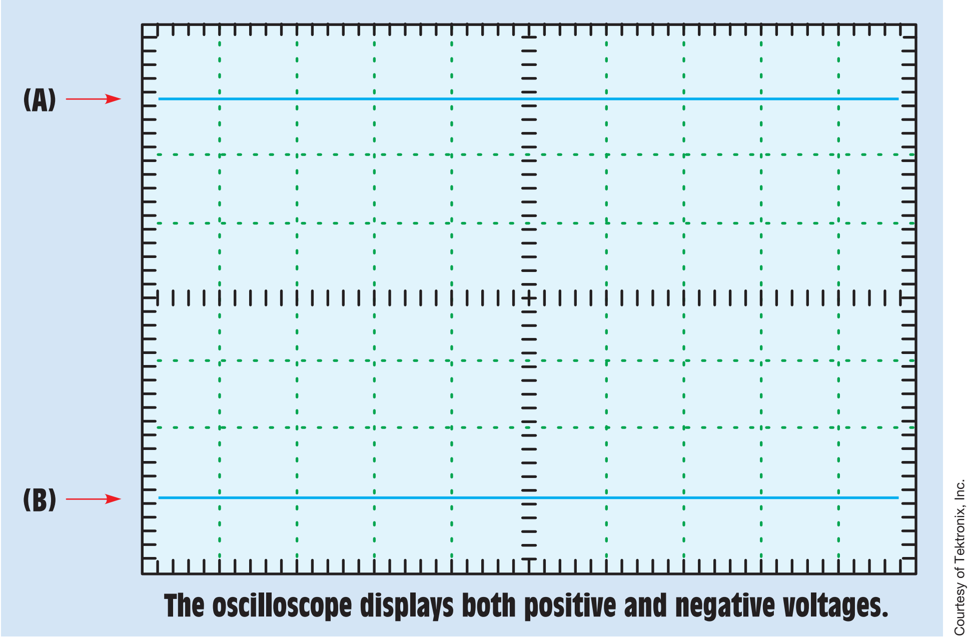


FIGURE 10–50 The oscilloscope displays both positive and negative voltages.

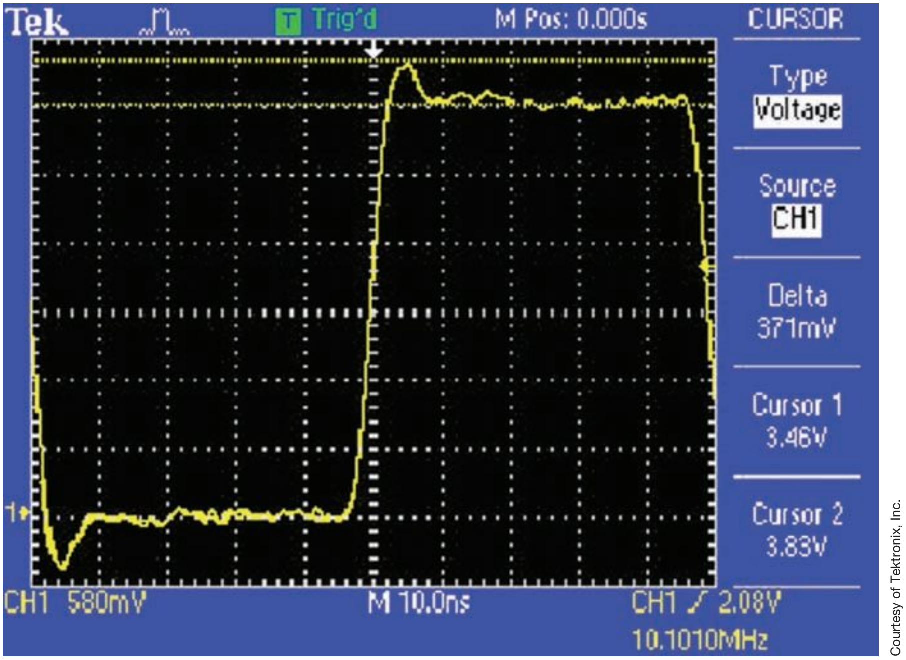
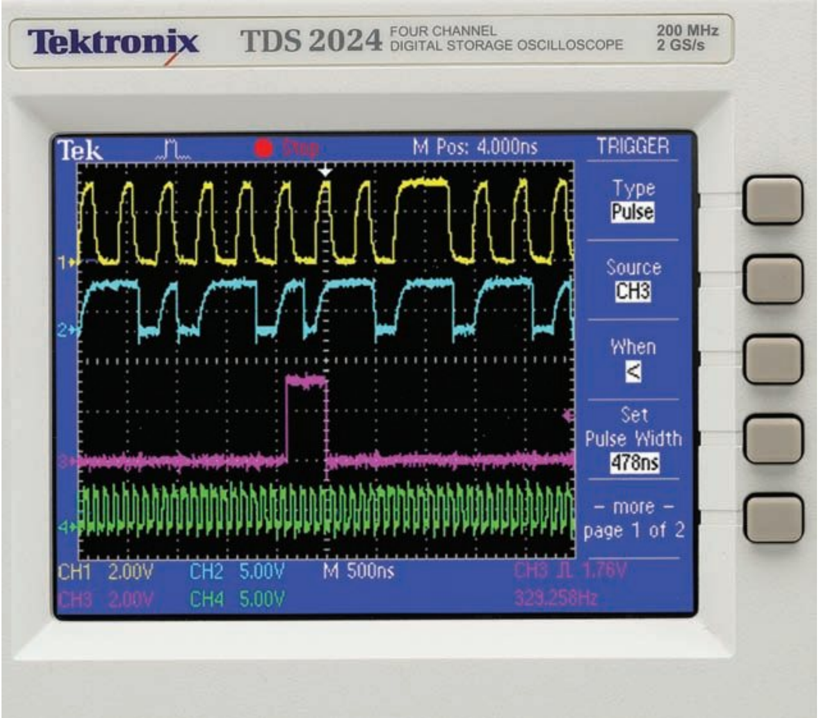


FIGURE 10–51 AC waveform.



Courtesy of Tektronix, Inc.

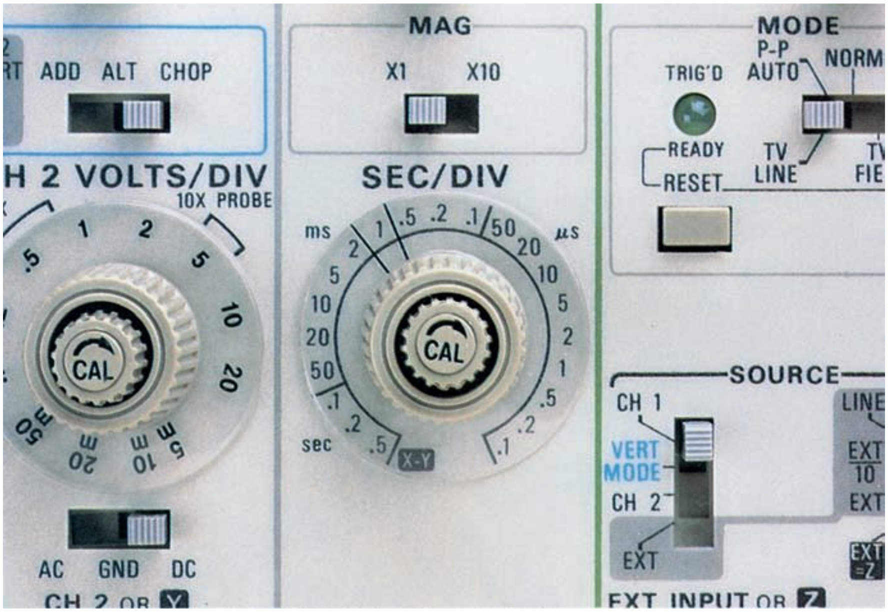
FIGURE 10–52 A four trace oscilloscope.

The Time Base

The next section of the oscilloscope to be discussed is the time base. The time base is calibrated in seconds per division and has ranges from seconds to microseconds. Analog-type oscilloscopes use a range selection switch similar to the one shown in *Figure 10–53*. The time base selection control for a typical digital-type oscilloscope is shown in *Figure 10–54*. Digital oscilloscopes generally indicate the time base setting on the display as shown in *Figure 10–49*. The lower middle section of the display shows M 100 microseconds, which indicates that the scope is set for 100 microseconds per division. With the time base set at this value, it would take the trace 1000 microseconds, or one millisecond, to sweep across the face of the display.

Measuring Frequency

Because the oscilloscope has the ability to display the voltage with respect to time, it is possible to calculate the frequency of the waveform. The frequency (f) of an AC waveform can be found by dividing 1 by the time (t) it takes to complete one cycle ($f = 1/t$). For example, the time base in *Figure 10–49* is set



Courtesy of Tektronix, Inc.

FIGURE 10–53 Time base of an analog oscilloscope.

Courtesy of Tektronix, Inc.

FIGURE 10–54 Time base control for a typical digital oscilloscope.

at 100 microseconds per division. The AC sine wave being displayed completes one complete cycle in 167 microseconds. The frequency is 5988 hertz, or 5.988 kilohertz. (1/0.000167). The oscilloscope display in *Figure 10–49* displays these values. Many oscilloscopes have the ability to measure frequency automatically and display the value for you.

Attenuated Probes

Most oscilloscopes use a probe that acts as an attenuator. An attenuator is a device that divides or makes smaller the input signal *(Figure 10–55)*. An attenuated probe is used to permit higher voltage readings than are normally possible. For example, most attenuated probes are 10 to 1. This means that if the voltage range switch is set for 5 volts per division, the display would actually indicate 50 volts per division. If the voltage range switch is set for 2 volts per division, each division on the display actually has a value of 20 volts per division.

Probe attenuators are made in different styles by different manufacturers. On some probes, the attenuator is located in the probe head itself, whereas on

Courtesy of Tektronix, Inc.

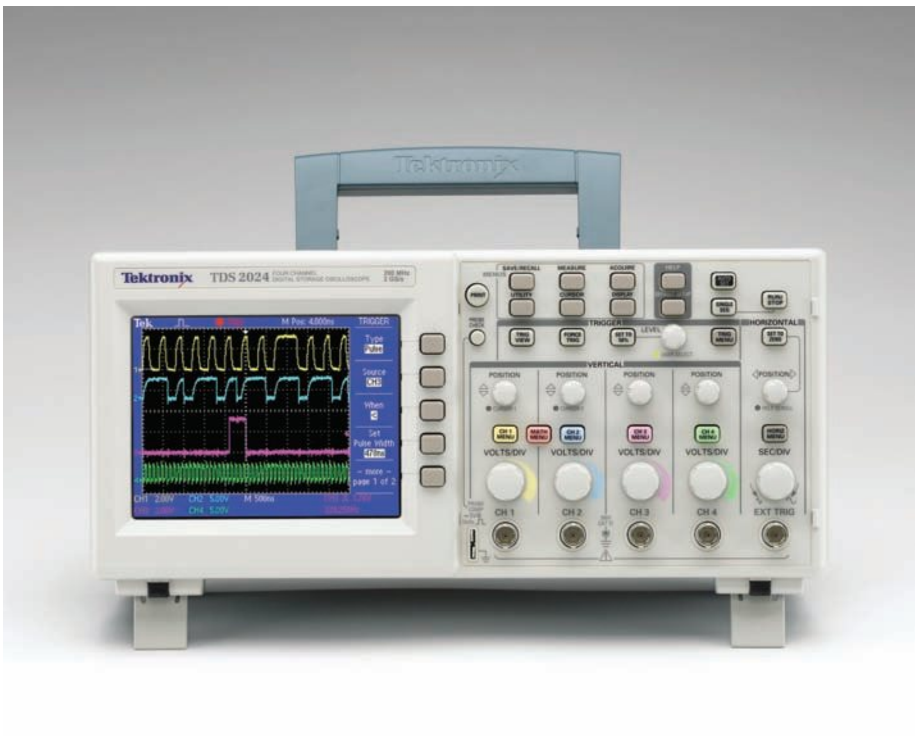
FIGURE 10–55 Oscilloscope attenuated probe.

others the attenuator is located at the scope input. Regardless of the type of attenuated probe used, it may have to be compensated or adjusted. In fact, probe compensation should be checked frequently. Different manufacturers use different methods for compensating their probes, so it is generally necessary to follow the procedures given in the operator's manual for the probe being used.

Oscilloscope Controls

The following is a list of common controls found on the oscilloscope. Refer to the oscilloscope shown in *Figure 10–56*.

1. **POWER**. The power switch is used to turn the oscilloscope ON or OFF.
2. **BEAM FINDER.** This control is used to locate the position of the trace if it is off the display. The BEAM FINDER button will indicate the approximate location of the trace. The position controls are then used to move the trace back on the display.
3. **PROBE ADJUST** (sometimes called calibrate). This is a reference voltage point used when compensating the probe. Most probe adjust points produce a square wave signal of about 0.5 volts.



Courtesy of Tektronix, Inc.

FIGURE 10–56 An oscilloscope.

4. **INTENSITY** and **FOCUS.** The INTENSITY control adjusts the brightness of the trace. A bright spot should never be left on the display because it will burn a spot on the face of the cathode ray tube (CRT). This burned spot results in permanent damage to the CRT. The FOCUS control sharpens the image of the trace.

5. **VERTICAL POSITION.** This is used to adjust the trace up or down on the display. If a dual-trace oscilloscope is being used, there will be two vertical POSITION controls. (A dual-trace oscilloscope contains two separate traces that can be used separately or together.)

6. **CH 1–BOTH–CH 2.** This control determines which channel of a dual-trace oscilloscope is to be used, or whether they are both to be used at the same time.

7. **ADD–ALT.–CHOP.** This control is active only when both traces are being displayed at the same time. The ADD adds the two waves together. ALT. stands for alternate. This alternates the sweep between Channel 1 and Channel 2. The CHOP mode alternates several times during one sweep. This generally makes the display appear more stable. The CHOP mode is generally used when displaying two traces at the same time.

8. **AC–GND–DC.** The AC is used to block any DC voltage when only the AC portion of the voltage is to be seen. For instance, assume an AC voltage of a few millivolts is riding on a DC voltage of several hundred volts. If the voltage range is set high enough so that 100 VDC can be seen on the display, the AC voltage cannot be seen. The AC section of this switch inserts a capacitor in series with the probe. The capacitor blocks the DC voltage and permits the AC voltage to pass. Because the 100 VDC has been blocked, the voltage range can be adjusted for millivolts per division, which will permit the AC signal to be seen.

   The GND section of the switch stands for ground. This section grounds the input so the sweep can be adjusted for 0 volt at any position on the display. The ground switch grounds at the scope and does not ground the probe. This permits the ground switch to be used when the probe is connected to a live circuit. The DC section permits the oscilloscope to display all of the voltage, both AC and DC, connected to the probe.

9. **HORIZONTAL POSITION.** This control adjusts the position of the trace from left to right.

10. **AUTO–NORMAL.** This determines whether the time base will be triggered automatically or operated in a free-running mode. If this control is operated in the NORM setting, the trigger signal is taken from the line to which the probe is connected. The scope is generally operated with the trigger set in the AUTO position.

11. **LEVEL.** The LEVEL control determines the amplitude the signal must be before the scope triggers.
12. **SLOPE.** The SLOPE permits selection as to whether the trace is triggered by a negative or positive waveform.
13. **INT.–LINE–EXT.** The *INT.* stands for internal. The scope is generally operated in this mode. In this setting, the trigger signal is provided by the scope. In the LINE mode, the trigger signal is provided from a sample of the line. The *EXT,* or external, mode permits the trigger pulse to be applied from an external source.

These are not all the controls shown on the oscilloscope in *Figure 10–56,* but they are the major controls. Most oscilloscopes contain these controls.

Interpreting Waveforms

The ability to interpret the waveforms on the display of the oscilloscope takes time and practice. When using the oscilloscope, one must keep in mind that the display shows the voltage with respect to time.

In *Figure 10–57,* it is assumed that the voltage range has been set for 0.5 volts per division, and the time base is set for 2 milliseconds per division. It is also assumed that 0 volt has been set on the center line of the display. The waveform shown is a square wave. The display shows that the voltage

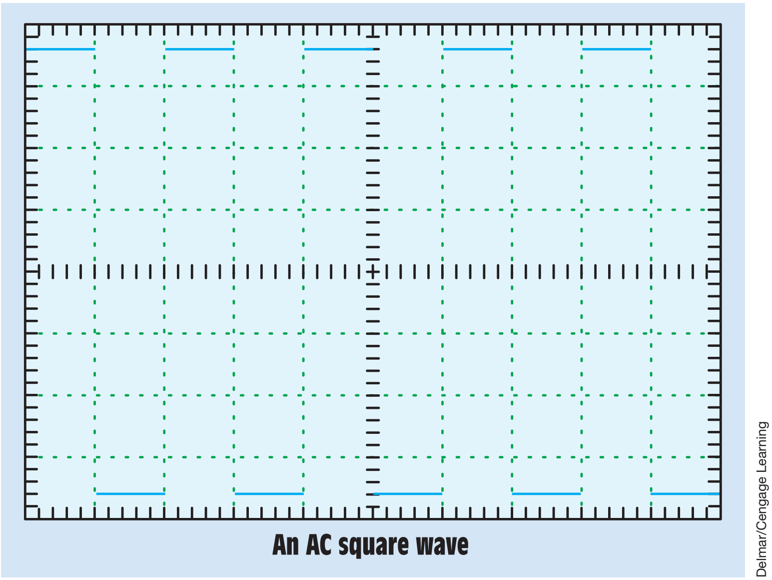


FIGURE 10–57 AC square wave.

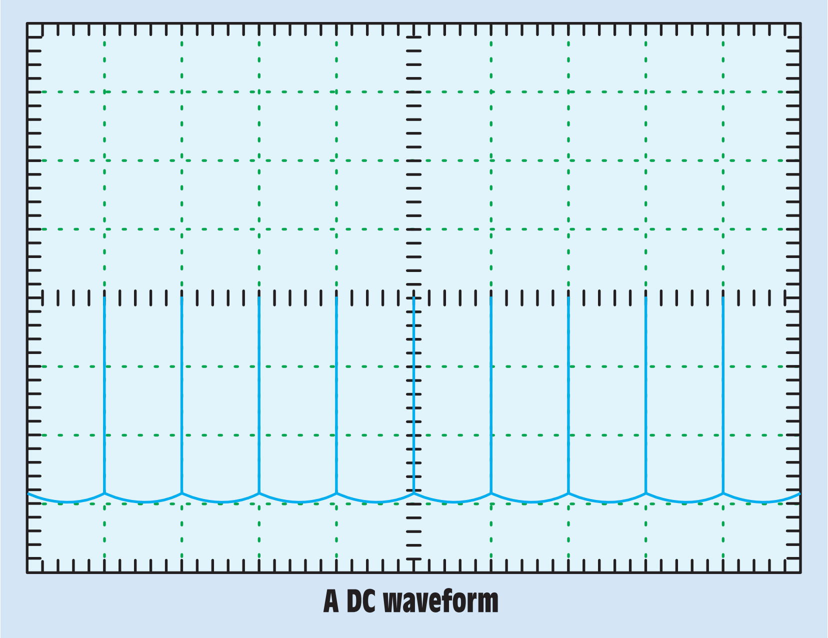


FIGURE 10–58 A DC waveform.

rises in the positive direction to a value of 1.4 volts and remains there for 2 milliseconds. The voltage then drops to 1.4 volts negative and remains there for 2 milliseconds before going back to positive. Because the voltage changes between positive and negative, it is an AC voltage. The length of one cycle is 4 milliseconds. The frequency is therefore 250 hertz (1/0.004s = 250 Hz).

In *Figure 10–58,* the oscilloscope has been set for 50 millivolts per division and 20 microseconds per division. The display shows a voltage that is negative to the probe's ground lead and has a peak value of 150 millivolts. The waveform lasts for 20 microseconds and produces a frequency of 50 kilohertz (1/0.000020s = 50,000 Hz). The voltage is DC because it never crosses the zero reference and goes in the positive direction. This type of voltage is called *pulsating DC.*

In *Figure 10–59,* assume the oscilloscope has been set for a value of 50 volts per division and 4 milliseconds per division. The waveform shown rises from 0 volts to about 45 volts in a period of about 1.5 milliseconds. The voltage gradually increases to about 50 volts in the space of 1 millisecond and then rises to a value of about 100 volts in the next 2 milliseconds. The voltage then decreases to 0 in the next 4 milliseconds. It then increases to a value of about 10 volts in 0.5 milliseconds and remains at that level for about 8 milliseconds. This is one complete cycle for the waveform. The length of the one cycle is about 16.6 milliseconds, which is a frequency of 60.2 hertz. (1/0.0166). The voltage is DC because it remains positive and never drops below the 0 line.

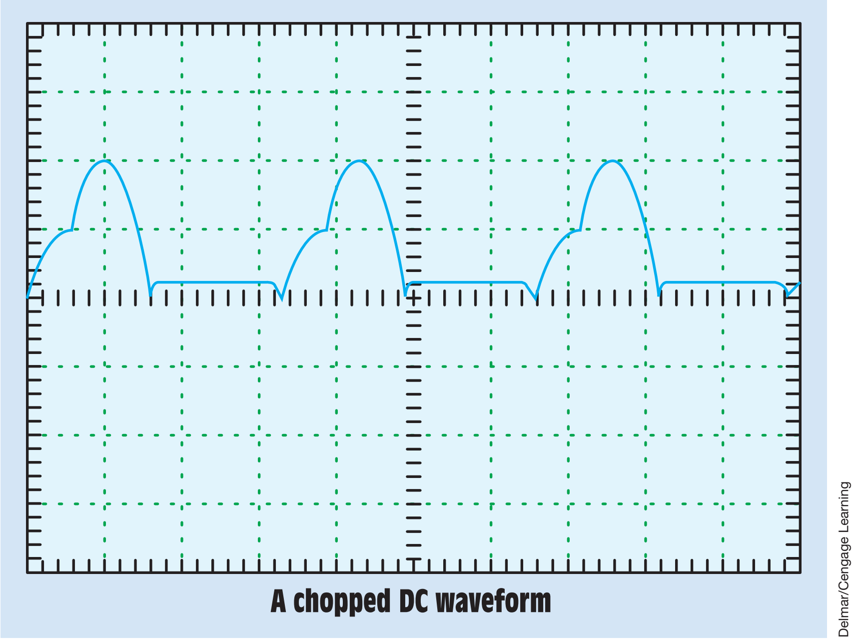


FIGURE 10–59 A chopped DC waveform.

Learning to interpret the waveforms seen on the display of an oscilloscope will take time and practice, but it is well worth the effort. The oscilloscope is the only means by which many of the waveforms and voltages found in electronic circuits can be understood. Consequently, the oscilloscope is the single most valuable piece of equipment a technician can use.

10–17 The Wattmeter

The **wattmeter** is used to measure true power in a circuit. There are two basic types of wattmeters, dynamic and electronic. Dynamic wattmeters differ from d'Arsonval-type meters in that they do not contain a permanent magnet. They contain an electromagnet and a moving coil *(Figure 10–60)*. The electromagnets are connected in series with the load in the same manner that an ammeter is connected. The moving coil has resistance connected in series with it and is connected directly across the power source in the same manner as a voltmeter *(Figure 10–61)*.

Because the electromagnet is connected in series with the load, the current flow through the load determines the magnetic field strength of the stationary magnet. The magnetic field strength of the moving coil is determined by the amount of line voltage. The turning force of the coil is proportional to the strength of these two magnetic fields. The deflection of the meter against the spring is proportional to the amount of current flow and voltage.

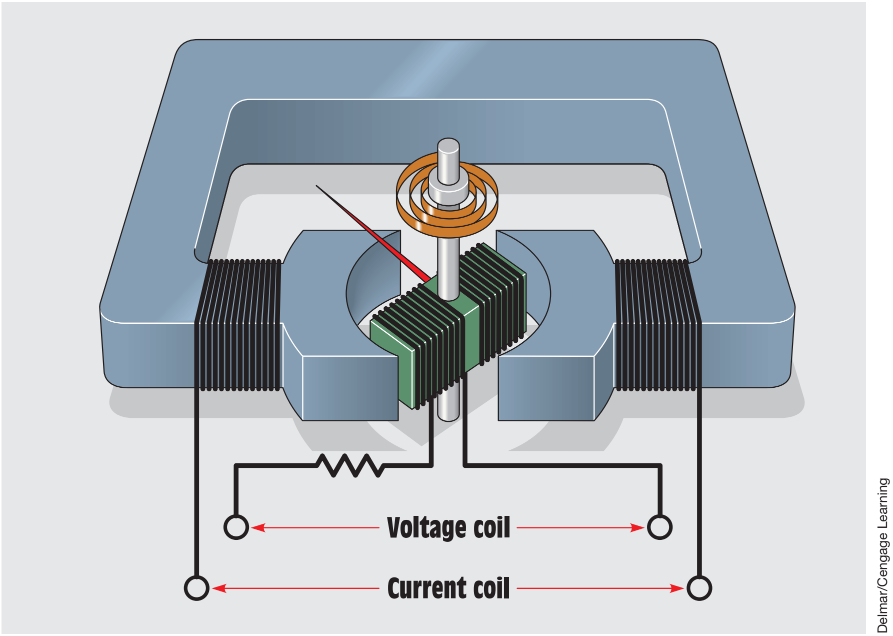


FIGURE 10–60 The wattmeter contains two coils—one for voltage and the other for current.

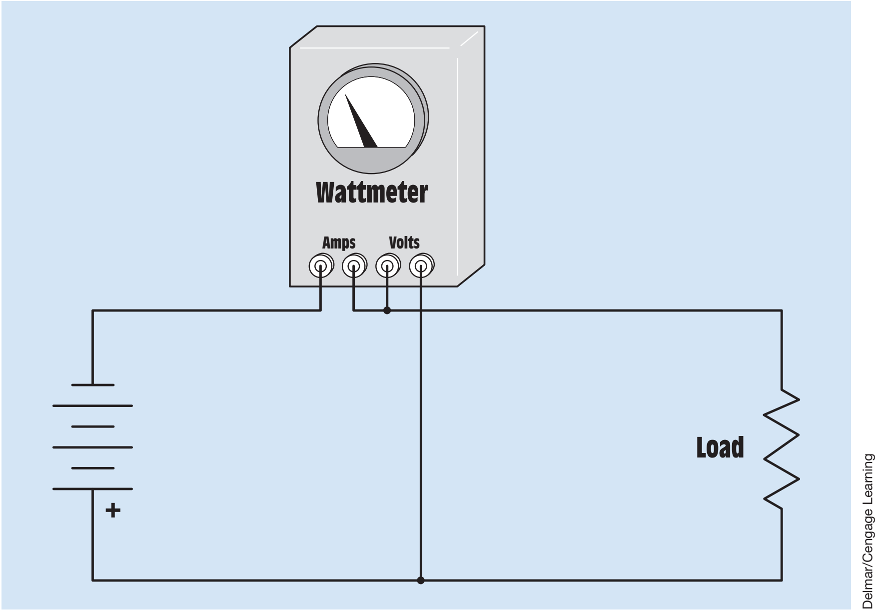


FIGURE 10–61 The current section of the wattmeter is connected in series with the load, and the voltage section is connected in parallel with the load.

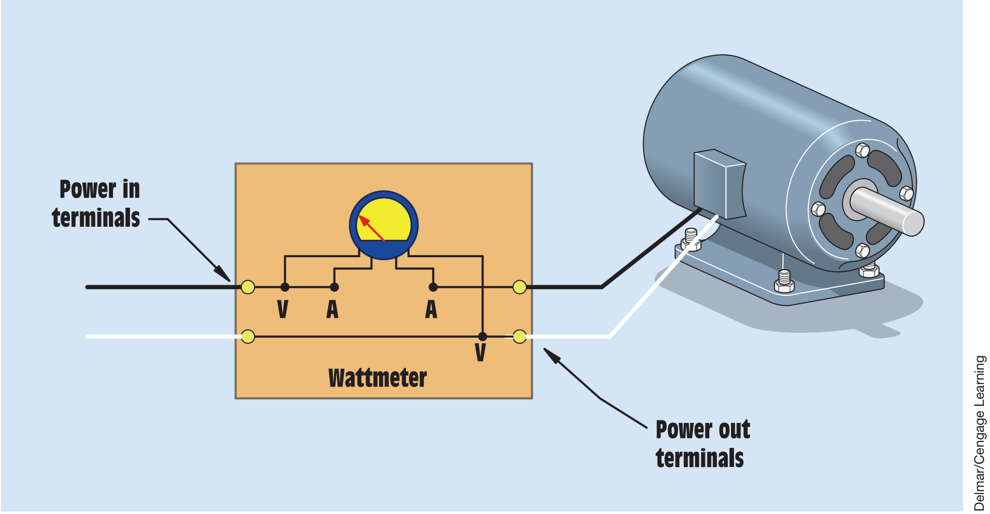


FIGURE 10–62 Portable wattmeters often make connection to the voltage and current terminals inside the meter.

Because the wattmeter contains an electromagnet instead of a permanent magnet, the polarity of the magnetic field is determined by the direction of current flow. The same is true of the polarity of the moving coil connected across the source of voltage. If the wattmeter is connected into an AC circuit, the polarity of the two coils will reverse at the same time, producing a continuous torque. For this reason, the wattmeter can be used to measure power in either a DC or an AC circuit. However, if the connection of the stationary coil or the moving coil is reversed, the meter will attempt to read backward.

Dynamic-type wattmeters are being replaced by wattmeters that contain electronic circuitry to determine true power. They are less expensive and generally more accurate than the dynamic type. Like dynamic wattmeters, electronic-type meters contain amperage terminals that connect in series with the load and voltage terminals that connect in parallel with the load. Portable-type wattmeters often have terminals labeled "power in" and "power out." Connection to the current and voltage section of the meter is made inside the meter *(Figure 10–62)*. Analog-type electronic wattmeters use a standard d'Arsonval-type movement to indicate watts. The electronic circuit determines the true power of the circuit and then supplies the appropriate power to the meter movement. Wattmeters with digital displays are also available.

10–18 Recording Meters

On occasion, it becomes necessary to make a recording of an electrical value over a long period of time. Recording meters produce a graph of metered values during a certain length of time. They are used to detect spike voltages, or currents of short duration, or sudden drops in voltage, current, or power. Recording meters can show the amount of voltage or current, its duration, and the time of occurrence. Some meters have the ability to store information in memory over a period of several days. This information can be recalled later by the service technician. Several types of recording meters are shown in *Figure 10–63*. The meter shown in *Figure 10–63A*

Courtesy of Advanced Test Products

FIGURE 10–63 **(A)** Single-line recording volt-ammeter. **(B)** A kilowatt-kiloVAR recording meter. **(C)** A single-phase or three-phase voltage and current recording meter.

is a single-line-recording volt-ammeter. It will record voltage or current or both for a single phase. A kilowatt-kiloVARs recording meter is shown in *Figure 10–63B*. This meter will record true power (kilowatts) or reactive power (kiloVARs) on a time-share basis. It can be used on single- or three-phase circuits and can also be used to determine circuit power factors. A chartless recorder is shown in *Figure 10–63C*. This instrument can record voltages and currents on single- or three-phase lines. The readings can be stored in memory for as long as 41 days.

10–19 Bridge Circuits

One of the most common devices used to measure values of resistance, inductance, and capacitance accurately is a **bridge circuit.** A bridge is constructed by connecting four components to form a parallel-series circuit. All four components are of the same type, such as four resistors, four inductors, or four capacitors. The bridge used to measure resistance is called a **Wheatstone bridge.** The basic circuit for a Wheatstone bridge is shown in *Figure 10–64*. The bridge operates on the principle that the sum of the voltage drops in a series circuit must equal the applied voltage. A galvanometer is used to measure

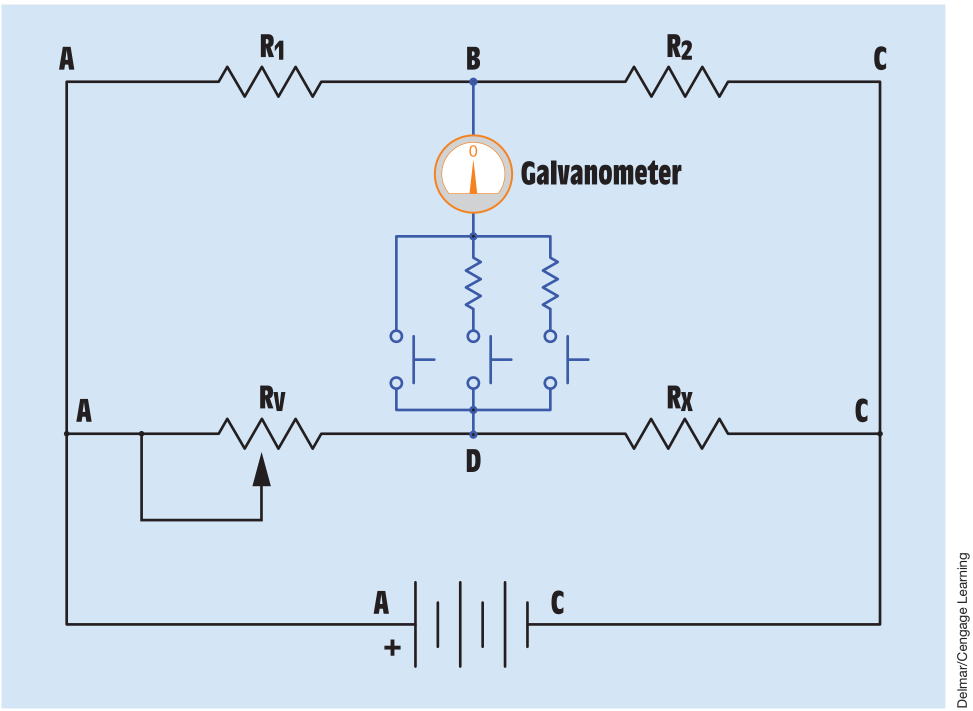
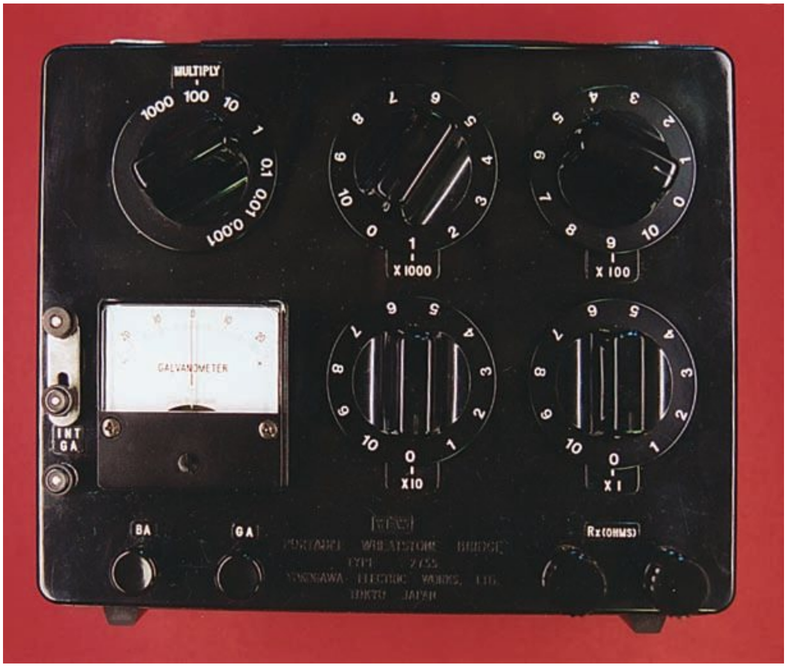


FIGURE 10–64 The Wheatstone bridge circuit is used to make accurate measurements of resistance and operates on the principle that the sum of the voltage drops in a series circuit must equal the applied voltage.

the voltage between points B and D. The galvanometer can be connected to different values of resistance or directly between points B and D. Values of resistance are used to determine the sensitivity of the meter circuit. When the meter is connected directly across the two points, its sensitivity is maximum.

In *Figure 10–64,* assume the battery has a voltage of 12 volts and that R_1 and R_2 are precision resistors and have the same value of resistance. Because R_1 and R_2 are connected in series and have the same value, each will have a voltage drop equal to one-half of the applied voltage, or 6 volts. This means that point B is 6 volts more negative than point A and 6 volts more positive than point C.

R_V (variable) and R_X (unknown) are connected in series with each other. R_X represents the unknown value of resistance to be measured. R_V can be adjusted for different resistive values. If the value of R_V is greater than the value of R_X, the voltage at point D will be more negative than the voltage at point B. This will cause the pointer of the zero-center galvanometer to move in one direction. If the value of R_V is less than R_X, the voltage at point D will be more positive than the voltage at point B, causing the pointer to move in the opposite direction. When the value of R_V becomes equal to that of R_X, the voltage at point D will become equal to the voltage at point B. When this occurs, the galvanometer will indicate zero. A Wheatstone bridge is shown in *Figure 10–65*.



Delmar/Cengage Learning

FIGURE 10–65 Wheatstone bridge.

Summary

- The d'Arsonval type of meter movement is based on the principle that like magnetic fields repel.
- The d'Arsonval movement operates only on DC.
- Voltmeters have a high resistance and are designed to be connected directly across the power line.
- The steps to reading a meter are as follows:
  a. Determine what quantity the meter is set to measure.
  b. Determine the full-range value of the meter.
  c. Read the meter.
- Ammeters have a low resistance and must be connected in series with a load to limit the flow of current.
- Shunts are used to change the value of DC ammeters.
- AC ammeters use a current transformer to change the range setting.
- Clamp-on ammeters measure the flow of current by measuring the strength of the magnetic field around a conductor.
- Ohmmeters are used to measure the resistance in a circuit.
- Ohmmeters contain an internal power source, generally batteries.
- Ohmmeters must never be connected to a circuit that has power applied to it.
- Digital multimeters display their value in digits instead of using a meter movement.
- Digital multimeters generally have an input impedance of 10 megohms on all ranges.
- The oscilloscope measures the amplitude of voltage with respect to time.
- The frequency of a waveform can be determined by dividing 1 by the time of one cycle ($f = 1/t$).
- Wattmeters contain a stationary coil and a movable coil.
- The stationary coil of a wattmeter is connected in series with the load, and the moving coil is connected to the line voltage.
- The turning force of the dynamic wattmeter is proportional to the strength of the magnetic field of the stationary coil and the strength of the magnetic field of the moving coil.

- Digital ohmmeters measure resistance by measuring the voltage drop across an unknown resistor when a known amount of current flows through it.
- Low-impedance voltage testers are not susceptible to indicating a voltage caused by a high-impedance ground or a feedback.
- A bridge circuit can be used to accurately measure values of resistance, inductance, and capacitance.

Review Questions

1. To what is the turning force of a d'Arsonval meter movement proportional?
2. What type of voltage must be connected to a d'Arsonval meter movement?
3. A DC voltmeter has a resistance of 20,000 Ω per volt. What is the resistance of the meter if the range selection switch is set on the 250-V range?
4. What is the purpose of an ammeter shunt?
5. Name two methods used to make a DC multirange ammeter.
6. How is an ammeter connected into a circuit?
7. How is a voltmeter connected into a circuit?
8. An ammeter shunt has a voltage drop of 50 mV when 50 A of current flow through it. What is the resistance of the shunt?
9. What type of meter contains its own separate power source?
10. What electrical quantity does the oscilloscope measure?
11. What is measured on the Y axis of an oscilloscope?
12. What is measured on the X axis of an oscilloscope?
13. A waveform shown on the display of an oscilloscope completes one cycle in 50 μs. What is the frequency of the waveform?
14. What is the major difference between a wattmeter and a d'Arsonval meter?
15. What two factors determine the turning force of a wattmeter?

Practical Applications

You are an electrician on the job. You have been give a multimeter that has the following AC voltage ranges: 30, 60, and 150. The meter states that it has a resistance of 5000 Ω/V. You need to be able to measure a voltage of 277 volts. How much resistance should be inserted in series with the meter to make the 30-volt range indicate a full scale value of 300 volts? ■

Practice Problems

Measuring Instruments

1. A d'Arsonval meter movement has a full-scale current value of 100 μA (0.000100 A) and a resistance of 5 kΩ (5000 Ω). What size resistor must be placed in series with this meter to permit it to indicate 10 V full scale?
2. The meter movement described in Question 1 is to be used to construct a multirange voltmeter. The meter is to have voltage ranges of 15 V, 60 V, 150 V, and 300 V *(Figure 10–66)*. Find the values of R_1, R_2, R_3, and R_4.

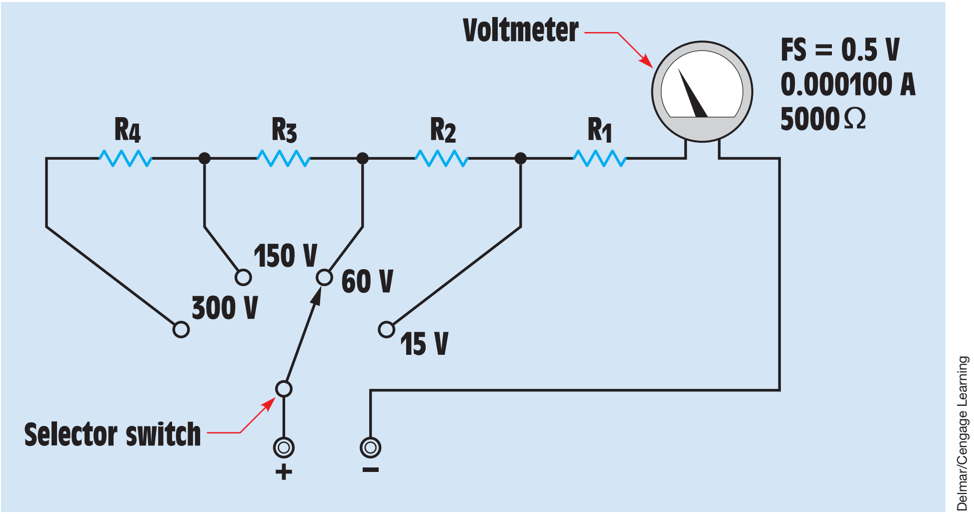


FIGURE 10–66 The multirange voltmeter operates by connecting different values of resistance in series with the meter movement.

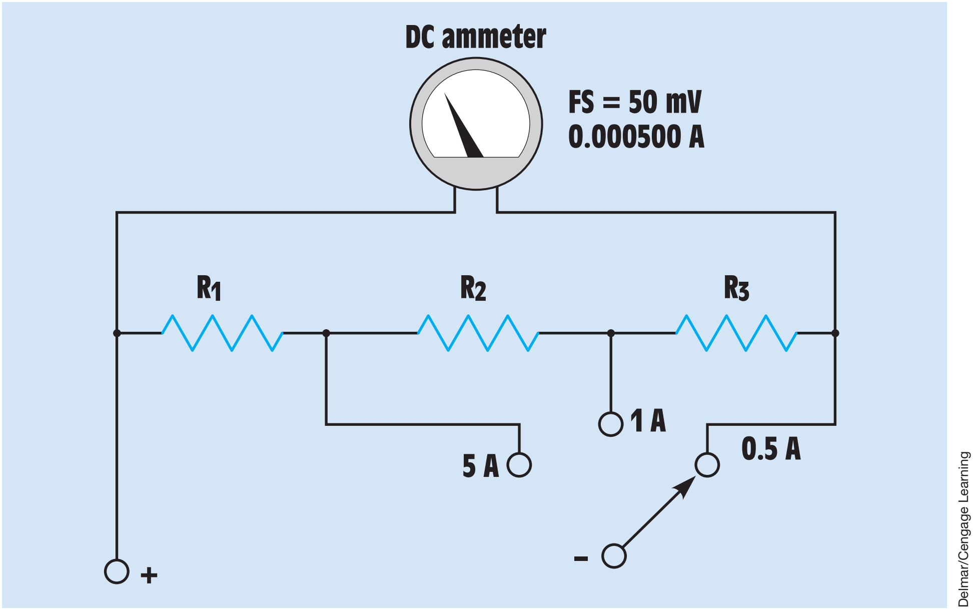


FIGURE 10–67 Ayrton shunt.

3. A meter movement has a full-scale value of 500 μA (0.000500 A) and 50 mV (0.050 V). A shunt is to be connected to the meter that permits it to have a full-scale current value of 2 A. What is the resistance of the shunt?

4. The meter movement in Question 3 is to be used as a multirange ammeter. An Ayrton shunt is to be used to provide full-scale current ranges of 5 A, 1 A, and 0.5 A *(Figure 10–67)*. Find the values of R_1, R_2, and R_3.

5. A digital voltmeter indicates a voltage of 2.5 V when 10 μA of current flow through a resistor. What is the resistance of the resistor?

Unit 11

Using Wire Tables and Determining Conductor Sizes

OUTLINE

KEY TERMS

Ambient air temperature
American Wire Gauge (AWG)
Ampacity (current-carrying ability)
Circular mil
Correction factor
Damp locations
Dry locations
Insulation
Maximum operating temperature
MEGGER
Mil-foot
National Electrical Code (*NEC*)
Parallel conductors
Wet locations

Why You Need to Know

Being able to determine the amount of current a conductor is permitted to carry or the size wire need for an installation is essential to any electrician, whether he or she works as an installation electrician or as a maintenance electrician. This unit

- explains how the amount of current a conductor is permitted to carry is not the same as selecting the proper wire for an installation and describes the differences.
- differentiates the different types of wire insulation and the appropriate use of each based on ambient temperatures.
- explains the method for using tools such as a MEGGER when determining the resistance of wire insulation.
- discusses how conductor length and size impact resistance and determine the required conductor size.
- provides the tools for determining ampacity rating of conductors when applying correction factors for wiring in a raceway.
- explains that, as a general rule, electricians select wire sizes from the *NEC*. However, there are instances where the wire run is too long or some special type of wire is being employed. In those instances, wire size and type are chosen by determining the maximum voltage drop and calculating the resistance of the wire. This unit explains how to determine wire size using the *NEC* and calculating wire resistance.

Courtesy of Niagara Mohawk Power Corporation.

Objectives

After studying this unit, you should be able to

- select a conductor from the proper wire table.
- discuss the different types of wire insulation.
- determine insulation characteristics.
- use correction factors to determine the proper ampacity rating of conductors.
- determine the resistance of long lengths of conductors.
- determine the proper wire size for loads located long distances from the power source.
- list the requirements for using parallel conductors.
- discuss the use of a MEGGER for testing insulation.

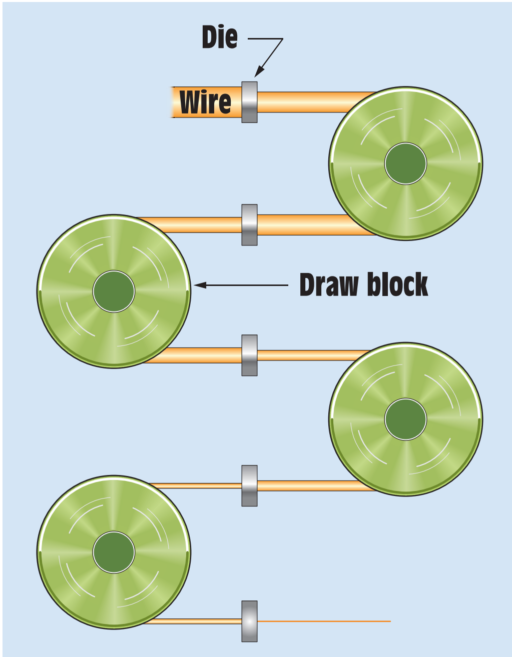
Preview

The size of the conductor needed for a particular application can be determined by several methods. The ***National Electrical Code (NEC)*** is used throughout industry to determine the conductor size for most applications. It is imperative that an electrician be familiar with Code tables and correction factors. In some circumstances, however, wire tables cannot be used, as in the case of extremely long wire runs or for windings of a transformer or motor. In these instances, the electrician should know how to determine the conductor size needed by calculating maximum voltage drop and resistance of the conductor. ■

11–1 The American Wire Gauge (AWG)

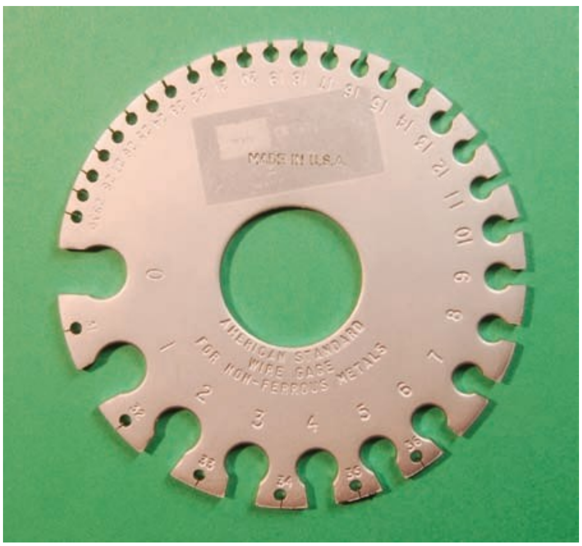
The American Wire Gauge was standardized in 1857 and is used mainly in the United States for the diameters of round, solid, nonferrous electrical wire. The gauge size is important for determining the current-carrying capacity of a conductor. Gauge sizes are determined by the number of draws necessary to produce a given diameter or wire. Electrical wire is made by drawing it through a succession of dies, *Figure 11–1*.

Each time a wire passes through a die, it is wrapped around a draw block several times. The draw block provides the pulling force necessary to draw the wire through the die. A 24 AWG wire would be drawn through 24 dies, each having a smaller diameter. In the field, wire size can be determined with a wire gauge, *Figure 11–2*. One side of the wire gauge lists the AWG size of the wire, *Figure 11–3*. The opposite side of the wire gauge indicates the diameter of the wire in thousandths of an inch, *Figure 11–4*. When determining wire size, first remove the insulation from around the conductor. The slots in the wire gauge, not the holes behind the slots, are used to determine the size, *Figure 11–5*.



Delmar/Cengage Learning

FIGURE 11–1 Wire is drawn through a succession of dies to produce the desired diameter.



Delmar/Cengage Learning

FIGURE 11–2 Wire gauge

The largest AWG size is 4/0, which has an area of 211,600 circular mills (CM). Conductors with a larger area are measured in thousand circular mills. The next largest conductor past 4/0 is 250 thousand circular mills (250 kcmil). Conductors can be obtained up to 2000 kcmil. In practice, large conductors

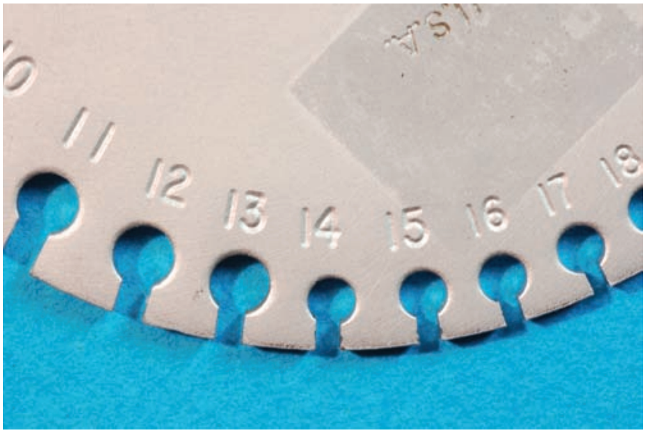


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FIGURE 11–3 One side of the wire gauge is marked with the AWG size.

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FIGURE 11–4 The other side of the wire gauge lists the diameter of the wire in thousandths of an inch.

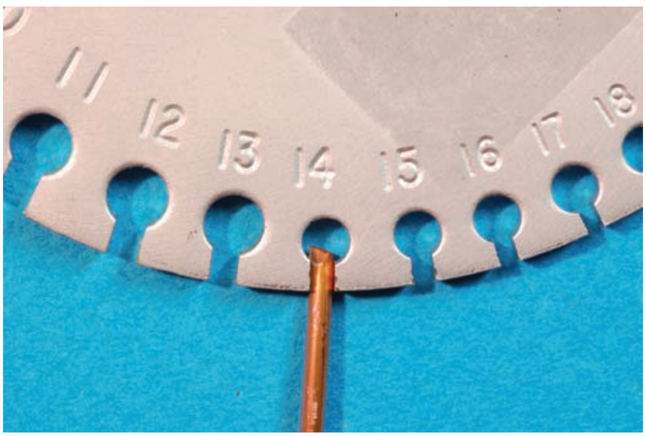

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FIGURE 11–5 The slot, not the hole, determines the wire size.

are difficult to pull through conduit. It is sometimes desirable to use parallel conductors instead of extremely large conductors.

11–2 Using the *NEC* Charts

NEC 310 deals with conductors for general wiring. *Table 310.15(B)(16)* through *Table 310.15(B)(19)* are generally used to select a wire size according to the requirements of the circuit. Each of these tables lists different conditions. The table used is determined by the wiring conditions. *Table 310.15(B)(16) (Figure 11–6)*

Table 310.15(B)16 Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F) Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Direct Burried), on Ambient Temperature of 30°C (86°F)

	Temperature Rating of Conductors [See Table 310.104(A)]						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
Size AWG or kcmil	Types TW,UF	Types RHW, THHW,THW, THWN,XHHW, USE,ZW	Types TBS,SA,SIS, FEP,FEPB,MI,RHH, RHW-2,THHN, THHW,THW-2, THWN-2,USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW,UF	Types RHW, THHW,THW, THWN,XHHW, USE,ZW	Types TBS,SA,SIS, FEP,FEPB,MI,RHH, RHW-2,THHN, THHW,THW-2, THWN-2,USE-2, XHH, XHHW, XHHW-2, ZW-2	Size AWG or kcmil
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
18	-	-	14	-	-	-	-
16	-	-	18	-	-	-	-
14**	15	20	25	-	-	-	-
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	350	420	475	285	340	385	600
700	385	460	520	310	375	425	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	445	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	525	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	555	665	750	470	560	630	2000

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30 ºC (86 ºF)

** Refer to 240.4(D) for conductor overcurrent protection limitations.

FIGURE 11–6 *NEC Table 310.16. (Reprinted with permission from NFPA 70-2011, National Electrical Code, Copyright © 2011, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)*

Table 310.15(B)17 Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts in Free Air, Based on Ambient Air temperature of 30°C (86°F)

Size AWG or kcmil	Temperature Rating of Conductors [See Table 310.104(A)]						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW,UF	Types RHW, THHW,THW, THWN,XHHW, ZW	Types TBS,SA,SIS, FEP,FEPB,MI,RHH, RHW-2,THHN, THHW,THW-2, THWN-2,USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW,UF	Types RHW, THHW,THW, THWN,XHHW, ZW	Types TBS,SA,SIS, FEP,FEPB,MI,RHH, RHW-2,THHN, THHW,THW-2, THWN-2,USE-2, XHH, XHHW, XHHW-2, ZW-2	
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
18	-	-	18	-	-	-	-
16	-	-	24	-	-	-	-
14**	25	30	35	-	-	-	-
12**	30	35	40	25	30	35	12**
10**	40	50	55	35	40	45	10**
8	60	70	80	45	55	60	8
6	80	95	105	60	75	85	6
4	105	125	140	80	100	115	4
3	120	145	165	95	115	130	3
2	140	170	190	110	135	150	2
1	165	195	220	130	155	175	1
1/0	195	230	260	150	180	205	1/0
2/0	225	265	300	175	210	235	2/0
3/0	260	310	350	200	240	270	3/0
4/0	300	360	405	235	280	315	4/0
250	340	405	455	265	315	355	250
300	375	445	500	290	350	395	300
350	420	505	570	330	395	445	350
400	455	545	615	355	425	480	400
500	515	620	700	405	485	545	500
600	575	690	780	445	540	615	600
700	630	755	850	500	595	670	700
750	655	785	885	515	620	700	750
800	680	815	920	535	645	725	800
900	730	870	980	580	700	790	900
1000	780	935	1055	625	750	845	1000
1250	890	1065	1200	710	855	965	1250
1500	980	1175	1325	795	950	1070	1500
1750	1070	1280	1445	875	1050	1185	1750
2000	1155	1385	1560	960	1150	1295	2000

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient termperature is other than 30 °C (86 °F)

**Refer to 240.4(D) for conductor overcurrent protection limitation.

FIGURE 11–7 *NEC Table 310.17. (Reprinted with permission from NFPA 70-2011, National Electrical Code, Copyright © 2011, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)*

lists **ampacities (current-carrying ability)** of not more than three single insulated conductors in raceway or cable or buried in the earth based on an **ambient** (surrounding) **air temperature** of 30°C (86°F). *Table 310.15(B)(17) (Figure 11–7)* lists ampacities of single insulated conductors in free air based on an ambient temperature of 30°C. *Table 310.15(B)(18) (Figure 11–8)* lists the ampacities of three single insulated conductors in raceway or cable based on an ambient temperature of 40°C (104°F). The conductors listed in *Table 310.15(B)(18)*

Table 310.15(B)18 Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 150°C Through 250°C (302°F Through 482°F) Not More Than Three Current-Carrying Conductors in Raceway or Cable Based on Ambient Air Temperature of 40°C (104°F)

	Temperature Rating of Conductors [See Table 310.104(A)]				
	150°C (302°F)	200°C (392°F)	250°C (482°F)	150°C (302°F)	
	Type Z	Types FEP, FEPB, PFA, SA	Types PFAH, TFE	Type Z	
Size AWG or kcmil	COPPER		NICKEL OR NICKEL-COATED COPPER	ALUMINUM OR COPPER-CLAD ALUMINUM	Size AWG or kcmil
14	34	36	39	-	-
12	43	45	54	30	12
10	55	60	73	44	10
8	76	83	93	57	8
6	96	110	117	75	6
4	120	125	148	94	4
3	143	152	166	109	3
2	160	171	191	124	2
1	186	197	215	145	1
1/0	215	229	244	169	1/0
2/0	251	260	273	198	2/0
3/0	288	297	308	227	3/0
4/0	332	346	361	260	4/0

*Refer to 310.15(B)(2)(b) for the ampacity correction factors where the ambient temperature is other than 40 °C (104 °F)

FIGURE 11–8 *NEC Table 310.18. (Reprinted with permission from NFPA 70-2011, National Electrical Code, Copyright © 2011, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety).*

and Table 310.15(B)(19) are generally used for high-temperature locations. The heading at the top of each table lists a different set of conditions.

11–3 Factors That Determine Ampacity

Conductor Material

One of the factors that determines the resistivity of wire is the material from which the wire is made. The wire tables list the current-carrying capacity of both copper and aluminum or copper-clad aluminum conductors. The currents listed in the left-hand half of *Table 310.15(B)(16)*, for example, are for copper wire. The currents listed in the right-hand half of the table are for aluminum or

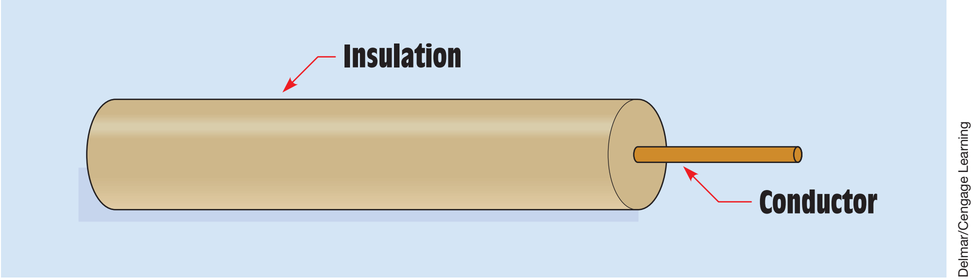

FIGURE 11–9 Insulation around conductor.

copper-clad aluminum. The table indicates that a copper conductor is permitted to carry more current than an aluminum conductor of the same size and insulation type. An 8 **American Wire Gauge (AWG)** copper conductor with Type TW insulation is rated to carry a maximum of 40 amperes. An 8 AWG aluminum conductor with Type TW insulation is rated to carry only 35 amperes. One of the columns of *Table 310.15(B)(18)* and *Table 310.15(B)(19)* gives the ampacity rating of nickel or nickel-coated copper conductors.

Insulation Type

Another factor that determines the amount of current a conductor is permitted to carry is the type of insulation used. This is due to the fact that different types of insulation can withstand more heat than others. The **insulation** is the nonconductive covering around the wire *(Figure 11–9)*. The voltage rating of the conductor is also determined by the type of insulation. The amount of voltage a particular type of insulation can withstand without breaking down is determined by the type of material it is made of and its thickness. *NEC Table 310.104(A)* (not shown due to space limitations) lists information concerning different types of insulation. The table is divided into columns that list the trade name; identification letters; **maximum operating temperature;** whether the insulation can be used in a wet, damp, or dry location; material; thickness; and outer covering.

EXAMPLE 11–1

Find the maximum operating temperature of Type RHW insulation. (Note: Refer to the *NEC*.)

Solution

Find Type RHW in the second column of *Table 310.104(A)*. The third column lists a maximum operating temperature of 75°C, or 167°F.

■ **EXAMPLE 11–2**

Can Type THHN insulation be used in wet locations?

Solution

Locate Type THHN insulation in the second column. The fourth column indicates that this insulation can be used in **dry** and **damp locations.** This type of insulation cannot be used in **wet locations.** For an explanation of the difference between damp and wet locations, consult "locations" in *Article 100* of the *NEC*.

A good thing to remember is that insulation materials that contain the letter *W*, such as RHW, THW, THWN, and so on may be used in wet locations.

11–4 Correction Factors

One of the main factors that determines the amount of current a conductor is permitted to carry is the ambient, or surrounding, air temperature. *Table 310.15(B)(16),* for example, lists the ampacity of not more than three conductors in a raceway in free air. These ampacities are based on an ambient air temperature of 30°C, or 86°F. If these conductors are to be used in a location that has a higher ambient temperature, the ampacity of the conductor must be reduced because the resistance of copper or aluminum increases with an increase of temperature. Temperature correction factors can be found in *Table 310.15(B)(2)(a)* and *310.15(B)(2)(b)*. *Table 310.15(B)(2)(a)* is for conductors rated at 30°C or 86°F. The ampacity of conductors in *Table 310.15(B)(16)* and *Table 310.15(B)(17)* are based on an ambient air temperature of 30°C. The correction factors for conductors rated at 40°C are found in *Table 310.15(B)(2)(b)*. The ampacity of conductors in *Table 310.15(B)(18)* and *Table 310.15(B)(19)* are based on an ambient temperature of 40°C. The correction factors found in Table *310.15(B)(2)(a)* are shown in *Figure 11-10.*

More Than Three Conductors in a Raceway

Table 310.15(B)(16) and *Table 310.15(B)(18)* list three conductors in a raceway. If a raceway is to contain more than three conductors, the ampacity of the conductors must be derated because the heat from each conductor combines with the heat dissipated by the other conductors to produce a higher temperature inside the raceway. *NEC Table 310.15(B)(3)(a) (Figure 11–11)* lists these correction factors. If the raceway is used in an area with a greater ambient

Table 310.15(B)(2)(a) Ambient Temperature Correction Factors Based on 30 °C (86 °F)				
For ambient temperatures other than 30 °C (86 °F) multiply the allowable ampacities specified in the ampacity tables by the appropriate correction factor shown below.				
Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11-15	1.22	1.15	1.12	51-59
16-20	1.15	1.11	1.08	60-68
21-25	1.08	1.05	1.04	69-77
26-30	1.00	1.00	1.00	78-86
31-35	0.91	0.94	0.96	87-95
36-40	0.82	0.88	0.91	96-104
41-45	0.71	0.82	0.87	105-113
46-50	0.58	0.75	0.82	114-122
51-55	0.41	0.67	0.76	123-131
56-60	-	0.58	0.71	132-140
61-65	-	0.47	0.65	141-149
66-70	-	0.33	0.58	150-158
71-75	-	-	0.50	159-167
76-80	-	-	0.41	168-176
80-85	-	-	0.29	177-185

FIGURE 11–10 *Ambient temperature correction factors. (Reprinted with permission from NFPA 70-2011, National Electrical Code, Copyright © 2011, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety).*

Table 310.15(B)(3)(a) Adjustment Factors for More Than Three Current-Carrying conductors in a Raceway or Cable	
Number of Conductors	Percent of Values in Table 310.15(B)(16) through Table 310.15(B)(19) as Adjusted for Ambient Temperature if Necessary
4-6	80
7-9	70
10-20	50
21-30	45
31-40	40
41 and above	35

FIGURE 11–11 *NEC Table 310.15(B)(3)(a). (Reprinted with permission from NFPA 70-2011, National Electrical Code, Copyright © 2011, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)*

temperature than that listed in the appropriate wire table, the temperature correction factor must also be applied.

Determining Conductor Size Using the *NEC*

Using the *NEC* to determine the amount of current a conductor is permitted to carry and the proper size conductor to use for a particular application are not

EXAMPLE 11–3

What is the maximum ampacity of a 4 AWG copper conductor with Type THWN insulation used in an area with an ambient temperature of 43°C?

Solution

Determine the ampacity of a 4 AWG copper conductor with Type THWN insulation from the wire table. Type THWN insulation is located in the second column of *Table 310.15(B)(16)*. The table lists an ampacity of 85 A for this conductor. Locate 43°C in the far left-hand column of the correction factor chart shown in *Figure 11-10*; 43°C falls between 41°C and 45°C. Follow across to the 75°C column. The chart lists a correction factor of 0.82. The ampacity of the conductor in the above wire table is to be multiplied by the correction factor:

$$85\text{ A} \times 0.82 = 69.7\text{ A}$$

EXAMPLE 11-4

What is the maximum ampacity of a 1/0 AWG copper-clad aluminum conductor with Type RHH insulation if the conductor is to be used in an area with an ambient air temperature of 100°F?

Solution

Locate the column that contains Type RHH insulation in the copper-clad aluminum section of *Table 310.15(B)(16)*. The table indicates a maximum ampacity of 135 A for this conductor. The chart shown in *Figure 11-10* is used to determine the correction factor for this temperature. Fahrenheit degrees are located in the far right-hand column of the chart; 100°F falls between 97°F and 104°F. The correction factor for this temperature is 0.91. Multiply the ampacity of the conductor by this factor:

$$135 \text{ A} \times 0.91 = 122.85 \text{ A}$$

EXAMPLE 11-5

Twelve 14 AWG copper conductors with Type RHW insulation are to be run in a conduit. The conduit is used in an area that has an ambient temperature of 110°F. What is the maximum ampacity of these conductors?

Solution

Find the ampacity of a 14 AWG copper conductor with Type RHW insulation. Type RHW insulation is located in the second column of *Table 310.15(B)(16)*. A 14 AWG copper conductor has an ampacity of 20 A. Next, use the correction factor for an ambient temperature of 110°F in *Table 310.15(B)(2)(a)* shown in *Figure 11-10*. A correction factor of 0.82 will be used:

$$20 \text{ A} \times 0.82 = 16.4 \text{ A}$$

The correction factor located in *Table 310.15(B)(3)(a)* must now be used. The table indicates a correction factor of 50% when 10 through 20 conductors are run in a raceway:

$$16.4 \text{ A} \times 0.50 = 8.2 \text{ A}$$
$$16.4 \text{ A} \times 0.50 = 8.2 \text{ A}$$

Each 14 AWG conductor has a maximum current rating of 8.2 A.

the same thing. The several factors that must be considered when selecting a conductor for a specific job are of no consequence when determining the ampacity of a conductor. One of these factors is whether the load is a continuous or noncontinuous load. The *NEC* defines a continuous load as one where the maximum current is expected to continue for three hours or more. Most industrial motor and lighting loads, for example, would be considered continuous loads. *NEC 210.19(A)(1)* states that conductors must have an ampacity not less than the noncontinuous load plus 125% of the continuous load. Basically, the ampacity of a conductor must be 125% greater than the current rating of a continuous load.

Another factor that affects the selection of a conductor is termination temperature limitations. *NEC 110.14(C)* states that the temperature rating of a conductor must be selected so as not to exceed the lowest temperature rating of any connected conductor, termination, or device. Because the termination temperature rating of most devices is not generally known, *NEC 110.14(C)(1)(a)* states that conductors for circuits rated at 100 amperes or less are to be selected from the 60°C column. This does not mean that conductors with a higher temperature rating cannot be used, but their size must be selected from the 60°C column. The only exception to this is motors that are marked with *NEMA* (National Electrical Manufacturers Association) code letters B, C, or D. *NEC 110.14(C)(1)(a)(4)* permits conductors for motors with these code letters to be selected from the 75°C column.

EXAMPLE 11–6

Assume that a motor with a full-load current rating of 28 A is to be connected with copper conductors that have Type THW insulation. The motor is located in an area with an ambient temperature of 30°C. The motor is not marked with *NEMA* code letters, and the termination temperature is not known. What size conductors should be used?

Solution

Because a motor load is continuous, multiply the full-load current rating by 125%:

$$28\text{ A} \times 1.25 = 35\text{ A}$$

Refer to *NEC Table 310.15(B)(16)*. Type THW insulation is located in the 75°C column. Although this conductor is located in the 75°C column, the wire size must be chosen from the 60°C column because the termination temperature is not known and the motor does not contain *NEMA* code letters. The nearest wire size without going under 35 A is an 8 AWG.

■ EXAMPLE 11-7

Assume that a bank of heating resistors is rated at 28 kW and is connected to 240 V. The resistors operate for more than three hours at a time and are located in an area with an ambient temperature of 86°F. Aluminum conductors with Type THWN-2 insulation are to be used to connect the heaters. What size conductors should be used?

Solution

Determine the amperage of the load using Ohm's law:

$$I = \frac{P}{E}$$

$$I = \frac{28{,}000\ \text{W}}{240\ \text{V}}$$

$$I = 116.667\ \text{A}$$

Because the load is continuous, the conductors must have an ampacity 125% greater than the load current.

$$I = 116.667\ \text{A} \times 1.25$$

$$I = 145.834\ \text{A or } 146\ \text{A}$$

Refer to *NEC Table 310.15(B)(16)*. Type THWN-2 insulation is located in the 90°C column. The conductor size, however, must be chosen from the 75°C column. The nearest size aluminum conductor without going less than 146 A is 3/0 AWG.

The requirements of *NEC 110.14(C)* also require that conductors be selected from *Table 310.15(B)(16)* as a general rule. *NEC Table 310.15(B)(17),* for example, lists the current-carrying capacity of conductors located in free air. Because the conductors are generally terminated inside an enclosure, however, they must be chosen from a table that lists the ampacity of conductors inside an enclosure.

For circuits with a current of 100 A or greater, *NEC 110.14(C)(1)(b)* permits conductors to be selected from the 75°C column.

Another factor to be considered when selecting a conductor for a particular application is the ambient temperature. *Table 310.15(B)(2)(a)* states: *"For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below."* The wire tables are used to determine the maximum current-carrying capacity of conductors based on the type of material from which they are made, the type of insulation, and the surrounding air temperature (ambient temperature). The correction factors listed have a value less than 1 for any temperature greater than 30°C (86°F) because conductors become more resistive as temperature increases. This reduces the amount of current they can safely carry.

When determining the conductor size needed for a particular application, you are not determining the maximum current a conductor can carry. You are determining the size conductor needed to carry the amount of current for the particular application. Therefore, when determining conductor size in an area where ambient temperature is a concern, you must divide the needed current by the correction factor instead of multiplying by it. Dividing by the correction factor will

EXAMPLE 11-8

An electric annealing oven is located in an area with an ambient temperature of 125°F. The oven contains a 50-kW electric heating element and is connected to 480 volts. The conductors are to be copper with type THHN insulation. The termination temperature is not known. The furnace is expected to operate more than three hours continuously. What size conductor should be employed to make this connection?

Solution

Determine the amount of current needed to operate the furnace.

$$I = \frac{P}{E}$$

$$I = \frac{50{,}000}{480}$$

$$I = 104.167 \text{ amperes}$$

Because the load is continuous, it must be increased by 125%:

$$104.167 \times 1.25 = 130.2 \text{ amperes}$$

The next step is to apply the correction factor for temperature. Type THHN insulation is located in the 90°C column. The correction factor for a temperature of 125°F is 0.76, as shown in *Figure 11-10*. To determine the current rating of the conductor at 125°F, divide the current by the correction factor:

$$I = \frac{130.2}{0.76}$$

$$I = 171.3 \text{ amperes}$$

Because the termination temperature is not known and the current is over 100 amperes, the conductor size will be selected from the 75°C column of *NEC Table 310.15(B)(16).* A 2/0 AWG conductor will be used.

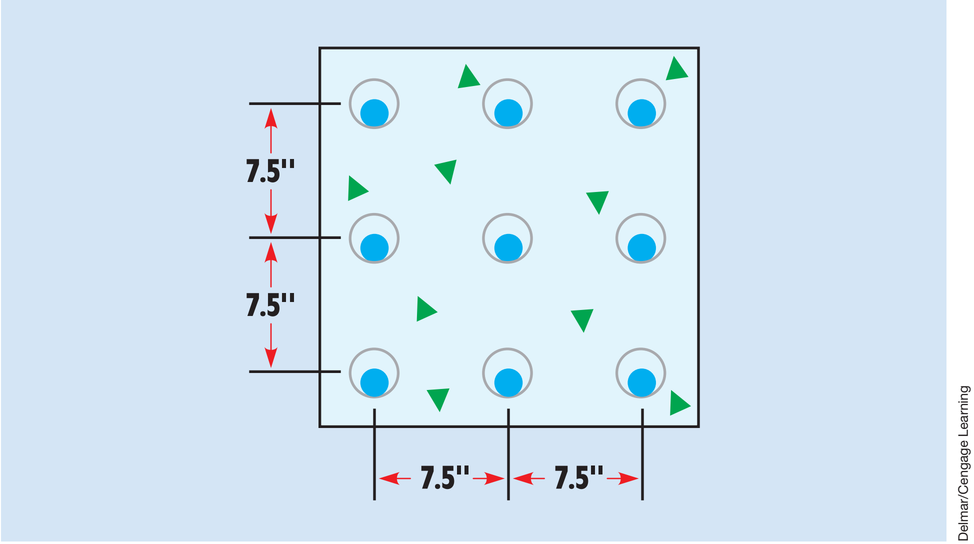

FIGURE 11–12 Electric duct banks.

result in an increase of the amperage used in selecting the conductor size. This increase is needed to offset the effects of higher temperature on the conductor.

Duct Banks

Duct banks are often used when it becomes necessary to bury cables in the ground. An electric duct can be a single metallic or nonmetallic conduit. An electric duct bank is a group of electric ducts buried together as shown in *Figure 11–12*. When a duct bank is used, the center points of individual ducts should be separated by a distance of not less than 7.5 inches.

11–5 Calculating Conductor Sizes and Resistance

Although the wire tables in the *NEC* are used to determine the proper size wire for most installations, there are instances in which these tables are not used. The formula in *310.15(c)* of the *NEC* is used for ampacities not listed in the wire tables:

$$I = \sqrt{\frac{TC - (TA + \Delta TD)}{RDC(1 + YC)RCA}}$$

where

$$TC = \text{conductor temperature in } ^\circ C$$
$$TA = \text{ambient temperature in } ^\circ C$$
$$\Delta TD = \text{dielectric loss temperature rise}$$
$$RDC = \text{DC resistance of conductor at temperature TC}$$

YC = component AC resistance resulting from skin effect and proximity effect

RCA = effective thermal resistance between conductor and surrounding ambient

Although this formula is seldom used by electricians, the *NEC* does permit its use under the supervision of an electrical engineer.

Long Wire Lengths

Another situation in which it becomes necessary to calculate wire sizes instead of using the tables in the *Code* is when the conductor becomes excessively long. The listed ampacities in the *Code* tables assume that the length of the conductor will not increase the resistance of the circuit by a significant amount. When the wire becomes extremely long, however, it is necessary to calculate the size of wire needed.

All wire contains resistance. As wire is added to a circuit, it has the effect of adding resistance in series with the load (*Figure 11–13*). Four factors determine the resistance of a length of wire:

1. *The type material from which the wire is made.* Different types of material have different wire resistances. A copper conductor will have less resistance than an aluminum conductor of the same size and length. An aluminum conductor will have less resistance than a piece of iron wire the same size and length.

2. *The diameter of the conductor.* The larger the diameter, the less resistance it will have. A large-diameter pipe, for example, will have less resistance to the flow of water than will a small-diameter pipe *(Figure 11–14)*. The cross-sectional area of round wire is measured in circular mils (CM). One mil equals 0.001 inch. A **circular mil** is the cross-sectional area of the wire in mils squared. For example, assume a wire has a diameter of 0.064 inch. Sixty-four thousandths should be written as a whole number, not as a decimal or a fraction (64^2 [64 mil × 64 mil] = 4096 CM).

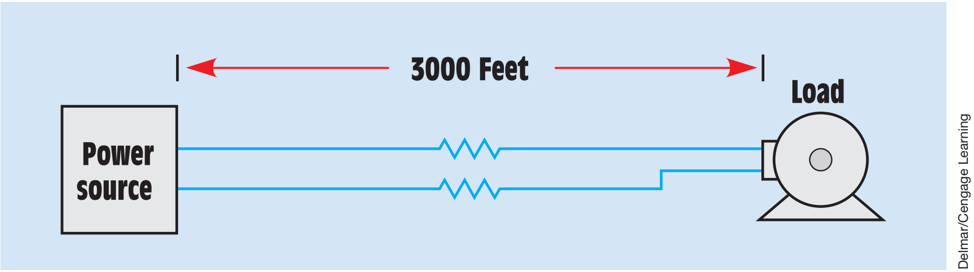

FIGURE 11–13 Long wire runs have the effect of adding resistance in series with the load.

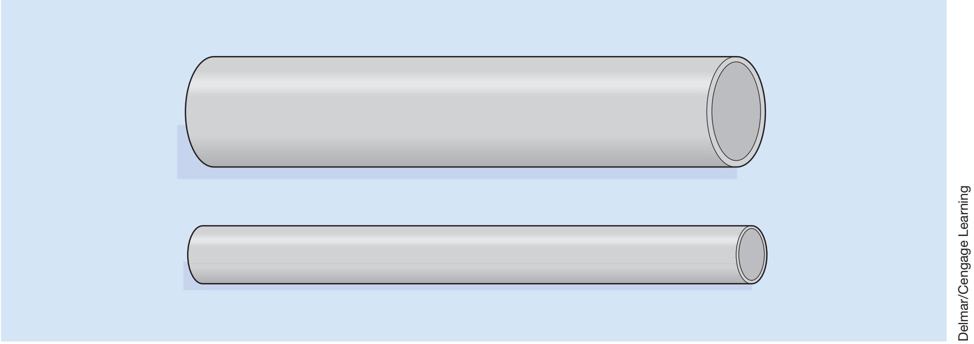

FIGURE 11–14 A large pipe has less resistance to the flow of water than a small pipe.

3. *The length of the conductor.* The longer the conductor, the more resistance it will have. Adding length to a conductor has the same effect as connecting resistors in series.

4. *The temperature of the conductor.* As a general rule, most conductive materials will increase their resistance with an increase of temperature. Some exceptions to this rule are carbon, silicon, and germanium. If the coefficient of temperature for a particular material is known, its resistance at different temperatures can be calculated. Materials that increase their resistance with an increase of temperature have a positive coefficient of temperature. Materials that decrease their resistance with an increase of temperature have a negative coefficient of temperature.

In the English system of measure, a standard value of resistance called the **mil-foot** is used to determine the resistance of different lengths and sizes of wire. A mil-foot is a piece of wire 1 foot long and 1 mil in diameter *(Figure 11–15)*. A chart showing the resistance of a mil-foot of wire at 20°C

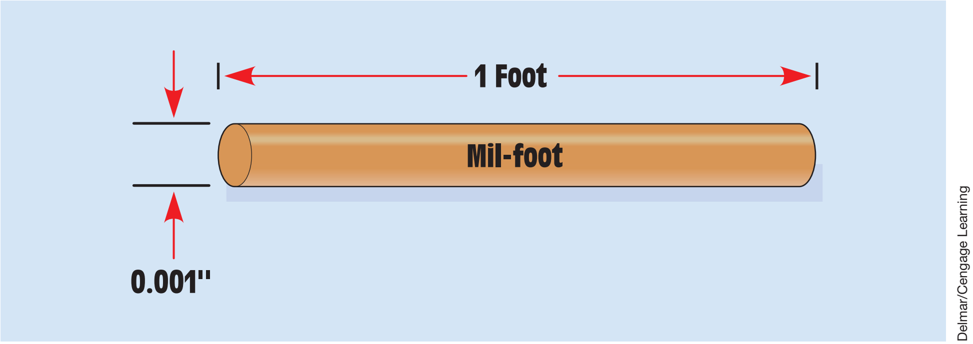

FIGURE 11–15 A mil-foot is equal to a piece of wire one foot long and one thousandth of an inch in diameter.

Resistivity (K) of Materials

Material	Ω = CM ft at 20°C	Temp. coeff. (Ω per °C)
Aluminum	17	0.004
Carbon	22,000 aprx.	−0.0004
Constantan	295	0.000002
Copper	10.4	0.0039
Gold	14	0.004
Iron	60	0.0055
Lead	126	0.0043
Manganin	265	0.000000
Mercury	590	0.00088
Nichrome	675	0.0002
Nickel	52	0.005
Platinum	66	0.0036
Silver	9.6	0.0038
Tungsten	33.8	0.005

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FIGURE 11–16 Resistivity of materials.

is shown in *Figure 11–16*. Notice the wide range of resistances for different materials. The temperature coefficient of the different types of conductors is listed also.

Calculating Resistance

Now that a standard measure of resistance for different types of materials is known, the resistance of different lengths and sizes of these materials can be calculated. The formula for calculating resistance of a certain length, size, and type of wire is

$$R = \frac{K \times L}{CM}$$

where

R = resistance of the wire

K = ohms-CM per foot

$$L = \text{length of wire in feet}$$
$$CM = \text{circular mil (area of the wire)}$$

This formula can be converted to calculate other values in the formula such as, to find the SIZE of wire to use

$$CM = \frac{K \times L}{R}$$

to find the LENGTH of wire to use

$$L = \frac{R \times CM}{K}$$

to find the TYPE of wire to use

$$K = \frac{R \times CM}{L}$$

EXAMPLE 11–9

Find the resistance of a piece of 6 AWG copper wire 550 ft long. Assume a temperature of 20°C. The formula to be used is

$$R = \frac{K \times L}{CM}$$

Solution

The value for K can be found in the table in *Figure 11–16*. The table indicates a value of 10.4 Ω-CM per foot for a copper conductor. The length, L, was given as 550 ft, and the circular mil area of 6 AWG wire is listed as 26,250 in the table shown in *Figure 11–17*.

$$R = \frac{10.4\ \Omega\text{-CM/ft} \times 550\text{ft}}{26{,}250\ \text{CM}}$$

$$R = \frac{5720\ \Omega\text{-CM}}{26{,}250\ \text{CM}}$$

$$R = 0.218\ \Omega$$

American Wire Gauge Table												
B & S Gauge No.	Diam. in Mils	Area in Circular Mils	Ohms per 1000 Ft. (ohms per 100 meters)						Pounds per 1000 Ft. (kg per 100 meters)			
			Copper*		Copper*		Aluminum		Copper		Aluminum	
			68°F	(20°C)	167°F	(75°C)	68°F	(20°C)				
0000	460	211,600	0.049	(0.016)	0.0596	(0.0195)	0.0804	(0.0263)	640	(95.2)	195	(29.0)
000	410	167,800	0.0618	(0.020)	0.0752	(0.0246)	0.101	(0.033)	508	(75.5)	154	(22.9)
00	365	133,100	0.078	(0.026)	0.0948	(0.031)	0.128	(0.042)	403	(59.9)	122	(18.1)
0	325	105,500	0.0983	(0.032)	0.1195	(0.0392)	0.161	(0.053)	320	(47.6)	97	(14.4)
1	289	83,690	0.1239	(0.0406)	0.151	(0.049)	0.203	(0.066)	253	(37.6)	76.9	(11.4)
2	258	66,370	0.1563	(0.0512)	0.191	(0.062)	0.256	(0.084)	201	(29.9)	61.0	(9.07)
3	229	52,640	0.1970	(0.0646)	0.240	(0.079)	0.323	(0.106)	159	(23.6)	48.4	(7.20)
4	204	41,740	0.2485	(0.0815)	0.302	(0.099)	0.408	(0.134)	126	(18.7)	38.4	(5.71)
5	182	33,100	0.3133	(0.1027)	0.381	(0.125)	0.514	(0.168)	100	(14.9)	30.4	(4.52)
6	162	26,250	0.395	(0.129)	0.481	(0.158)	0.648	(0.212)	79.5	(11.8)	24.1	(3.58)
7	144	20,820	0.498	(0.163)	0.606	(0.199)	0.817	(0.268)	63.0	(9.37)	19.1	(2.84)
8	128	16,510	0.628	(0.206)	0.764	(0.250)	1.03	(0.338)	50.0	(7.43)	15.2	(2.26)
9	114	13,090	0.792	(0.260)	0.963	(0.316)	1.30	(0.426)	39.6	(5.89)	12.0	(1.78)
10	102	10,380	0.999	(0.327)	1.215	(0.398)	1.64	(0.538)	31.4	(4.67)	9.55	(1.42)
11	91	8,234	1.260	(0.413)	1.532	(0.502)	2.07	(0.678)	24.9	(3.70)	7.57	(1.13)
12	81	6,530	1.588	(0.520)	1.931	(0.633)	2.61	(0.856)	19.8	(2.94)	6.00	(0.89)
13	72	5,178	2.003	(0.657)	2.44	(0.80)	3.29	(1.08)	15.7	(2.33)	4.80	(0.71)
14	64	4,107	2.525	(0.828)	3.07	(1.01)	4.14	(1.36)	12.4	(1.84)	3.80	(0.56)
15	57	3,257	3.184	(1.044)	3.98	(1.27)	5.22	(1.71)	9.86	(1.47)	3.00	(0.45)
16	51	2,583	4.016	(1.317)	4.88	(1.60)	6.59	(2.16)	7.82	(1.16)	2.40	(0.36)
17	45.3	2,048	5.06	(1.66)	6.16	(2.02)	8.31	(2.72)	6.20	(0.922)	1.90	(0.28)
18	40.3	1,624	6.39	(2.09)	7.77	(2.55)	10.5	(3.44)	4.92	(0.713)	1.50	(0.22)
19	35.9	1,288	8.05	(2.64)	9.79	(3.21)	13.2	(4.33)	3.90	(0.580)	1.20	(0.18)
20	32	1,022	10.15	(3.33)	12.35	(4.05)	16.7	(5.47)	3.09	(0.459)	0.94	(0.14)
21	28.5	810	12.8	(4.2)	15.6	(5.11)	21.0	(6.88)	2.45	(0.364)	0.745	(0.11)
22	25.4	642	16.1	(5.3)	19.6	(6.42)	26.5	(8.69)	1.95	(0.290)	0.591	(0.09)
23	22.6	510	20.4	(6.7)	24.8	(8.13)	33.4	(10.9)	1.54	(0.229)	0.468	(0.07)
24	20.1	404	25.7	(8.4)	31.2	(10.2)	42.1	(13.8)	1.22	(0.181)	0.371	(0.05)
25	17.9	320	32.4	(10.6)	39.4	(12.9)	53.1	(17.4)	0.97	(0.14)	0.295	(0.04)
26	15.9	254	40.8	(13.4)	49.6	(16.3)	67.0	(22.0)	0.77	(0.11)	0.234	(0.03)
27	14.2	202	51.5	(16.9)	62.6	(20.5)	84.4	(27.7)	0.61	(0.09)	0.185	(0.03)
28	12.6	160	64.9	(21.3)	78.9	(25.9)	106	(34.7)	0.48	(0.07)	0.147	(0.02)
29	11.3	126.7	81.8	(26.8)	99.5	(32.6)	134	(43.9)	0.384	(0.06)	0.117	(0.02)
30	10	100.5	103.2	(33.8)	125.5	(41.1)	169	(55.4)	0.304	(0.04)	0.092	(0.01)
31	8.93	79.7	130.1	(42.6)	158.2	(51.9)	213	(69.8)	0.241	(0.04)	0.073	(0.01)
32	7.95	63.2	164.1	(53.8)	199.5	(65.4)	269	(88.2)	0.191	(0.03)	0.058	(0.01)
33	7.08	50.1	207	(68)	252	(82.6)	339	(111)	0.152	(0.02)	0.046	(0.01)
34	6.31	39.8	261	(86)	317	(104)	428	(140)	0.120	(0.02)	0.037	(0.01)
35	5.62	31.5	329	(108)	400	(131)	540	(177)	0.095	(0.01)	0.029	
36	5	25	415	(136)	505	(165)	681	(223)	0.076	(0.01)	0.023	
37	4.45	19.8	523	(171)	636	(208)	858	(281)	0.0600	(0.01)	0.0182	
38	3.96	15.7	660	(216)	802	(263)	1080	(354)	0.0476	(0.01)	0.0145	
39	3.53	12.5	832	(273)	1012	(332)	1360	(446)	0.0377	(0.01)	0.0115	
40	3.15	9.9	1049	(344)	1276	(418)	1720	(564)	0.0299	(0.01)	0.0091	
41	-											
42	2.5											
43	-											
44	1.97											

* Resistance figures are given for standard annealed copper. For hard-drawn copper add 2%

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FIGURE 11–17 American Wire Gauge table.

EXAMPLE 11–10

An aluminum wire 2250 ft long cannot have a resistance greater than 0.2 Ω. What size aluminum wire must be used?

Solution

To find the size of wire, use

$$CM = \frac{K \times L}{R}$$

$$CM = \frac{17\ \Omega\text{-CM/ft} \times 2250\ \text{ft}}{0.2\ \Omega}$$

$$CM = \frac{38{,}250\ \Omega\text{-CM}}{0.2\ \Omega}$$

$$CM = 191{,}250$$

The nearest standard size conductor for this installation can be found in the American Wire Gauge table. Because the resistance cannot be greater than 0.2 Ω, the conductor cannot be smaller than 191,250 CM. The nearest standard conductor size is 0000 AWG.

Good examples of when it becomes necessary to calculate the wire size for a particular installation can be seen in the following problems.

EXAMPLE 11–11

A manufacturing plant has a cooling pond located 4000 ft from the plant. Six pumps are used to circulate water between the pond and the plant. In cold weather, however, the pumps can freeze and fail to supply water. The plant owner decides to connect electric-resistance heaters to each pump to prevent this problem. The six heaters are connected to a two-conductor cable from the plant at a junction box *(Figure 11–18)*. The heaters operate on 480 V and have a total current draw of 50 A. What size copper conductors should be used to supply power to the heaters if the voltage drop at the junction box is to be kept to 3% of the applied voltage? Assume an average ambient temperature of 20°C.

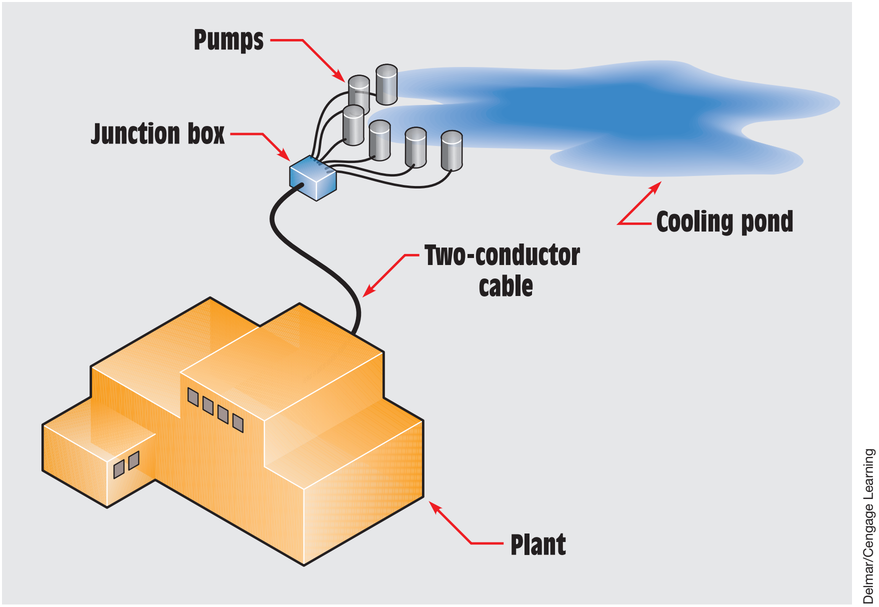

FIGURE 11–18 Calculating long wire lengths.

Solution

The first step in the solution of this problem is to determine the maximum amount of resistance the conductors can have without producing a voltage drop greater than 3% of the applied voltage. The maximum amount of voltage drop can be calculated by multiplying the applied voltage by 3%:

$$480\text{ V} \times 0.03 = 14.4\text{ V}$$

The maximum amount of resistance can now be calculated using Ohm's law:

$$R = \frac{E}{I}$$

$$R = \frac{14.4\text{ V}}{50\text{ A}}$$

$$R = 0.288\ \Omega$$

The distance to the pond is 4000 ft. Because two conductors are used, the resistance of both conductors must be considered. Two conductors 4000 ft long will have the same resistance as one conductor 8000 ft long. For this reason, a length of 8000 ft is used in the formula:

$$CM = \frac{K \times L}{R}$$

$$CM = \frac{10.4\ \Omega\text{-CM/ft} \times 8000\ \text{ft}}{0.288\ \Omega}$$

$$CM = \frac{83{,}200\ \Omega\text{-CM}}{0.288\ \Omega}$$

$$CM = 288{,}888.9$$

For this installation 300-kcmil (thousand circular mils) cable will be used.

EXAMPLE 11-12

The next problem concerns conductors used in a three-phase system. Assume that a motor is located 2500 ft from its power source and operates on 560 V. When the motor starts, it has a current draw of 168 A. The voltage drop at the motor terminals cannot be permitted to be greater than 5% of the source voltage during starting. What size aluminum conductors should be used for this installation?

Solution

The solution to this problem is very similar to the solution in the previous example. First, find the maximum voltage drop that can be permitted at the load by multiplying the source voltage by 5%:

$$E = 560\ \text{V} \times 0.05$$

$$E = 28\ \text{V}$$

The second step is to determine the maximum amount of resistance of the conductors. To calculate this value, the maximum voltage drop is divided by the starting current of the motor:

$$R = \frac{E}{I}$$

$$R = \frac{28\ \text{V}}{168\ \text{A}}$$

$$R = 0.167\ \Omega$$

The next step is to calculate the length of the conductors. In the previous example, the lengths of the two conductors were added to find the total amount of wire resistance. In a single-phase system, each conductor must carry the same amount of current. During any period of time, one conductor is supplying current from the source to the load, and the other conductor completes the circuit by permitting the same amount of current to flow from the load to the source.

In a balanced three-phase circuit, three currents are 120° out of phase with each other *(Figure 11–19)*. These three conductors share the flow of current between source and load. In *Figure 11–19*, two lines labeled A and B have been drawn through the three current waveforms. Notice that at position A the current flow in phase 1 is maximum and in a positive direction. The current flow in phases 2 and 3 is less than maximum and in a negative direction. This condition corresponds to the example shown in *Figure 11–20*. Notice that maximum current is flowing in only one conductor. Less than maximum current is flowing in the other two conductors.

Observe the line marking position B in *Figure 11–19*. The current flow in phase 1 is zero, and the currents flowing in phases 2 and 3 are in opposite directions and less than maximum. This condition of current flow is illustrated in *Figure 11–21*. Notice that only two of the three phase lines are conducting current and that the current in each line is less than maximum.

Because the currents flowing in a three-phase system are never maximum at the same time, and at other times the current is divided between two phases, the total conductor resistance will not be the sum of two conductors. To calculate

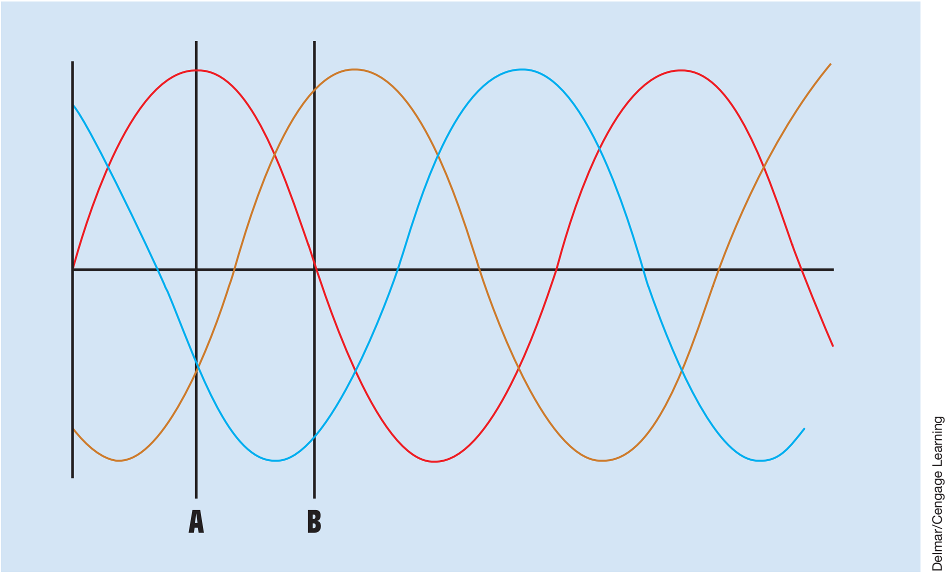

FIGURE 11–19 The line currents in a three-phase system are 120° out of phase with each other.

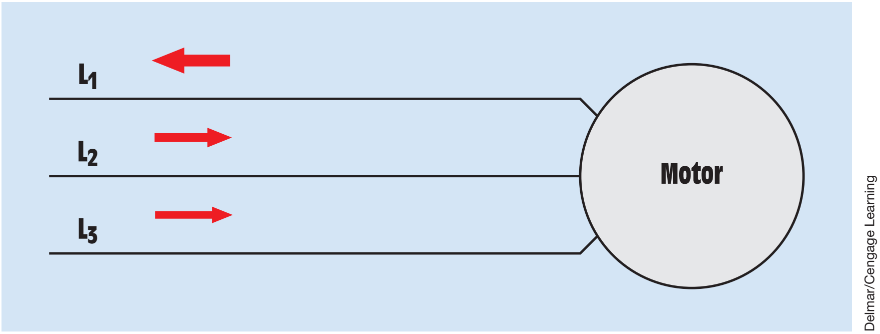

FIGURE 11–20 Current flows from lines 2 and 3 to line 1.

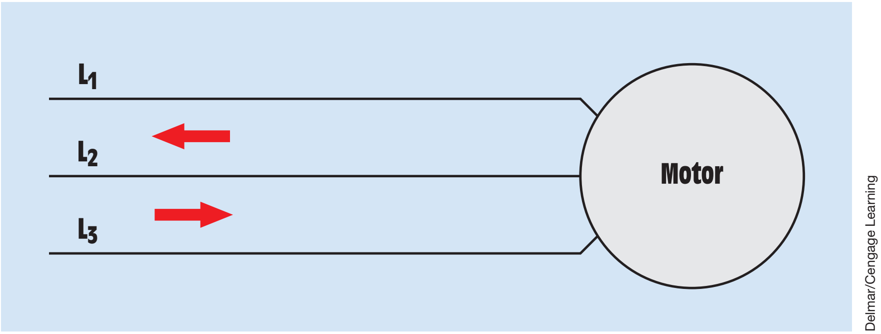

FIGURE 11–21 Current flows from line 3 to line 2.

the resistance of conductors in a three-phase system, a demand factor of 0.866 is used.

In this problem, the motor is located 2500 ft from the source. The conductor length is calculated by doubling the length of one conductor and then multiplying by 0.866:

$$L = 2500 \text{ ft} \times 2 \times 0.866$$
$$L = 4330 \text{ ft}$$

Now that all the factors are known, the size of the conductor can be calculated using the formula

$$CM = \frac{K \times L}{R}$$

where

$$K = \frac{17\ \Omega\text{-CM}}{\text{ft}}$$

$$L = 4{,}330\ \text{ft}$$

$$R = 0.167\ \Omega$$

$$CM = \frac{17\ \Omega\text{-CM/ft} \times 4330\ \text{ft}}{0.167\ \Omega}$$

$$CM = \frac{73{,}601\ \Omega\text{-CM}}{0.167\ \Omega}$$

$$CM = 440{,}778.443$$

Three 500-kcmil conductors will be used.

11–6 Calculating Voltage Drop

Sometimes it is necessary to calculate the voltage drop of an installation when the length, size of wire, and current are known. The following formula can be used to find the voltage drop of conductors used on a single-phase system:

$$E_D = \frac{2\ KIL}{CM}$$

where

E_D = voltage drop
K = ohms per mil ft
I = current
L = length of conductor in ft
CM = circular mil area of the conductor

EXAMPLE 11–13

A single-phase motor is located 250 ft from its power source. The conductors supplying power to the motor are 10 AWG copper. The motor has a full-load current draw of 24 A. What is the voltage drop across the conductors when the motor is in operation?

Solution

$$E_D = \frac{2 \times 10.4\ \Omega\text{-CM/ft} \times 24\ A \times 250\ ft}{10{,}380\ CM}$$

$$E_D = 12.023\ V$$

A slightly different formula can be used to calculate the voltage drop on a three-phase system. Instead of multiplying KIL by 2, multiply KIL by the square root of 3:

$$E_D = \frac{\sqrt{3}\ KIL}{CM}$$

EXAMPLE 11–14

A three-phase motor is located 175 ft from its source of power. The conductors supplying power to the motor are 1/0 AWG aluminum. The motor has a full-load current draw of 88 A. What is the voltage drop across the conductors when the motor is operating at full load?

Solution

$$E_D = \frac{1.732 \times 17\ \Omega\text{-CM/ft} \times 98\ A \times 175}{105.500\ CM}$$

$$E_D = 4.298\ V$$

Coefficient of Temperature

The temperature of a conductor can greatly affect its resistance. Figure 11–16 lists the ohms-per-mil foot (K) at 20°C for various materials. The resistance of a material is generally given at 20°C because it is the standard used in the *American Engineers Handbook* and is considered a standard throughout the United States. The temperature coefficient can be used to determine the resistance of a material at different temperatures. Most conductors will increase their resistance with an increase of temperature. Semiconductor materials such as silicon, germanium, and carbon will exhibit a decrease of resistance with an increase of temperature. These materials have a negative coefficient of temperature.

EXAMPLE 11–15

Determine the ohms-per-mil foot at 75°C for a copper conductor?

Solution

Use the formula

$$R = R_{ref}[1 + \alpha(T - T_{ref})]$$

where

R = Conductor resistance at temperature "T"

R_{ref} = Conductor resistance at reference temperature (20°C in this example)

α = Coefficient of resistance for the conductor material

T = Conductor temperature in °C

T_{ref} = Reference temperature that α is specified at for the conductor material.

$$R = 10.4[1 + 0.0039(75 - 20)]$$
$$R = 10.4[1 + 0.0039(55)]$$
$$R = 10.4[1 + 0.2145]$$
$$R = 10.4[1.2145]$$
$$R = 12.63$$

At a temperature of 75°C, copper would have a resisance of 12.63 ohms-per-mil foot.

11–7 Parallel Conductors

Under certain conditions, it may become necessary or advantageous to connect conductors in parallel. One such condition for **parallel conductors** is when the conductor is very large as in the earlier example, where it was calculated that the conductors supplying a motor 2500 feet from its source would have to be 500 kcmil. A 500-kcmil conductor is very large and difficult to handle. Therefore, it may be preferable to use parallel conductors for this installation. The *NEC* lists five conditions that must be met when conductors are connected in parallel *(310.10 (H))*. These conditions are listed here:

1. The conductors must be the same length.
2. The conductors must be made of the same material. For example, all parallel conductors must be either copper or aluminum. It is not permissible to use copper for one of the conductors and aluminum for the other.
3. The conductors must have the same circular mil area.
4. The conductors must use the same type of insulation.
5. The conductors must be terminated or connected in the same manner.

In the example, the actual conductor size needed was calculated to be 440,778.443 CM. This circular mil area could be obtained by connecting two 250-kcmil conductors in parallel for each phase, or three 000 (3/0) conductors in parallel for each phase. [Note: Each 000 (3/0) conductor has an area of 167,800 CM. This is a total of 503,400 CM.]

Another example of when it may be necessary to connect wires in parallel is when conductors of a large size must be run in a conduit. Conductors of a single phase are not permitted to be run in metallic conduits as shown in *Figure 11–22* [*NEC 300.5(I), NEC 300.20(A),* and *NEC 300.20(B)*], because when current flows through a conductor, a magnetic field is produced around the conductor. In an AC circuit, the current continuously changes direction and magnitude, which causes the magnetic field to cut through the wall of the metal conduit *(Figure 11–23)*. This cutting action of the magnetic field induces a current, called an *eddy current,* into the metal of the conduit. Eddy currents are currents that are induced into metals. They tend to move in a circular fashion similar to the eddies of a river, hence the name eddy currents *(Figure 11–24)*. Eddy currents can produce enough heat in high-current circuits to melt the insulation surrounding the conductors. All metal conduits can

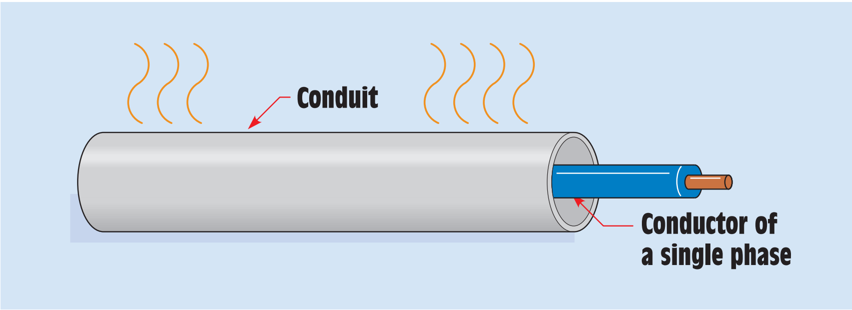

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FIGURE 11–22 A single-phase conductor causes heat to be produced in the conduit.

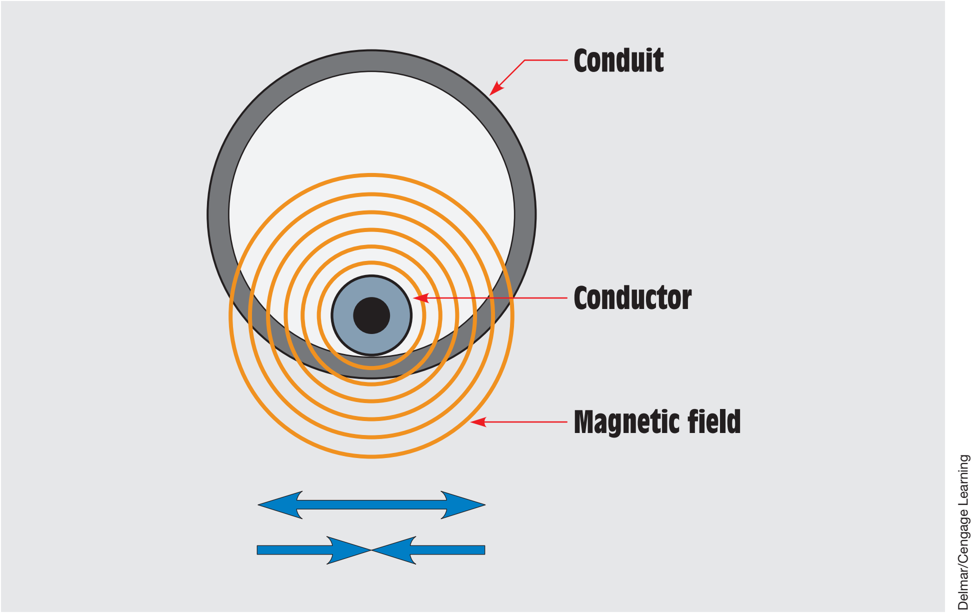

FIGURE 11–23 The magnetic field expands and contracts.

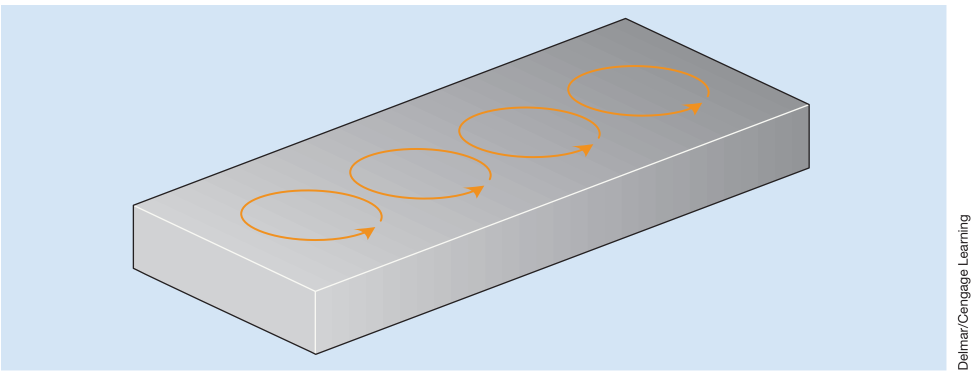

FIGURE 11–24 Eddy currents are currents induced in metals.

have eddy current induction, but conduits made of magnetic materials such as steel have an added problem with hysteresis loss. Hysteresis loss is caused by molecular friction *(Figure 11–25)*. As the direction of the magnetic field reverses, the molecules of the metal are magnetized with the opposite polarity and swing to realign themselves. This continuous aligning and realigning of the molecules produces heat caused by friction. Hysteresis losses become greater with an increase in frequency.

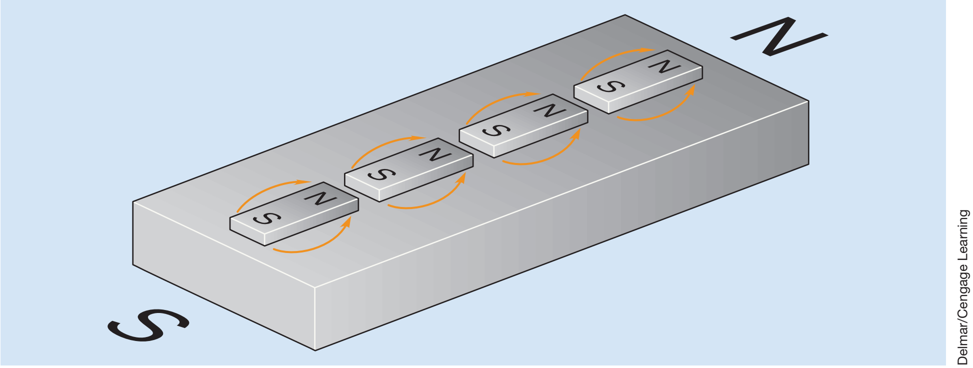

FIGURE 11–25 The molecules reverse direction each time the magnetic field changes direction.

To correct this problem, a conductor of each phase must be run in each conduit *(Figure 11–26)*. When all three phases are contained in a single conduit, the magnetic fields of the separate conductors cancel each other resulting in no current being induced in the walls of the conduit.

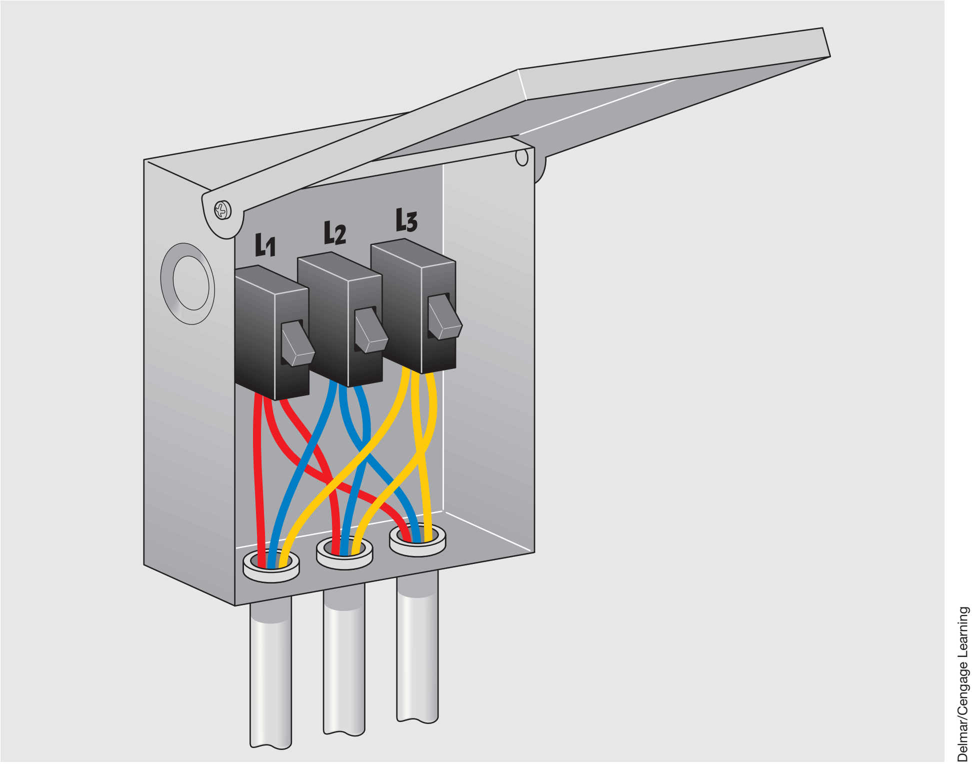

FIGURE 11–26 Each conduit contains a conductor from each phase. This permits the magnetic fields to cancel each other.

11–8 Testing Wire Installations

After the conductors have been installed in conduits or raceways, it is accepted practice to test the installation for grounds and shorts. This test requires an ohmmeter, which not only measures resistance in millions of ohms but also provides a high enough voltage to ensure that the insulation will not break down when rated line voltage is applied to the conductors. Most ohmmeters operate with a maximum voltage that ranges from 1.5 volts to about 9 volts depending on the type of ohmmeter and the setting of the range scale. To test wire insulation, a special type of ohmmeter, called a **MEGGER,** is used. The MEGGER is a megohmmeter that can produce voltages that range from about 250 to 5000 volts depending on the model of the meter and the range setting. One model of a MEGGER is shown in *Figure 11–27*. This instrument contains a hand crank that is connected to the rotor of a brushless AC generator. The advantage of this particular instrument is that it does not require the use of batteries. A range-selector switch permits the meter to be used as a standard ohmmeter or as a megohmmeter. When it is used as a megohmmeter, the selector switch permits the test voltage to be selected. Test voltages of 100 volts, 250 volts, 500 volts, and 1000 volts can be obtained.

MEGGER can also be obtained in battery-operated models *(Figure 11–28)*. These models are small, lightweight, and particularly useful when it becomes necessary to test the dielectric of a capacitor.

Wire installations are generally tested for two conditions, shorts and grounds. Shorts are current paths that exist between conductors. To test an installation for shorts, the MEGGER is connected across two conductors at a time *(Figure 11–29)*. The circuit is tested at rated voltage or slightly higher. The MEGGER indicates the resistance between the two conductors. Because both conductors are insulated, the resistance between them should

Courtesy of Megger

FIGURE 11–27 A hand-crank MEGGER.

Courtesy of Megger

FIGURE 11–28 Battery-operated MEGGER.

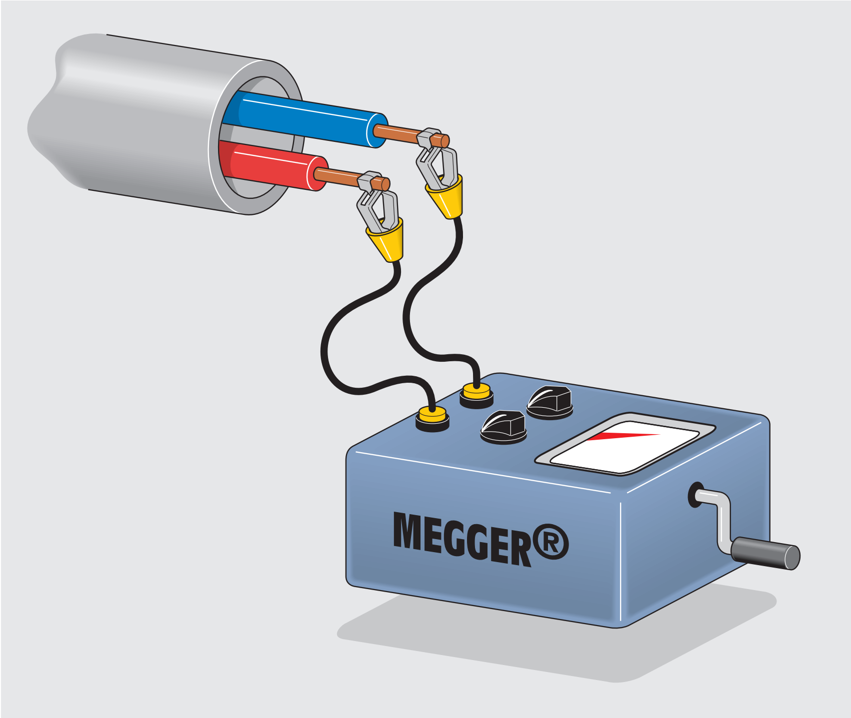

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FIGURE 11–29 Testing for shorts with a MEGGER.

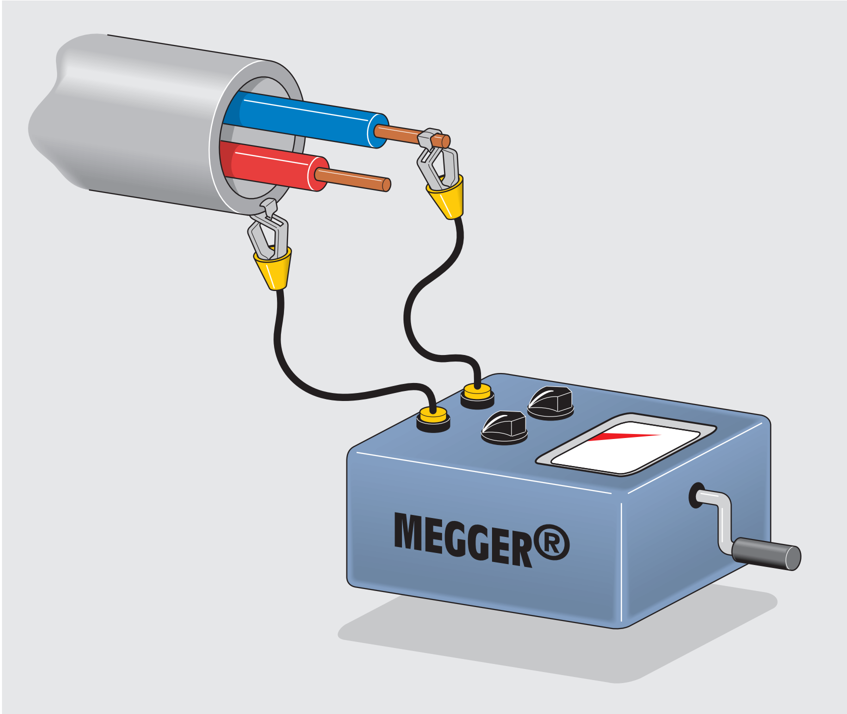

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FIGURE 11–30 Testing for grounds with a MEGGER.

be extremely high. Each conductor should be tested against every other conductor in the installation.

To test the installation for grounds, one lead of the MEGGER is connected to the conduit or raceway *(Figure 11–30)*. The other meter lead is connected to one of the conductors. The conductor should be tested at rated voltage or slightly higher. Each conductor should be tested.

Summary

- The *NEC* is used to determine the wire size for most installations.
- The resistance of a wire is determined by four factors:

  a. the type of material from which the conductor is made

  b. the length of the conductor

  c. the area of the conductor

  d. the temperature of the conductor

- When conductors are used in high-temperature locations, their current capacity must be reduced.
- When there are more than three conductors in a raceway, their current-carrying capacity must be reduced.
- The amount of current a conductor can carry is affected by the type of insulation around the wire.
- In the English system, the mil foot is used as a standard for determining the resistance of different types of wire.
- After wires have been installed, they should be checked for shorts or grounds with a MEGGER.

Review Questions

Use of the *NEC* will be required to answer some of the following questions.

1. What is the maximum temperature rating of Type XHHW insulation when used in a wet location?
2. Name two types of conductor insulation designed to be used underground.
3. A 10 AWG copper conductor with Type THW insulation is to be run in free air. What is the maximum ampacity of this conductor if the ambient air temperature is 40°C?
4. Six 1/0 aluminum conductors are to be run in a conduit. Each conductor has Type THWN insulation, and the ambient air temperature is 30°C. What is the ampacity of each conductor?
5. Name five conditions that must be met for running conductors in parallel.
6. What is the largest solid (nonstranded) conductor listed in the wire tables?
7. Can Type TW cable be used in an area that has an ambient temperature of 65°C?
8. How is the grounded conductor in a flat multiconductor cable 4 or larger identified?
9. What three colors are ungrounded conductors not permitted to be?
10. Twenty-five 12 AWG copper conductors are run in conduit. Each conductor has Type THHN insulation. The conduit is located in an area that has an ambient temperature of 95°F. What is the ampacity of each conductor?

11. A single-phase load is located 2800 ft from its source. The load draws a current of 86 A and operates on 480 V. The maximum voltage drop at the load cannot be greater than 3%. What size aluminum conductors should be installed to operate this load?

12. It is decided to use parallel 0000 conductors to supply the load in Question 11. How many 0000 conductors will be needed?

13. A three-phase motor operates on 480 V and is located 1800 ft from the power source. The starting current is 235 A. What size copper conductors will be needed to supply this load if the voltage must not be permitted to drop below 6% of the terminal voltage during starting?

Practical Applications

You have been hired by a company to connect an outside lighting system to a panel box located 55 ft from the point of attachment. The conductors are to have Type THWN-2 insulation and the wire is copper. The termination temperature of the connections is not known. The lighting system is rated at 20 kW. The voltage is 240 V. Because the lights are expected to operate more than three hours at a time, they are considered continuous duty. Using the *NEC*, determine the wire size needed to make this connection. ■

Practical Applications

You are a journeyman electrician in an industrial plant. You have been assigned the task of connecting a 25-kW electric heater to a 240-V, single-phase panel. The heater is located in an area with an ambient temperature of 90°F. The conductors are to be copper with Type TW insulation. The heater is expected to operate for more than three hours at a time. What size conductors would you use to connect this heater? ■

Practical Applications

You are an electrician working in an industrial plant. The company is constructing a maintenance shop located 225 feet from the main plant electrical system. You are to install a 400-ampere three-phase wire system in the new maintenance shop. The service is supplied by the existing plant service. The voltage is 480 volts and the voltage drop is to be kept at 3% or below at full load. The conductors are to be aluminum. What size conductors should be installed for the new service? Express your answer to the nearest standard wire size. (Note: Determine the wire size by calculating length, resistance, and voltage drop as opposed to using the *National Electrical Code*.) ■

Practical Applications

Using the above example, determine the wire size needed for the 400-ampere service in accordance with the *National Electrical Code*. Assume that the conductors have type THWH insulation. (Note: As a general rule, for each 100 feet of conductor length the wire size is increased one standard size because of voltage drop.) ■

Practice Problems

Using Wire Tables and Determining Conductor Sizes

1. A 2 AWG copper conductor is 450 ft long. What is the resistance of this wire? Assume the ambient temperature to be 20°C.
2. An 8 AWG conductor is 500 ft long and has a resistance of 1.817 Ω. The ambient temperature is 20°C. Of what material is the wire made?
3. Three 500-kcmil copper conductors with Type RHH insulation are to be used in an area that has an ambient temperature of 58°C. What is the maximum current-carrying capacity of these conductors?
4. Eight 10 AWG aluminum conductors with Type THWN insulation are installed in a single conduit. What is the maximum current-carrying capacity of these conductors? Assume an ambient temperature of 30°C.
5. A three-phase motor is connected to 480 V and has a starting current of 522 A. The motor is located 300 ft from the power source. The voltage

drop to the motor cannot be greater than 5% during starting. What size copper conductors should be connected to the motor?

6. A 50-hp DC motor is connected to 250 volts. The motor does not contain a NEMA code. The motor is expected to operate for more than three hours at a time. The conductors are to be copper with type RHW-2 insulation. The motor is located in an area with an ambient temperature of 112°F. The two conductors are to be run in conduit. What size conductors should be used to connect this motor? (Note: 1 hp = 746 watts.)
7. A bank of electric heaters has a power rating of 25 kW. The heaters are connected to 480 volts. The heaters will operate for more than three hours at a time. The conductors supplying the heaters are to be aluminum with type THWN-2 insulation. The heaters are located in an area with an ambient temperature of 48°C. There will be six conductors in the conduit. What size conductors should be used for this installation?
8. A 15-hp squirrel-cage induction motor is connected to 240 volts. The motor has a NEMA code B. The motor will operate for more than three hours at a time. The motor is in an area with an ambient temperature of 86°F. There are to be three conductors in the raceway. The conductors are copper with THW-2 insulation. What size conductors should be used for this installation? (Note: 1 hp = 746 watts.)
9. Determine the resistance of a 16 AWG copper conductor located in an area with an ambient temperature of 188.6°F (87°C) with a length of 250 feet (76.2 m).
10. Determine the ohms-per-mill foot of an aluminum conductor located in an area with a temperature of 104°F (40°C).

Use the *NEC* to determine the ampacity of the following conductors.

Size	**Material**	**Insulation**	**Ambient Temperature**	**Conductors in Raceway**	**Amps**
#10 AWG	Copper	RHW	44°C	3	
350 kcmil	Copper	XHH	128°F	6	
#2 AWG	Aluminum	TW	86°F	2	
3/0 AWG	Aluminum	XHHW-2	38°C	9	
500 kcmil	Copper	THWN	48°C	6	
#6 AWG	Copper	THW-2	150°F	3	
2/0 AWG	Aluminum	UF	86°F	12	
750 kcmil	Aluminum	RHW-2	34°F	6	

IV Small Sources of Electricity

Courtesy of Getty Images, Inc.

Unit 12

Conduction in Liquids and Gases

OUTLINE

12–1 The Ionization Process: Magnesium and Chlorine
12–2 Other Types of Ions
12–3 Electroplating
12–4 Electrolysis
12–5 Conduction in Gases
12–6 Ionization in Nature

KEY TERMS

Acids
Alkalies
Anode
Arc
Cathode
Copper sulfate
Cuprous cyanide
Electrolysis
Electrolytes
Electron impact
Electroplating
Ion
Ionization potential
Metallic salt
Sulfuric acid
X-rays

Why You Need to Know

If you want to understand how batteries produce electricity, how fluorescent lights work, or how it is possible to electroplate objects, you need to have an understanding of how electricity is conducted in gases and liquids. This unit.

- explains how electricity is conducted in gases and liquids and how it is different from conduction through metals such as silver, copper, or aluminum. Whereas metals rely on the conduction of electrons, gases and liquids rely on the movement of ions.
- explains the process of separating elements electrically.
- describes what X-rays are and how they are used.
- defines the ionization potential.

Courtesy of PPG Industries, Inc.

Objectives

After studying this unit, you should be able to

- define positive and negative ions.
- discuss electrical conduction in a gas.
- discuss electrical conduction in a liquid.
- discuss several processes that occur as a result of ionization.

Preview

The conduction of electric current is generally thought of as electrons moving through a wire. Many processes, however, depend on electric current flowing through a gas or liquid. Batteries, for example, would not work if conduction could not take place through a liquid, and fluorescent lighting operates on the principle of conduction through a gas. Conduction through a gas or liquid does not depend on the flow of individual electrons as is the case with metallic conductors. Conduction in gases and liquids depends on the movement of ions. ■

12–1 The Ionization Process: Magnesium and Chlorine

An **ion** is a charged atom. Atoms that have a deficiency of electrons are known as positive ions. Atoms that have gained extra electrons are known as negative ions.

A good example of how ionization occurs can be seen by the combination of two atoms, magnesium and chlorine. The magnesium atom contains two valence electrons and is considered to be a metal. Chlorine contains seven valence electrons and is considered a nonmetal *(Figure 12–1)*.

When magnesium is heated in the presence of chlorine gas, a magnesium atom combines with two chlorine atoms to form a **metallic salt** called magnesium chloride *(Figure 12–2)*. When this process occurs, the magnesium atom gives up its two valence electrons to the two chlorine atoms. These atoms are no longer called atoms; they are now called ions. Because the magnesium atom gave up two electrons, it has a positive charge and has become a positive ion. The two chlorine atoms have each gained an electron and are now negative ions.

Magnesium chloride is similar to table salt, which is sodium chloride. Both are formed by combining a metal, sodium or magnesium, with chlorine. If either of these salts is mixed with a nonconducting liquid, such as distilled water, it will become a conductor. A simple experiment can be performed to demonstrate conduction through a liquid. In *Figure 12–3*, copper electrodes have been placed in a glass. One electrode is connected to a lamp. The other is connected to one side of a 120-volt circuit. The other side of the lamp is connected to the other side of the circuit. The lamp acts as a load to prevent the circuit from drawing excessive current. If pure water is poured into the glass,

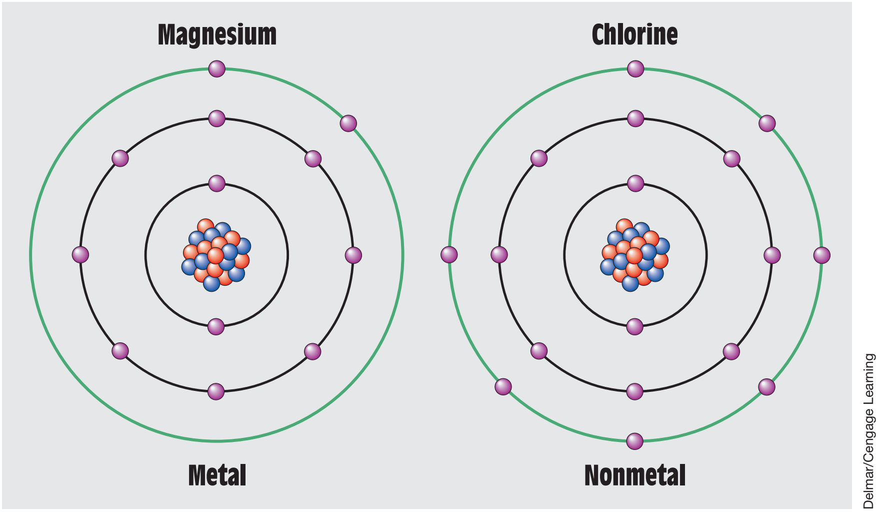

FIGURE 12–1 Magnesium and chlorine atoms.

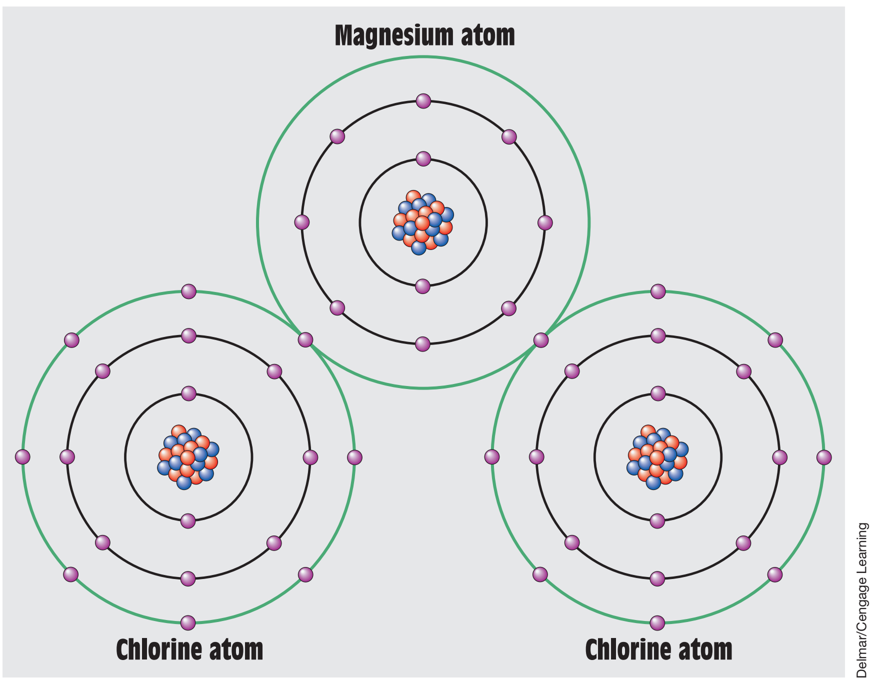

FIGURE 12–2 Magnesium and chlorine atoms combine to form magnesium chloride.

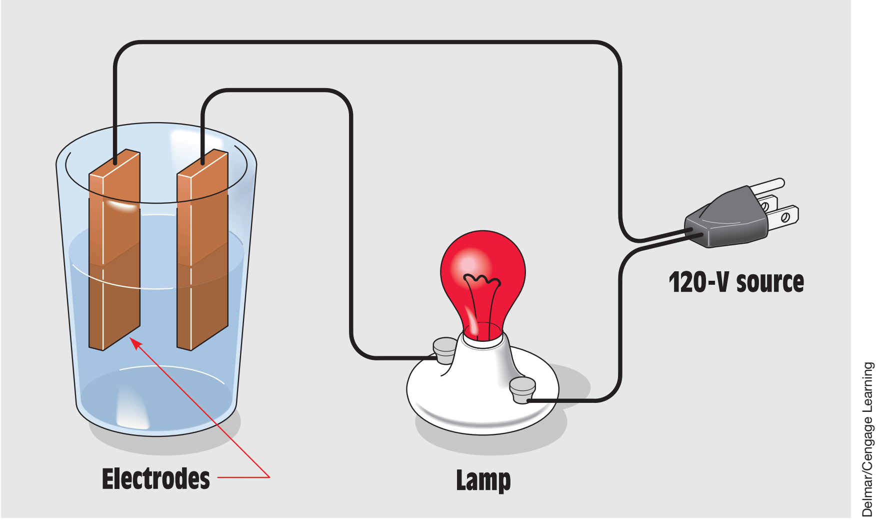

FIGURE 12–3 Conduction in a liquid.

nothing seems to happen because pure water is an insulator. If salt is added to the water, the lamp begins to glow *(Figure 12–4)*. The lamp glows dimly at first and increases in brightness as salt is added to the water. The glow continues to brighten until the solution becomes saturated with salt and current is limited by the resistance of the filament in the lamp.

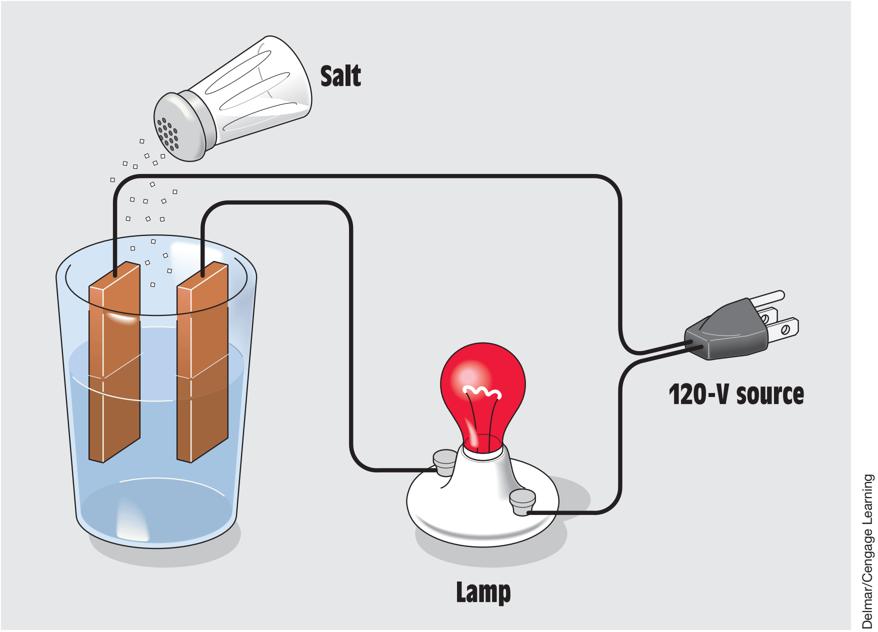

FIGURE 12–4 Adding salt to the water causes the lamp to glow.

Salt is not the only compound that can be used to promote conduction in a liquid. **Acids, alkalies,** and other types of metallic salts can be used. These solutions are often referred to as **electrolytes.**

12–2 Other Types of Ions

The ions discussed so far are formed by charging a single atom. There are other types of ions, however, that are formed from groups of atoms. These ions are extremely useful to the electric industry.

Sulfuric Acid

One of the most useful ion compounds is **sulfuric acid.** It is the electrolyte for the lead-acid batteries used in automobiles. The chemical formula for sulfuric acid, H_2SO_4, indicates that one molecule of sulfuric acid contains two atoms of hydrogen, one atom of sulfur, and four atoms of oxygen. Sulfuric acid in its pure form is not useful as an electrolyte. When it is combined with water, H_2O, the molecules separate into ions of H^+, H^+, and SO_4^{--}. The plus sign indicates that each of two hydrogen atoms has lost its electrons and is now a positive ion. The SO_4^{--} is called a sulfate ion and indicates that the two electrons lost by the hydrogen atoms are connected to the sulfur atom and four oxygen atoms. The two extra electrons actually hold the sulfate ion together.

Copper Sulfate

Another useful compound is **copper sulfate,** $CuSO_4$. In its natural form, copper sulfate is in the form of blue crystals. When it is mixed with water, it dissolves and forms two separate ions, Cu^{++} and SO_4^{--}. The Cu^{++} is called a cupric ion and indicates that a copper atom has lost two of its electrons. The SO_4^{--} is the same sulfate ion formed when sulfuric acid is mixed with water. This copper sulfate solution is used in copper electroplating processes.

Cuprous Cyanide

Cuprous cyanide is used to electroplate copper to iron. It is a very poisonous solid that becomes Cu^+ and CN^- when mixed in solution. The Cu^+ is a cuprous ion, and CN^- is a cyanide ion.

12–3 Electroplating

Electroplating is the process of depositing atoms of one type of metal on another. Several factors are always true in an electroplating process:

1. *The electrolyte solution must contain ions of the metal to be plated.*
2. *Metal ions are always positively charged.*

3. *The object to be plated must be connected to the negative power terminal.* The negative terminal is called the **cathode** and refers to the terminal where electrons enter the circuit.
4. *Direct current is used as the power source.*
5. *The positive terminal is made of the same metal that is to form the coating.* The positive terminal is referred to as the **anode** and refers to the terminal where electrons leave the circuit.

An example of the electroplating process is shown in *Figure 12–5*. Note that the object to be plated has been connected to the negative battery terminal, or cathode, and the copper bar has been connected to the positive terminal, or anode. Both objects are submerged in a cuprous cyanide solution. When power is applied to the circuit, positively charged copper ions in the solution move toward the object to be plated, and the negatively charged cyanide ions move toward the copper bar. When the copper ion contacts the object, it receives an electron and becomes a neutral copper atom. These neutral copper atoms form a copper covering over the object to be plated. The thickness of the coating is determined by the length of time the process is permitted to continue.

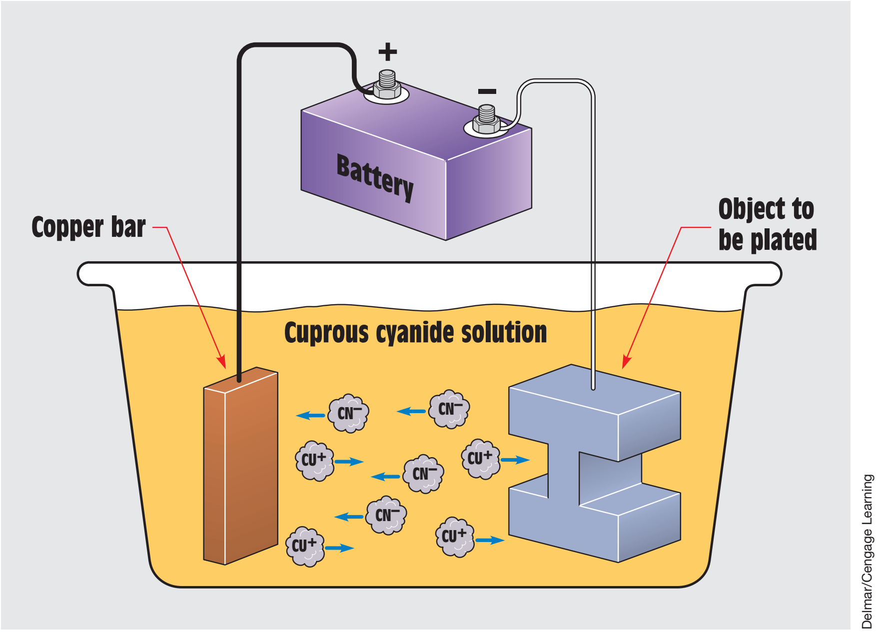

FIGURE 12–5 The electroplating process.

When the negatively charged cyanide ions contact the positive copper bar, copper atoms on the surface of the bar lose an electron and become positive ions. The copper ion is attracted into the solution and flows toward the object to be plated. Just as many copper ions are being formed as are being attracted to the object to be plated. The solution therefore remains at a constant strength.

One of the most common uses for electroplating is the production of pure metals. Impure, or raw, copper is connected to the positive terminal, and pure copper is connected to the negative terminal. Because only pure atoms of copper become ions, impurities remain in solution or never leave the positive plate. Impure copper has a high resistance and is not suitable for use as an electrical conductor. Wire manufacturers require electrolytically purified copper because of its low-resistance characteristics.

12–4 Electrolysis

The term **electrolysis** refers to the process of separating elements electrically. Elements are often chemically combined with other elements and must be separated. Although aluminum oxide is an abundant compound, aluminum was once very rare because extracting aluminum from aluminum oxide was difficult and expensive. Aluminum became inexpensive when a process was discovered for separating the aluminum and oxygen atoms electrically. In this process, electrons are removed from oxygen ions and returned to aluminum ions. The aluminum ions then become aluminum atoms.

12–5 Conduction in Gases

At atmospheric pressure, air is an excellent insulator. In *Figure 12–6,* two electrodes are separated by an air gap. The electrodes are connected to a variable-voltage power supply. Assume that the output voltage of the power supply is zero when the switch is turned on. As the output voltage is increased, the ammeter will remain at zero until the voltage reaches a certain potential. Once this potential has been reached, an **arc** will be established across the electrodes and current will begin to flow *(Figure 12–7)*. The amount of current is limited by the impedance of the rest of the circuit, because once an arc has been established, it has a very low resistance. For example, once the arc has been established, the voltage can be reduced and the arc will continue because molecules of air become ionized and conduction is maintained by the ionized gas. One factor that determines the voltage required is the distance between the two conductors. The farther apart they are, the higher the voltage must be. When using an electric arc welder, the arc is first established by touching the electrode to the object to be welded and then withdrawing the electrode once conduction begins. Recall that once an arc has been established, the amount of voltage required to maintain it is reduced.

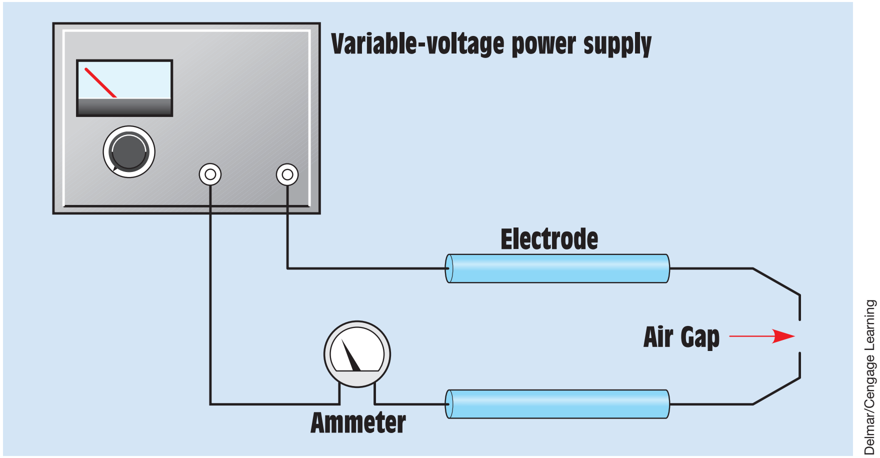

FIGURE 12–6 Air acts as an insulator.

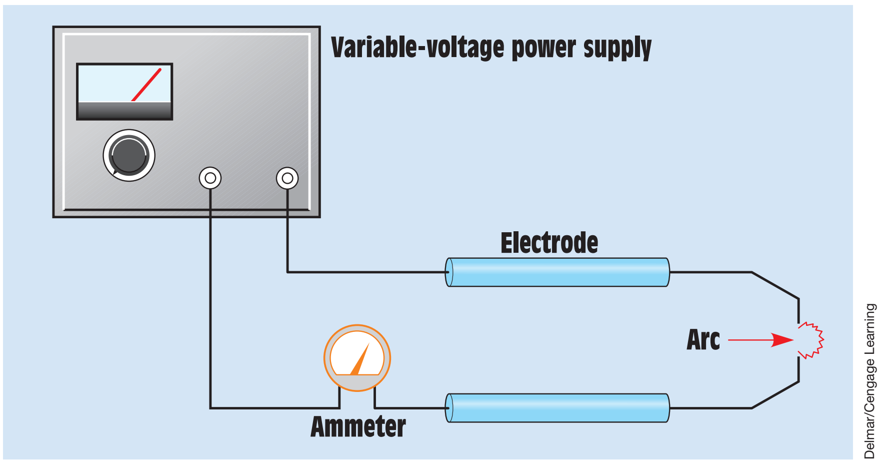

FIGURE 12–7 When the voltage becomes high enough, an arc is established.

Ionization Potential in a Gas

The amount of voltage, or potential, an electron must possess to cause ionization is called the **ionization potential.** The following factors determine the amount of voltage required to cause conduction in a gas-filled envelope.

1. *Atmospheric pressure.* The amount of air pressure greatly influences the voltage required to reach ionization potential. Atmospheric pressure is 14.7 pounds per square inch (PSI) at sea level. If the pressure is increased, such as in an automobile engine, the amount of voltage required to reach

ionization potential increases greatly. The ignition system of most automobiles produces voltages that range from 20,000 volts to 70,000 volts.

If the atmospheric pressure is reduced, the amount of voltage required to reach ionization potential is reduced. This is the principle of operation of the gas-filled tubes that have been used in industry for many years. Gas-filled tubes operate with lower than normal atmospheric pressure inside the tube.

2. *The type of gas in the surrounding atmosphere*. The type of gas in the atmosphere can greatly influence the amount of voltage required to cause ionization. Sodium vapor, for example, requires a potential of approximately 5 volts. Mercury vapor requires 10.4 volts; neon, 21.5 volts; and helium, 24.5 volts. Before an electron can ionize an atom of mercury, it must possess a potential difference of 10.4 volts.

Electron Impact

Conduction in a gas is different from conduction in a liquid or metal. The most important factor in the ionization of a gas is **electron impact.** The process begins when an electron is freed from the negative terminal inside a gas-filled tube or envelope and begins to travel toward the positive terminal *(Figure 12–8)*. The electron is repelled from the negative terminal and attracted to the positive terminal. The speed the electron attains is proportional to the applied voltage and the distance it travels before striking a gas molecule. If the electron's speed (potential) is great enough, it will liberate other electrons from the gas molecule, which in turn flow toward the positive terminal and strike other molecules *(Figure 12–9)*. These electrons are very energetic and are the main source of current flow in a gas. When electrons are removed from the molecules, the molecules become positive ions similar to those in a liquid.

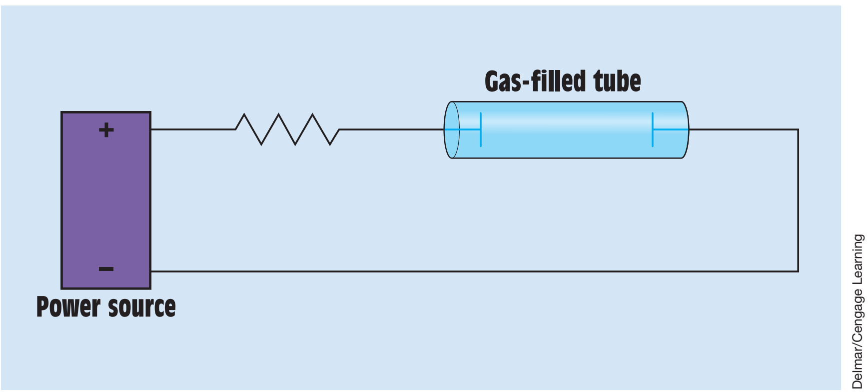

FIGURE 12–8 Conduction in a gas.

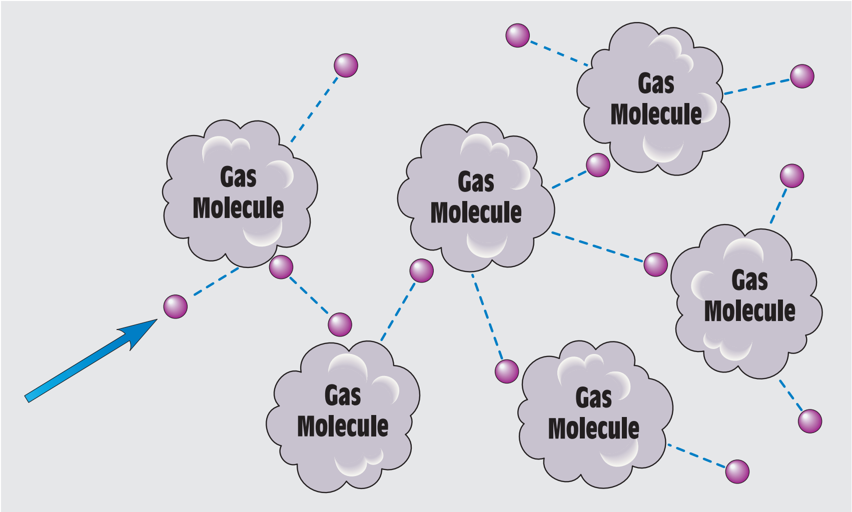

FIGURE 12–9 Electron impact frees other electrons from gas molecules.

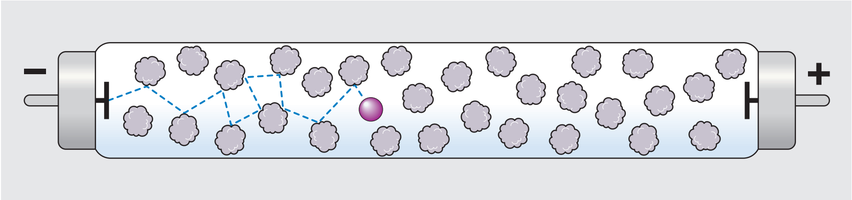

FIGURE 12–10 Under high pressure, the electron can travel only a short distance between impacts with gas molecules.

These positive ions are attracted to the negative terminal, where they receive electrons and become neutral molecules again.

If the electron does not possess enough potential to cause ionization, it bounces off and begins traveling toward the positive terminal again. The pressure inside the tube determines the density of the gas molecules *(Figure 12–10)*. If the pressure is too high, the gas molecules are so dense that the electron cannot gain enough potential to cause ionization. In this case, the electron will bounce from one molecule to another until it finally reaches the positive terminal. If the pressure is low, however, the electron can travel a great enough distance to attain ionization potential *(Figure 12–11)*.

Useful Applications

Ionization in a gas can be very useful. One use is the production of light. Often, when an electron strikes a gas molecule that does not have enough energy to

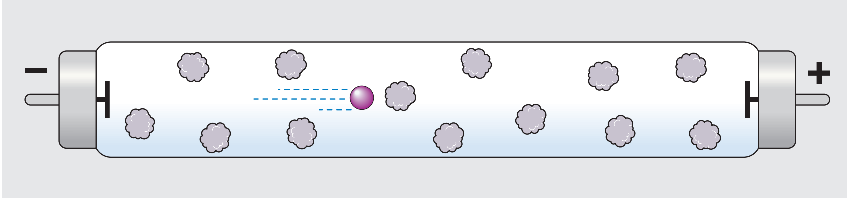

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FIGURE 12–11 Under low pressure, the electron can travel a greater distance before striking a gas atom.

release other electrons, the molecule will emit light to rid itself of the excess energy. The color of the light is characteristic of the type of gas. Some examples of this type of lighting are sodium vapor, mercury vapor, and neon.

Another useful device that operates on the principle of conduction in a gas was invented in 1895 by Wilhelm Roentgen. During experimentation in his laboratory, he discovered that when cathode rays struck metal or glass, a new kind of radiation was produced. These new rays passed through wood, paper, and air without effect. They passed through thin metal better than through thick metal and through flesh easier than through bone. Roentgen named these new rays **X-rays.** Today, X-rays are used by doctors throughout the world.

Probably one of the most familiar devices that operates on the principle of conduction in a gas is the cathode ray tube. In 1897 J. J. Thomson measured the weight of the negative particle of the electric charge. He also found that a beam of negative particles could be bent by magnetic fields *(Figure 12–12)*. Today the cathode ray tube is used in television sets, computer display terminals, and oscilloscopes.

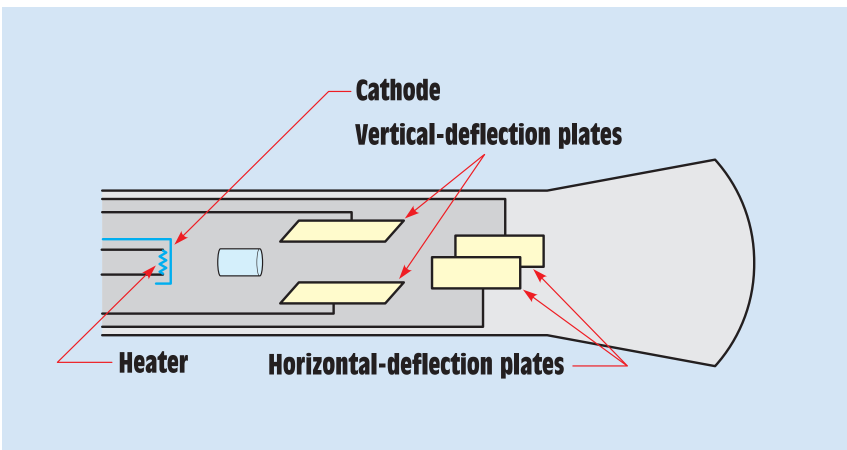

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FIGURE 12–12 Cathode ray tube.

12–6 Ionization in Nature

One of the most familiar phenomena caused by ionization of gas is the aurora borealis, or northern lights. During an expedition to the arctic, Kristian Birkeland hypothesized that disturbances in the sun cause large amounts of electrons and high-speed protons to be given off and blown into space. When these highly energetic particles reach the earth, they strike the very thin layers of the upper atmosphere and cause ionization to occur. The different colors are caused by different layers of the atmosphere being ionized.

A buildup in the atmosphere of charged particles that are not strong enough to cause lightning will often produce a continuous discharge of light around objects such as the masts of ships or church steeples. This glowing discharge is often referred to as Saint Elmo's fire by sailors.

Summary

- Electrical conduction in a liquid is caused by a movement of charged atoms called ions.
- Pure water is an insulator and becomes a conductor if an acid, an alkali, or a metallic salt is added.
- Solutions of acids, alkalies, and metallic salts are referred to as electrolytes.
- Electroplating is the process of depositing the atoms of one type of metal onto another.
- Several factors that affect the electroplating of metals are

  a. the electrolyte solution must contain ions of the metal to be plated.

  b. metal ions are always positively charged.

  c. the object to be plated must be connected to the negative power terminal.

  d. direct current is used as the power source.

  e. the positive terminal is made of the same metal that forms the coating.
- The negative terminal of a device is called the cathode.
- The positive terminal of a device is called the anode.
- One of the most common uses for electroplating is the production of pure metals.
- The term *electrolysis* refers to the process of separating elements electrically.
- Conduction through a gas depends on the ionization of gas molecules.

- The amount of voltage required to cause ionization of a gas is called the ionization potential.
- Gas can be ionized more easily when it is at a low pressure than when it is at a high pressure.
- The ionization potential is different for different gases.
- The most important factor in the ionization of a gas is electron impact.

Review Questions

1. Conduction in a liquid depends on the movement of ________.
2. What is a negative ion?
3. What is a positive ion?
4. Name three basic substances that can be used to produce ionization in a liquid.
5. What is an electrolyte?
6. What is used to hold a sulfate ion together?
7. What is the negative terminal of a power source called?
8. What is the positive terminal of a power source called?
9. What determines the thickness of the coating during an electroplating process?
10. What is electrolysis?
11. What is ionization potential?
12. What is the most important factor in the ionization of a gas?
13. Name two factors that determine the speed an electron attains inside a gas environment.
14. What determines the density of the molecules in a gas environment?
15. What determines the color of light emitted by a gas-filled tube?

Unit 13

Batteries and Other Sources of Electricity

Why You Need to Know

Methods other than conductors cutting through magnetic fields can be employed to produce electricity. Although magnetic devices such as generators and alternators are certainly the greatest producers of electricity, they are not the only ones. Batteries are common in everyday life, and an understanding of how they operate is essential. This unit

- discusses different types of batteries and how to identify their current capacity for correct use. Some batteries can be recharged and others cannot, and you must understand those differences.
- explains why different types of batteries produce different voltages and what determines the amount of current a battery can produce.
- illustrates how to calculate the voltage and current capacity of batteries by connecting them in series and/or parallel.
- discusses solar cells, thermocouples, and piezoelectricity.

OUTLINE

KEY TERMS

Battery
Cell
Current capacity
Electromotive series of metals
Hydrometer
Internal resistance
Load test
Nickel-cadmium (nicad) cell
Piezoelectricity
Primary cell
Secondary cell
Specific gravity
Thermocouple
Voltaic cell
Voltaic pile

Objectives

After studying this unit, you should be able to

- discuss the differences between primary and secondary cells.
- list voltages for different types of cells.
- discuss different types of primary cells.
- construct a cell from simple materials.
- discuss different types of secondary cells.
- connect batteries in series and parallel to obtain desired voltage and ampere hour (A-hr) ratings.
- discuss the operation of solar cells.
- connect solar cells in series or parallel to produce the desired output voltage and current capacity.
- discuss the operation of thermocouples.
- discuss the piezoelectric effect.

Courtesy of Power-Sonic Corporation.

Preview

Most of the electric power in the world is produced by large rotating machines called alternators. There are other sources of electricity, however, that are smaller and are used for emergency situations or for the operation of portable electric devices. The most common of these small power sources is the battery. Batteries are used to start automobiles and to operate toys, flashlights, portable communications equipment, computers, watches, calculators, and hundreds of other devices. They range in size from small enough to fit into a hearing aid to large enough to operate electric forklifts and start diesel trucks. ■

13–1 History of the Battery

In 1791, Luigi Galvani was conducting experiments in anatomy using dissected frog legs preserved in a salt solution. Galvani suspended the frog legs by means of a copper wire. He noticed that when he touched the leg with an iron scalpel the leg would twitch. Galvani realized that the twitch was caused by electricity, but he thought that the electricity was produced by the muscular contraction of the frog's leg. This was the first recorded incident of electricity being produced by chemical action.

In 1800, Alessandro Volta repeated Galvani's experiment. Volta, however, concluded that the electricity was produced by the chemical action of the copper wire, the iron scalpel, and the salt solution. Further experiments led Volta

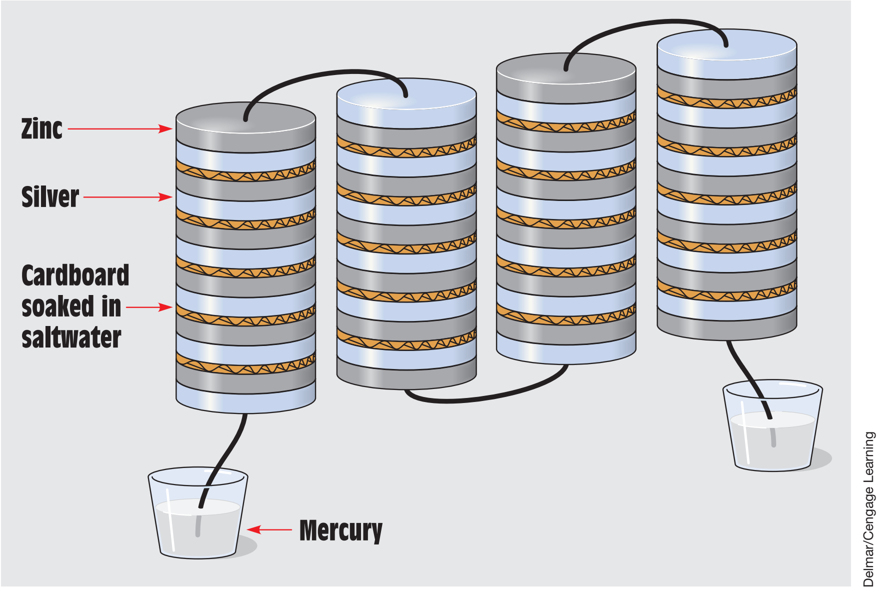

FIGURE 13–1 A voltaic pile.

to produce the first practical battery *(Figure 13–1)*. The battery was constructed using zinc and silver discs separated by a piece of cardboard soaked in brine, or saltwater. Volta called his battery a **voltaic pile** because it was a series of individual cells connected together. Each cell produced a certain amount of voltage depending on the materials used to make the cell. A **battery** is actually several cells connected together, although the word *battery* is often used in reference to a single cell. The schematic symbols for an individual **cell** and for a battery are shown in *Figure 13–2*.

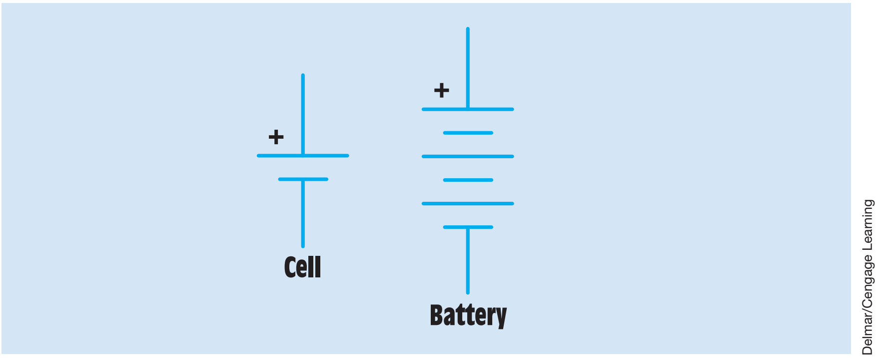

FIGURE 13–2 Schematic symbols used to represent an individual cell and a battery.

13–2 Cells

A **voltaic cell** can be constructed using virtually any two unlike metals and an acid, alkaline, or salt solution. A very simple cell can be constructed as shown in *Figure 13–3*. In this example, a copper wire is inserted in one end of a potato and an aluminum wire is inserted in the other. The acid in the potato acts as the electrolyte. If a high-impedance voltmeter is connected to the wires, a small voltage can be measured.

Another example of a simple voltaic cell is shown in *Figure 13–4*. In this example, two coins of different metal, a nickel and a penny, are separated by a

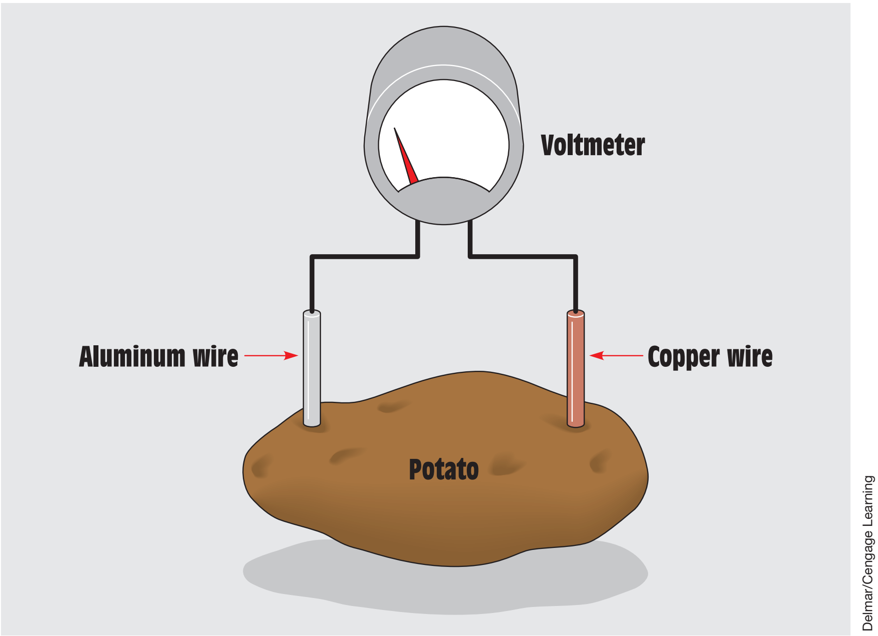

FIGURE 13–3 Simple voltaic cell constructed from a potato and two different metals.

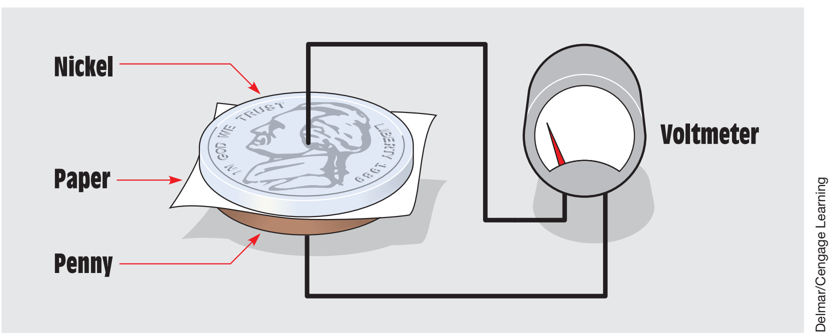

FIGURE 13–4 A voltaic cell constructed from two coins and a piece of paper.

piece of paper. The paper has been wetted with saliva from a person's mouth. The saliva contains acid or alkali that acts as the electrolyte. When a high-impedance voltmeter is connected across the two coins, a small voltage is produced.

13–3 Cell Voltage

The amount of voltage produced by an individual cell is determined by the materials from which it is made. When a voltaic cell is constructed, the plate metals are chosen on the basis of how easily one metal will give up electrons compared with the other. A special list of metals called the **electromotive series of metals** is shown in *Figure 13–5*. This table lists metals in the order of their ability to accept or receive electrons. The metals at the top accept electrons more easily than those at the bottom. The farther apart the metals are on the list, the higher the voltage developed by the cell. One of the first practical cells to be constructed was the zinc-copper cell. This cell uses zinc and copper as the active metals and a solution of water and hydrochloric acid as the electrolyte. Notice that zinc is located closer to the top of the list

ELECTROMOTIVE SERIES OF METALS (Partial list)
Lithium
Potassium
Calcium
Sodium
Magnesium
Aluminum
Manganese
Zinc
Chromium
Iron
Cadmium
Cobalt
Nickel
Tin
Lead
Antimony
Copper
Silver
Mercury
Platinum
Gold

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FIGURE 13–5 A partial list of the electromotive series of metals.

CELL	NEGATIVE PLATE	POSITIVE PLATE	ELECTROLYTE	VOLTS PER CELL
Primary Cells				
Carbon-zinc (Leclanche)	Zinc	Carbon, manganese dioxide	Ammonium chloride	1.5
Alkaline	Zinc	Manganese dioxide	Potassium hydroxide	1.5
Mercury	Zinc	Mercuric oxide	Potassium hydroxide	1.35
Silver-zinc	Zinc	Silver Oxide	Potassium hydroxide	1.6
Zinc-air	Zinc	Oxygen	Potassium hydroxide	1.4
Edison-Lalande	Zinc	Copper oxide	Sodium hydroxide	0.8
Secondary Cells				
Lead-acid	Lead	Lead dioxide	Dilute sulfuric acid	2.2
Nickel-iron (Edison)	Iron	Nickel oxide	Potassium hydroxide	1.4
Nickel-cadmium	Cadmium	Nickel hydroxide	Potassium hydroxide	1.2
Silver-zinc	Zinc	Silver oxide	Potassium hydroxide	1.5
Silver-cadium	Cadmium	Silver oxide	Potassium hydroxide	1.1

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FIGURE 13–6 Voltaic cells.

than copper. Because zinc accepts electrons more readily than copper, zinc is the negative electrode and copper is the positive.

Although it is possible to construct a cell from virtually any two unlike metals and an electrolyte solution, not all combinations are practical. Some metals corrode rapidly when placed in an electrolyte solution, and some produce chemical reactions that cause a buildup of resistance. In practice, relatively few metals can be used to produce a practical cell.

The table in *Figure 13–6* lists common cells. The table is divided into two sections. One section lists primary cells and the other lists secondary cells. A **primary cell** is a cell that *cannot be recharged*. The chemical reaction of a primary cell causes one of the electrodes to be eaten away as power is produced. When a primary cell becomes discharged, it should be replaced with a new cell. A **secondary cell** *can be recharged*. The recharging process is covered later in this unit.

13–4 Primary Cells

An example of a primary cell is the zinc-copper cell shown in *Figure 13–7*. This cell consists of two electrodes (terminals that conduct electricity into or away from a conducting substance), one zinc and one copper, suspended in a solution of water and hydrochloric acid. This cell will produce approximately 1.08 volts. The electrolyte contains positive H^+ ions, which attract electrons from the zinc

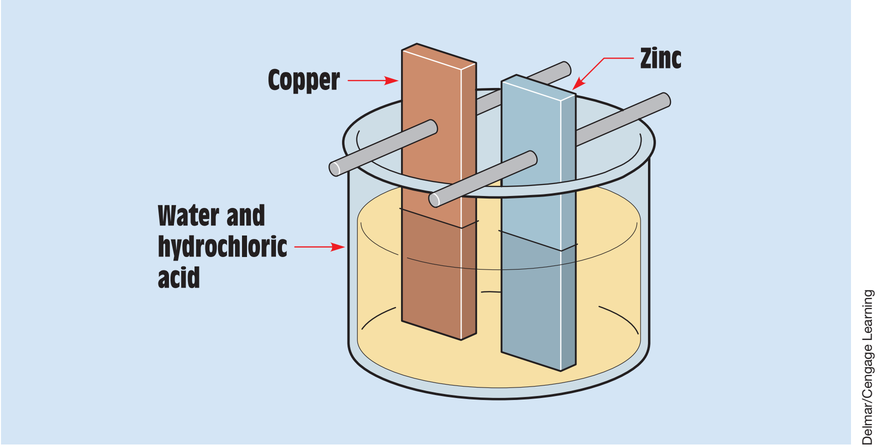

FIGURE 13–7 Zinc-copper cell.

atoms, which have two valence electrons. When an electron bonds with the H^+ ion, it becomes a neutral H atom. The neutral H atoms combine to form H_2 molecules of hydrogen gas. This hydrogen can be seen bubbling away in the electrolyte solution. The zinc ions, Zn^{++}, are attracted to negative Cl^- ions in the electrolyte solution.

The copper electrode provides another source of electrons that can be attracted by the H^+ ions. When a circuit is completed between the zinc and copper electrodes *(Figure 13–8)*, electrons are attracted from the zinc electrode to replace the electrons in the copper electrode that are attracted into the solution. After some period of time, the zinc electrode dissolves as a result of the zinc ions being distributed in the solution.

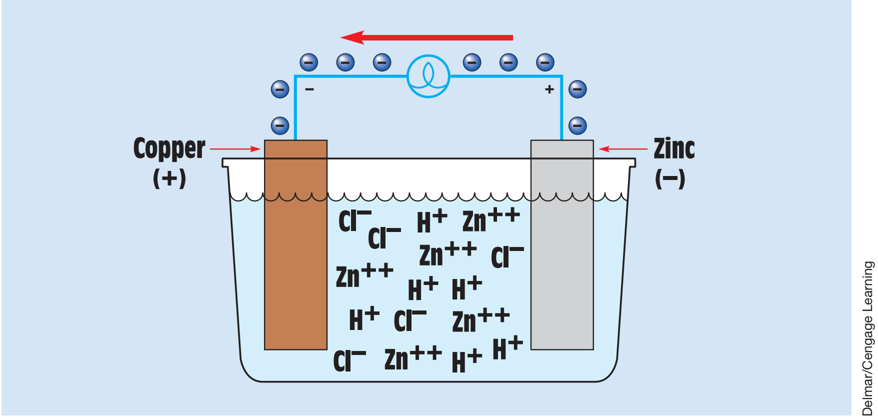

FIGURE 13–8 Electrons flow from the zinc to the copper electrode.

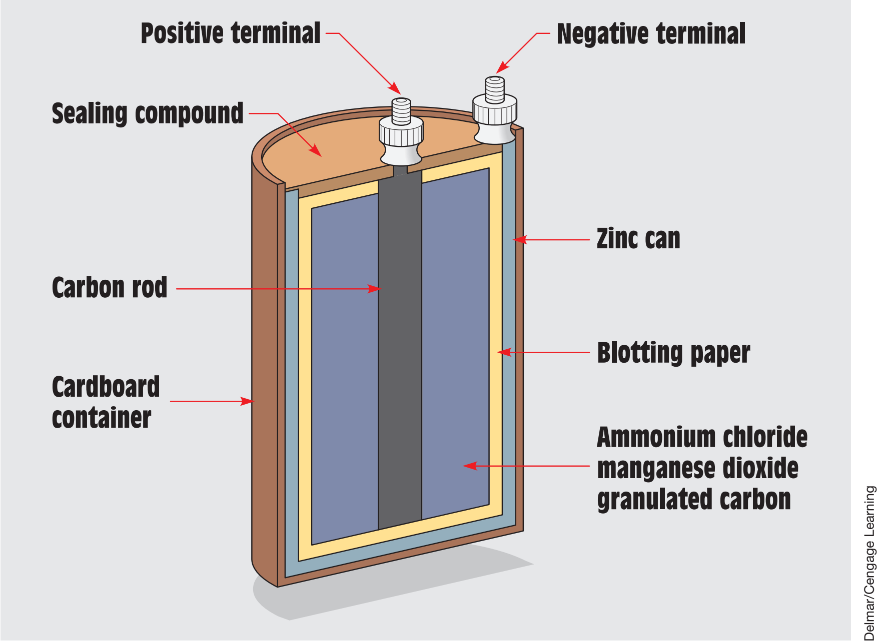

FIGURE 13–9 Carbon-zinc cell.

The Carbon-Zinc Cell

One of the first practical primary cells was invented by Leclanché. It is known as the carbon-zinc cell, or the Leclanché cell. Leclanché used a carbon rod as an electrode, instead of copper, and a mixture of ammonium chloride, manganese dioxide, and granulated carbon as the electrolyte. The mixture was packed inside a zinc container that acted as the negative electrode *(Figure 13–9)*. This cell is often referred to as a dry cell because the electrolyte is actually a paste instead of a liquid. The use of a paste permits the cell to be used in any position without spilling the electrolyte. As the cell is discharged, the zinc container is eventually dissolved. When the container has dissolved, the cell should be discarded immediately and replaced. Failure to discard the cell can result in damage to equipment.

Alkaline Cells

Another primary cell very similar to the carbon-zinc cell is the alkaline cell. This cell uses a zinc can as the negative electrode and manganese dioxide, MnO_2, as the positive electrode. The major electrolytic ingredient is potassium hydroxide. Like the carbon-zinc cell, the alkaline cell contains a paste electrolyte and is considered a dry cell also. The voltage developed is the same as in the carbon-zinc cell, 1.5 volts. The major advantage of the alkaline cell is longer life. The average alkaline cell can supply from three to five

Courtesy of GE Industrial Systems

FIGURE 13–10 Alkaline-manganese cell.

times the power of a carbon-zinc cell, depending on the discharge rate when the cell is being used. The major disadvantage is cost. Although some special alkaline cells can be recharged, the number of charge and discharge cycles is limited. In general, the alkaline cell is considered to be a nonrechargeable cell. A D-size alkaline-manganese cell is shown in *Figure 13–10*. Several different sizes and case styles of alkaline and mercury cells are shown in *Figure 13–11*.

One of the devices shown in *Figure 13–11* is a true battery and not a cell. The battery is rectangular and has two snap-on type terminal connections at the top. This battery actually contains six individual cells rated at 1.5 volts each. The cells are connected in series and provide a terminal voltage of 9 volts. The internal makeup of the battery is shown in *Figure 13–12*.

Button Cells

Another common type of primary cell is the button cell. The button cell is so named because it resembles a button. Button cells are commonly used in cameras, watches, hearing aids, and handheld calculators. Most button cells are constructed using mercuric oxide as the anode, zinc as the cathode, and potassium hydroxide as the electrolyte *(Figure 13–13)*. Although these cells are more expensive than other cells, they have a high-energy density and a long life. The mercury-zinc cell has a voltage of 1.35 volts.

Courtesy of GE Industrial Systems

FIGURE 13–11 Different sizes and case styles of primary cells.

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FIGURE 13–12 Internal makeup of a 9-V battery.

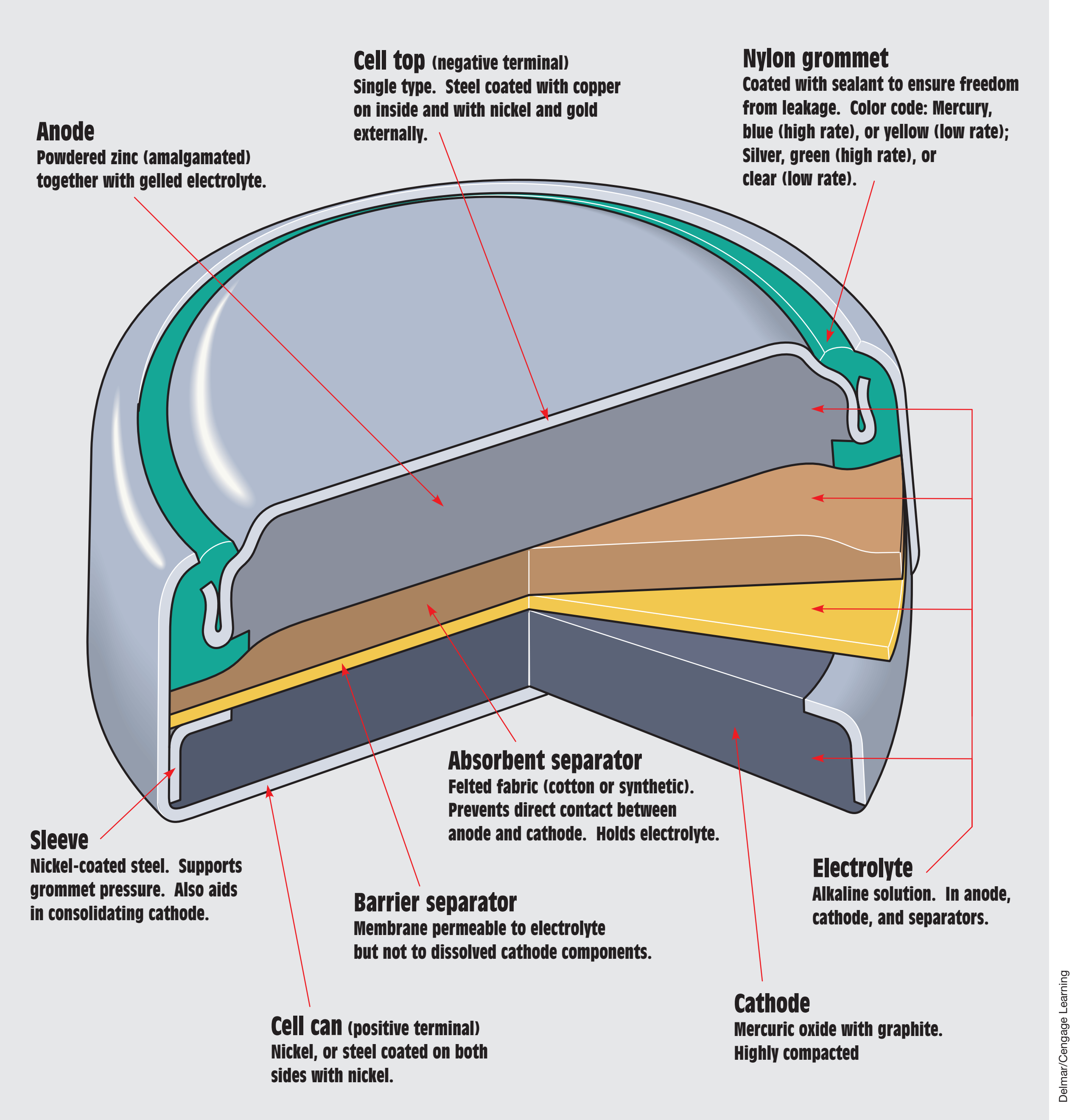

FIGURE 13–13 Mercury button cell.

Another type of button cell that is less common because of its higher cost is the silver-zinc cell. This cell is the same as the mercury-zinc cell except that it uses silver oxide as the cathode material instead of mercuric oxide. The silver-zinc cell does have one distinct advantage over the mercury-zinc cell. The silver-zinc cell develops a voltage of 1.6 volts as compared with the 1.35 volts developed by the mercury-zinc cell. This higher voltage can be of major importance in some electronic circuits.

A variation of the silver-zinc cell uses divalent silver oxide as the cathode material instead of silver oxide. The chemical formula for silver oxide is Ag_2O. The chemical formula for divalent silver oxide is Ag_2O_2. One of the factors that determines the energy density of a cell is the amount of oxygen in the cathode material. Although divalent silver oxide contains twice as much oxygen as silver oxide, it does not produce twice the energy density. The increased energy density is actually about 10% to 15%. Using divalent silver oxide does have one disadvantage, however. The compound is less stable, which can cause the cell to have a shorter shelf life.

Lithium Cells

Lithium cells should probably be referred to as the lithium system because there are several different types of lithium cells. Lithium cells can have voltages that range from 1.9 volts to 3.6 volts, depending on the material used to construct the cell. Lithium is used as the anode material because of its high affinity for oxygen. In fact, for many years lithium had to be handled in an airless and moisture-free environment because of its extreme reactivity with oxygen. Several different cathode materials can be used, depending on the desired application. One type of lithium cell uses a solid electrolyte of lithium hydroxide. The use of a solid electrolyte produces a highly stable compound, resulting in a shelf life that is measured in decades. This cell produces a voltage of 1.9 volts but has an extremely low current capacity. The output current of the lithium cell is measured in microamperes (millionths of an ampere) and is used to power watches with liquid crystal displays and to maintain memory circuits in computers.

Other lithium cells use liquid electrolytes and can provide current outputs comparable to alkaline-manganese cells. Another lithium system uses a combination electrolyte-cathode material. One of these is sulfur dioxide, SO_2. This combination produces a voltage of 2.9 volts. In another electrolyte-cathode system, sodium chloride, NaCl, is used. This combination provides a terminal voltage of 3.6 volts.

Although lithium cells are generally considered to be primary cells, some types are rechargeable. The amount of charging current, however, is critical for these cells. An incorrect amount of charging current can cause the cell to explode.

Current Capacity and Cell Ratings

The amount of current a particular type of cell can deliver is determined by the surface area of its plates. A D cell can deliver more current than a C cell, and a C cell can deliver more current than an AA cell. The amount of power a cell can deliver is called its **current capacity.** To determine a cell's current capacity, several factors must be included, such as the type of cell, the rate of current flow, the voltage, and the length of time involved. Primary cells are generally limited by size and weight and therefore do not contain a large amount of power.

One of the common ratings for primary cells is the milliampere-hour (mA-hr). A milliampere (mA) is 1/1000 of an ampere. Therefore, if a cell can provide a current of 1 milliampere for 1 hour it will have a rating of 1 milliampere-hour. An average D-size alkaline cell has a capacity of approximately 10,000 milliampere-hours. Some simple calculations would reveal that this cell should be able to supply 100 milliamperes of current for a period of 100 hours, or 200 milliamperes of current for 50 hours.

Another common measure of a primary cell's current capacity is watt-hours (W-hr). Watt-hours are determined by multiplying the cell's milliampere-hour rating by its terminal voltage. If the alkaline-manganese cell just discussed has a voltage of 1.5 volts, its watt-hour capacity would be 15 watt-hours (10,000 mA-hr $\times$ 1.5 V = 15,000 mW-hr, or 15 W-hr). The chart in *Figure 13–14* shows the watt-hour capacity for several sizes of alkaline-manganese cells. The chart lists the cell size, the volume of the cell, and the watt-hours per cubic inch.

The amount of power a cell contains depends not only on the volume of the cell but also on the type of cell being used. The chart in *Figure 13–15* compares the watt-hours per cubic inch for different types of cells.

Internal Resistance

Batteries actually have two voltage ratings, one at no load and the other at normal load. The cell's rated voltage at normal load is the one used. The no-load voltage of a cell is greater because of the **internal resistance** of the cell. All cells have some amount of internal resistance. For example, the alkaline cell discussed previously had a rating of 10,000 milliampere-hours, or 10 ampere-hours (A-hr).

ALKALINE-MANGANESE CELL SIZE	VOLUME IN CUBIC INCHES	WATT-HOURS PER CUBIC INCH
D cell	3.17	4.0
C cell	1.52	4.2
AA cell	0.44	4.9
AAA cell	0.20	5.1

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FIGURE 13–14 Watt-hours per cubic inch for different size cells.

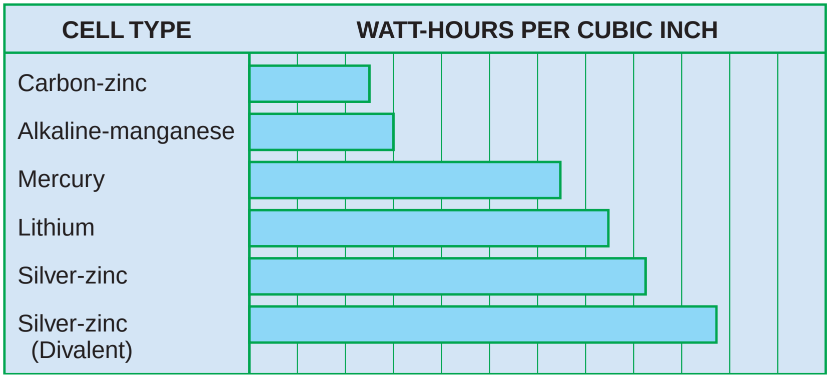

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FIGURE 13–15 Watt-hours per cubic inch for different types of cells.

Theoretically, the cell should be able to deliver 10 amperes of current for one hour or 20 amperes of current for a half-hour. In practice, the cell could not deliver 10 amperes of current even under a short-circuit condition. *Figure 13–16* illustrates what happens when a DC ammeter is connected directly across the terminals of a D-size alkaline cell. Assume that the ammeter indicates a current flow of 4.5 amperes and that the terminal voltage of the cell has dropped to 0.5 volt. By applying Ohm's law, it can be determined that the cell has an internal resistance of 0.111 ohm (0.5 V/4.5 A = 0.111 Ω).

As the cell ages and power is used, the electrodes and electrolyte begin to deteriorate. This causes them to become less conductive, which results in an increase of internal resistance. As the internal resistance increases, the terminal voltage decreases.

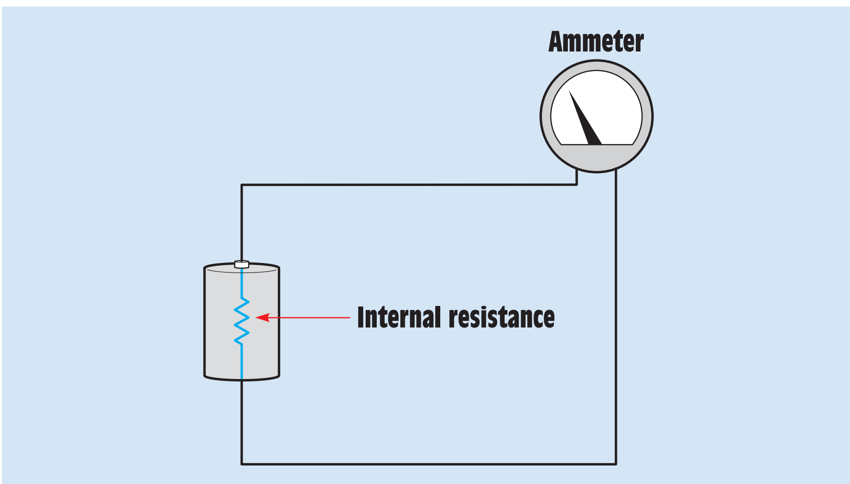

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FIGURE 13–16 Short-circuit current is limited by internal resistance.

13–5 Secondary Cells: Lead-Acid Batteries

The secondary cell is characterized by the fact that once its stored energy has been depleted, it can be recharged. One of the most common types of secondary cells is the lead acid. A string of individual cells connected to form one battery is shown in *Figure 13–17*. A single lead-acid cell consists of one plate made of pure lead, Pb; a second plate of lead dioxide, PbO_2; and an electrolyte of dilute sulfuric acid, H_2SO_4, with a specific gravity that can range from 1.215 to 1.28, depending on the application and the manufacturer *(Figure 13–18)*. **Specific gravity** is a measure of the amount of acid contained in the water. Water has a specific gravity of 1.000. A device used for measuring the specific gravity of a cell is called a **hydrometer** *(Figure 13–19)*.

Discharge Cycle

When a load is connected between the positive and negative terminals, the battery begins to discharge its stored energy through the load *(Figure 13–20)*. The process is called the discharge cycle. Each of the lead atoms on the surface of the negative plate loses two electrons to become a Pb^{++} ion. These positive ions attract SO_4^{--} ions from the electrolyte. As a result, a layer of lead sulfate, $PbSO_4$, forms on the negative lead plate.

The positive plate is composed of lead dioxide, PbO_2. Each of the Pb atoms lacks four electrons that were given to the oxygen atom when the compound was formed and the Pb became a Pb^{++++} ion. Each of the Pb^{++++} ions takes two electrons from the load circuit to become a Pb^{++} ion. The Pb^{++} ions cannot hold the oxygen atoms that are released into the electrolyte solution and combine with hydrogen atoms to form molecules of water, H_2O. The remaining Pb^{++} ions combine with SO_4^{--} ions and form a layer of lead sulfate around the positive plate.

As the cell is discharged, two H^+ ions contained in the electrolyte combine with an oxygen atom liberated from the lead dioxide to form water. For this reason, the hydrometer can be used to test the specific gravity of the cell to determine the state of charge. The more discharged the cell becomes, the more water is formed in the electrolyte and the lower the specific gravity reading becomes.

Charging Cycle

The secondary cell can be recharged by reversing the chemical action that occurred during the discharge cycle. This process, called the charging cycle, is accomplished by connecting a DC power supply or generator to the cell. The positive output of the power supply connects to the positive terminal of the cell, and the negative output of the power supply connects to the negative terminal of the cell *(Figure 13–21)*.

The terminal voltage of the power supply must be greater than that of the cell or battery. As current flows through the cell, hydrogen is produced at the negative plate

Courtesy of GNB Industrial Power

FIGURE 13–17 Lead-acid storage batteries.

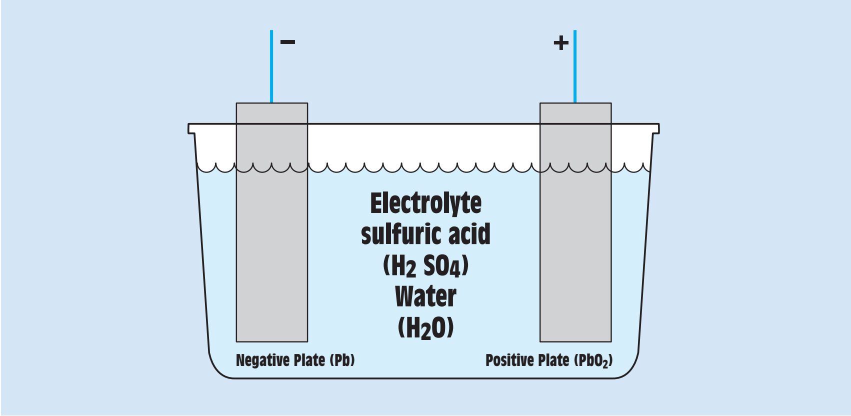

FIGURE 13–18 Basic lead-acid cell.

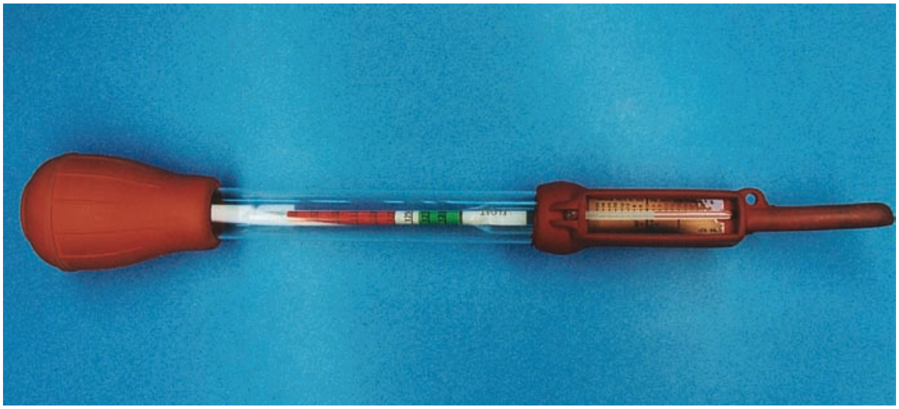

FIGURE 13–19 Hydrometer.

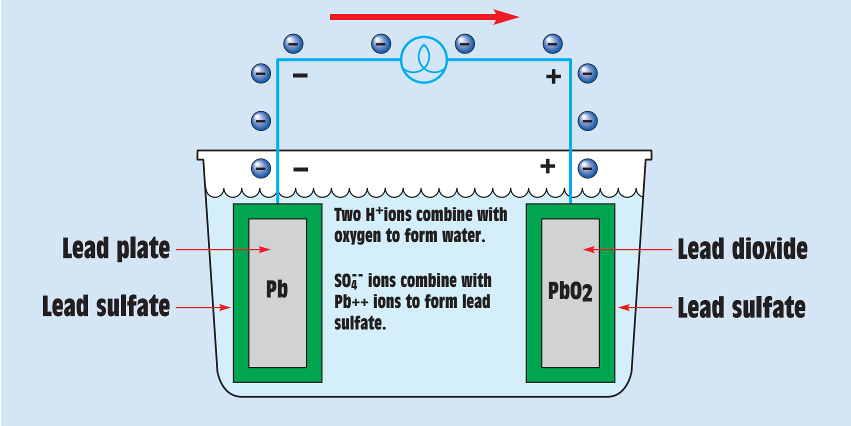

FIGURE 13–20 Discharge cycle of a lead-acid cell.

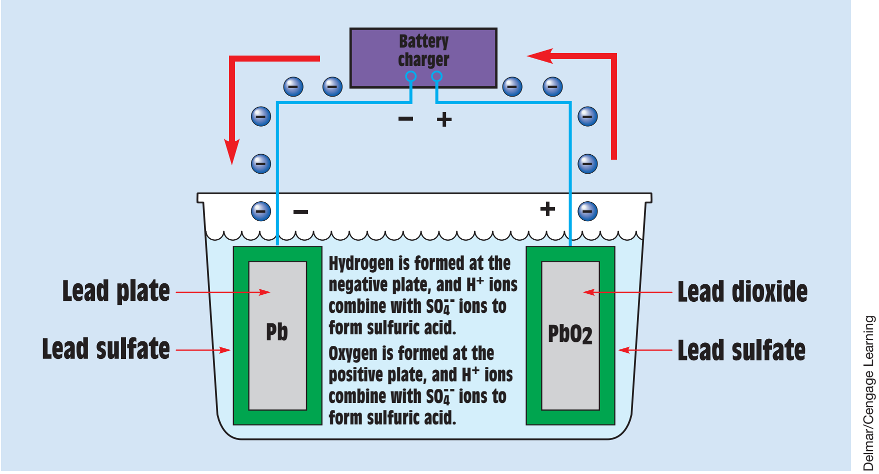

FIGURE 13–21 A lead-acid cell during the charging cycle.

and oxygen is produced at the positive plate. If the cell is in a state of discharge, both plates are covered with a layer of lead sulfate. The H^+ ions move toward the negative plate and combine with SO_4^{--} ions to form new molecules of sulfuric acid. As a result, Pb^{++} ions are left at the plate. These ions combine with electrons being supplied by the power supply and again become neutral lead atoms.

At the same time, water molecules break down at the positive plate. The hydrogen atoms combine with SO_4^{--} ions in the electrolytic solution to form sulfuric acid. The oxygen atom recombines with the lead dioxide to form a Pb^{++} ion. As electrons are removed from the lead dioxide by the power supply, the Pb^{++} ions become Pb^{++++} ions.

As the cell is charged, sulfuric acid is again formed in the electrolyte. The hydrometer can again be used to determine the state of charge. When the cell is fully charged, the electrolyte should be back to its original strength.

Most lead-acid cells contain multiple plates *(Figure 13–22)*. One section of plates is connected together to form a single positive plate, while the other section forms a single negative plate. This arrangement increases the surface area and thus the current capacity of the cell.

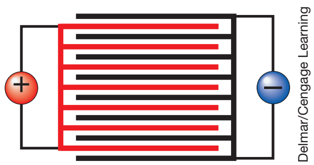

FIGURE 13–22 Multiple plates increase the surface area and the amount of current the cell can produce.

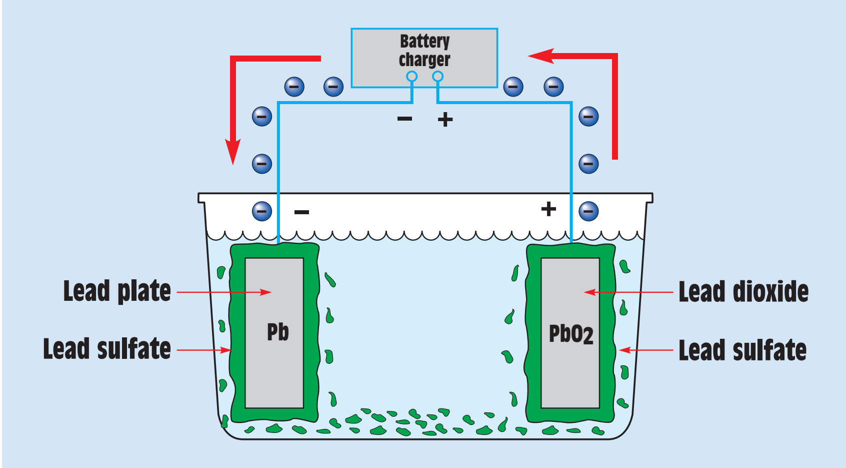

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FIGURE 13–23 Improper charging can cause lead sulfate to flake off and fall to the bottom of the cell.

Cautions Concerning Charging

Theoretically, a secondary cell should be able to be discharged and recharged indefinitely. In practice, however, it cannot. If the cell is overcharged, that is, the amount of charge current is too great, the lead sulfate does not have a chance to dissolve back into the electrolyte and become acid. High charging current or mechanical shock can cause large flakes of lead sulfate to break away from the plates and fall to the bottom of the cell *(Figure 13–23)*. These flakes can no longer recombine with the H^+ ions to become sulfuric acid. Therefore, the electrolyte is permanently weakened. If the flakes build up to a point that they touch the plates, they cause a short circuit and the cell can no longer operate.

CAUTION: ***Overcharging can also cause hydrogen gas to form:*** Because hydrogen is the most explosive element known, sparks or open flames should be kept away from batteries or cells, especially during the charging process. Overcharging also causes excess heat that can permanently damage the cell. The accepted temperature limit for most lead-acid cells is 110°F (43°C).

The proper amount of charging current can vary from one type of battery to another, and manufacturers' specifications should be followed when possible. A general rule concerning charging current is that the current should not be greater than 1/10 the ampere-hour capacity. An 80-ampere-hour battery, for instance, should not be charged with a current greater than 8 amperes. ■

Courtesy of Power-Sonic Corporation

FIGURE 13–24 Sealed lead-acid and nicad cells and batteries.

Sealed Lead-Acid Batteries

Sealed lead-acid batteries have become increasingly popular in the past several years. They come in different sizes, voltage ratings, ampere-hour ratings, and case styles *(Figure 13–24)*. These batteries are often referred to as gel cells because the sulfuric acid electrolyte is suspended in an immobilized gelatin state. This treatment prevents spillage and permits the battery to be used in any position. Gel cells use a cast grid constructed of lead-calcium, which is free of antimony. The calcium is used to add strength to the grid. The negative plate is actually a lead paste material, and the positive plate is made of lead-dioxide paste. A one-way pressure-relief valve set to open at 2–6 PSI is used to vent any gas buildup during charging.

Ratings for Lead-Acid Batteries

One of the most common ratings for lead-acid batteries is the ampere-hour rating. The ampere-hour rating for lead-acid batteries is determined by measuring the battery's ability to produce current for a 20-hour period at 80°F. A battery with the ability to produce a current of 4 amperes for 20 hours would have a rating of 80 ampere-hours.

Another common battery rating, especially for automotive batteries, is cold-cranking amperes. This rating has nothing to do with the ampere-hour rating of the battery. Cold-cranking amperes are the maximum amount of initial current the battery can supply at 68°F (20°C).

Testing Lead-Acid Batteries

It is sometimes necessary to test the state of charge or condition of a lead-acid battery. The state of charge can often be tested with a hydrometer, as previously described. As batteries age, however, the specific gravity remains low even after the battery has been charged. When this happens, it is an indication that the battery has lost part of its materials because of lead sulfate flaking off the plates and falling to the bottom of the battery. When this occurs there is no way to recover the material.

Another standard test for lead-acid batteries is the **load test.** This test will probably reveal more information concerning the condition of the battery than any other test. To perform a load test, the amount of test current should be three times the ampere-hour capacity. The voltage should not drop below 80% of the terminal voltage for a period of three minutes. For example, an 80-ampere-hour, 12-volt battery is to be load tested. The test current will be 240 amperes ($80\text{ A} \times 3$), and the voltage should not drop below 9.6 volts ($12\text{ V} \times 0.80$) for a period of three minutes.

13–6 Other Secondary Cells

Nickel-Iron Batteries (Edison Battery)

The nickel-iron cell is often referred to as the Edison cell, or Edison battery. The nickel-iron battery was developed in 1899 for use in electric cars being built by the Edison Company. The negative plate is a nickeled steel grid that contains powdered iron. The positive plates are nickel tubes that contain nickel oxides and nickel hydroxides. The electrolyte is a solution of 21% potassium hydroxide.

The nickel-iron cell weighs less than lead-acid cells but has a lower energy density. The greatest advantage of the nickel-iron cell is its ability to withstand deep discharges and to recover without harm to the cell. The nickel-iron cell can also be left in a state of discharge for long periods of time without harm. Because these batteries need little maintenance, they are sometimes found in portable and emergency lighting equipment. They are also used to power electric mine locomotives and electric forklifts.

The nickel-iron battery does have two major disadvantages. One is high cost. These batteries cost several times more than comparable lead-acid batteries. The second disadvantage is high internal resistance. Nickel-iron batteries do not have the ability to supply the large initial currents needed to start gasoline or diesel engines.

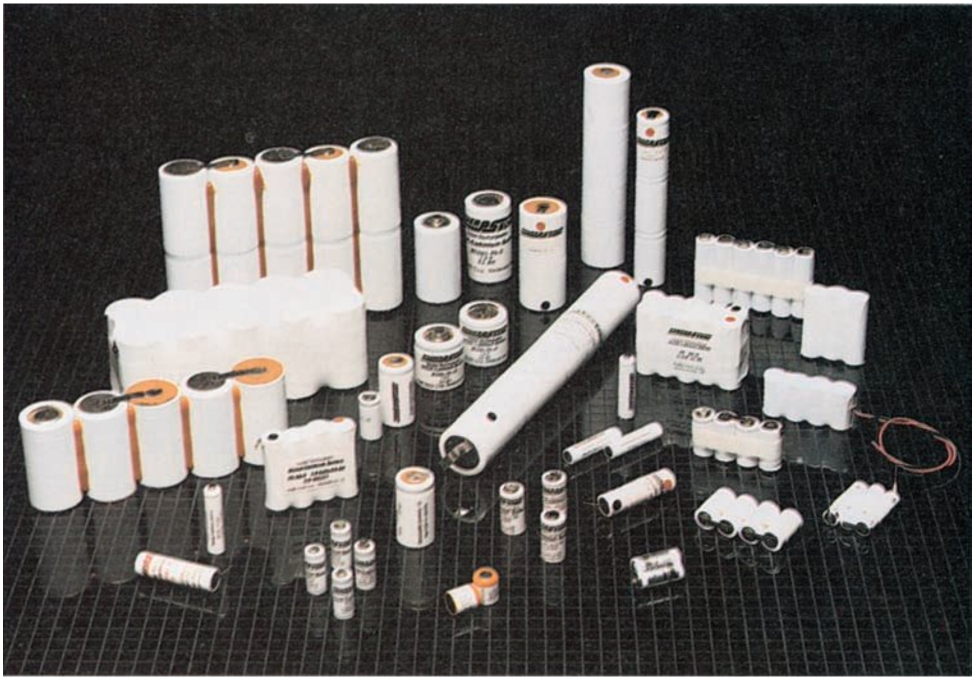

FIGURE 13–25 Nickel-cadmium batteries.

Nickel-Cadmium Batteries

The **nickel-cadmium (nicad) cell** was first developed in Sweden by Junger and Berg in 1898. The positive plate is constructed of nickel hydroxide mixed with graphite. The graphite is used to increase conductivity. The negative plate is constructed of cadmium oxide, and the electrolyte is potassium hydroxide with a specific gravity of approximately 1.2. Nicad batteries have extremely long life spans. On the average, they can be charged and discharged about 2000 times. Nicad batteries can be purchased in a variety of case styles *(Figure 13–25)*.

Nickel-cadmium batteries have the ability to produce large amounts of current, similar to the lead-acid battery, but do not experience the voltage drop associated with the lead-acid battery *(Figure 13–26)*.

Nickel-cadmium batteries do have some disadvantages:

1. The nicad battery develops only 1.2 volts per cell as compared with 1.5 volts for carbon-zinc and alkaline primary cells, or 2 volts for lead-acid cells.

2. Nicad batteries cost more initially than lead-acid batteries.

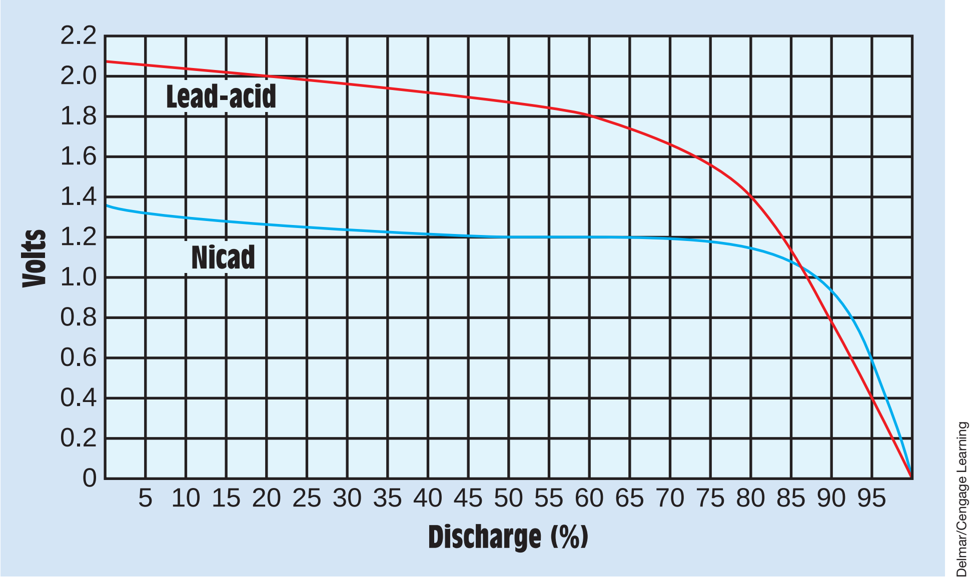

FIGURE 13–26 Typical discharge curves for nicad and lead-acid cells.

3. Nicad batteries remember their charge-discharge cycles. If they are used at only low currents and are permitted to discharge through only part of a cycle and are then recharged, over a long period of time they will develop a characteristic curve to match this cycle.

Nickel-Metal Hydride Cells

Nickel-metal hydride cells (Ni-MH) are similar to nickel-cadmium cells in many respects. Both exhibit a voltage of 1.2 volts per cell, and both have very similar charge and discharge curves. Nickel-metal hydride cells exhibit some improved characteristics over nickel-cadmium cells, however. They have about a 40% higher energy density, and they do not exhibit as great a problem of memory accumulation. Nickel-metal hydride cells are also more environmentally friendly than nickel-cadmium cells. The positive electrode is made of nickel oxyhydroxide (Ni00H), and the negative electrode is made of metal hydride. The electrolyte is an aqueous (watery) potassium-hydroxide solution. Nickel-metal hydride cells are replacing nickel-cadmium cells in many applications because they have a greater energy density and very little problem with memory accumulation.

Lithium-Ion Cells

Lithium-ion cells are very popular for portable equipment such as notebook computers, video cameras, cell phones, and many others. Lithium-ion cells can be recharged and offer a very high energy density for their size and weight.

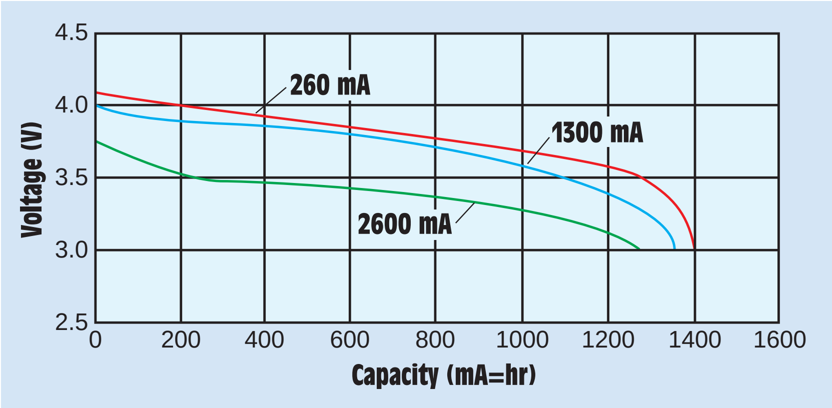

FIGURE 13–27 Typical discharge curves for lithium-ion cells.

They exhibit a voltage of 3.6 volts per cell, which is the same voltage that can be obtained by connecting three nickel-cadmium (Ni-Cd) or three nickel-metal hydride (Ni-MH) cells in series. Lithium-ion cells also exhibit a weight-energy density that is about three times greater than nickel-cadmium cells. Under proper charging conditions, these cells can be recharged about 500 times. They also exhibit a rather flat discharge curve *(Figure 13–27)*, which makes them an ideal choice for electronic devices that require a constant voltage. Unlike nickel-cadmium cells and to some extent nickel-metal hydride cells, lithium-ion cells do not have the problem of memory accumulation. They can be recharged to their full capacity each time they are charged.

Lithium-ion cells can safely be recharged because they do not contain metallic lithium. The positive electrode or anode is made of lithium metallic oxide, and the negative electrode or cathode is made of carbon. These cells work by transferring lithium ions between the cathode and anode during discharging and charging. Although lithium-ion cells are safe to recharge, they do require a special charger. Chargers for these cells generally produce a constant voltage and constant current. Overcurrent or overvoltage during charging can cause early deterioration of the cell.

13–7 Series and Parallel Battery Connections

When batteries or cells are connected in series, their voltages add and their current capacities remain the same. In *Figure 13–28*, four batteries, each having a voltage of 12 volts and 60 ampere-hours, are connected in series. Connecting them in series has the effect of maintaining the surface area of the plates and increasing the number of cells. The connection shown in *Figure 13–28* will have an output voltage of 48 volts and a current capacity of 60 ampere-hours.

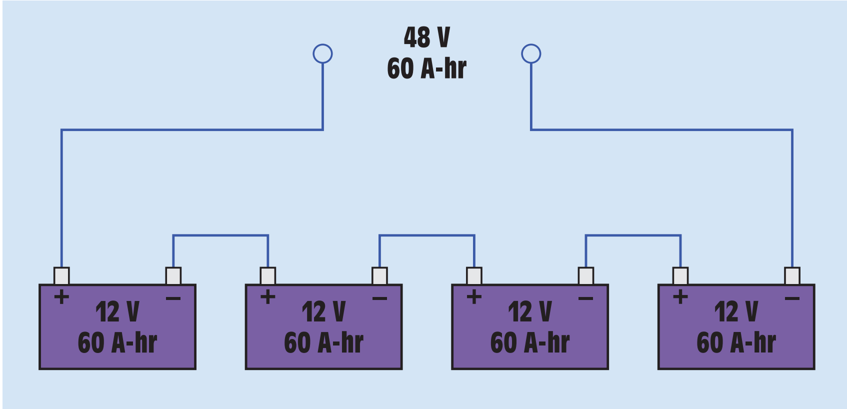

FIGURE 13–28 When batteries are connected in series, their voltages add and their ampere-hour capacities remain the same.

Connecting batteries or cells in parallel *(Figure 13–29)* has the effect of increasing the area of the plates. In this example, the same four batteries are connected in parallel. The output voltage remains 12 volts, but the ampere-hour capacity has increased to 240 ampere-hours.

CAUTION: ***Batteries of different voltages should never be connected in parallel. The batteries could be damaged or one of the batteries could explode.*** ■

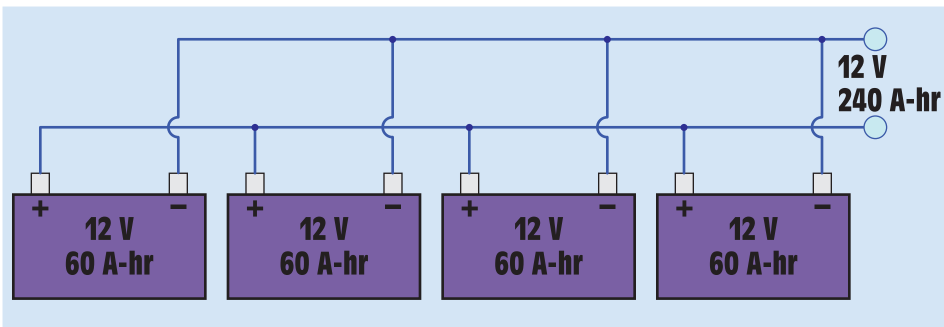

FIGURE 13–29 When batteries are connected in parallel, their voltages remain the same and their ampere-hour capacities add.

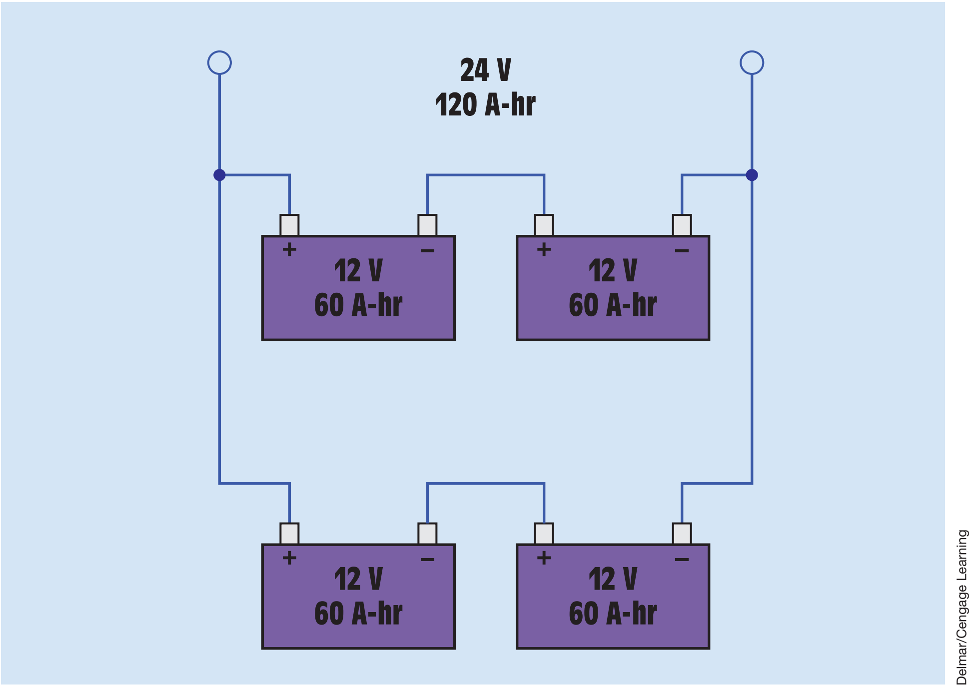

FIGURE 13–30 Series-parallel connection.

Batteries can also be connected in a series-parallel combination. In *Figure 13–30*, the four batteries have been connected in such a manner that the output has a value of 24 volts and 120 ampere-hours. To make this connection, the four batteries were divided into two groups of two batteries each. The batteries of each group were connected in series to produce an output of 24 volts at 60 ampere-hours. These two groups were then connected in parallel to provide an output of 24 volts at 120 ampere-hours.

13–8 Other Small Sources of Electricity

Solar Cells

Although batteries are the largest source of electricity after alternators and generators, they are not the only source. One source of electricity is the photovoltaic cell or solar cell. Solar cells are constructed from a combination of P- and N-type semiconductor material. Semiconductors are made from materials that contain four valence electrons. The most common semiconductor materials are silicon and germanium. Impurities must be added to the pure semiconductor material to form P- and N-type materials. If a material containing three valence electrons is added to a pure semiconductor material, P-type material is formed. P-type material has a lack of electrons. N-type material is formed when a

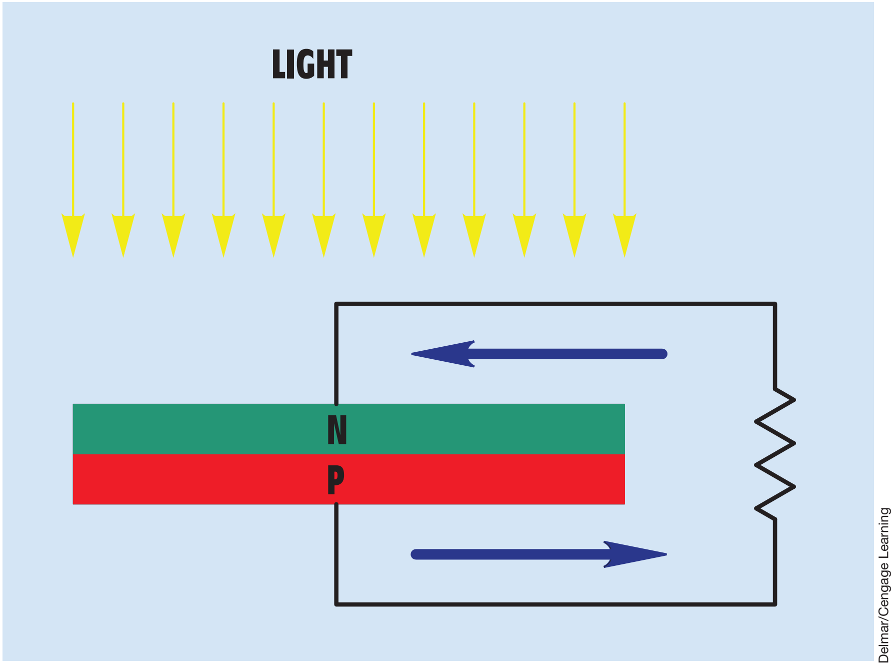

FIGURE 13–31 Solar cells are formed by bonding P- and N-type semiconductor materials.

material containing five valence electrons is added to a pure semiconductor material. N-type material has an excess of electrons.

Light is composed of particles called photons. A photon is a small package of pure energy that contains no mass. When photons strike the surface of the photocell, the energy contained in the photon is given to a free electron. This additional energy causes the electron to cross the junction between the two types of semiconductor material and produce a voltage *(Figure 13–31)*.

GREEN TIP: Solar cells can produce electricity without the use of any fossil fuels. Solar cell arrays are often used to charge batteries that in turn supply power to rural locations where access to power lines is not available. ■

The amount of voltage produced by a solar cell is determined by the material from which it is made. Silicon solar cells produce an open-circuit voltage of 0.5 volts per cell in direct sunlight. The amount of current a cell can deliver is determined by the surface area of the cell. Because the solar cell produces

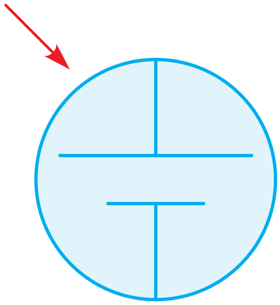

FIGURE 13–32 Schematic symbol for a solar cell.

a voltage in the presence of light, the schematic symbol for a solar cell is the same as that used to represent a single voltaic cell with the addition of an arrow to indicate it is receiving light *(Figure 13–32)*.

GREEN TIP: Solar collectors are a very efficient method of heating water. Many countries throughout the world depend almost entirely on solar energy for heating residential water. ■

It is often necessary to connect solar cells in series or parallel or both to obtain desired amounts of voltage and current. For example, assume that an array of photovoltaic cells is to be used to charge a 12-volt lead-acid battery. The charging voltage is to be 14 volts, and the charging current should be 0.5 ampere. Now assume that each cell produces 0.5 volt with a short-circuit current of 0.25 ampere. In order to produce 14 volts, it will be necessary to connect 28 solar cells in series. An output of 14 volts with a current capacity of 0.25 ampere will be produced. To produce an output of 14 volts with a current capacity of 0.5 ampere, it will be necessary to connect a second set of 28 cells in series and parallel this set with the first set *(Figure 13–33)*.

Thermocouples

In 1822, a German scientist named Seebeck discovered that when two dissimilar metals are joined at one end and that junction is heated, a voltage is produced *(Figure 13–34)*. This is known as the Seebeck effect. The device produced by the joining of two dissimilar metals for the purpose of producing electricity with heat is called a **thermocouple.** The amount of voltage produced by a thermocouple is determined by

1. the type of materials used to produce the thermocouple.
2. the temperature difference between the junction and the open ends.

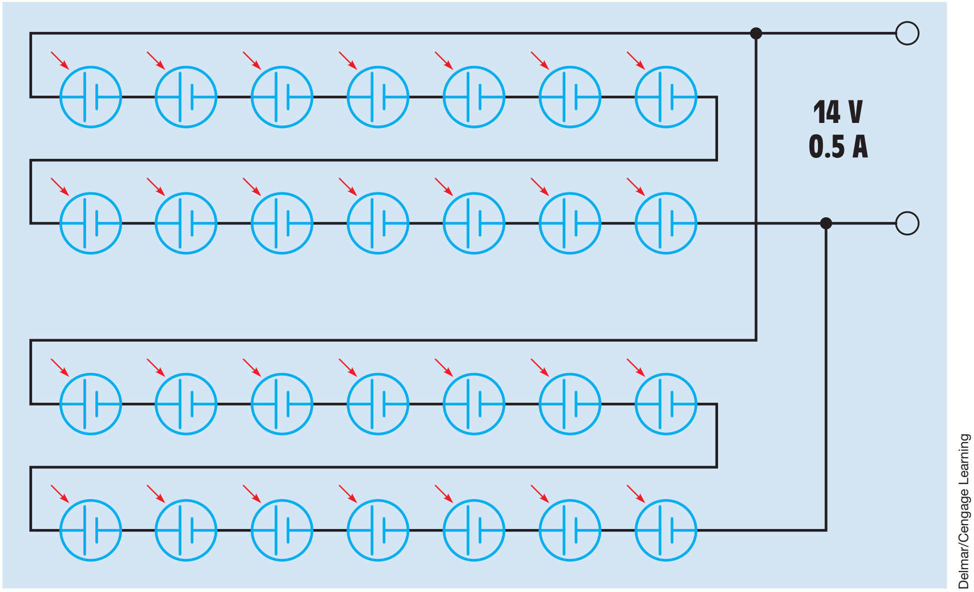

FIGURE 13–33 Series-parallel connection of solar cells.

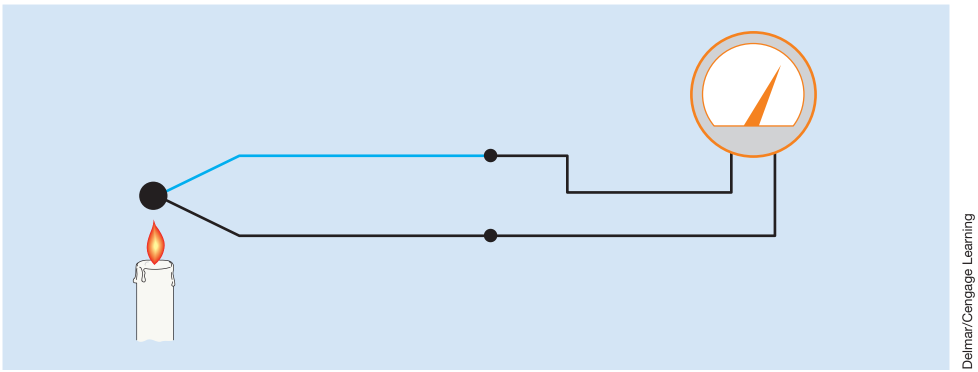

FIGURE 13–34 The thermocouple is made by forming a junction of two different types of metal.

The chart in *Figure 13–35* shows common types of thermocouples. The different metals used in the construction of thermocouples are shown, as well as the normal temperature ranges of the thermocouples.

The amount of voltage produced by a thermocouple is small, generally on the order of millivolts (1 mV = 0.001 V). The polarity of the voltage of some thermocouples is determined by the temperature. For example, a type J thermocouple produces 0 volt at about 32°F. At temperatures above 32°F, the iron wire is positive and the constantan wire is negative. At temperatures below 32°F, the iron wire becomes negative and the constantan wire becomes positive. At a temperature of 300°F, a type J thermocouple will produce a voltage

TYPE	MATERIAL		Degrees F	Degrees C
J	Iron	Constantan	–328 to +32 +32 to +1432	–200 to 0 0 to 778
K	Chromel	Alumel	–328 to +32 +32 to +2472	–200 to 0 0 to 1356
T	Copper	Constantan	–328 to +32 +32 to 752	–200 to 0 0 to 400
E	Chromel	Constantan	–328 to +32 +32 to 1832	–200 to 0 0 to 1000
R	Platinum 13% rhodium	Platinum	–32 to +3232	0 to 1778
S	Platinum 10% rhodium	Platinum	–32 to +3232	0 to 1778
B	Platinum 6% rhodium	Platinum	–32 to +3092	0 to 1700

Delmar/Cengage Learning

FIGURE 13–35 Thermocouple chart.

of about 7.9 millivolts. At a temperature of −300°F, it will produce a voltage of about −7.9 millivolts.

Because thermocouples produce such low voltages, they are often connected in series, as shown in *Figure 13–36*. This connection is referred to as a thermopile. Thermocouples and thermopiles are generally used for measuring temperature and are sometimes used to detect the presence of a pilot light in appliances that operate with natural gas. The thermocouple is heated by the pilot light. The current produced by the thermocouple is used to produce a magnetic field, which holds a gas valve open to permit gas to flow to the main burner. If the pilot light goes out, the thermocouple ceases to produce current and the valve closes *(Figure 13–37)*.

Piezoelectricity

The word *piezo*, pronounced "pee-ay-zo," is derived from the Greek word for pressure. **Piezoelectricity** is produced by some materials when they are

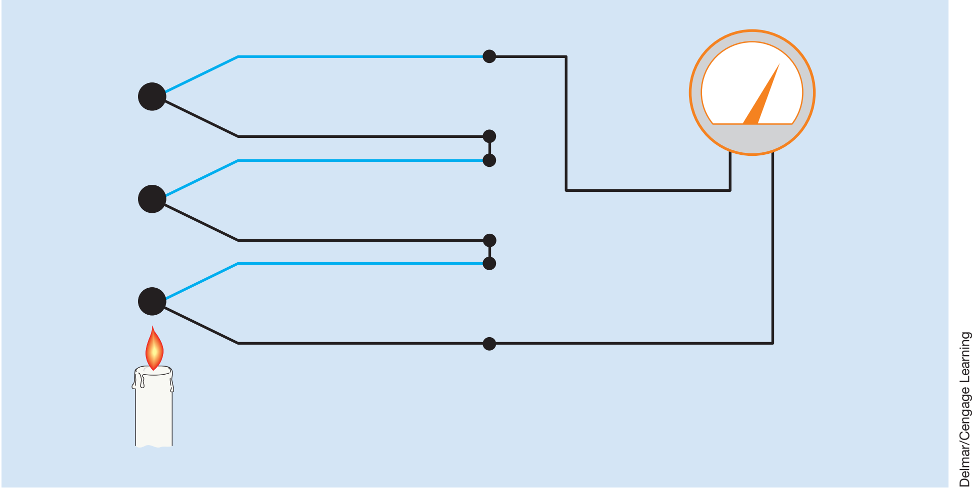

FIGURE 13–36 A thermopile is a series connection of thermocouples.

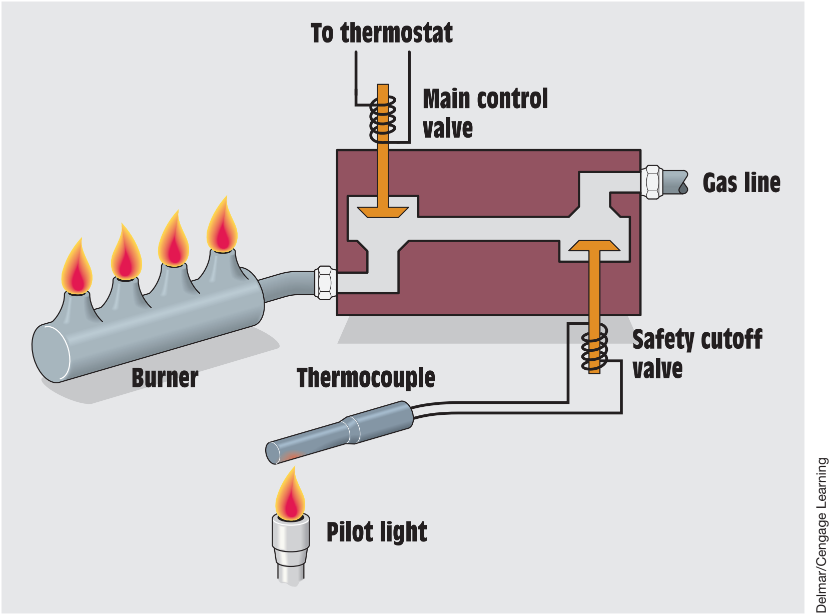

FIGURE 13–37 A thermocouple provides power to the safety cutoff valve.

placed under pressure. The pressure can be caused by compression, twisting, bending, or stretching. Rochelle salt (sodium potassium tartrate) is often used as the needle, or stylus, of a phonograph. Grooves in the record cause the crystal to be twisted back and forth, producing an alternating voltage. This voltage is amplified and is heard as music or speech. Rochelle salt crystals are also used as the pickup for microphones. The vibrations caused by sound waves produce stress on the crystals. This stress causes the crystals to produce an alternating voltage that can be amplified.

Another crystal used to produce the piezoelectric effect is barium titanate. Barium titanate can actually produce enough voltage and current to flash a small neon lamp when struck by a heavy object *(Figure 13–38)*. Industry uses the crystal's ability to produce voltage in transducers for sensing pressure and mechanical vibration of machine parts.

Quartz crystal has been used for many years as the basis for crystal oscillators. In this application, an AC voltage close to the natural mechanical vibration frequency of a slice of quartz is applied to opposite surfaces of the crystal. This causes the quartz to vibrate at its natural frequency. The frequency is extremely constant for a particular slice of quartz. Quartz crystals have been used to change the frequency range of two-way radios for many years.

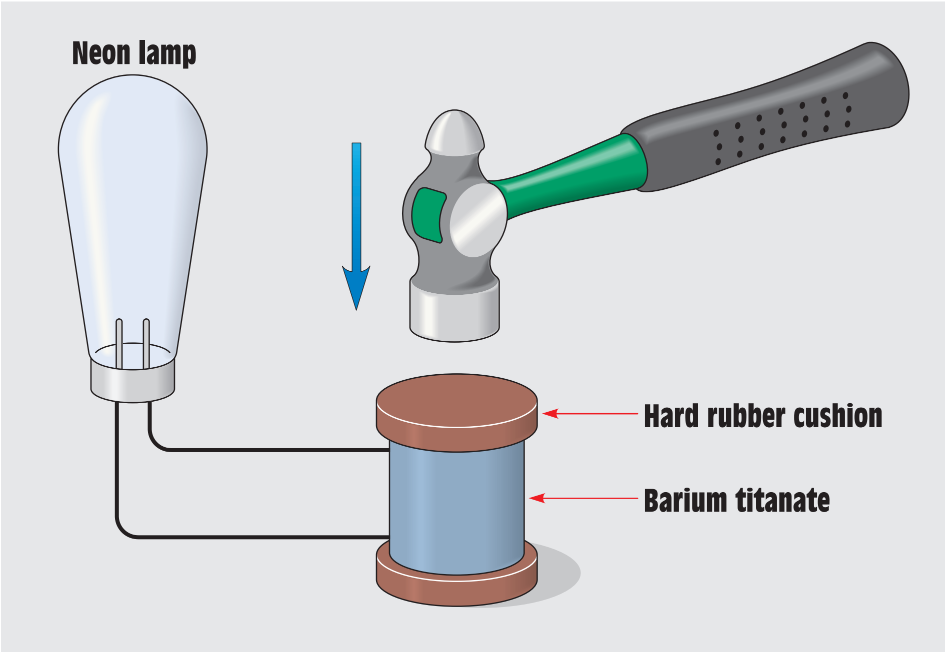

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FIGURE 13–38 Voltage produced by piezoelectric effect.

Fuel Cells

Another device that employs chemical processes to produce electricity is the fuel cell. Similar to voltaic cells, the fuel cell transfers electrons from one material to another. An important difference between the voltaic cell and the fuel cell, however, is that the material giving the electrons and the material accepting the electrons are not consumed in the process. Fuel cells require high-purity fuel and a catalytic surface for the reaction to take place. They also require auxiliary equipment such as gas containers and pressure controls. Research is under way to develop fuel cells for powering automobiles and as a source of power for homes.

A common type of fuel cell is the hydrogen-oxygen cell (*Figure 13–39*.)

The cell contains hollow, porous, carbon electrodes immersed in a potassium hydroxide solution. Hydrogen gas is supplied to one electrode and oxygen gas is supplied to the other. The carbon electrodes contain metal or metal oxide that acts as a catalyst. A catalyst is a substance that aids the chemical reaction. In this case, the catalyst helps hydrogen molecules, which are pairs of hydrogen atoms, to separate into single atoms that combine with the negatively charged hydroxide ions of the electrolyte. The combination of the hydrogen

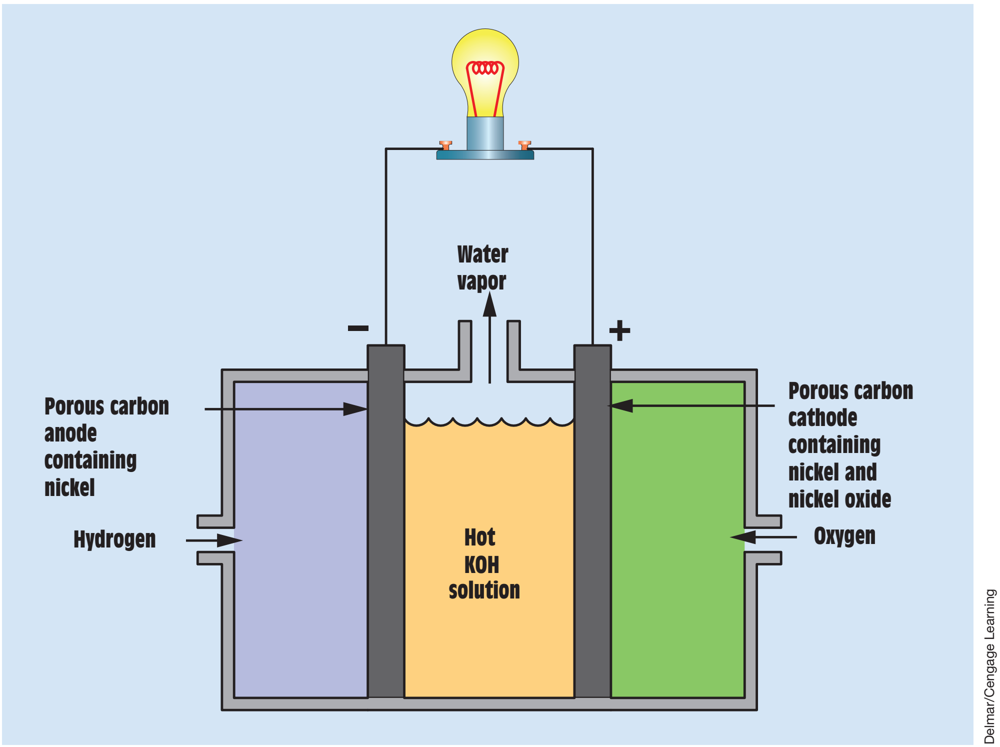


FIGURE 13–39 Basic hydrogen-oxygen fuel cell.

and hydroxide ion forms a molecule of water, H_2O, with one electron left over. The excess electrons are attracted to the carbon electrode that is supplied with oxygen. The hydroxide ions are re-formed at the cathode at the same rate as they are used up at the anode. The result is that hydrogen and oxygen are converted into water.

The alkaline-hydrogen-oxygen fuel cell just discussed was one the very early types introduced in the 1960s. There are other types of fuel cells today that offer different characteristics and advantages.

The Polymer Electrolyte Membrane (PEM) Fuel Cell

Polymer electrolyte membrane fuel cells are often called proton exchange membrane fuel cells. These cells offer high-power density combined with low weight and volume compared with other types of fuel cells. PEM fuel cells employ a solid polymer as the electrolyte. The electrodes are porous carbon combined with a platinum catalyst. They require only hydrogen, oxygen from the air, and water to operate. They do not need corrosive fluids like some other fuel cells. PEM fuel cells operate at a relatively low temperature, around 176°F (80°C).

Direct Methanol Fuel Cells

Direct methanol fuel cells are power by pure methanol mixed with steam. The methanol-steam mixture is fed directly to the fuel cell anode. These fuel cells have an advantage in that they do not have the fuel storage problems of cells that rely on pure hydrogen. Because methanol is a liquid, it is much easier to store. Methanol also has a higher energy density than hydrogen, although it does not contain as much energy as gasoline or diesel fuel.

Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte. The acid is contained in a Teflon-bonded silicon carbide matrix. The electrodes are composed of porous carbon containing a platinum catalyst. This cell is considered the first generation of modern fuel cells and has been used commercially for stationary power generation and to power large vehicles such as city buses.

Molten Carbonate Fuel Cells

Molten carbonate fuel cells are being developed for natural gas and coal-fired power plants. These fuel cells operate at very high temperatures, typically 1200°F (650°C) and above. The high operating temperature has an advantage in that nonprecious metals can be used as a catalyst in the anode and cathode electrodes, resulting in much lower cost. Molten carbonate fuel cells can reach efficiencies as high as 60%.

Solid Oxide Fuel Cells

Solid oxide fuel cells use a hard nonporous ceramic compound as the electrolyte. Because the electrolyte is a solid, the fuel cell does not have to be constructed in the plate-like configuration typical of other types of fuel cells. These fuel cells operate at very high temperatures, 1,830°F (1000°C). The high operating temperature has an advantage in that nonprecious metals can be used as a catalyst in the electrodes. Also, the high operating temperature of the solid oxide fuel cell permits re-forming of fuels internally, enabling the use of a variety of fuels, which helps reduce the cost of adding a re-former to the system. Solid oxide fuel cells have an efficiency of 50% to 60%.

GREEN TIP: Fuel cells can be used to produce electricity with very little harmful effect to the environment. ■

Summary

- The first practical battery was invented by Alessandro Volta in 1800.
- A voltaic cell converts chemical energy into electrical energy.
- A battery is a group of cells connected together.
- Primary cells cannot be recharged.
- Secondary cells can be recharged.
- The amount of voltage produced by a cell is determined by the materials from which it is made.
- A voltaic cell can be constructed from almost any two unlike metals and an electrolyte of acid, alkali, or salt.
- Voltaic cells depend on the movement of ions in solution to produce electricity.
- The amount of current a cell can provide is determined by the area of the cell plates.
- Primary cells are often rated in milliampere-hours or watt-hours.
- The amount of energy a battery can contain is called its capacity or energy density.
- Secondary cells can be recharged by reversing the current flow through them.

- A hydrometer is a device for measuring the specific gravity of the electrolyte.
- When lead-acid batteries are charged, hydrogen gas is produced.
- Nickel-cadmium batteries have a life span of about 2000 charge-discharge cycles.
- When cells are connected in series, their voltages add and their ampere-hour capacities remain the same.
- When cells are connected in parallel, their voltages remain the same and their ampere-hour capacities add.
- Cells or batteries of different voltages should never be connected in parallel.
- Solar cells produce electricity in the presence of light.
- The amount of voltage produced by a solar cell is determined by the materials from which it is made.
- The amount of current produced by a solar cell is determined by the surface area.
- Thermocouples produce a voltage when the junction of two unlike metals is heated.
- The amount of voltage produced by a thermocouple is determined by the type of materials used and the temperature difference between the ends of the junction.
- The voltage polarity of some thermocouples is determined by the temperature.
- Thermocouples connected in series to produce a higher voltage are called a thermopile.
- Some crystals can produce a voltage when placed under pressure.
- The production of voltage by application of pressure is called the piezoelectric effect.

Review Questions

1. What is a voltaic cell?
2. What factors determine the amount of voltage produced by a cell?
3. What determines the amount of current a cell can provide?
4. What is a battery?
5. What is a primary cell?
6. What is a secondary cell?

7. What material is used as the positive electrode in a zinc-mercury cell?
8. What is another name for the Leclanché cell?
9. What is used as the electrolyte in a carbon-zinc cell?
10. What is the advantage of the alkaline cell as compared with the carbon-zinc cell?
11. What material is used as the positive electrode in an alkaline cell?
12. How is the A-hr capacity of a lead-acid battery determined?
13. What device is used to test the specific gravity of a cell?
14. A 6-V lead-acid battery has an A-hr rating of 180 A-hr. The battery is to be load tested. What should be the test current, and what are the maximum permissible amount and duration of the voltage drop?
15. Three 12-V, 100-A-hr batteries are connected in series. What are the output voltage and A-hr capacity of this connection?
16. What is the voltage produced by a silicon solar cell?
17. What determines the current capacity of a solar cell?
18. A solar cell can produce a voltage of 0.5 V and has a current capacity of 0.1 A. How many cells should be connected in series and parallel to produce an output of 6 V at 0.3 A?
19. What determines the amount of voltage produced by a thermocouple?
20. A thermocouple is to be used to measure a temperature of 2800°F. Which type or types of thermocouples can be used to measure this temperature?
21. What materials are used in the construction of a type J thermocouple?
22. What does the word *piezo* mean?

Practical Applications

Your job is to order and connect lead-acid cells used to supply an uninterruptible power supply (UPS). The battery output voltage must be 126 V and have a current capacity of not less than 250 A-hr. Each cell has a rating of 2 V and 100 A-hr. How many cells must be ordered and how would you connect them? ■

Practical Applications

A bank of nickel-cadmium cells is used as the emergency lighting supply for a hospital. There are 100 cells connected in series and each has an A-hr rating of 120 A-hr. The bank has to be replaced, and the manufacturer is no longer supplying nickel-cadmium cells. It is decided to replace the cells with lead-acid cells. How many lead-acid cells will be required if each has an A-hr rating of 60 A-hr, and how should they be connected? ■

Practical Applications

An office building uses a bank of 63 lead-acid cells connected in series with a capacity of 80 amp-hours each to provide battery backup for their computers. The lead-acid cells are to be replaced with nickel-metal hydride cells with a capacity of 40 amp-hours each. How many nickel-metal hydride cells will be required to replace the lead-acid cells and how should they be connected? ■

Unit 14

Magnetic Induction

Why You Need to Know

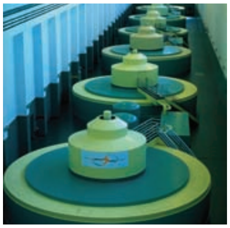
Magnetic induction is one of the most important concepts in the study of electricity. Devices such as generators, alternators, motors, and transformers operate on this principle. This unit

- explains why current cannot rise in an inductor instantly.
- describes what determines the amount of inducted voltage and its polarity.
- describes what a voltage spike is, when it occurs, and how to control it.
- illustrates how an induced current produces a magnetic field around a coil.
- explains how the amount of voltage induced in a conductor relates to magnetic induction and lines of flux.
- discusses time constants and how the rise time of current in an inductor can be determined.
- introduces the exponential curve. Understanding the exponential curve is important because so many things in both science and nature operate on this principle. Not only does the current in an inductor rise at an exponential rate, but also clothes hung on a line dry at an exponential rate.

OUTLINE

KEY TERMS

Eddy current
Electromagnetic induction
Exponential curve
Henry (H)
Hysteresis loss
Left-hand generator rule
Lenz's law
Metal oxide varistor (MOV)
R-L time constant
Speed
Strength of magnetic field
Turns of wire
Voltage spike
Weber (Wb)


Courtesy of Tennessee Valley Authority

Objectives

After studying this unit, you should be able to

- discuss electromagnetic induction.
- list factors that determine the amount and polarity of an induced voltage.
- discuss Lenz's law.
- discuss an exponential curve.
- list devices used to help prevent induced voltage spikes.

Preview

Electromagnetic induction is one of the most important concepts in the electrical field. It is the basic operating principle underlying alternators, transformers, and most AC motors. It is imperative that anyone desiring to work in the electrical field have an understanding of the principles involved. ■

14–1 Electromagnetic Induction

In Unit 4, it was stated that one of the basic laws of electricity is that whenever current flows through a conductor, a magnetic field is created around the conductor *(Figure 14–1)*. The direction of the current flow determines the polarity of the magnetic field, and the amount of current determines the strength of the magnetic field.

That basic law in reverse is the principle of **electromagnetic induction,** which states that ***whenever a conductor cuts through magnetic lines of flux, a voltage is induced into the conductor.*** The conductor in *Figure 14–2* is connected to a zero-center microammeter, creating a complete circuit. When the conductor is moved downward through the magnetic lines of flux, the induced voltage causes electrons to flow in the direction indicated by the arrows. This flow of electrons causes the pointer of the meter to be deflected from the zero-center position.

If the conductor is moved upward, the polarity of induced voltage is reversed and the current flows in the opposite direction *(Figure 14–3)*. Consequently, the pointer is deflected in the opposite direction.

The polarity of the induced voltage can also be changed by reversing the polarity of the magnetic field *(Figure 14–4)*. In this example, the conductor is again moved downward through the lines of flux, but the polarity of the magnetic field has been reversed. Therefore, the polarity of the induced voltage is the opposite of that in *Figure 14–2,* and the pointer of the meter is deflected in

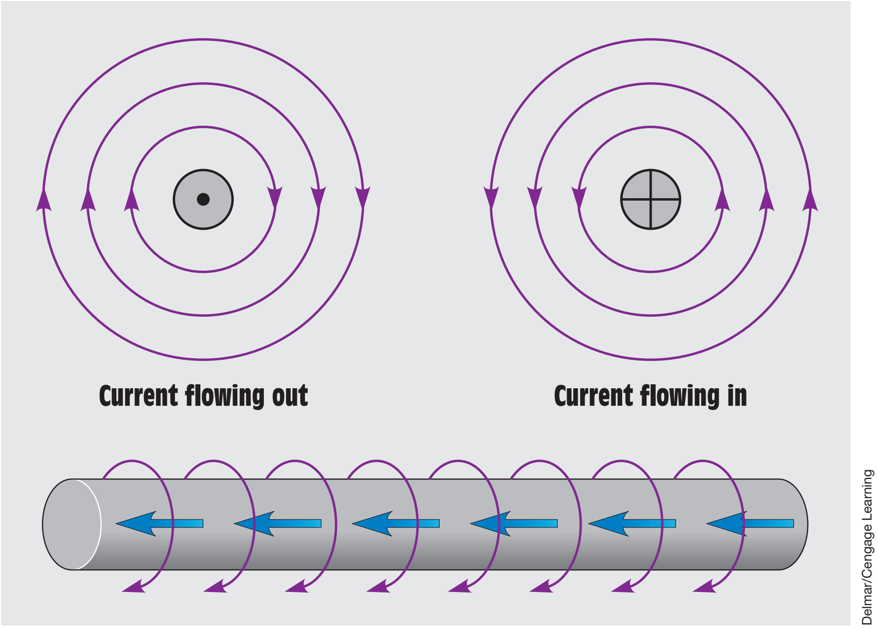


FIGURE 14–1 Current flowing through a conductor produces a magnetic field around the conductor.

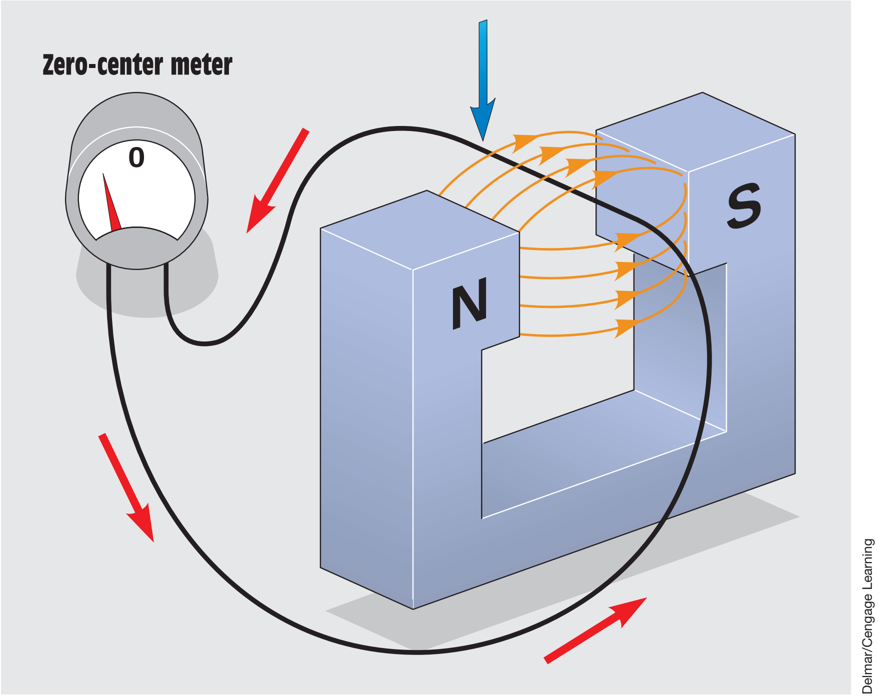


FIGURE 14–2 A voltage is induced when a conductor cuts magnetic lines of flux.

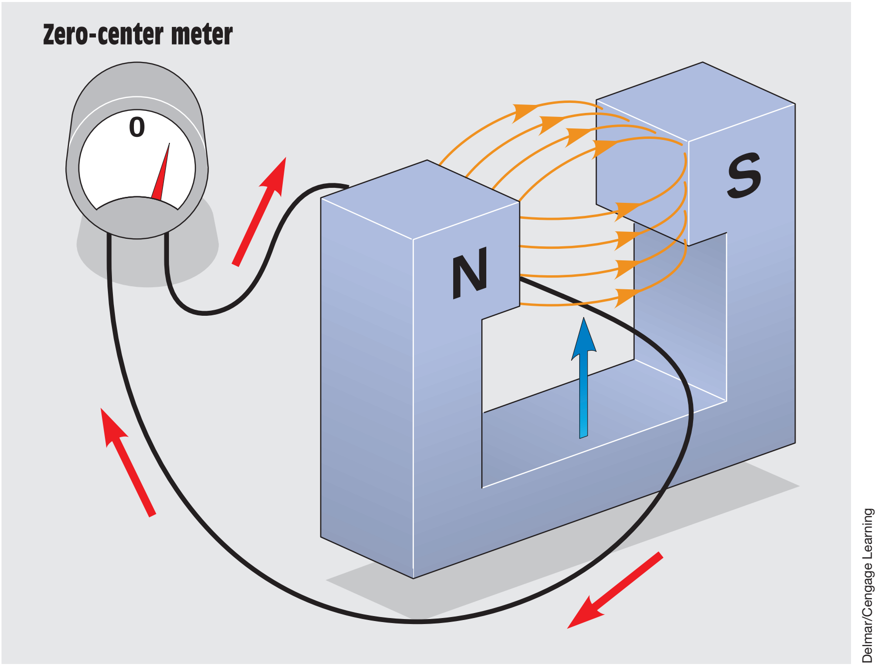


FIGURE 14–3 Reversing the direction of movement reverses the polarity of the voltage.

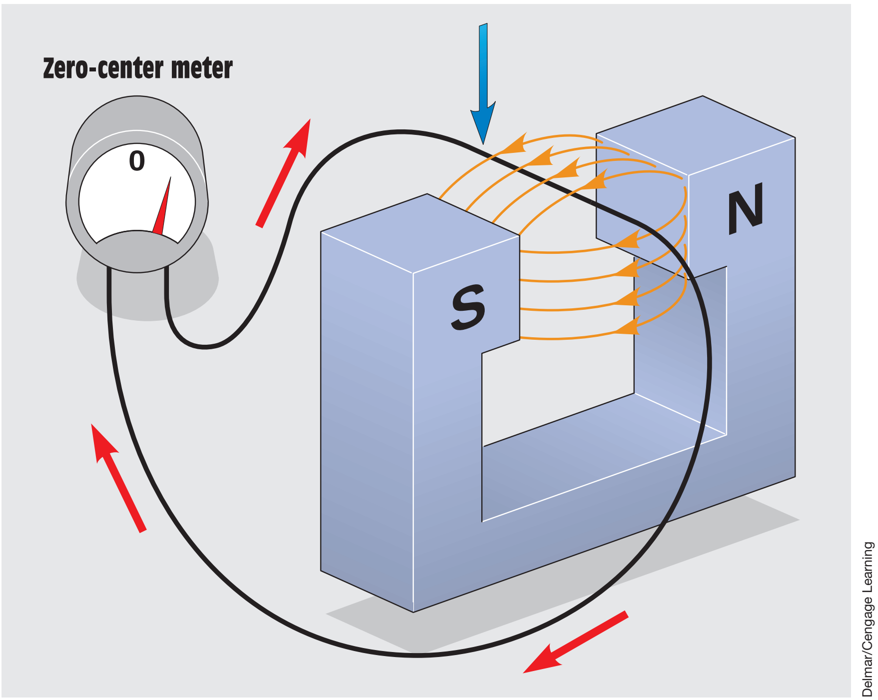


FIGURE 14–4 Reversing the polarity of the magnetic field reverses the polarity of the voltage.

the opposite direction. It can be concluded that ***the polarity of the induced voltage is determined by the polarity of the magnetic field in relation to the direction of movement.***

14–2 Fleming's Left-Hand Generator Rule

Fleming's **left-hand generator rule** can be used to determine the relationship of the motion of the conductor in a magnetic field to the direction of the induced current. To use the left-hand rule, place the thumb, forefinger, and center finger at right angles to each other, as shown in *Figure 14–5*. ***The forefinger points in the direction of the field flux,*** assuming that magnetic lines of force are in a direction of north to south. ***The thumb points in the direction of thrust,*** or movement of the conductor, ***and the center finger shows the direction of the current induced into the armature.*** An easy method of remembering which finger represents which quantity follows:

THumb = **TH**rust
Forefinger = **F**lux
Center finger = **C**urrent

The left-hand rule can be used to clearly illustrate that if the polarity of the magnetic field is changed or if the direction of armature rotation is changed, the direction of induced current also changes.

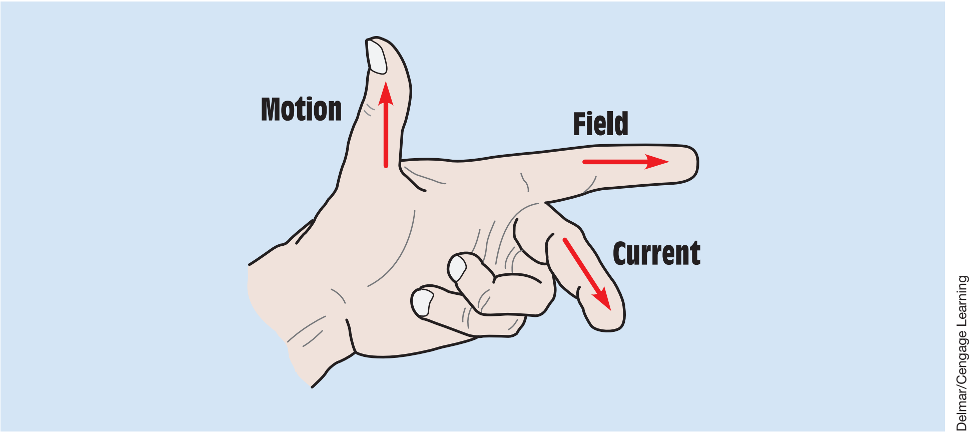


FIGURE 14–5 Left-hand generator rule.

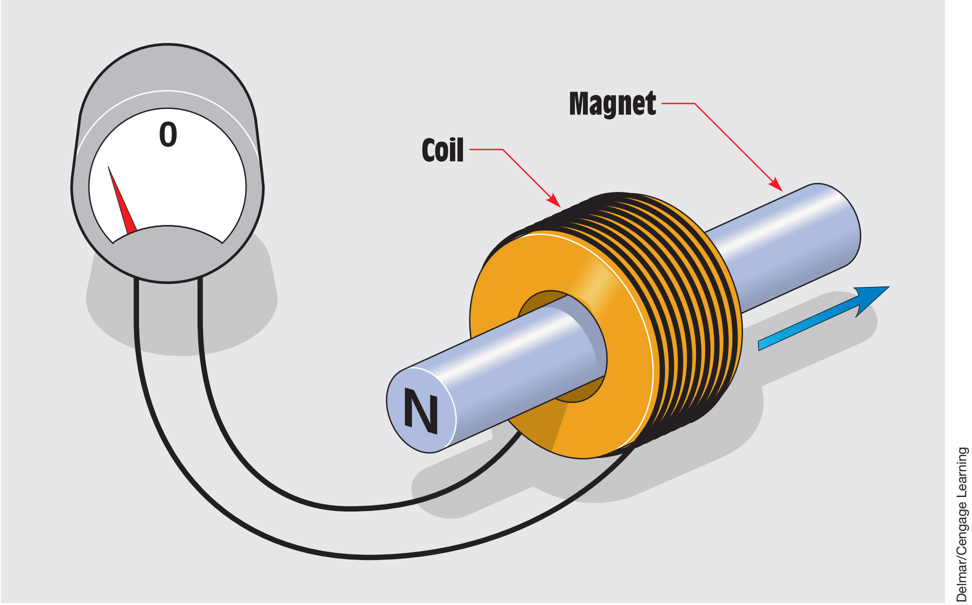


FIGURE 14–6 Voltage is induced by a moving magnetic field.

14–3 Moving Magnetic Fields

The important factors concerning electromagnetic induction are a conductor, a magnetic field, and relative motion. In practice, it is often desirable to move the magnet instead of the conductor. Most AC generators or alternators operate on this principle. In *Figure 14–6,* a coil of wire is held stationary while a magnet is moved through the coil. As the magnet is moved, the lines of flux cut through the windings of the coil and induce a voltage into them.

14–4 Determining the Amount of Induced Voltage

Three factors determine the amount of voltage that will be induced in a conductor:

1. the number of **turns of wire**
2. the **strength of the magnetic field** (flux density)
3. the **speed** of the cutting action

In order to induce 1 volt in a conductor, the conductor must cut 100,000,000 lines of magnetic flux in 1 second. In magnetic measurement, 100,000,000 lines of flux are equal to 1 **weber (Wb).** Therefore, if a conductor cuts magnetic lines of flux at a rate of 1 weber per second, a voltage of 1 volt is induced.

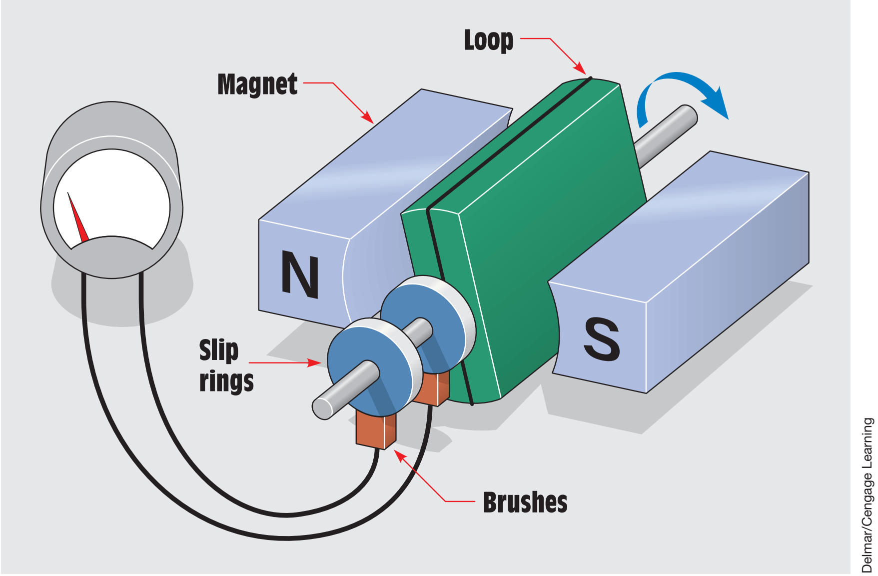


FIGURE 14–7 A single-loop generator.

A simple one-loop generator is shown in *Figure 14–7*. The loop is attached to a rod that is free to rotate. This assembly is suspended between the poles of two stationary magnets. If the loop is turned, the conductor cuts through magnetic lines of flux and a voltage is induced into the conductor.

If the speed of rotation is increased, the conductor cuts more lines of flux per second and the amount of induced voltage increases. If the speed of rotation remains constant and the strength of the magnetic field is increased, there will be more lines of flux per square inch. When there are more lines of flux, the number of lines cut per second increases and the induced voltage increases. If more turns of wire are added to the loop *(Figure 14–8),* more flux lines are cut per second and the amount of induced voltage increases again. Adding more turns has the effect of connecting single conductors in series, and the amount of induced voltage in each conductor adds.

14–5 Lenz's Law

When a voltage is induced in a coil and there is a complete circuit, current flows through the coil *(Figure 14–9)*. When current flows through the coil, a magnetic field is created around the coil. This magnetic field develops a polarity opposite that of the moving magnet. The magnetic field developed by the induced current acts to attract the moving magnet and pull it back inside the coil.

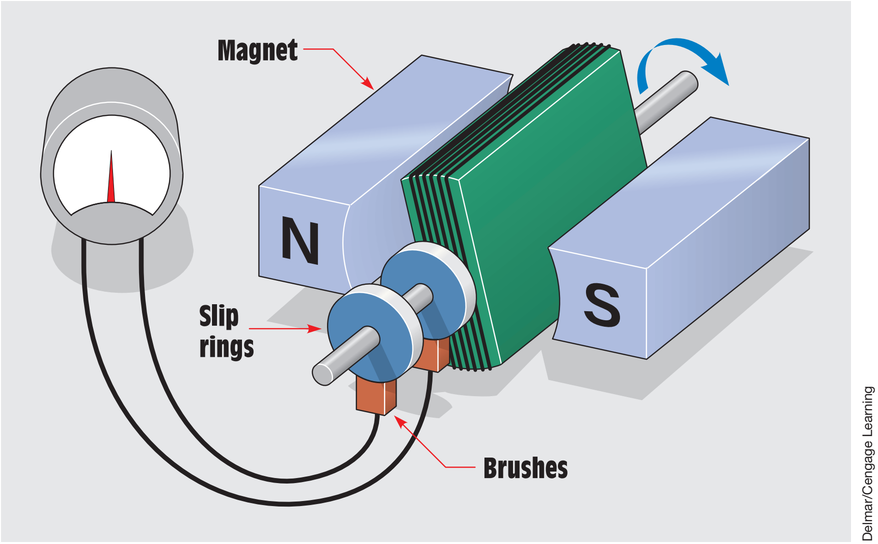


FIGURE 14–8 Increasing the number of turns increases the induced voltage.

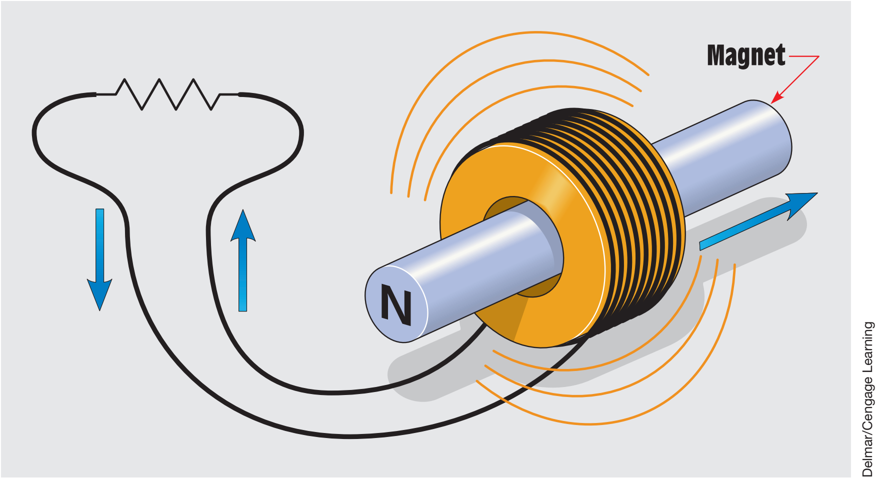


FIGURE 14–9 An induced current produces a magnetic field around the coil.

If the direction of motion is reversed, the polarity of the induced current is reversed, and the magnetic field created by the induced current again opposes the motion of the magnet. This principle was first noticed by Heinrich Lenz many years ago and is summarized in **Lenz's law,** which states that ***an induced voltage or current opposes the motion that causes it.*** From this basic principle, other laws concerning inductors have been developed. One is that

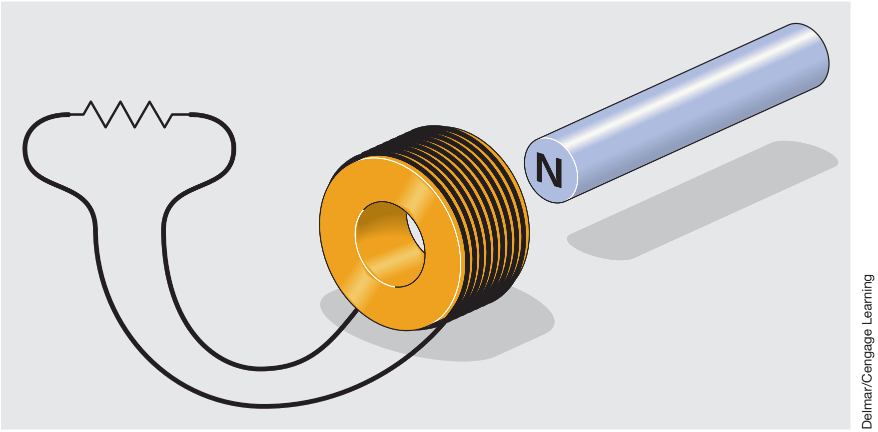


FIGURE 14–10 No current flows through the coil.

inductors always oppose a change of current. The coil in *Figure 14–10,* for example, has no induced voltage and therefore no induced current. If the magnet is moved toward the coil, however, magnetic lines of flux begin to cut the conductors of the coil and a current is induced in the coil. The induced current causes magnetic lines of flux to expand outward around the coil *(Figure 14–11)*. As this expanding magnetic field cuts through the conductors of the coil, a voltage is induced in the coil. The polarity of the voltage is such that it opposes the induced current caused by the moving magnet.

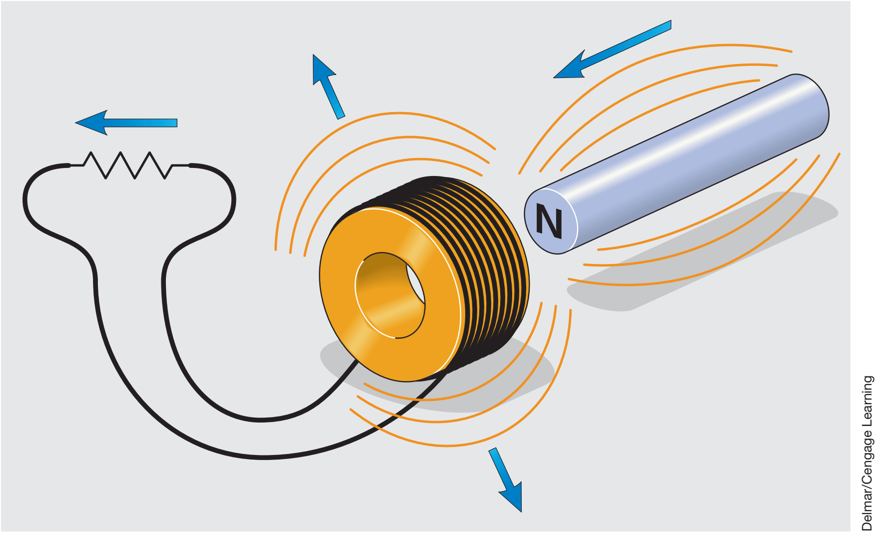
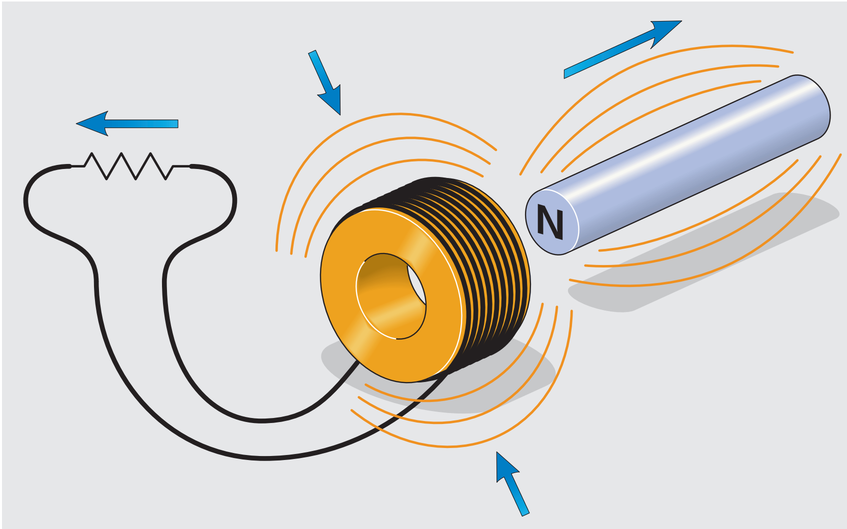


FIGURE 14–11 Induced current produces a magnetic field around the coil.



Delmar/Cengage Learning

FIGURE 14–12 The induced voltage forces current to flow in the same direction.

If the magnet is moved away, the magnetic field around the coil collapses and induces a voltage in the coil *(Figure 14–12)*. Because the direction of movement of the collapsing field has been reversed, the induced voltage is opposite in polarity, forcing the current to flow in the same direction.

14–6 Rise Time of Current in an Inductor

When a resistive load is suddenly connected to a source of DC *(Figure 14–13),* the current instantly rises to its maximum value. The resistor shown in *Figure 14–13* has a value of 10 ohms and is connected to a 20-volt source. When the switch is closed, the current instantly rises to a value of 2 amperes (20 V/10 Ω = 2 A).

If the resistor is replaced with an inductor that has a wire resistance of 10 ohms and the switch is closed, the current cannot instantly rise to its maximum value of 2 amperes *(Figure 14–14)*. As current begins to flow through an inductor, the expanding magnetic field cuts through the conductors, inducing a voltage into them. In accord with Lenz's law, the induced voltage is opposite in polarity to the applied voltage. The induced voltage therefore acts like a resistance to hinder the flow of current through the inductor *(Figure 14–15)*.

The induced voltage is proportional to the rate of change of current (speed of the cutting action). When the switch is first closed, current flow through the coil tries to rise instantly. This extremely fast rate of current change

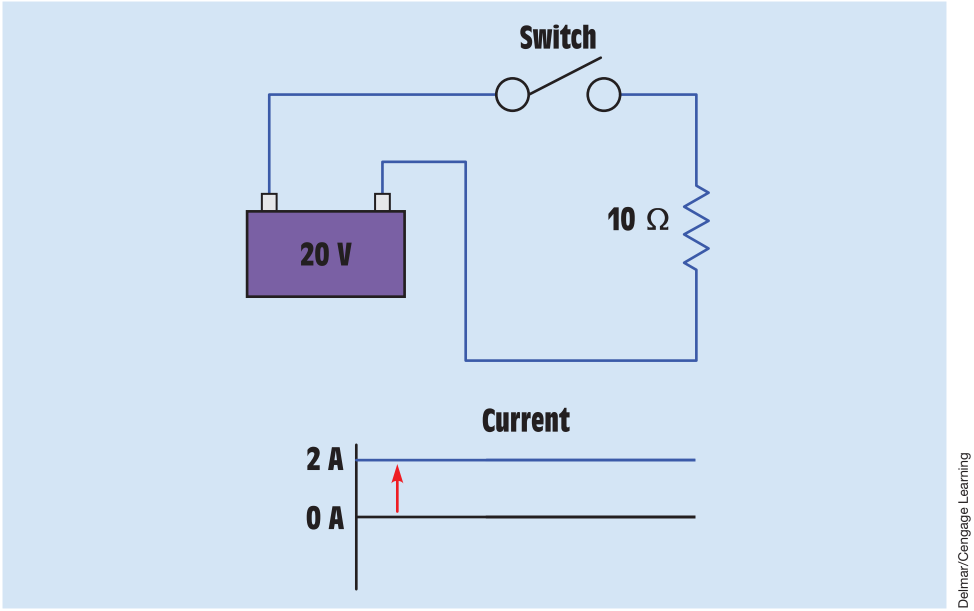


FIGURE 14–13 The current rises instantly in a resistive circuit.

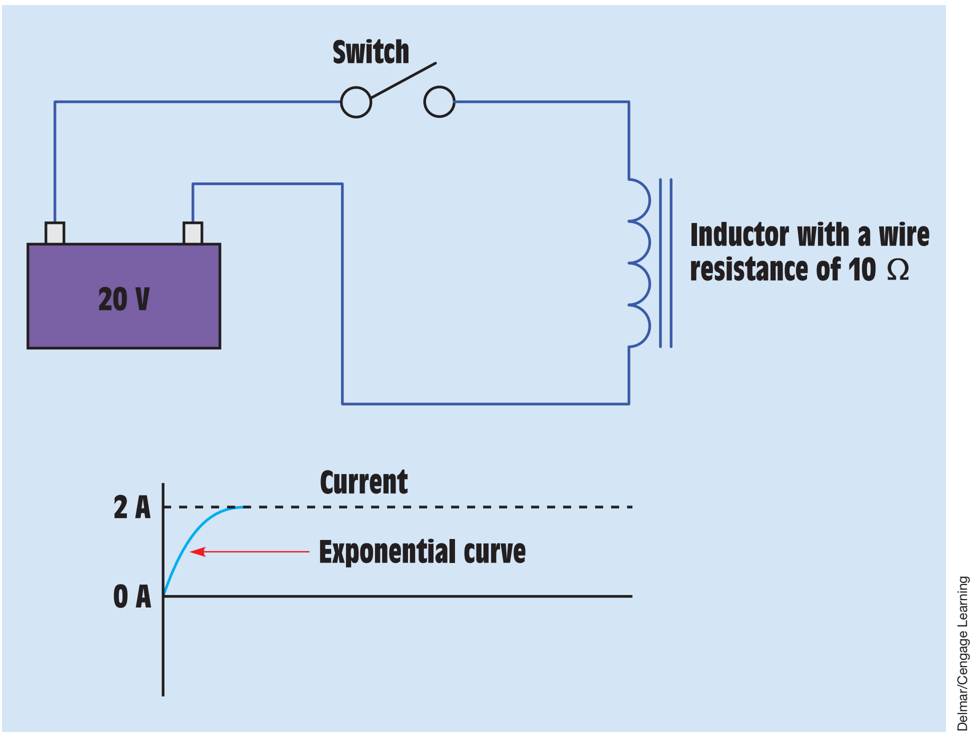


FIGURE 14–14 Current rises through an indicator at an exponential rate.

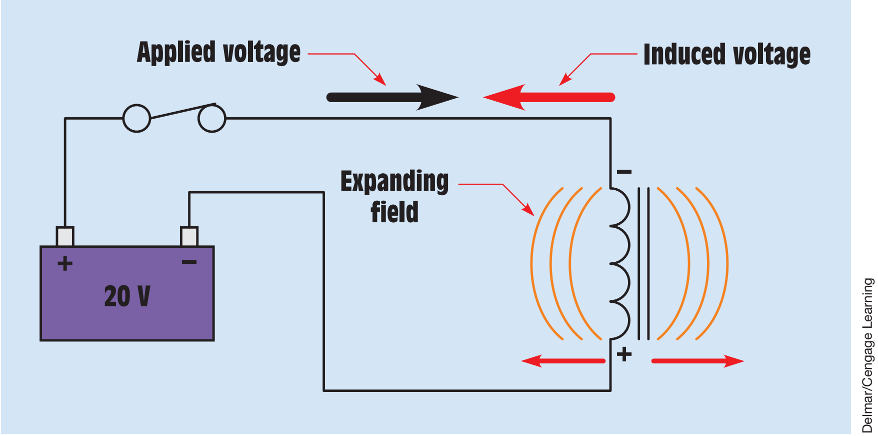


FIGURE 14–15 The applied voltage is opposite in polarity to the induced voltage.

induces maximum voltage in the coil. As the current flow approaches its maximum Ohm's law value—in this example, 2 amperes—the rate of change becomes less and the amount of induced voltage decreases.

14–7 The Exponential Curve

The **exponential curve** describes the rate of certain occurrences. The curve is divided into five time constants. During each time constant, the current rises an amount equal to 63.2% of some value. An exponential curve is shown in *Figure 14–16*. In this example, current must rise from zero to a value of 1.5 amperes at an exponential rate. In this example, 100 milliseconds are required for the current to rise to its full value. Because the current requires a total of 100 milliseconds to rise to its full value, each time constant is 20 milliseconds (100 ms/5 time constants = 20 ms per time constant). During the first time constant, the current rises from 0 to 63.2% of its total value, or 0.984 ampere (1.5 A × 0.632 = 0.948 A). The remaining current is now 0.552 ampere (1.5 A − 0.948 A = 0.552 A).

During the second time constant, the current rises 63.2% of the remaining value or 0.349 ampere (0.552 A × 0.632 = 0.349 A). At the end of the second time constant, the current has reached a total value of 1.297 amperes (0.948 A + 0.349 A = 1.297 A). The remaining current is now 0.203 ampere (1.5 A − 1.297 A = 0.203 A). During the third time constant, the current rises 63.2% of the remaining 0.203 ampere or 0.128 ampere (0.203 A × 0.632 = 0.128 A). The total current at the end of the third time constant is 1.425 amperes (1.297 A + 0.128 A = 1.425 A).

Because the current increases at a rate of 63.2% during each time constant, it is theoretically impossible to reach the total value of 1.5 amperes. After five

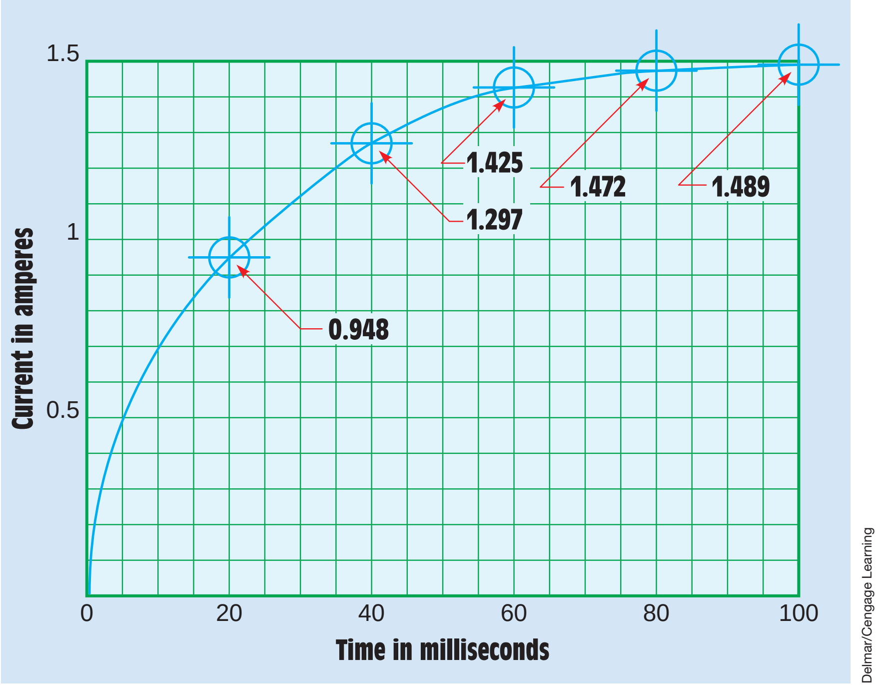


FIGURE 14–16 An exponential curve.

time constants, however, the current has reached approximately 99.3% of the maximum value and for all practical purposes is considered to be complete.

The exponential curve can often be found in nature. If clothes are hung on a line to dry, they will dry at an exponential rate. Another example of the exponential curve can be seen in *Figure 14–17*. In this example, a bucket has been

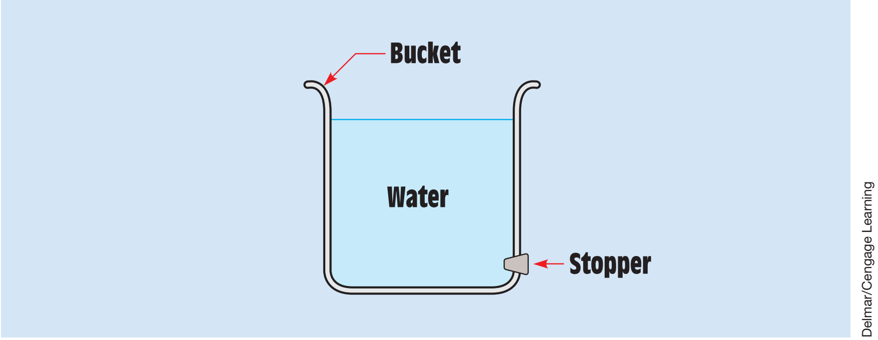


FIGURE 14–17 Exponential curves can be found in nature.

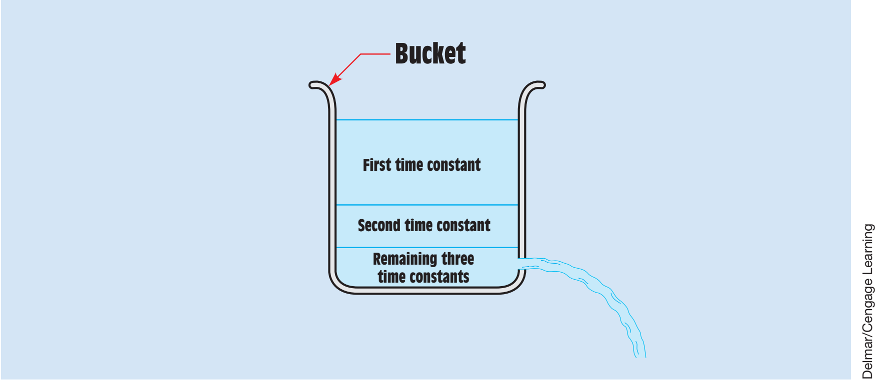


FIGURE 14–18 Water flows from a bucket at an exponential rate.

filled to a certain mark with water. A hole has been cut at the bottom of the bucket and a stopper placed in the hole. When the stopper is removed from the bucket, water flows out at an exponential rate. Assume, for example, it takes five minutes for the water to flow out of the bucket. Exponential curves are always divided into five time constants, so in this case each time constant has a value of one minute. In *Figure 14–18,* if the stopper is removed and water is permitted to drain from the bucket for a period of one minute before the stopper is replaced, during that first time constant 63.2% of the water in the bucket will drain out. If the stopper is again removed for a period of one minute, 63.2% of the water remaining in the bucket will drain out. Each time the stopper is removed for a period of one time constant, the bucket will lose 63.2% of its remaining water.

14–8 Inductance

The unit of measurement for inductance is the **henry (H),** and inductance is represented by the letter *L*. ***A coil has an inductance of 1 henry when a current change of 1 ampere per second results in an induced voltage of 1 volt.***

The amount of inductance a coil has is determined by its physical properties and construction. A coil wound on a nonmagnetic core material such as wood or plastic is referred to as an *air-core* inductor. If the coil is wound on a core made of magnetic material such as silicon steel or soft iron, it is referred to as an *iron-core* inductor. Iron-core inductors produce more inductance with fewer turns than air-core inductors because of the good magnetic path provided by the core material. Iron-core inductors cannot be used for high-frequency applications, however, because of **eddy current** loss and **hysteresis loss** in the core material.

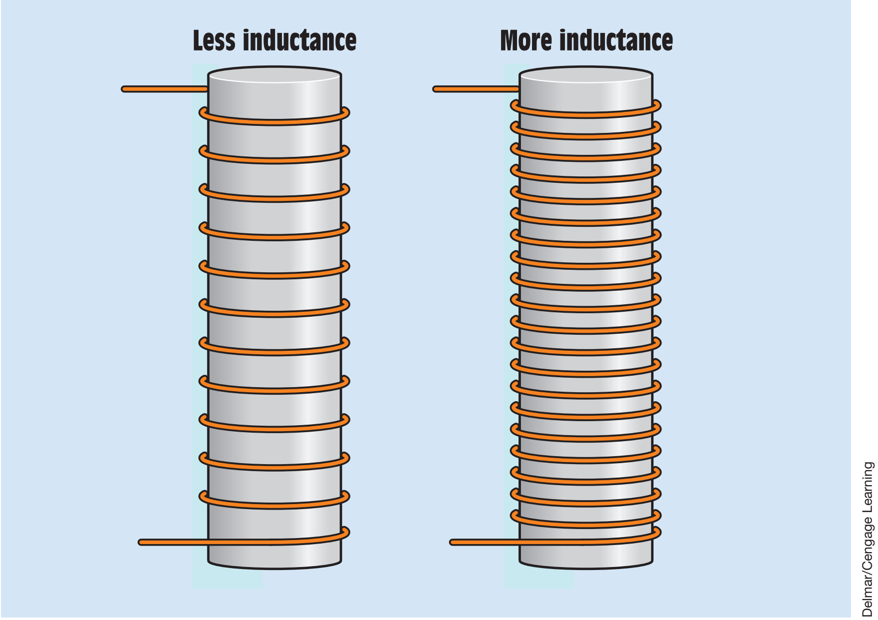


FIGURE 14–19 Inductance is determined by the physical construction of the coil.

Another factor that determines inductance is how far the windings are separated from each other. If the turns of wire are far apart, they will have less inductance than turns wound closer together *(Figure 14–19)*.

The inductance of a coil can be determined using the formula

$$L = \frac{0.4\pi N^2 \mu A}{l}$$

where

L = inductance in henrys

π = 3.1416

N = number of turns of wire

μ = permeability of the core material

A = cross-sectional area of the core

l = length of the core

The formula indicates that the inductance is proportional to the number of turns of wire, the type of core material used, and the cross-sectional area of the core, but inversely proportional to core length. An inductor is basically an electromagnet that changes its polarity at regular intervals. Because the inductor is an electromagnet, the same factors that affect magnets affect inductors. The permeability of the core material is just as important to an inductor as it is to any other electromagnet. Flux lines pass through a core material with a high permeability (such as silicon, steel, or soft iron) better than through a material with a low permeability (such as brass, copper, or aluminum). Once the core material has become saturated, however, the permeability value becomes approximately 1 and an increase in turns of wire has only a small effect on the value of inductance.

14–9 R-L Time Constants

The time necessary for current in an inductor to reach its full Ohm's law value, called the **R-L time constant,** can be computed using the formula

$$T = \frac{L}{R}$$

where

$$T = \text{time in seconds}$$
$$L = \text{inductance in henrys}$$
$$R = \text{resistance in ohms}$$

This formula computes the time of one time constant.

EXAMPLE 14–1

A coil has an inductance of 1.5 H and a wire resistance of 6 Ω. If the coil is connected to a battery of 3 V, how long will it take the current to reach its full Ohm's law value of 0.5 A (3 V/6 Ω = 0.5 A)?

Solution

To find the time of one time constant, use the formula

$$T = \frac{L}{R}$$

$$T = \frac{1.5\ \text{H}}{6\ \Omega}$$

$$T = 0.25\ \text{s}$$

The time for one time constant is 0.25 s. Because five time constants are required for the current to reach its full value of 0.5 A, 0.25 s will be multiplied by 5:

$$0.25\ \text{s} \times 5 = 1.25\ \text{s}$$

14–10 Induced Voltage Spikes

A **voltage spike** may occur when the current flow through an inductor stops, and the current also decreases at an exponential rate *(Figure 14–20)*. As long as a complete circuit exists when the power is interrupted, there is little or no problem. In the circuit shown in *Figure 14–21,* a resistor and inductor are connected in parallel. When the switch is closed, the battery supplies current

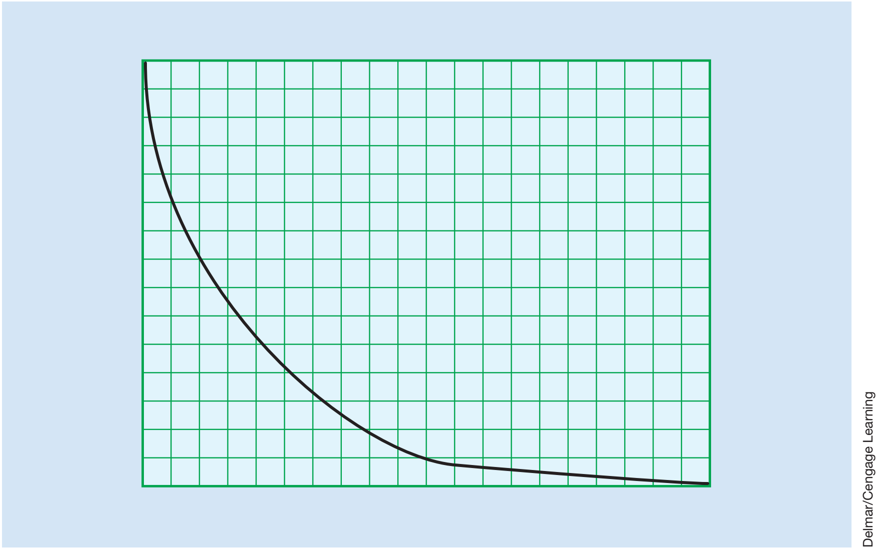


FIGURE 14–20 Current flow through an inductor decreases at an exponential rate.

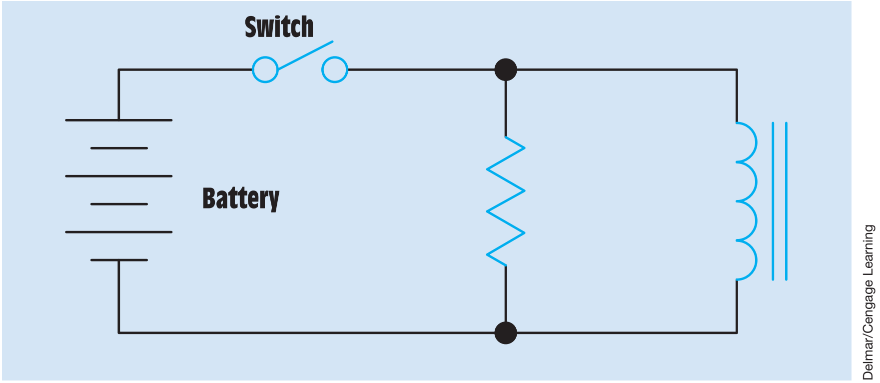


FIGURE 14–21 The resistor helps prevent voltage spikes caused by the inductor.

to both. When the switch is opened, the magnetic field surrounding the inductor collapses and induces a voltage into the inductor. The induced voltage attempts to keep current flowing in the same direction. Recall that inductors oppose a change of current. The amount of current flow and the time necessary for the flow to stop is determined by the resistor and the properties of the inductor. The amount of voltage produced by the collapsing magnetic field is determined by the maximum current in the circuit and the total resistance in the circuit. In the circuit shown in *Figure 14–21,* assume that the inductor has a wire resistance of 6 ohms and the resistor has a resistance of 100 ohms. Also assume that when the switch is closed, a current of 2 amperes will flow through the inductor. These spikes can be on the order of hundreds or even thousands of volts and can damage circuit components, especially in circuits containing solid-state devices such as diodes, transistors, intergrated circuits, and so on. The amount of induced voltage can be determined if the inductance of the coil, the amount of current change, and the amount of time change are known, by using the formula

$$\text{EMF} = -\text{L}\left(\frac{\Delta \text{I}}{\Delta \text{t}}\right)$$

where

L = inductance in henrys (A negative sign is placed in front of the L because the induced voltage is always opposite in polarity to the voltage that produces it.)

ΔI = change of current

Δt = change of time

Assume that a 1.5-henry inductor has a current flow of 2.5 amperes. When a switch is opened, the current changes from 2.5 amperes to 0.5 amperes in 0.005 second. How much voltage is induced into the inductor?

$$EMF = -L\left(\frac{\Delta I}{\Delta t}\right)$$

$$EMF = -1.5\ H\left(\frac{2\ A}{0.005\ s}\right)$$

$$EMF = -1.5\ H \times 400$$

$$EMF = -600\ V$$

When the switch is opened, a series circuit exists composed of the resistor and inductor *(Figure 14–22)*. The maximum voltage developed in this circuit would be 212 volts (2 A × 106 Ω = 212 V). If the circuit resistance were increased, the induced voltage would become greater. If the circuit resistance were decreased, the induced voltage would become less.

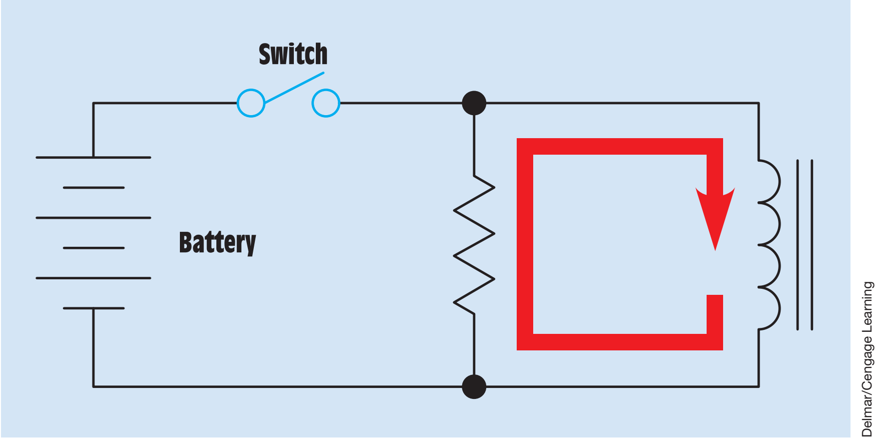


FIGURE 14–22 When the switch is opened, a series path is formed by the resistor and inductor.

Another device often used to prevent induced voltage spikes when the current flow through an inductor is stopped is the diode *(Figure 14–23)*. The diode is an electronic component that operates like an electric check valve. The diode permits current to flow through it in only one direction. The diode is connected in parallel with the inductor in such a manner that when voltage is applied to the circuit, the diode is reverse biased and acts like an open switch. When the diode is reverse biased, no current flows through it.

When the switch is opened, the induced voltage produced by the collapsing magnetic field is opposite in polarity to the applied voltage. The diode

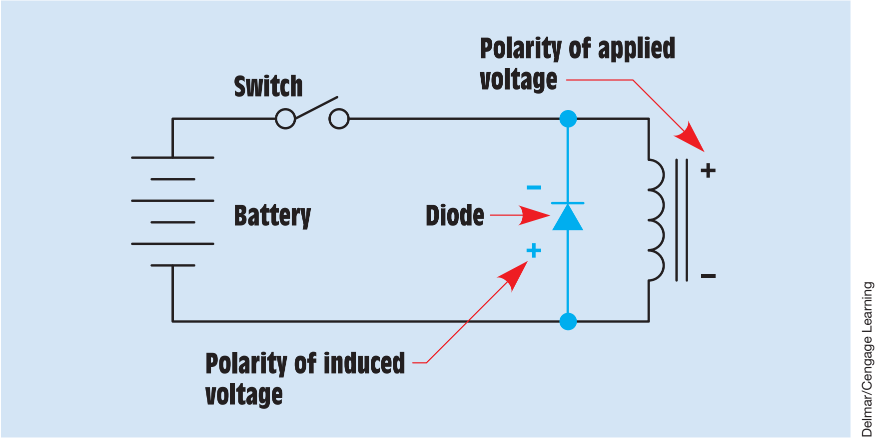


FIGURE 14–23 A diode is used to prevent induced voltage spikes.

then becomes forward-biased and acts like a closed switch. Current can now flow through the diode and complete a circuit back to the inductor. A silicon diode has a forward voltage drop of approximately 0.7 volts regardless of the current flowing through it. When the switch opens, the diode becomes the load, and the induced voltage caused by the collapsing magnetic field of the inductor becomes the source. The diode and inductor are now series connected. In a series circuit, the applied or source voltage must equal the sum of the voltage drops in the circuit. In this case, the diode is the total connected load. Because the diode will not permit a voltage drop greater than about 0.7 volt, the source voltage is limited to 0.7 volt also. The circuit energy is dissipated as heat by the diode. The diode can be used for this purpose in DC circuits only; it cannot be used for this purpose in AC circuits.

A device that can be used for spike suppression in either DC or AC circuits is the **metal oxide varistor (MOV).** The MOV is a bidirectional device, which means that it conducts current in either direction and can therefore be used in AC circuits. The MOV is an extremely fast-acting solid-state component that exhibits a change of resistance when the voltage reaches a certain point. Assume that the MOV shown in *Figure 14–24* has a voltage rating of 140 volts and that the voltage applied to the circuit is 120 volts. When the switch is closed and current flows through the circuit, a magnetic field is established around the inductor *(Figure 14–25)*. As long as the voltage applied to the MOV is less than 140 volts, it will exhibit an extremely high resistance, in the range of several hundred thousand ohms.

When the switch is opened, current flow through the coil suddenly stops and the magnetic field collapses. This sudden collapse of the magnetic field causes an extremely high voltage to be induced in the coil. When this induced voltage reaches 140 volts, however, the MOV suddenly changes from a high resistance to a low resistance, preventing the voltage from becoming greater than 140 volts *(Figure 14–26)*.

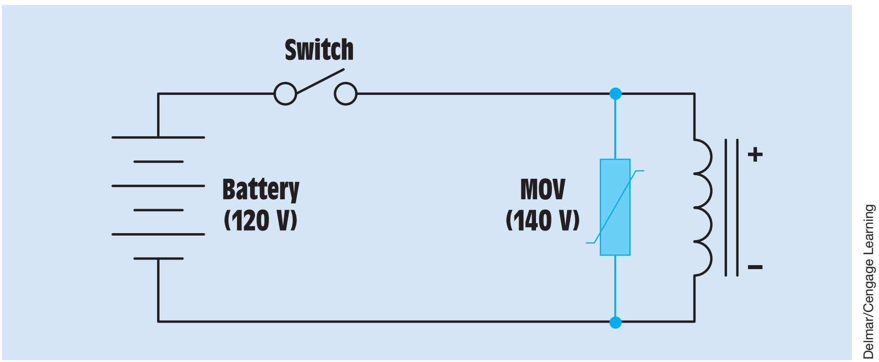


FIGURE 14–24 Metal oxide varistor used to suppress a voltage spike.

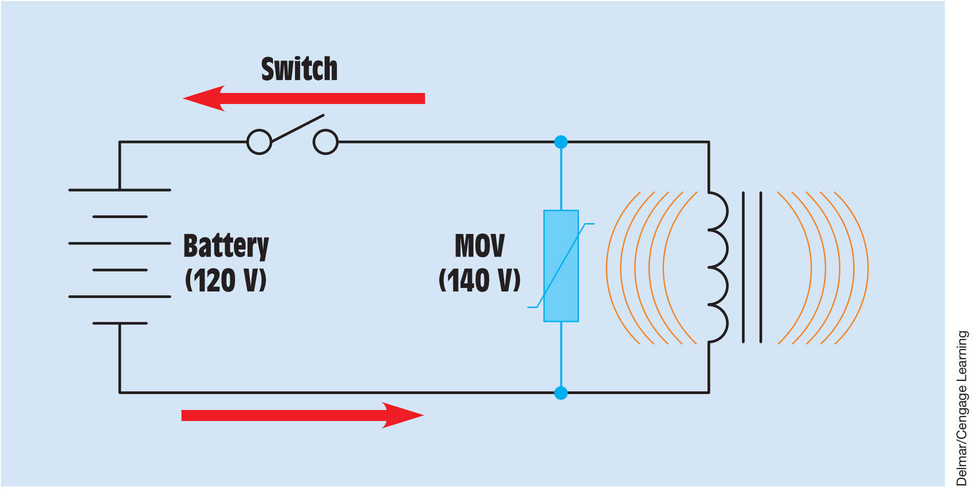


FIGURE 14–25 When the switch is closed, a magnetic field is established around the inductor.

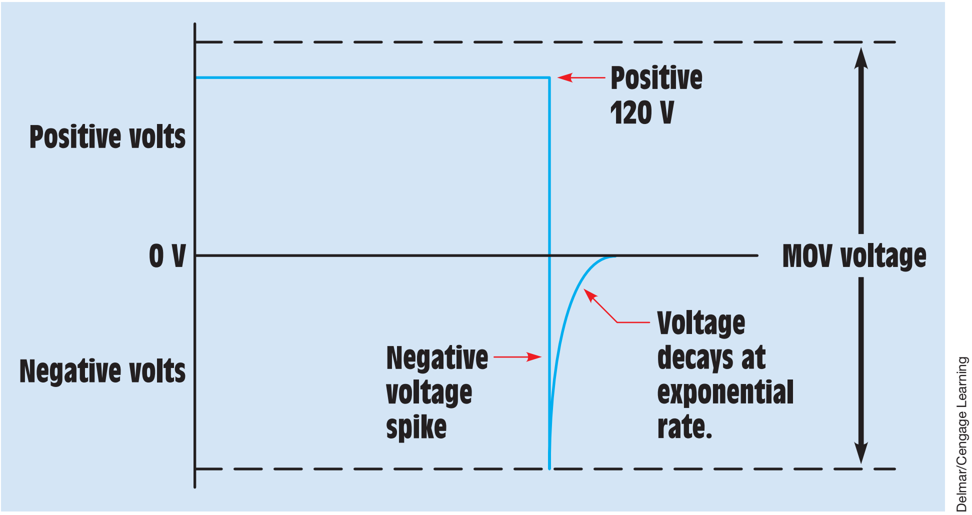


FIGURE 14–26 The MOV prevents the spike from becoming too high.

Metal oxide varistors are extremely fast acting. They can typically change resistance values in less than 20 nanoseconds (ns). They are often found connected across the coils of relays and motor starters in control systems to prevent voltage spikes from being induced back into the line. They are also found in the surge protectors used to protect many home appliances, such as televisions, stereos, and computers.

If nothing is connected in the circuit with the inductor when the switch opens, the induced voltage can become extremely high. In this instance, the resistance of the circuit is the air gap of the switch contacts, which is practically

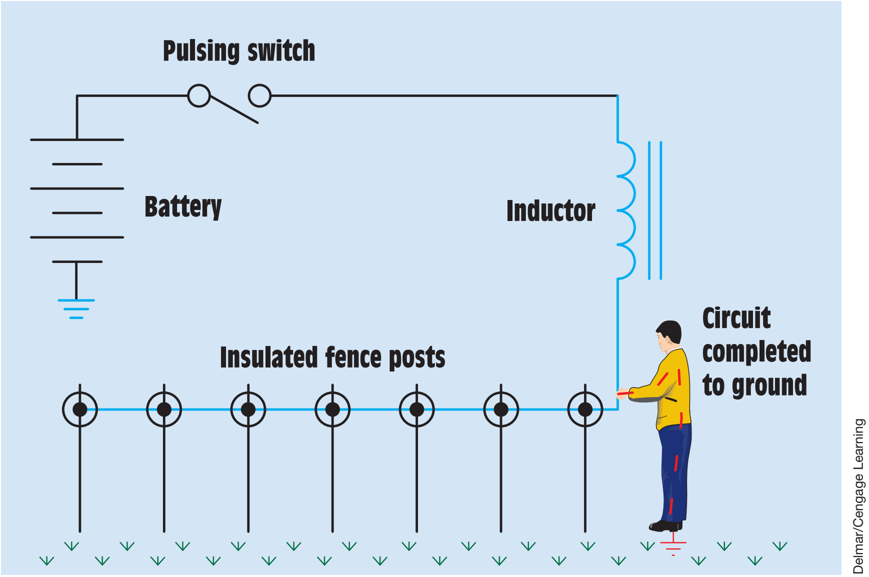


FIGURE 14–27 An inductor is used to produce a high voltage for an electric fence.

infinite. The inductor will attempt to produce any voltage necessary to prevent a change of current. Inductive voltage spikes can reach thousands of volts. This is the principle of operation of many high-voltage devices, such as the ignition systems of many automobiles.

Another device that uses the collapsing magnetic field of an inductor to produce a high voltage is the electric fence charger *(Figure 14–27)*. The switch is constructed in such a manner that it pulses on and off. When the switch closes, current flows through the inductor and a magnetic field is produced around the inductor. When the switch opens, the magnetic field collapses and induces a high voltage across the inductor. If anything or anyone standing on the ground touches the fence, a circuit is completed through the object or person and the ground. The coil is generally constructed of many turns of very small wire. This construction provides the coil with a high resistance and limits current flow when the field collapses.

Summary

- When current flows through a conductor, a magnetic field is created around the conductor.
- When a conductor is cut by a magnetic field, a voltage is induced in the conductor.

- The polarity of the induced voltage is determined by the polarity of the magnetic field in relation to the direction of motion.
- Three factors that determine the amount of induced voltage are

  a. the number of turns of wire.

  b. the strength of the magnetic field.

  c. the speed of the cutting action.
- One volt is induced in a conductor when magnetic lines of flux are cut at a rate of 1 weber per second.
- Induced voltage is always opposite in polarity to the applied voltage.
- Inductors oppose a change of current.
- Current rises in an inductor at an exponential rate.
- An exponential curve is divided into five time constants.
- Each time constant is equal to 63.2% of some value.
- Inductance is measured in units called henrys (H).
- A coil has an inductance of 1 henry when a current change of 1 ampere per second results in an induced voltage of 1 volt.
- Air-core inductors are inductors wound on cores of nonmagnetic material.
- Iron-core inductors are wound on cores of magnetic material.
- The amount of inductance an inductor will have is determined by the number of turns of wire and the physical construction of the coil.
- Inductors can produce extremely high voltages when the current flowing through them is stopped.
- Two devices used to help prevent large spike voltages are the resistor and the diode.

Review Questions

1. What determines the polarity of magnetism when current flows through a conductor?
2. What determines the strength of the magnetic field when current flows through a conductor?
3. Name three factors that determine the amount of induced voltage in a coil.
4. How many lines of magnetic flux must be cut in 1 s to induce a voltage of 1 V?

5. What is the effect on induced voltage of adding more turns of wire to a coil?
6. Into how many time constants is an exponential curve divided?
7. Each time constant of an exponential curve is equal to what percentage of the maximum amount of charge?
8. An inductor has an inductance of 0.025 H and a wire resistance of 3 Ω. How long will it take the current to reach its full Ohm's law value?
9. Refer to the circuit shown in *Figure 14–21*. Assume that the inductor has a wire resistance of 0.2 Ω and the resistor has a value of 250 Ω. If a current of 3 A is flowing through the inductor, what will be the maximum induced voltage when the switch is opened?
10. What electronic component is often used to prevent large voltage spikes from being produced when the current flow through an inductor is suddenly terminated?

Practical Applications

You are an electrician working in a plant that uses programmable controllers to perform much of the logic for the motor controls. The plant produces highly flammable chemicals, so the programmable controllers use a 24-volt VDC output that is intrinsically safe in a hazardous area. You are having trouble with the output modules of the programmable controllers that are connected to DC control relays. These outputs are going bad at an unusually high rate, and you suspect that spike voltages produced by the relay coils are responsible. To test your theory, you connect an oscilloscope to an output that is operating a DC relay coil and watch the display when the programmable controller turns the relay off. You discover that there is a high voltage spike produced by the relay. What device would you use to correct this problem, and how would you install it? ■

V

Basics of Alternating Current

Courtesy of Getty Images, Inc.

Unit 15

Basic Trigonometry and Vectors

OUTLINE

KEY TERMS

Adjacent
Cosine
Hypotenuse
Opposite
Oscar Had A Heap Of Apples
Parallelogram method
Pythagoras
Pythagorean theorem
Right angle
Right triangle
Sine
Tangent
Vector
Vector addition

Why You Need to Know

In DC circuits, the product of the current and voltage always equals the power or watts. You will find that this is not true in AC circuits, however, because the voltage and current can become out of phase with each other. This can be illustrated through the use of basic trigonometry. This unit

- explains how the phase difference between voltage and current is determined by the type of load or loads connected to the circuit.
- explains how voltage and current relationships in AC circuits are based on right triangles.
- describes several different methods, all of them involving vectors, that can be employed to determine these phase relationships.
- illustrates how the Pythagorean theorem provides the formula needed for electricians to understand 90° angles and how to calculate voltages and current in AC circuits.

Courtesy of DeVry University

Objectives

After studying this unit, you should be able to

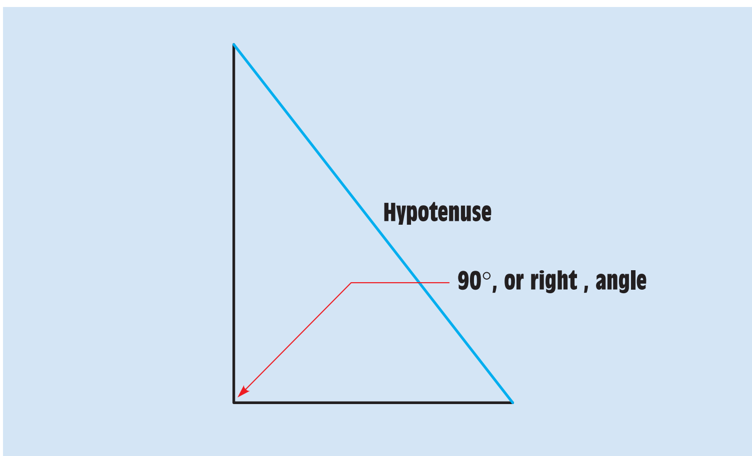
- define a right triangle.
- discuss the Pythagorean theorem.
- solve problems concerning right triangles using the Pythagorean theorem.
- solve problems using sines, cosines, and tangents.

Preview

Before beginning the study of AC, a brief discussion of right triangles and the mathematical functions involving them is appropriate. Many AC formulas are based on right triangles, because, depending on the type of load, the voltage and current in an AC circuit can be out of phase with each other by approximately 90°. The exact amount of the out-of-phase condition is determined by different factors, which are covered in later units. ■

15–1 Right Triangles

A **right triangle** is a triangle that contains a **right** or (90°), **angle** *(Figure 15–1)*. The **hypotenuse** is the longest side of a right triangle and is always opposite the right angle. Several thousand years ago, a Greek mathematician named **Pythagoras** made some interesting discoveries concerning triangles that contain right angles. One of these discoveries was that if the two sides of a



Delmar/Cengage Learning

FIGURE 15–1 A right triangle.

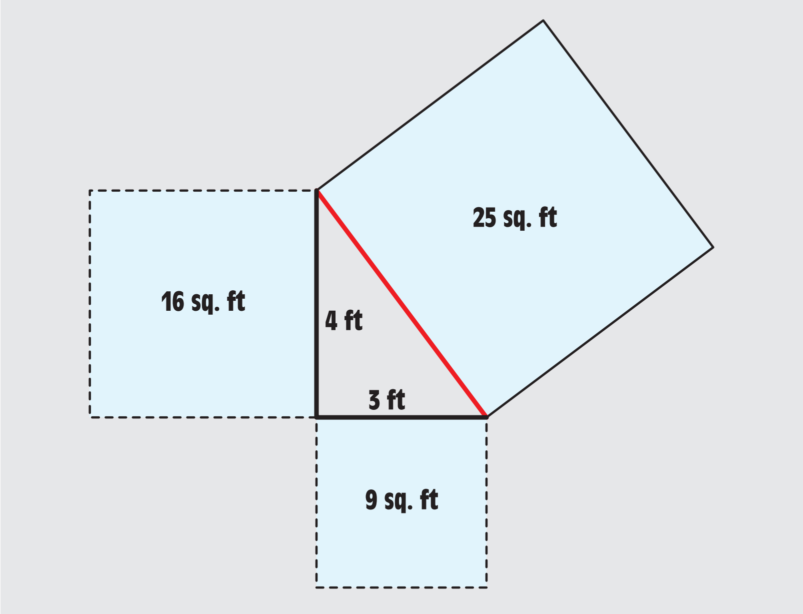


FIGURE 15–2 The Pythagorean theorem states that the sum of the squares of the sides of a right triangle is equal to the square of the hypotenuse.

right triangle are squared, their sum equals the square of the hypotenuse. For example, assume a right triangle has one side 3 feet long and the other side is 4 feet long *(Figure 15–2)*. If the side that is 3 feet long is squared, it produces an area of 9 square feet (3 ft × 3 ft = 9 sq. ft). If the side that is 4 feet long is squared, it produces an area of 16 square feet (4 ft × 4 ft = 16 sq. ft). The sum of the areas of these two sides equals the square area formed by the hypotenuse. In this instance, the hypotenuse has an area of 25 square feet (9 sq. ft + 16 sq. ft = 25 sq. ft). Now that the area, or square, of the hypotenuse is known, its length can be determined by finding the square root of its area. The length of the hypotenuse is 5 feet, because the square root of 25 is 5.

15–2 The Pythagorean Theorem

From this knowledge concerning the relationship of the length of the sides to the length of the hypotenuse, Pythagoras derived a formula known as the **Pythagorean theorem:**

$$c^2 = a^2 + b^2$$

where

c = the length of the hypotenuse

a = the length of one side

b = the length of the other side

If the lengths of the two sides are known, the length of the hypotenuse can be found using the formula

$$c = \sqrt{a^2 + b^2}$$

It is also possible to determine the length of one of the sides if the length of the other side and the length of the hypotenuse are known. Because the sum of the squares of the two sides equals the square of the hypotenuse, the square of one side equals the difference between the square of the hypotenuse and the square of the other side.

EXAMPLE 15-1

The triangle shown in *Figure 15–3* has a hypotenuse (C) 18 in. long. One side (B) is 7 in. long. What is the length of the second side (A)?

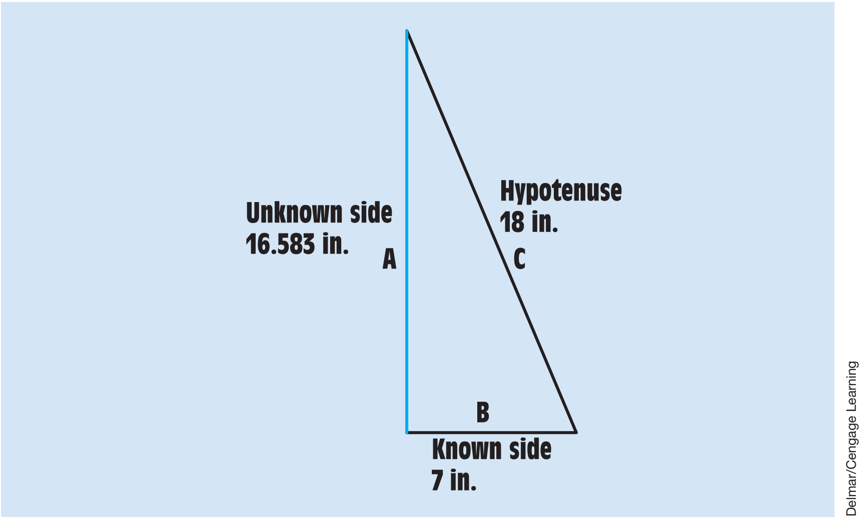


FIGURE 15–3 Using the Pythagorean theorem to find the length of one side.

Solution

Transpose the formula $c^2 = a^2 + b^2$ to find the value of a. This can be done by subtracting b^2 from both sides of the equation. The result is the formula:

$$a^2 = c^2 - b^2$$

Now take the square root of each side of the equation so that the answer is equal to a, not a^2:

$$a = \sqrt{c^2 - b^2}$$

The formula can now be used to find the length of the unknown side:

$$a = \sqrt{(18 \text{ in.})^2 - (7 \text{ in.})^2}$$

$$a = \sqrt{324 \text{ in.}^2 - 49 \text{ in.}^2}$$

$$a = \sqrt{275 \text{ in.}^2}$$

$$a = 16.583 \text{ in.}$$

15–3 Sines, Cosines, and Tangents

A second important concept concerning right triangles is the relationship of the length of the sides to the angles. Because one angle is always 90°, only the two angles that are not right angles are of concern. Another important fact concerning triangles is that the sum of the angles of any triangle equals 180°; because one angle of a right triangle is 90°, the sum of the two other angles must equal 90°.

It was discovered long ago that the number of degrees in each of these two angles is proportional to the lengths of the three sides. This relationship is expressed as the *sine, cosine,* or *tangent* of a particular angle. The function used is determined by which sides are known and which of the two angles is to be found.

When using sines, cosines, or tangents, the sides are designated the *hypotenuse,* the **opposite,** and the **adjacent.** The hypotenuse is always the longest side of a right triangle, but the opposite and adjacent sides are determined by which of the two angles is to be found. In *Figure 15–4,* a right triangle has its sides labeled A, B, and HYPOTENUSE. The two unknown angles are labeled X and Y. To determine which side is opposite an angle, draw a line bisecting the angle. This bisect line would intersect the opposite side. In *Figure 15–5,* side A is opposite angle X, and side B is opposite angle Y. If side A is opposite angle X,

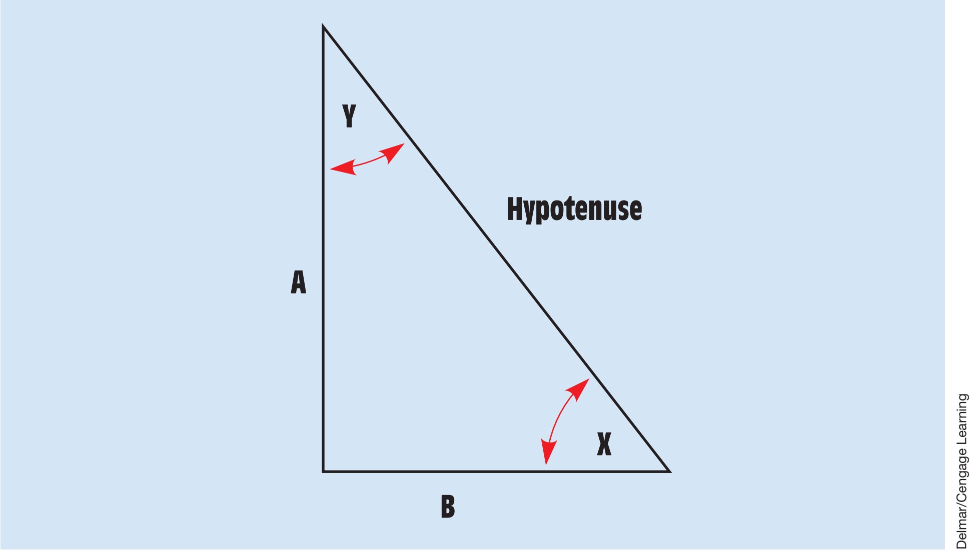


FIGURE 15–4 Determining which side is opposite and which is adjacent.

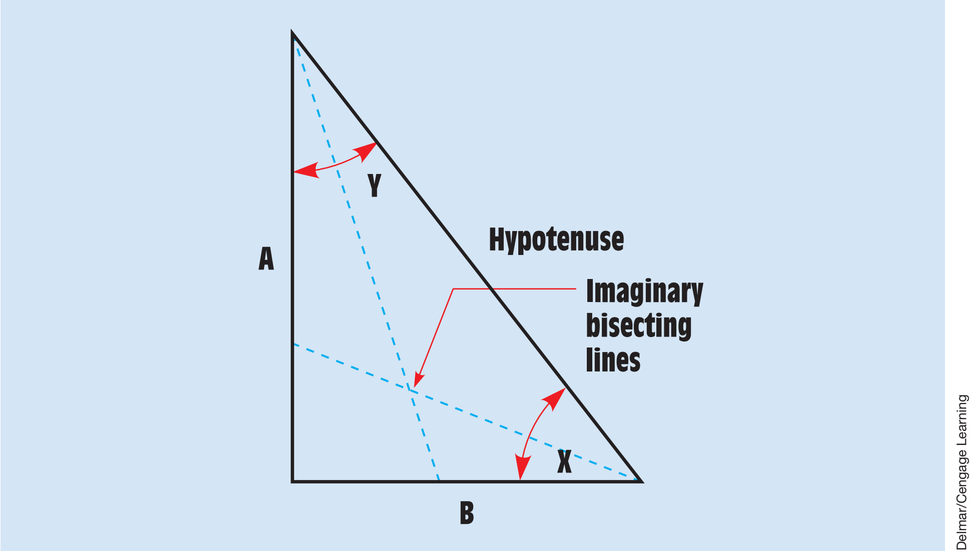


FIGURE 15–5 Side A is opposite angle X, and side B is opposite angle Y.

then side B is adjacent to angle X; and if side B is opposite angle Y, then side A is adjacent to angle Y *(Figure 15–6)*.

The **sine** function is equal to the opposite side divided by the hypotenuse:

$$\text{sine} \angle X = \frac{\text{opposite}}{\text{hypotenuse}}$$

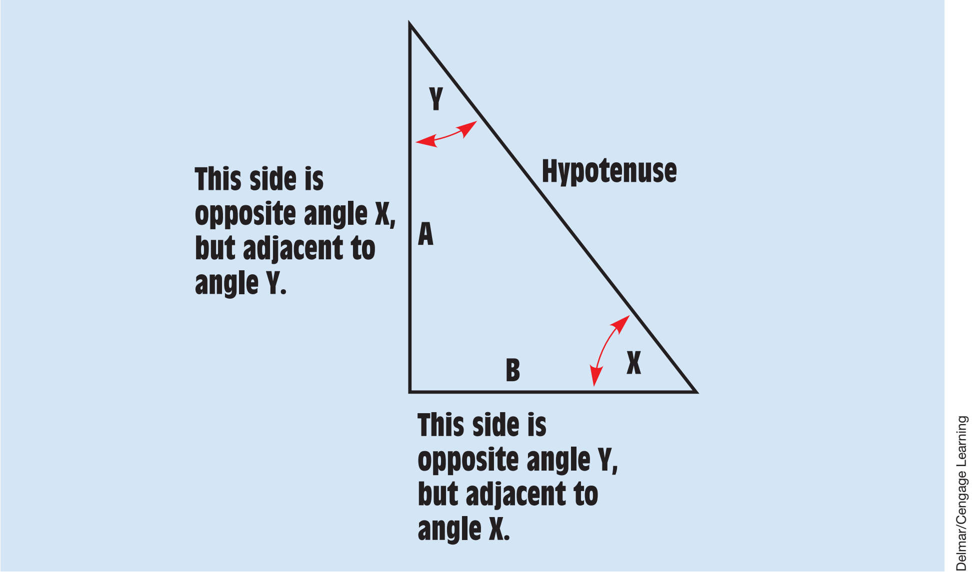


FIGURE 15–6 Determining opposite and adjacent sides.

The **cosine** function is equal to the adjacent side divided by the hypotenuse:

$$\text{cosine} \angle X = \frac{\text{adjacent}}{\text{hypotenuse}}$$

The **tangent** function is equal to the opposite side divided by the adjacent side:

$$\text{tangent} \angle X = \frac{\text{opposite}}{\text{adjacent}}$$

A simple saying is often used to help remember the relationship of the trigonometric function and the side of the triangle. This saying is **Oscar Had A Heap Of Apples.** To use this simple saying, write down *sine, cosine, and tangent*. The first letter of each word becomes the first letter of each of the sides. *O* stands for opposite, *H* stands for hypotenuse, and *A* stands for adjacent:

$$\text{sine} \angle X = \frac{\text{Oscar}}{\text{Had}} \qquad \begin{matrix}\text{(Opposite)}\\ \text{(Hypotenuse)}\end{matrix}$$

$$\text{cosine} \angle X = \frac{\text{A}}{\text{Heap}} \qquad \begin{matrix}\text{(Adjacent)}\\ \text{(Hypotenuse)}\end{matrix}$$

$$\text{tangent} \angle X = \frac{\text{Of}}{\text{Apples}} \qquad \begin{matrix}\text{(Opposite)}\\ \text{(Adjacent)}\end{matrix}$$

Once the sine, cosine, or tangent of the angle has been determined, the angle can be found by using the trigonometric functions on a scientific calculator or from the trigonometric tables located in Appendices A and B.

EXAMPLE 15-2

The triangle in *Figure 15–7* has a hypotenuse 14 in. long, and side A is 9 in. long. How many degrees are in angle X?

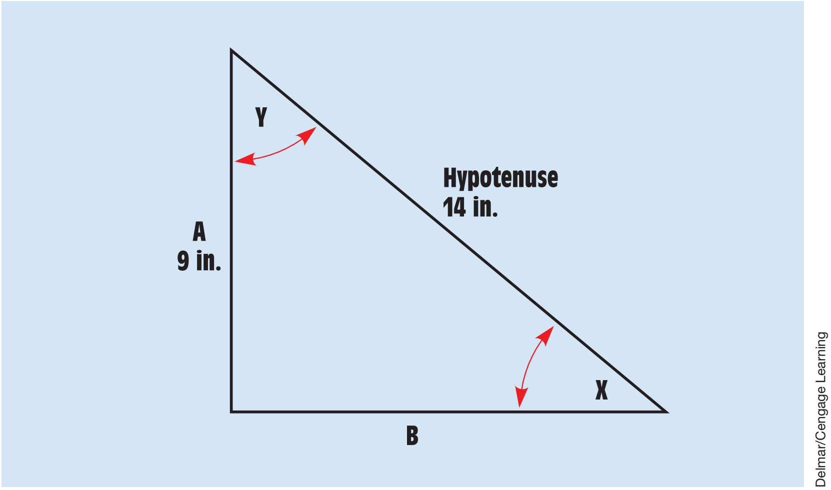


FIGURE 15–7 Finding the angles using trigonometric functions.

Solution

Because the lengths of the hypotenuse and the opposite side are known, the sine function is used to find the angle:

$$\text{sine} \angle X = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\text{sine} \angle X = \frac{9}{14}$$

$$\text{sine} \angle X = 0.643$$

Note that 0.643 is the sine of the angle, not the angle. To find the angle, use the SIN function on a scientific calculator. If you are using a scientific calculator, it will be necessary to use the ARC SIN function or INV SIN function to find the answer. If the number 0.643 is entered and the SIN key is pressed, an answer of 0.0112 results. This is the sine of a 0.643° angle. If the sine, cosine, or tangent of an angle is known, the ARC key or INV key (depending on the manufacturer of the calculator) must be pressed before the SIN, COS, or TAN key is pressed:

$$\text{SIN}^{-1} \text{ or ARCSIN } 0.643 = 40°$$

EXAMPLE 15-3

Using the same triangle *(Figure 15–7),* determine the number of degrees in angle Y.

Solution

In this example, the lengths of the hypotenuse and the adjacent side are known. The cosine function can be used to find the angle:

$$\text{cosine } \angle Y = \frac{\text{adjacent}}{\text{hypotenuse}}$$

$$\text{cosine } \angle Y = \frac{9}{14}$$

$$\text{cosine } \angle Y = 0.643$$

To find what angle corresponds to the cosine of 0.643, use the trigonometric tables in Appendices A and B or the COS function of a scientific calculator:

$$\text{COS}^{-1} \text{ or ARC COS } 0.643 = 50^\circ$$

15–4 Formulas

Some formulas that can be used to find the angles and lengths of different sides follow:

$$\sin \angle\theta = \frac{O}{H} \qquad \cos \angle\theta = \frac{A}{H} \qquad \tan \angle\theta = \frac{O}{A}$$

$$\text{Adj.} = \cos \angle\theta \times \text{Hyp.} \qquad \text{Adj.} = \frac{O}{\tan \angle\theta}$$

$$\text{Opp} = \sin \angle\theta \times \text{Hyp.} \qquad \text{Opp.} = \text{Adj.} \times \tan \angle\theta$$

$$\text{Hyp.} = \frac{O}{\sin \angle\theta} \qquad \text{Hyp.} = \frac{A}{\cos \angle\theta}$$

15–5 Practical Application

Although the purpose of this unit is to provide preparation for the study of AC circuits, basic trigonometry can provide answers to other problems that may be encountered on the job. Assume that it is necessary to know the height of a

FIGURE 15–8 Using trigonometry to measure the height of a tall building.

tall building *(Figure 15–8)*. Now assume that the only tools available to make this measurement are a 1-foot ruler, a tape measure, and a scientific calculator. To make the measurement, find a relatively flat area in the open sunlight. Hold the ruler upright and measure the shadow cast by the sun *(Figure 15–9)*. Assume the length of the shadow to be 7.5 inches. Using the length of the

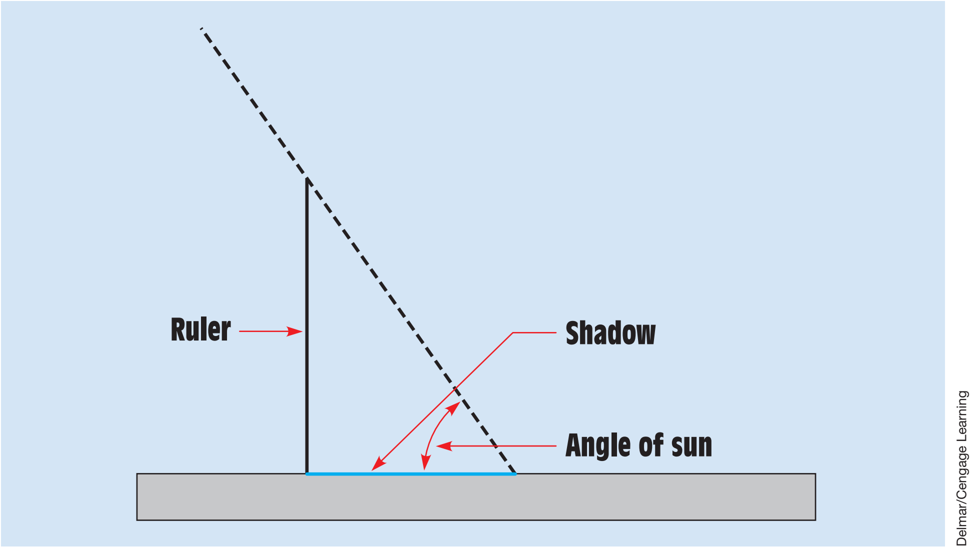


FIGURE 15–9 Determining the angle of the sun.

shadow as one side of a right triangle and the ruler as the other side, the angle of the sun can now be determined. The two known sides are the opposite and the adjacent. The tangent function corresponds to these two sides. The angle of the sun is

$$\tan \angle\theta = \frac{O}{A}$$

$$\tan \angle\theta = \frac{12}{7.5}$$

$$\tan \angle\theta = 1.6$$

$$= 57.99°$$

The tape measure can now be used to measure the shadow cast by the building on the ground. Assume the length of the shadow to be 35 feet. If the height of the building is used as one side of a right triangle and the shadow is used as the other side, the height can be found because the angle of the sun is known *(Figure 15–10)*.

$$\text{Opp.} = \text{Adj.} \times \tan \angle\theta$$

$$\text{Opp.} = 35\text{ ft} \times \tan 57.99°$$

$$\text{Opp.} = 35\text{ ft} \times 1.6$$

$$\text{Opp.} = 56\text{ ft}$$

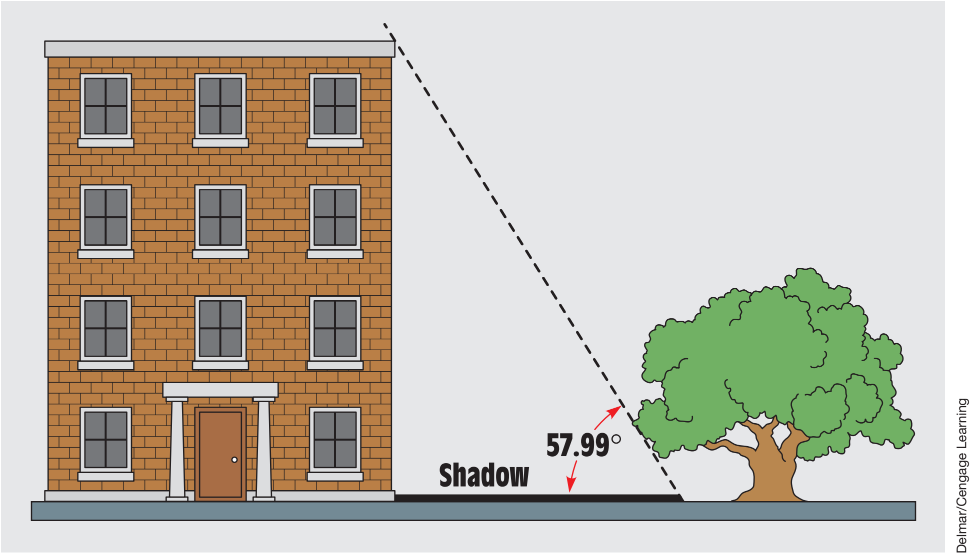


FIGURE 15–10 Measuring the building's shadow.

Vectors

Using the right triangle is just one method of graphically showing how angular quantities can be added. Another method of illustrating this concept is with the use of vectors. A **vector** is a line that indicates both magnitude and direction. The magnitude is indicated by its length, and the direction is indicated by its angle of rotation from 0°. Vectors should not be confused with *scalars,* which are used to represent magnitude only and do not take direction into consideration. Imagine, for example, that you are in a strange city and you ask someone for directions to a certain building. If the person said, "Walk three blocks," that would be a scalar because it contains only the magnitude, three blocks. If the person said, "Walk three blocks south," it would be a vector because it contains both the magnitude, three blocks, and the direction, south.

Zero degrees is indicated by a horizontal line. An arrow is placed at one end of the line to indicate direction. The magnitude can represent any quantity such as inches, meters, miles, volts, amperes, ohms, power, and so on. A vector with a magnitude of 5 at an angle of 0° is shown in *Figure 15–11*. Vectors rotate in a counterclockwise direction. Assume that a vector with a magnitude of 3 is to be drawn at a 45° angle from the first vector *(Figure 15–12)*. Now assume that a third vector with a magnitude of 4 is to be drawn in a direction of 120° *(Figure 15–13)*. Notice that the direction of the third vector is referenced from the horizontal 0° line and not from the second vector line, which was drawn at an angle of 45°.

FIGURE 15–11 A vector with a magnitude of 5 and an angle of 0°.

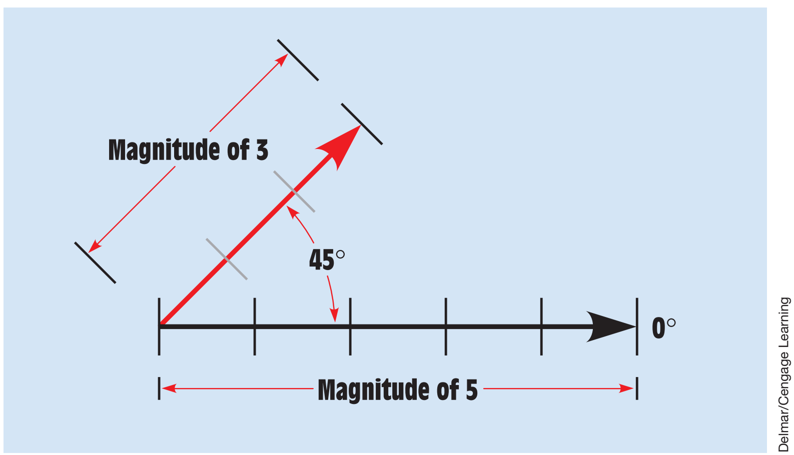


FIGURE 15–12 A second vector with a magnitude of 3 and a direction of 45°.

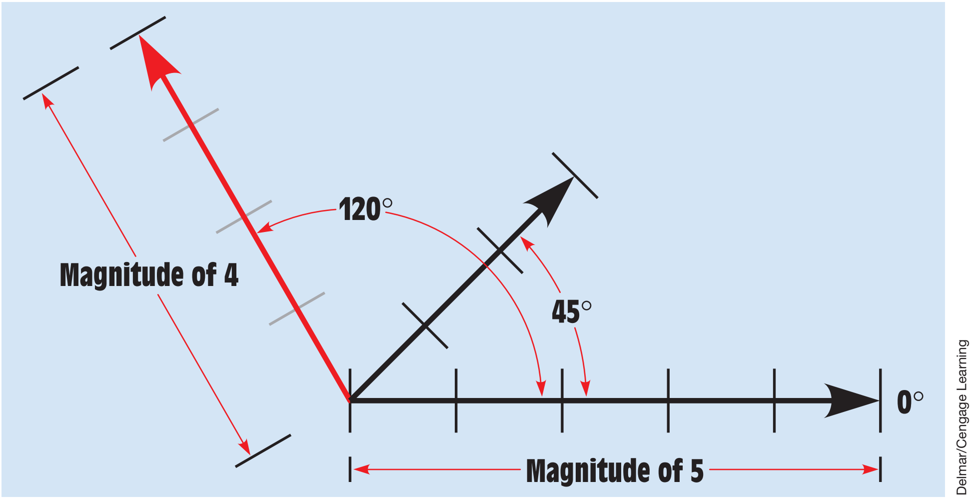


FIGURE 15–13 A third vector with a magnitude of 4 and a direction of 120° is added.

Adding Vectors

Because vectors are used to represent quantities such as volts, amperes, ohms, power, and so on, they can be added, subtracted, multiplied, and divided. In electrical work, however, addition is the only function needed, so it is the only one discussed. Several methods can be used to add vectors. Regardless of the method used, because vectors contain both magnitude and direction, they must be added with a combination of geometric and algebraic addition. This method is often referred to as **vector addition.**

One method is to connect the starting point of one vector to the end point of another. This method works especially well when all vectors are in the same direction. Consider the circuit shown in *Figure 15–14*. In this circuit, two batteries, one rated at 6 volts and the other rated at 4 volts, are connected in such a manner that their voltages add. If vector addition is used, the starting point of one vector is placed at the end point of the other. Notice that the sum of the two vector quantities is equal to the sum of the two voltages, 10 volts. Another example of this type of vector addition is shown in *Figure 15–15*. In this example, three resistors are connected in series. The first resistor has a resistance of 80 ohms; the second, a resistance of 50 ohms; and the third, a resistance of 30 ohms. Because there is no phase angle shift of voltage or current, the impedance is 160 ohms, which is the sum of the resistances of the three resistors.

Adding Vectors with Opposite Directions

To add vectors that are exactly opposite in direction (180° apart), subtract the magnitude of the larger vector from the magnitude of the smaller. The resultant

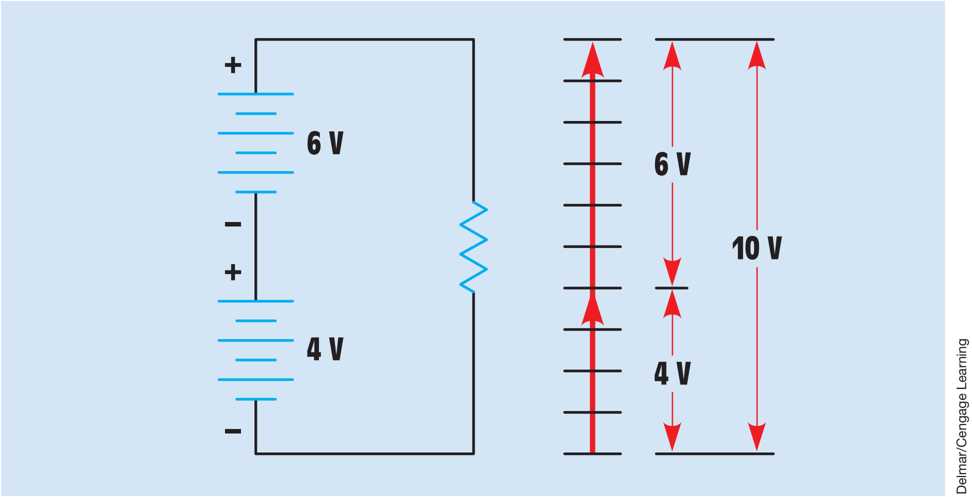


FIGURE 15–14 Adding vectors in the same direction.

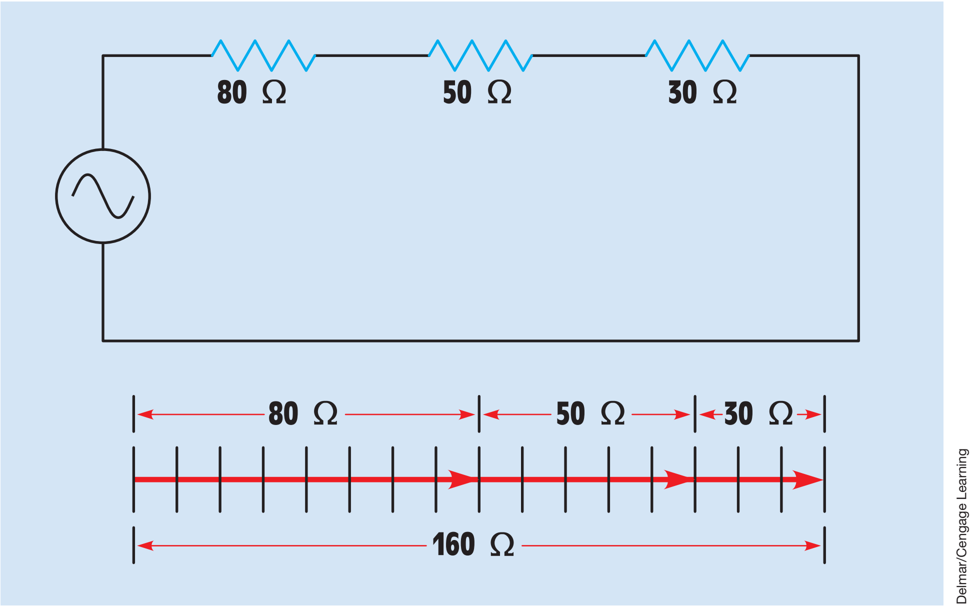


FIGURE 15–15 Addition of series resistors.

is a vector with the same direction as the vector with the larger magnitude. If one of the batteries in *Figure 15–14* were reversed, the two voltages would oppose each other *(Figure 15–16)*. This means that 4 volts of the 6-volt battery A would have to be used to overcome the voltage of battery B. The resultant would be a vector with a magnitude of 2 volts in the same direction as the

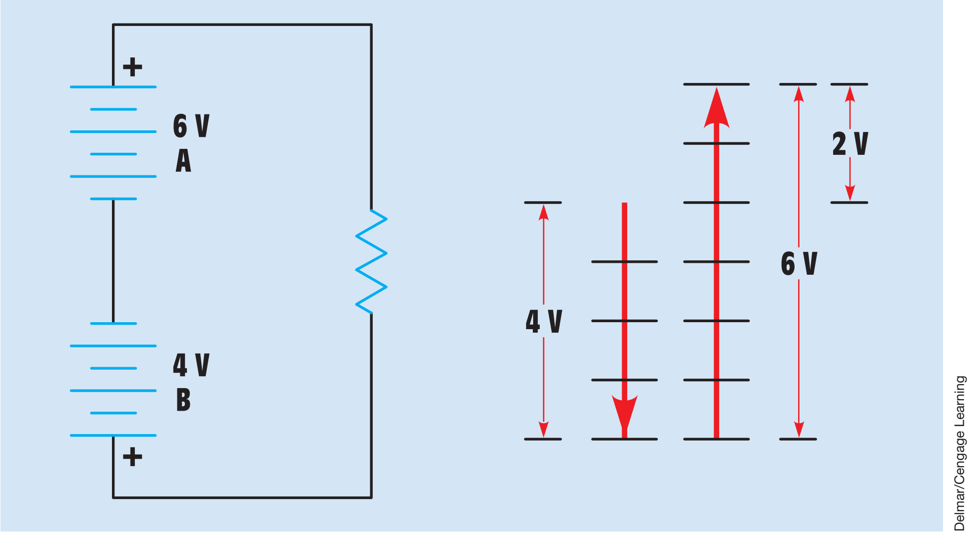


FIGURE 15–16 Adding vectors with opposite directions.

6-volt battery. In algebra, this is the same operation as adding a positive number and a negative number ($+6 + [-4] = +2$). When the -4 is brought out of brackets, the equation becomes $6 - 4 = 2$.

Adding Vectors of Different Directions

Vectors that have directions other than 180° from each other can also be added. *Figure 15–17* illustrates the addition of a vector with a magnitude of 4 and a direction of 15° to a vector with a magnitude of 3 and a direction of 60°. The addition is made by connecting the starting point of the second vector to the ending point of the first vector. The resultant is drawn from the starting point of the first vector to the ending point of the second. It is possible to add several different vectors using this method. *Figure 15–18* illustrates the addition of several different vectors and the resultant.

The Parallelogram Method of Vector Addition

The **parallelogram method** can be used to find the resultant of two vectors that originate at the same point. A parallelogram is a four-sided figure whose opposite sides form parallel lines. A rectangle, for example, is a parallelogram with 90° angles. Assume that a vector with a magnitude of 24 and a direction of 26° is to be added to a vector with a magnitude of 18 and a direction of 58°. Also assume that the two vectors originate from the same point

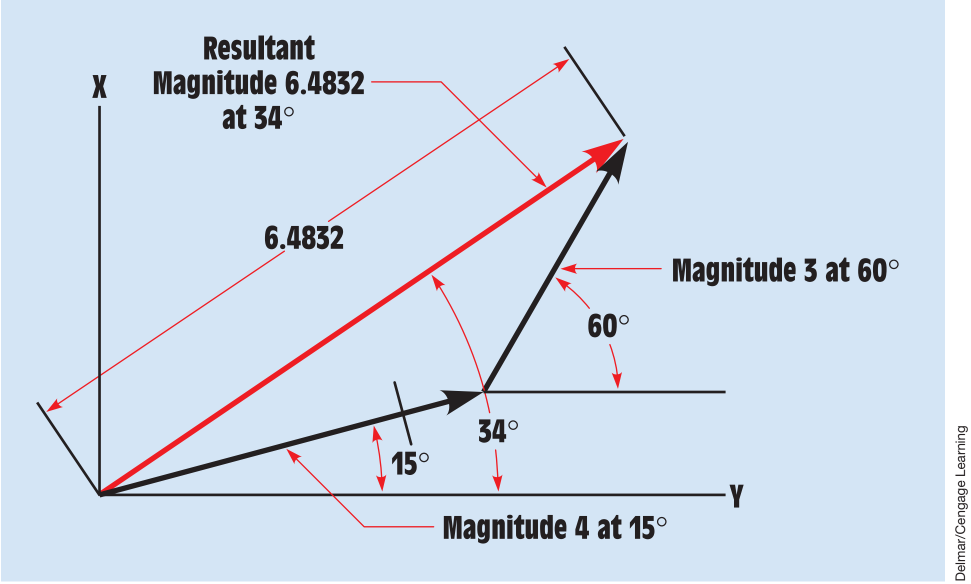


FIGURE 15–17 Adding two vectors with different directions.

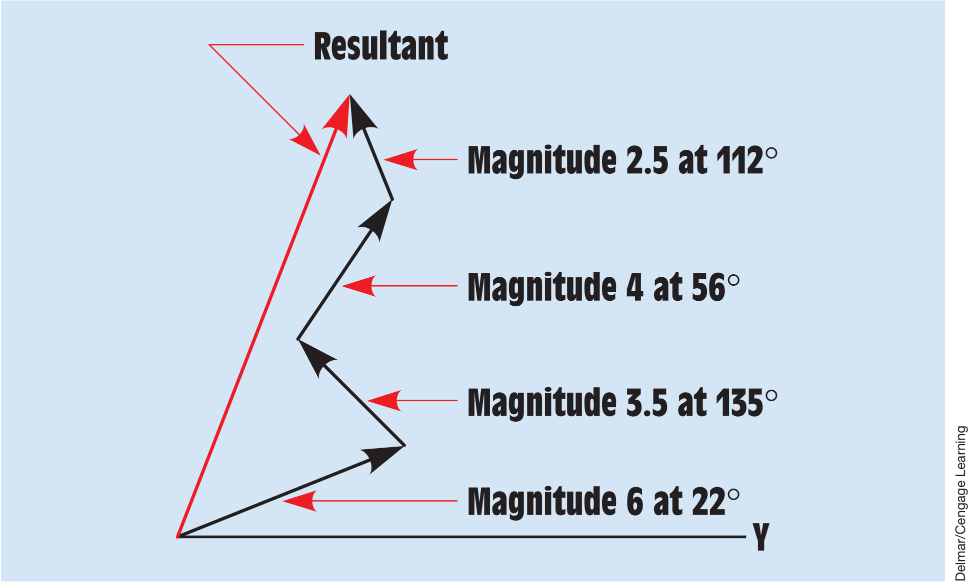


FIGURE 15–18 Adding vectors with different magnitudes and directions.

(Figure 15–19). To find the resultant of these two vectors, form a parallelogram using the vectors as two of the sides. The resultant is drawn from the corner of the parallelogram where the two vectors intersect to the opposite corner *(Figure 15–20)*.

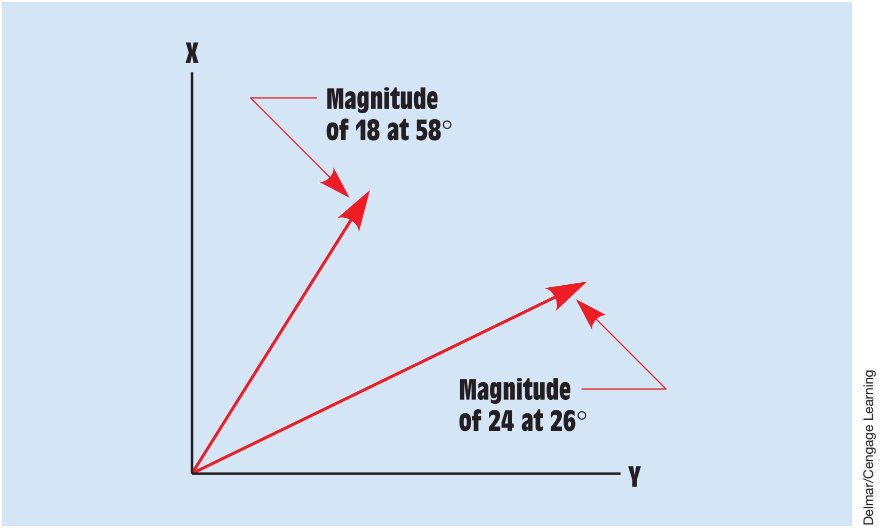


FIGURE 15–19 Vectors that originate from the same point.

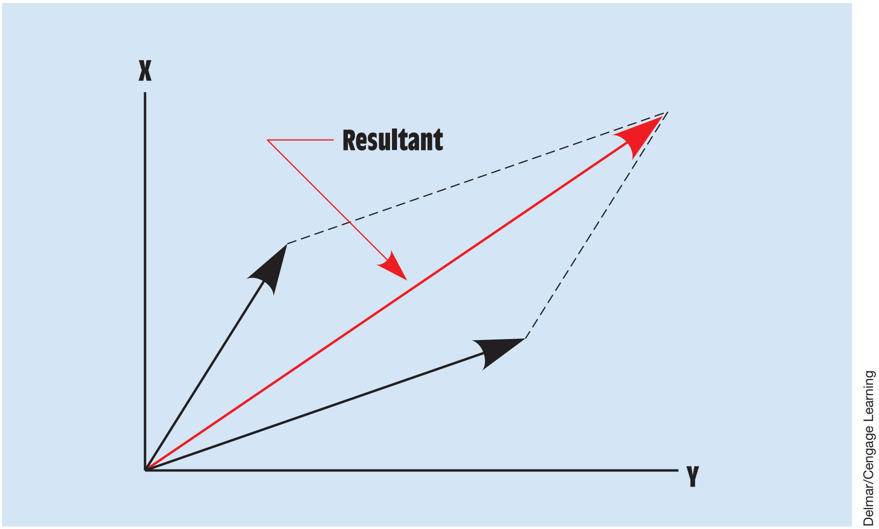


FIGURE 15–20 The parallelogram method of vector addition.

Another example of the parallelogram method of vector addition is shown in *Figure 15–21*. In this example, one vector has a magnitude of 50 and a direction of 32°. The second vector has a magnitude of 60 and a direction of 120°. The resultant is found by using the two vectors as two of the sides of a parallelogram.

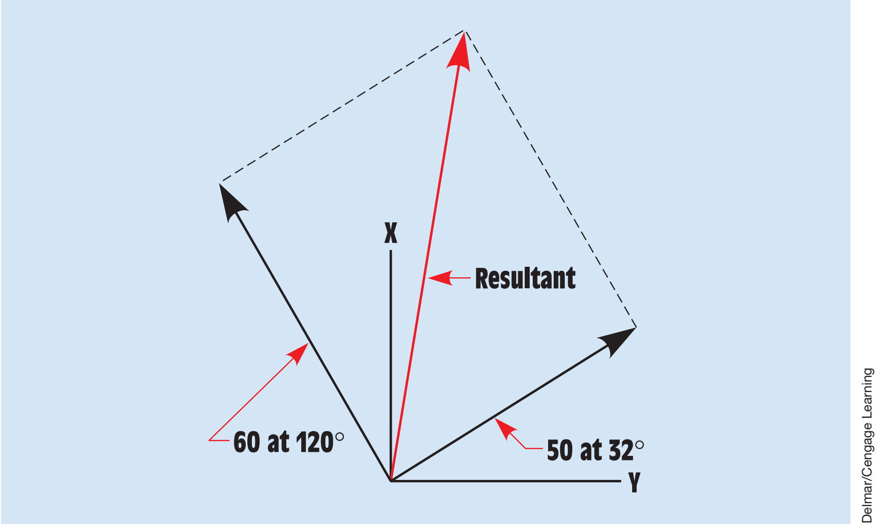


FIGURE 15–21 The parallelogram method of vector addition, second example.

Summary

- Many AC formulas are based on right triangles.
- A right triangle is a triangle that contains a 90°, or right, angle.
- The Pythagorean theorem states that the sum of the squares of the sides of a right triangle equals the square of the hypotenuse.
- The sum of the angles of any triangle is 180°.
- The relationship of the length of the sides of a right triangle to the number of degrees in its angles can be expressed as the sine, cosine, or tangent of a particular angle.
- The sine function is the relationship of the opposite side divided by the hypotenuse.
- The cosine function is the relationship of the adjacent side divided by the hypotenuse.
- The tangent function is the relationship of the opposite side divided by the adjacent side.
- The hypotenuse is always the longest side of a right triangle.

- A simple saying that can be used to help remember the relationship of the trigonometric functions to the sides of a right triangle is *Oscar Had A Heap Of Apples*.
- Vectors are lines that indicate both magnitude and direction.
- Scalars indicate magnitude only.

Review Questions

1. Which trigonometric function is used to find the angle if the length of the hypotenuse and of the adjacent side are known?

Refer to *Figure 15–22* to answer the following questions.

2. If side A has a length of 18.5 ft and side B has a length of 28 ft, what is the length of the hypotenuse?
3. Side A has a length of 12 m, and angle Y is 12°. What is the length of side B?
4. Side A has a length of 6 in. and angle Y is 45°. What is the length of the hypotenuse?
5. The hypotenuse has a length of 65 in., and side A has a length of 31 in. What is angle X?

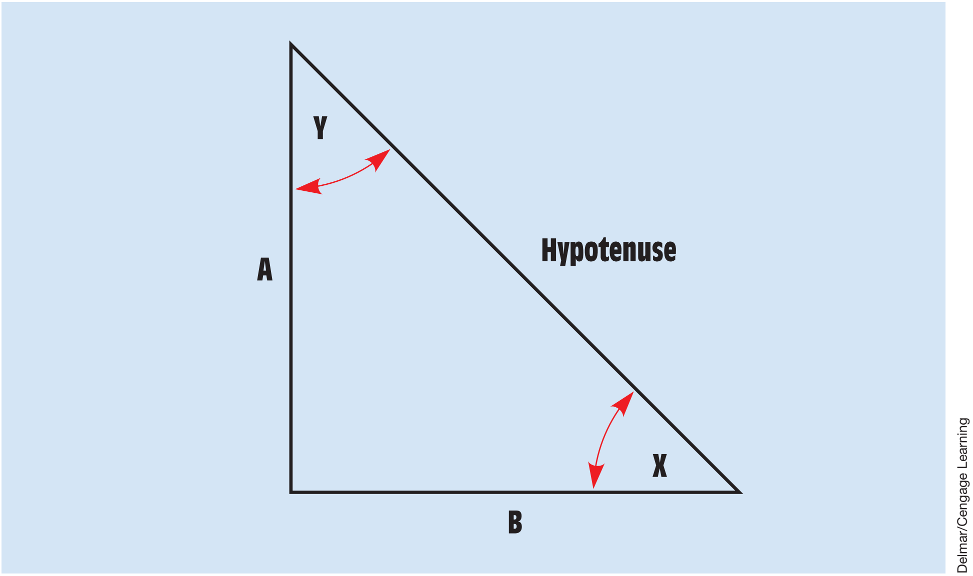


FIGURE 15–22 Finding the values of a right triangle.

6. The hypotenuse has a length of 83 ft and side B has a length of 22 ft. What is the length of side A?
7. Side A has a length of 1.25 in., and side B has a length of 2 in. What is angle Y?
8. Side A has a length of 14 ft, and angle X is 61°. What is the length of the hypotenuse?
9. Using the dimensions in Question 8, what is the length of side B?
10. Angle Y is 36°. What is angle X?

Practical Applications

A parking lot is 275 ft by 200 ft *(Figure 15–23)*. A trade size 4 conduit has been buried 2 ft beneath the concrete. The conduit runs at an angle from one corner of the parking lot to the other. Two pull boxes have been placed in the conduit run. The pull boxes are equally spaced along the length of conduit. Your job is to pull conductors through the conduit from one end of the run to the other.

(A) Allowing 12 ft of extra conductor, what is the length of each conductor? The conductors are not to be spliced.

(B) How much cable will be required to pull these conductors through the conduit, allowing an extra 5 ft at one end that is to be connected to the pulling device and 3 ft extra that is to be used to connect the conductors to the cable? ■

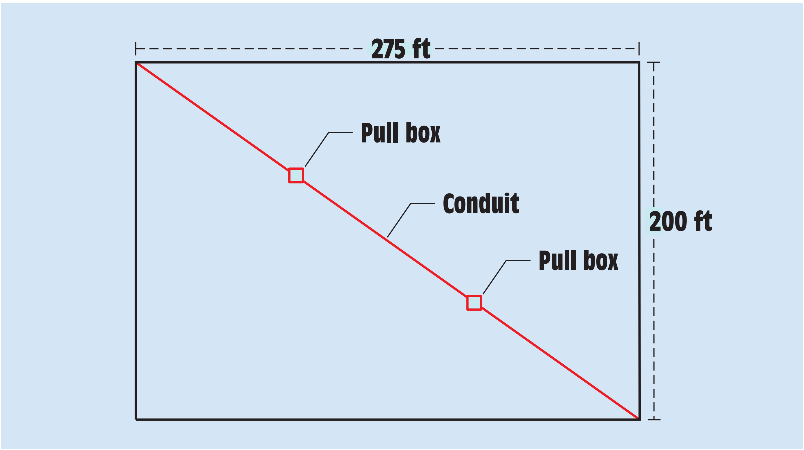


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FIGURE 15–23 Determining length.

Practical Applications

You desire to add a solar heating system to your swimming pool to extend the length of time you can use the pool. For maximum efficiency, the collector should be placed on an angle that will permit the sun's rays to strike the collector at a 90° angle *(Figure 15–24)*. When the sun is at its highest point of the day, you place a yardstick perpendicular to a flat concrete surface. The stick casts a shadow 3.5 ft long. At what angle with respect to the ground should the solar collector be placed? ■

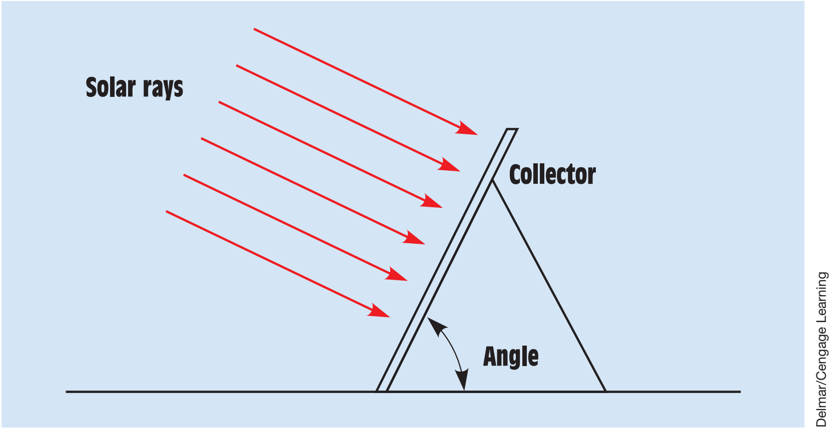

FIGURE 15–24 The sun's rays should strike the face of the solar collector at a 90° angle.

Practice Problems

Basic Trigonometry

Refer to *Figure 15–22* to find the missing values in the following chart.

∠X	∠Y	Side A	Side B	Hyp.
40°				8
	33°	72		
		38		63
52°			14	
	42°		156	

Unit 16

DVD VIDEO

Alternating Current

Why You Need to Know

Most of the electric power in the world is AC. Electricians work with AC about 99% of the time. In this unit, you will learn about different types of waveforms, different methods employed to measure AC values, and the relationship of voltage and current in a circuit that contains pure resistance. This unit

- introduces the sine wave. The most common of all AC waveforms is the sine wave, because it is produced by a rotating machine. All rotating machines operate on the principle of the sine wave. The pistons in an internal combustion engine, for example, travel up and down inside the cylinder in a sine wave pattern because they are connected to a rotating crankshaft.
- explains that the main advantage for the use of AC is that AC voltage can be transformed and DC voltage cannot.
- presents the concepts of eddy currents and skin effect that act as resistance to the flow of current in an AC circuit.
- explains the differences between peak, RMS, and average voltage values. These are very important concepts and should be understood by anyone working in the electrical field. Some electric components such as capacitors and solid-state devices are very sensitive to voltage value. Many of these devices list a peak rating of voltage instead of the RMS value. It then becomes imperative that you know how to determine the peak value from the RMS value.

OUTLINE

KEY TERMS

Amplitude
Average
Cycle
Effective
Frequency
Hertz (Hz)
In phase
Linear wave
Oscillators
Peak
Resistive loads
Ripple
RMS (root-mean-square) value
Sine wave
Skin effect
Triangle wave
True power

Objectives

After studying this unit, you should be able to

- discuss differences between DC and AC.
- compute instantaneous values of voltage and current for a sine wave.
- compute peak, RMS, and average values of voltage and current.
- discuss the phase relationship of voltage and current in a pure resistive circuit.

Courtesy of Niagara Mohawk Power Corporation.

Preview

Most of the electric power produced in the world is AC. It is used to operate everything from home appliances, such as television sets, computers, microwave ovens, and electric toasters, to the largest motors found in industry. AC has several advantages over DC that make it a better choice for the large-scale production of electric power. ■

16–1 Advantages of AC

Probably the single greatest advantage of AC is the fact that AC can be transformed and DC cannot. A transformer permits voltage to be stepped up or down. Voltage can be stepped up for the purpose of transmission and then stepped back down when it is to be used by some device. Transmission voltages of 69 kilovolts, 138 kilovolts, and 345 kilovolts are common. The advantage of high-voltage transmission is that less current is required to produce the same amount of power. The reduction of current permits smaller wires to be used, which results in a savings of material.

In the very early days of electric power generation, Thomas Edison, an American inventor, proposed powering the country with low-voltage DC. He reasoned that low-voltage DC was safer for people to use than higher-voltage AC. A Serbian immigrant named Nikola Tesla, however, argued that DC was impractical for large-scale applications. The disagreement was finally settled at the 1904 World's Fair held in St. Louis, Missouri. The 1904 World's Fair not only introduced the first ice cream cone and the first iced tea but was also the first World's Fair to be lighted with "electric candles." At that time, the only two companies capable of providing electric lighting for the World's Fair were the Edison Company, headed by Thomas Edison, and the Westinghouse Company, headed by George Westinghouse, a close friend of Nikola Tesla. The Edison Company submitted a bid of over $1 per lamp to light the fair with low-voltage DC. The Westinghouse Company submitted a bid of less than 25 cents per lamp to light the fair using higher-voltage AC. This set the precedent for how electric power would be supplied throughout the world.

16–2 AC Waveforms

Square Waves

AC differs from DC in that AC reverses its direction of flow at periodic intervals *(Figure 16–1)*. AC waveforms can vary depending on how the current is produced. One waveform frequently encountered is the square wave *(Figure 16–2)*. It is assumed that the oscilloscope in *Figure 16–2* has been adjusted so that 0 volts is represented by the center horizontal line. The waveform shows that the voltage is in the positive direction for some length of time and then changes polarity. The voltage remains negative for some length of time and then changes back to positive again. Each time the voltage reverses polarity, the current flow through the circuit changes direction. A square wave could be produced by a simple single-pole double-throw switch connected to two

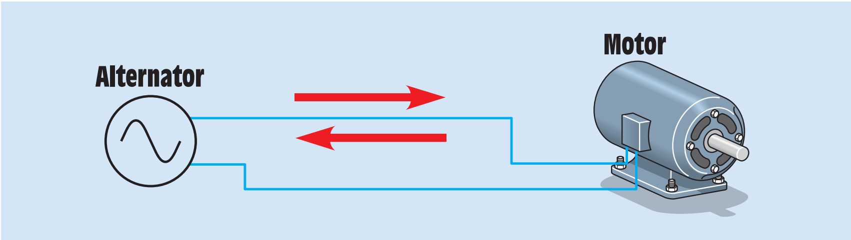

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FIGURE 16–1 AC flows first in one direction and then in the other.

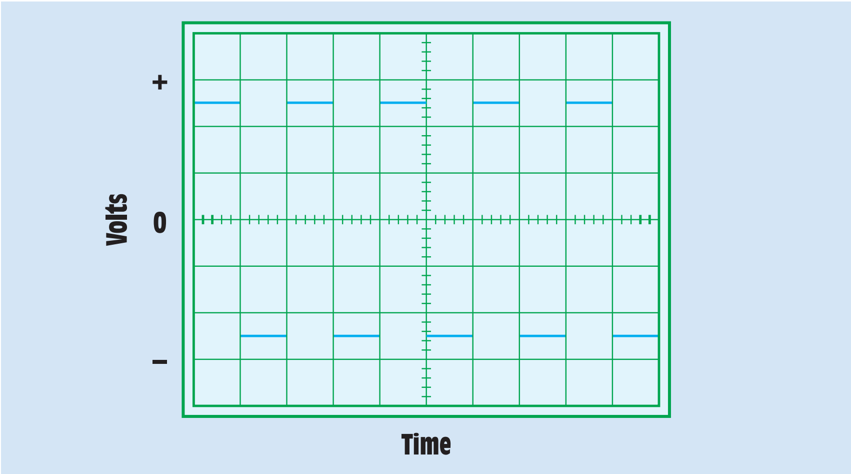

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FIGURE 16–2 Square wave AC.

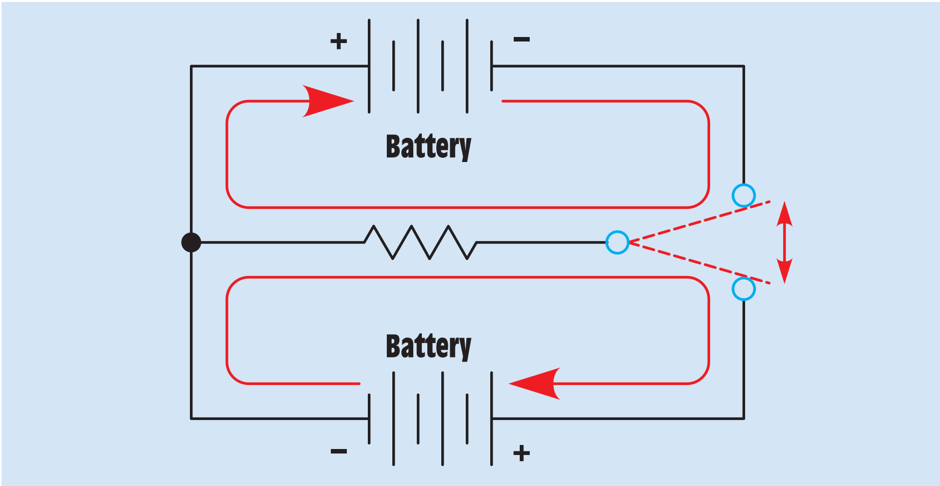

FIGURE 16–3 Square wave AC produced with a switch and two batteries.

batteries as shown in *Figure 16–3*. Each time the switch position is changed, current flows through the resistor in a different direction. Although this circuit will produce a square wave AC, it is not practical. Square waves are generally produced by electronic devices called **oscillators.** The schematic diagram of a simple square wave oscillator is shown in *Figure 16–4*. In this circuit, two bipolar transistors are used as switches to reverse the direction of current flow through the windings of the transformer.

Triangle Waves

Another common AC waveform is the **triangle wave** shown in *Figure 16–5*. The triangle wave is a **linear wave,** one in which the voltage rises at a constant rate with respect to time. Linear waves form straight lines when plotted on a graph. For example, assume that the waveform shown in *Figure 16–5* reaches a maximum

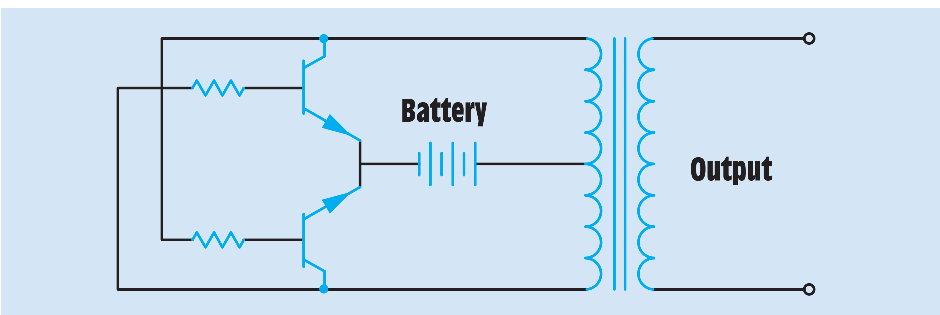

FIGURE 16–4 Square wave oscillator.

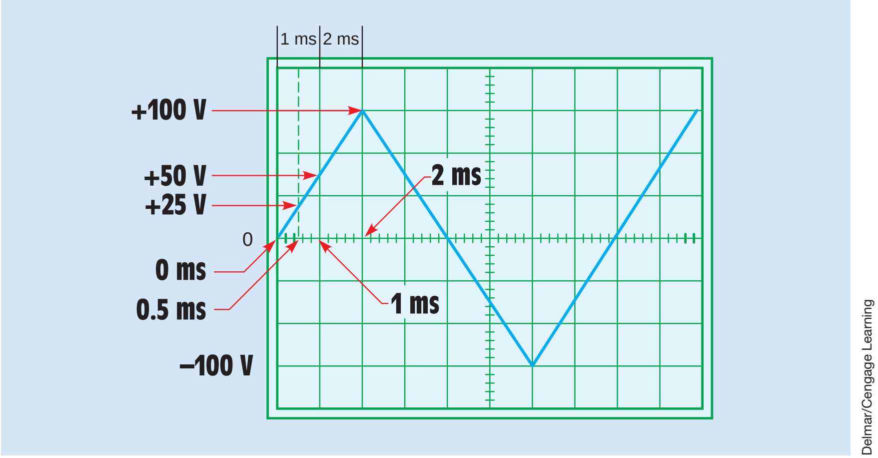

FIGURE 16–5 Triangle wave.

positive value of 100 volts after 2 milliseconds. The voltage will be 25 volts after 0.5 milliseconds, 50 volts after 1 milliseconds, and 75 volts after 1.5 milliseconds.

Sine Waves

The most common of all AC waveforms is the **sine wave** *(Figure 16–6)*. Sine waves are produced by all rotating machines. The sine wave contains a total of 360 electric degrees. It reaches its peak positive voltage at 90°, returns to a value of 0 volts at 180°, increases to its maximum negative voltage at 270°, and returns to 0 volts at 360°. Each complete waveform of 360° is called a **cycle.** The number

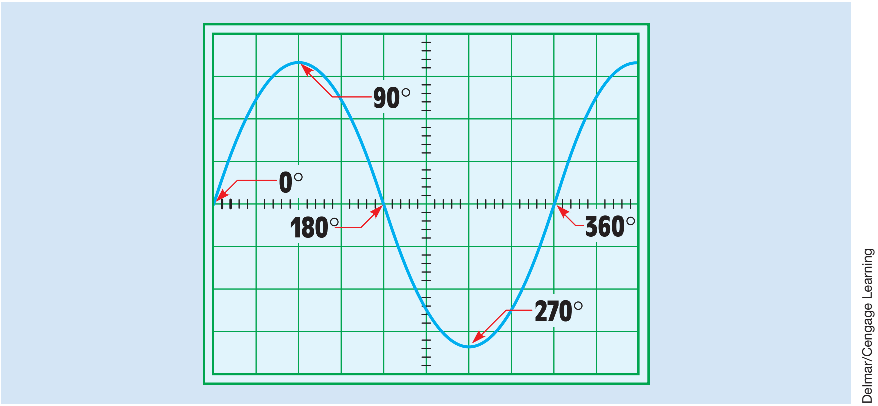

FIGURE 16–6 Sine wave.

of complete cycles that occur in one second is called the **frequency.** Frequency is measured in **hertz (Hz).** The most common frequency in the United States and Canada is 60 hertz. This means that the voltage increases from zero to its maximum value in the positive direction, returns to zero, increases to its maximum value in the negative direction, and returns to zero 60 times each second.

Sine waves are so named because the voltage at any point along the waveform is equal to the maximum, or peak, value times the sine of the angle of rotation. *Figure 16–7* illustrates one half of a loop of wire cutting through lines of magnetic flux. The flux lines are shown with equal spacing between each line, and the arrow denotes the arc of the loop as it cuts through the lines of flux. Notice the number of flux lines that are cut by the loop during the first 30° of rotation. Now notice the number of flux lines that are cut during the second and third 30° of rotation. Because the loop is cutting the flux lines at an angle, it must travel a greater distance between flux lines during the first degrees of rotation. Consequently, fewer flux lines are cut per second, which results in a lower induced voltage. Recall that 1 volt is induced in a conductor when it cuts lines of magnetic flux at a rate of 1 weber per second (Wb/s). One weber is equal to 100,000,000 lines of flux.

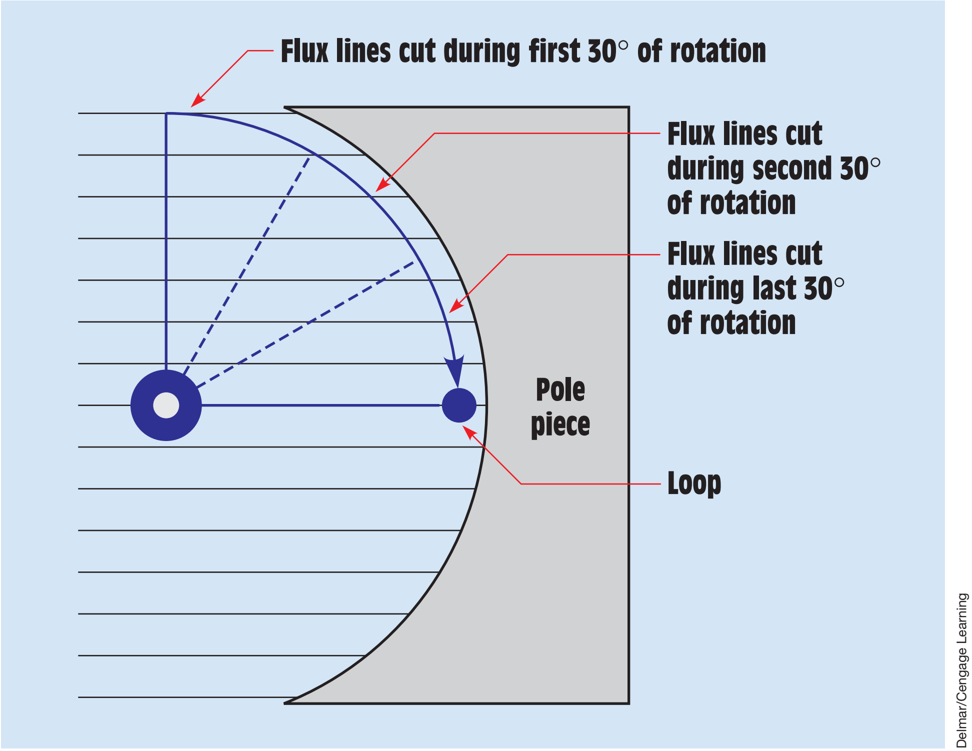

FIGURE 16–7 As the loop approaches 90° of rotation, the flux lines are cut at a faster rate.

When the loop has rotated 90°, its direction of motion is perpendicular to the flux lines and is cutting them at the maximum rate, which results in the highest, or peak, voltage being induced in the loop. The voltage at any point during the rotation is equal to the maximum induced voltage times the sine of the angle of rotation. For example, if the induced voltage after 90° of rotation is 100 volts, the voltage after 30° of rotation will be 50 volts because the sine of a 30° angle is 0.5 (100 × 0.5 = 50 V). The induced voltage after 45° of rotation is 70.7 volts because the sine of a 45° angle is 0.707 (100 × 0.707 = 70.7 V). A sine wave showing the instantaneous voltage values after different degrees of rotation is shown in *Figure 16–8*. The instantaneous voltage value is the value of voltage at any instant on the waveform.

The following formula can be used to determine the instantaneous value at any point along the sine wave:

$$E_{(INST)} = E_{(MAX)} \times \sin \angle\theta$$

where

$E_{(INST)}$ = the voltage at any point on the waveform
$E_{(MAX)}$ = the maximum, or peak, voltage
$\sin \angle\theta$ = the sine of the angle of rotation

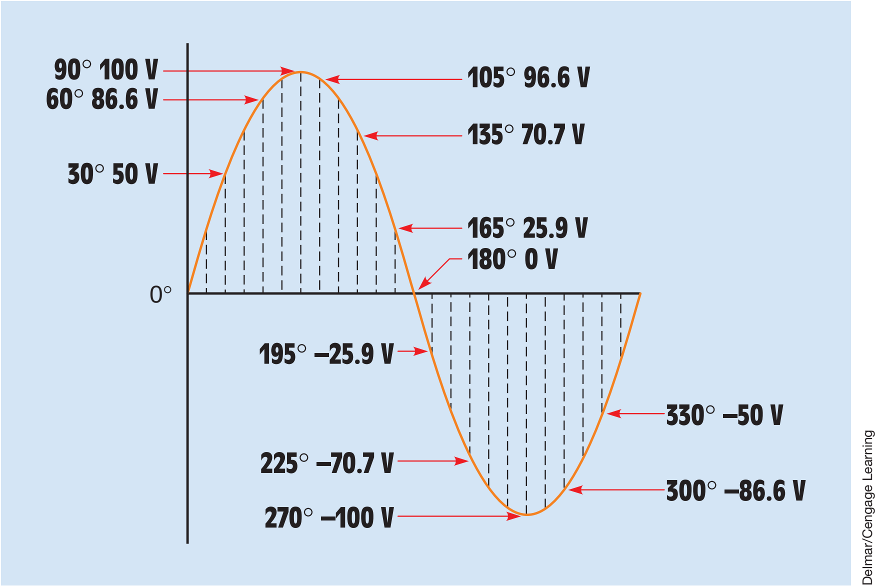

FIGURE 16–8 Instantaneous values of voltage along a sine wave.

EXAMPLE 16–1

A sine wave has a maximum voltage of 138 V. What is the voltage after 78° of rotation?

Solution

$$E_{(INST)} = E_{(MAX)} \sin \angle\theta$$

$$E_{(INST)} = 138 \times 0.978 \text{ (sin of } 78^\circ)$$

$$E_{(INST)} = 134.964 \text{ V}$$

The formula can be changed to find the maximum value if the instantaneous value and the angle of rotation are known or to find the angle if the maximum and instantaneous values are known:

$$E_{(MAX)} = \frac{E_{(INST)}}{\sin \angle\theta}$$

$$\sin \angle\theta = \frac{E_{(INST)}}{E_{(MAX)}}$$

EXAMPLE 16–2

A sine wave has an instantaneous voltage of 246 V after 53° of rotation. What is the maximum value the waveform will reach?

Solution

$$E_{(MAX)} = \frac{E_{(INST)}}{\sin \angle\theta}$$

$$E_{(MAX)} = \frac{246 \text{ V}}{0.799}$$

$$E_{(MAX)} = 307.885 \text{ V}$$

■ EXAMPLE 16–3

A sine wave has a maximum voltage of 350 V. At what angle of rotation will the voltage reach 53 V?

Solution

$$\sin \angle\theta = \frac{E_{(INST)}}{E_{(MAX)}}$$

$$\sin \angle\theta = \frac{53\text{ V}}{350\text{ V}}$$

$$\sin \angle\theta = 0.151$$

Note: 0.151 is the *sine* of the angle, not the angle.

$$\angle\theta = 8.685°$$

16–3 Sine Wave Values

Several measurements of voltage and current are associated with sine waves. These measurements are peak to peak, peak, RMS, and average. A sine wave showing peak to peak, peak, and RMS measurements is shown in *Figure 16–9*.

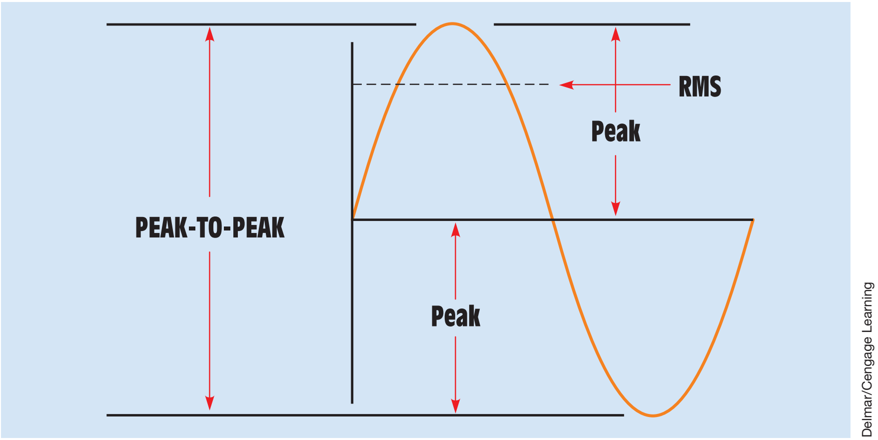

FIGURE 16–9 Sine wave values.

Peak-to-Peak and Peak Values

The peak-to-peak value is measured from the maximum value in the positive direction to the maximum value in the negative direction. The peak-to-peak value is often the simplest measurement to make when using an oscilloscope.

The **peak** value, or **amplitude,** is measured from zero to the highest value obtained in either the positive or negative direction. The peak value is one-half of the peak-to-peak value.

RMS Values

In *Figure 16–10,* a 100-volt battery is connected to a 100-ohm resistor. This connection will produce 1 ampere of current flow, and the resistor will dissipate 100 watts of power in the form of heat. An AC alternator that produces a peak voltage of 100 volts is also shown connected to a 100-ohm resistor. A peak current of 1 ampere will flow in the circuit, but the resistor will dissipate only 50 watts in the form of heat. The reason is that the voltage produced by a pure source of DC, such as a battery, is one continuous value *(Figure 16–11)*. The AC sine wave, however, begins at zero, increases to the maximum value, and decreases back to zero during an equal period of time. Because the sine wave has a value of 100 volts for only a short period of time and is less than 100 volts during the rest of the half-cycle, it cannot produce as much power as 100 volts of DC.

The solution to this problem is to use a value of AC voltage that will produce the same amount of power as a like value of DC voltage. This AC value

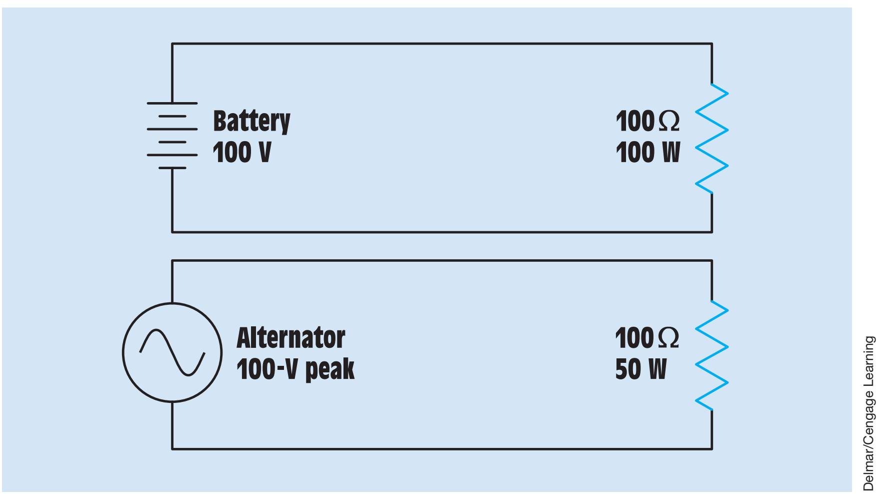

FIGURE 16–10 DC compared with a sine wave AC.

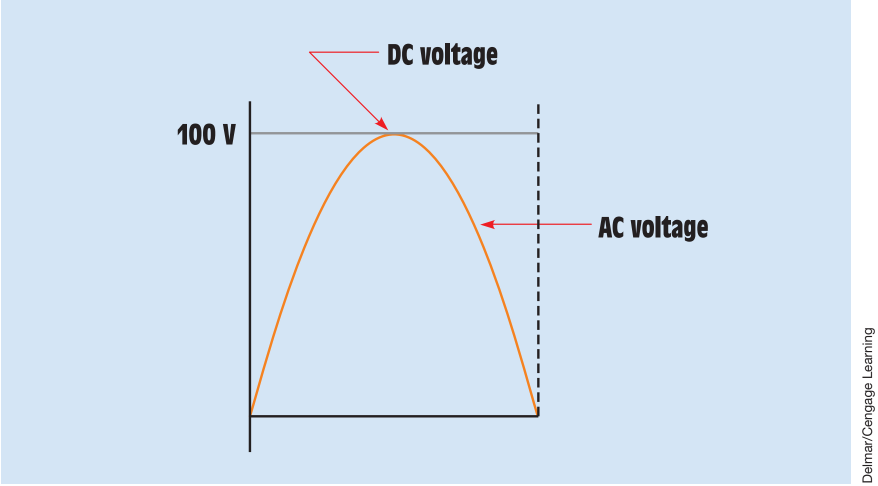

FIGURE 16–11 The DC voltage remains at a constant value during a half cycle of AC voltage.

is called the **RMS,** or **effective, value.** It is the value indicated by almost all AC voltmeters and ammeters. ***RMS stands for root-mean-square, which is an abbreviation for the square root of the mean of the square of the instantaneous currents.*** The RMS value can be found by dividing the peak value by the square root of 2 (1.414) or by multiplying the peak value by 0.707 (the reciprocal of 1.414). The formulas for determining the RMS and peak values are

$$\text{RMS} = \text{peak} \times 0.707$$
$$\text{peak} = \text{RMS} \times 1.414$$

EXAMPLE 16–4

A sine wave has a peak value of 354 V. What is the RMS value?

Solution

$$\text{RMS} = \text{peak} \times 0.707$$
$$\text{RMS} = 354\ \text{V} \times 0.707$$
$$\text{RMS} = 250.278\ \text{V}$$

■ **EXAMPLE 16-5**

An AC voltage has a value of 120 V RMS. What is the peak value of voltage?

Solution

$$\text{peak} = \text{RMS} \times 1.414$$
$$\text{peak} = 120\text{ V} \times 1.414$$
$$\text{peak} = 169.68\text{ V}$$

When the RMS values of voltage and current are used, the result is the same amount of power as like values of DC voltage and current. If 100 V RMS is applied to a 100-Ω resistor, the resistor will produce 100 W of heat. AC voltmeters and ammeters indicate the RMS value, not the peak value. Oscilloscopes, however, display the peak-to-peak value of voltage. All values of AC voltage and current used from now on in this text are RMS values unless otherwise stated.

Average Values

Average values of voltage and current are actually DC values. The average value must be found when a sine wave AC voltage is changed into DC with a rectifier *(Figure 16–12)*. The rectifier shown is a bridge-type rectifier that produces full-wave rectification. This means that both the positive and negative half of the AC waveform are changed into DC. The average value is the amount of voltage

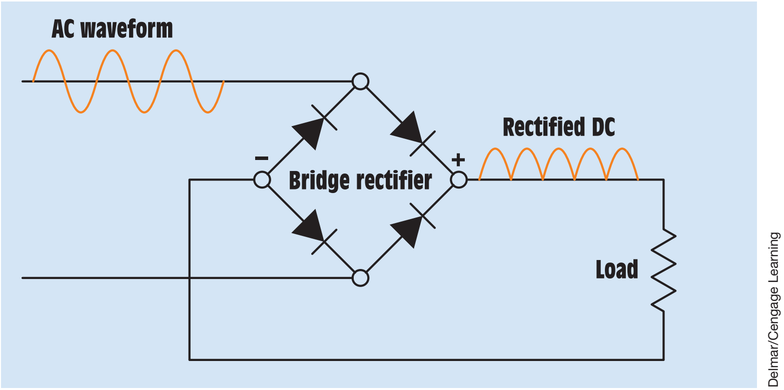

FIGURE 16–12 The bridge rectifier changes AC voltage into DC voltage.

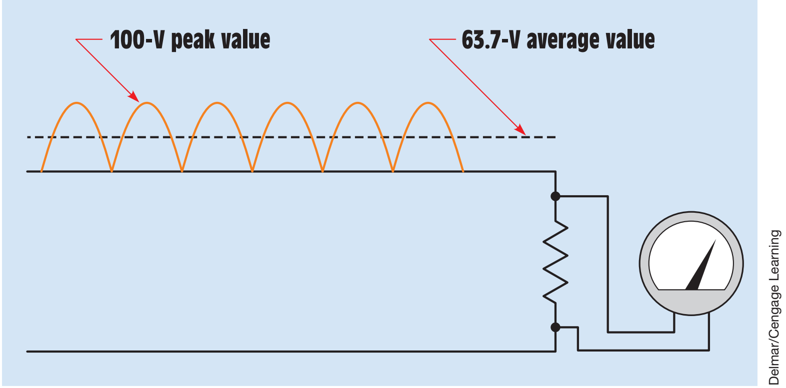

FIGURE 16–13 A DC voltmeter indicates the average value.

that would be indicated by a DC voltmeter if it were connected across the load resistor. The average voltage is proportional to the peak, or maximum, value of the waveform and to the length of time it is on as compared with the length of time it is off *(Figure 16–13)*. Notice in *Figure 16–13* that the voltage waveform turns on and off, but it never changes polarity. The current, therefore, never reverses direction. This is called pulsating DC. The pulses are often referred to as **ripple.** The average value of voltage will produce the same amount of power as a nonpulsating source of voltage such as a battery *(Figure 16–14)*. For a full-wave rectified sine wave, the average value of voltage is found by multiplying the peak value by 0.637 or by multiplying the RMS value by 0.9.

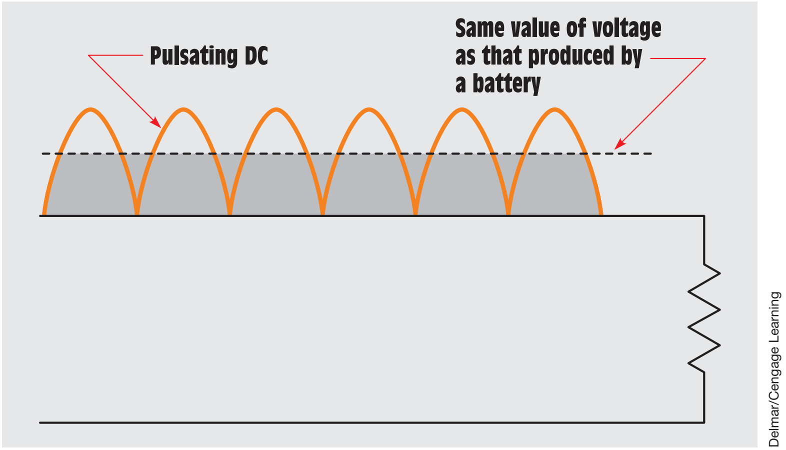

FIGURE 16–14 The average value produces the same amount of power as a nonpulsating source of voltage.

EXAMPLE 16-6

An AC sine wave with an RMS value of 120 V is connected to a full-wave rectifier. What is the average DC voltage?

Solution

The problem can be solved in one of two ways. The RMS value can be changed into peak and then the peak value can be changed to the average value:

$$\text{peak} = \text{RMS} \times 1.414$$
$$\text{peak} = 120\text{ V} \times 1.414$$
$$\text{peak} = 169.68\text{ V}$$

$$\text{average} = \text{peak} \times 0.637$$
$$\text{average} = 169.68\text{ V} \times 0.637$$
$$\text{average} = 108.086\text{ V}$$

The second method of determining the average value is to multiply the RMS value by 0.9:

$$\text{average} = \text{RMS} \times 0.9$$
$$\text{average} = 120\text{ V} \times 0.9$$
$$\text{average} = 108\text{ V}$$

The conversion factors given are for full-wave rectification. If a half-wave rectifier is used *(Figure 16–15),* only one half of the AC waveform is converted

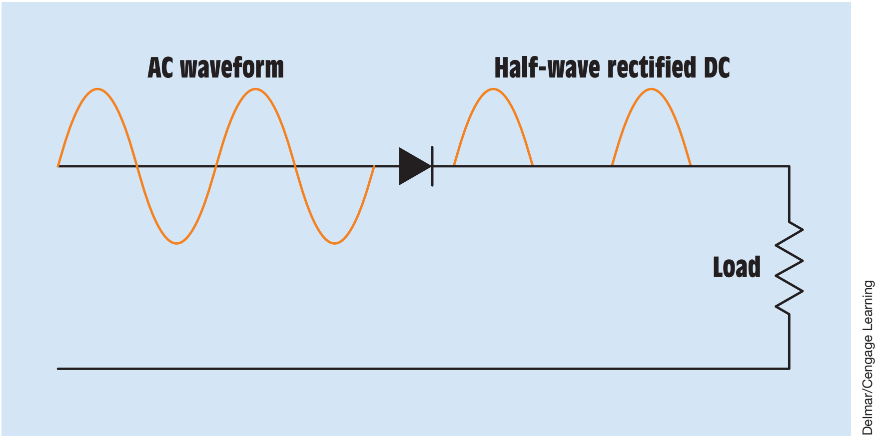

FIGURE 16–15 A half-wave rectifier converts only one half of the AC waveform into DC.

into DC. To determine the average voltage for a half-wave rectifier, multiply the peak value by 0.637 or the RMS value by 0.9 and then divide the product by 2. Because only half of the AC waveform has been converted into DC, the average voltage will be only half that of a full-wave rectifier *(Figure 16–16)*.

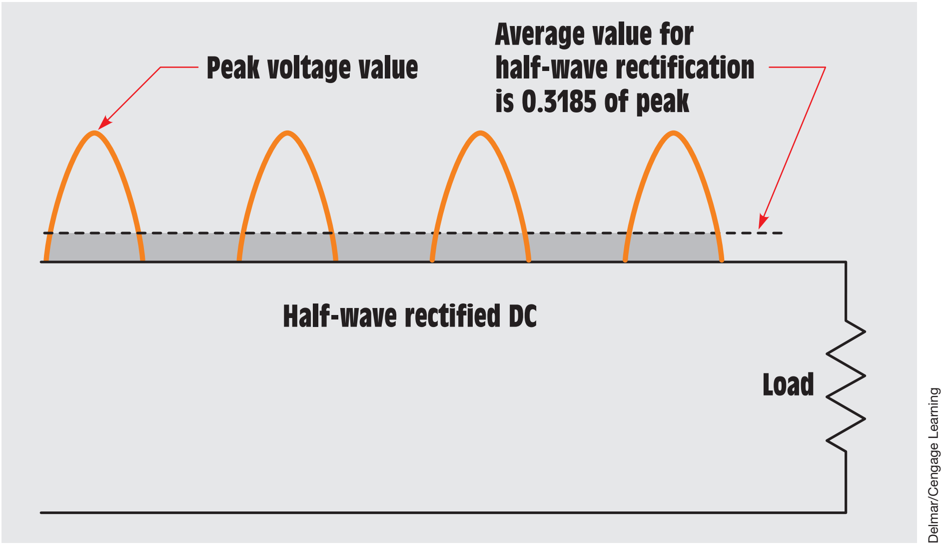

FIGURE 16–16 The average value for a half-wave rectifier is only half that of a full wave.

EXAMPLE 16-7

A half-wave rectifier is connected to 277 VAC. What is the average DC voltage?

Solution

$$\text{average} = \text{RMS} \times \frac{0.9}{2}$$

$$\text{average} = 277 \text{ V} \times \frac{0.9}{2}$$

$$\text{average} = 124.65 \text{ V}$$

Wavelength

When current flows through a conductor, a magnetic field is created around the conductor. When high-frequency AC is used to produce a magnetic field, the field will radiate away from the source at the speed of light, which is approximately 186,000 miles per second, or 300,000,000 meters per second *(Figure 16–17)*. *Wavelength* is the distance the radiating field or signal can travel during one cycle of alternating voltage. Wavelength is generally represented by the Greek letter lambda (λ) and can be computed using the formula:

$$\lambda = \frac{\text{speed of light in meters per second}}{\text{frequency}}$$

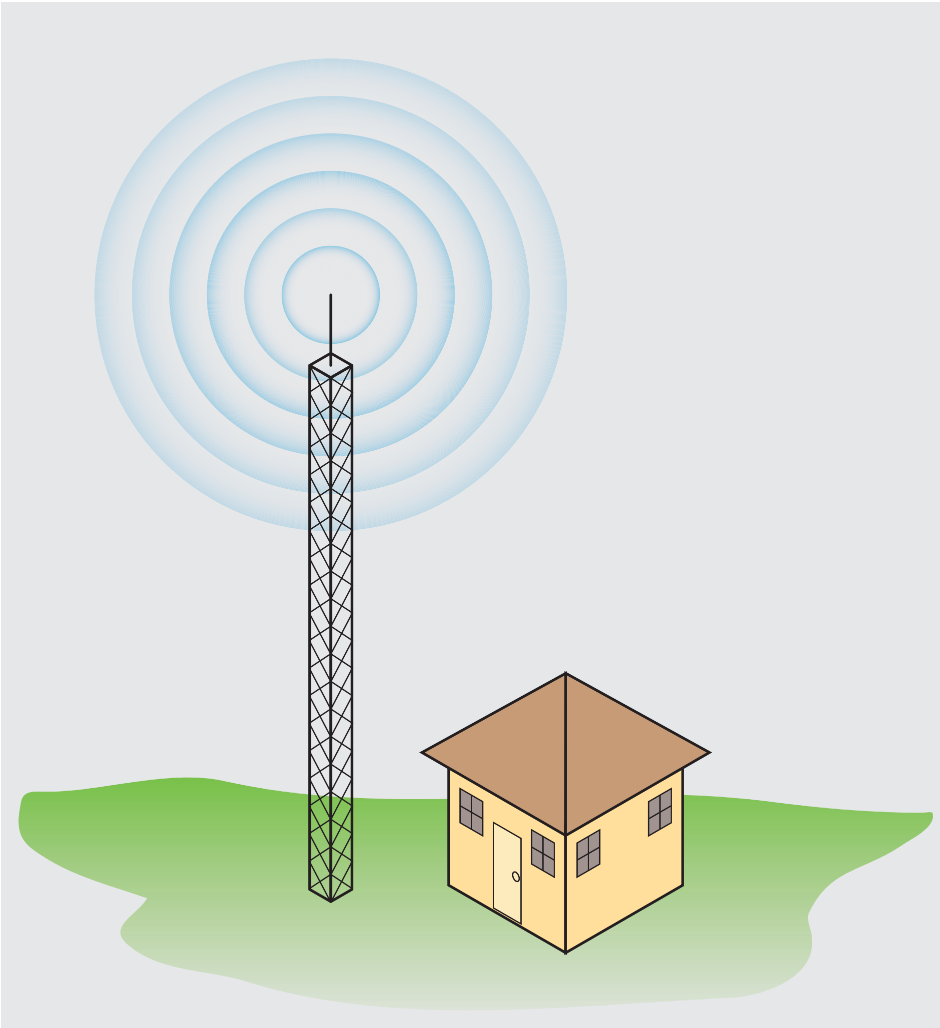

FIGURE 16–17 High-frequency AC causes a magnetic field to radiate at the speed of light.

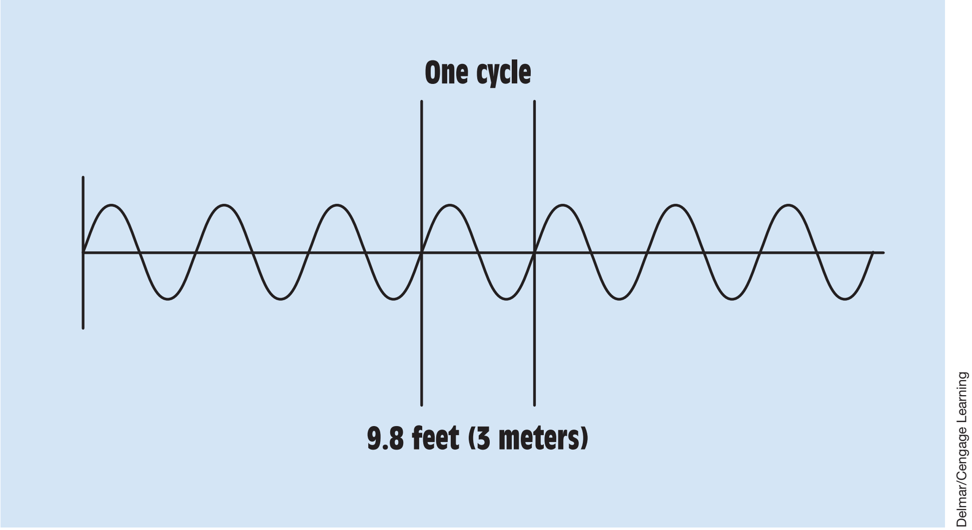

FIGURE 16–18 Wavelength is the distance traveled by the signal during one cycle.

Assume that a radio transmitter is operating at a frequency of 100 MHz. What is the wavelength of the signal?

$$\lambda = \frac{300{,}000{,}000 \text{ m/s}}{100{,}000{,}000 \text{ Hz}}$$

$$\lambda = 3 \text{ m}$$

At a frequency of 100 MHz, the signal will travel 9.8 ft (3 m) during one cycle *(Figure 16–18)*.

16–4 Resistive Loads

In DC circuits, there is only one basic type of load, which is resistive. Even motor loads appear to be resistive because there is a conversion of electrical energy into mechanical energy. In this type of load, the **true power,** or watts, is the product of the volts times the amperes. In AC circuits, the type of load can vary depending on several factors. AC loads are generally described as being resistive, inductive, or capacitive, depending on the phase-angle relationship of voltage and current and the amount of true power produced by the circuit. Inductive and capacitive loads are discussed in later units. **Resistive loads** are loads that contain pure resistance, such as electric heating

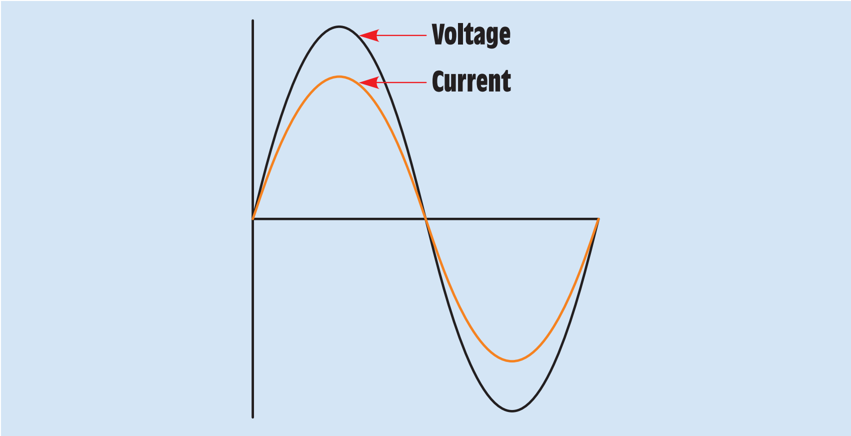

FIGURE 16–19 In a pure resistive circuit, the voltage and current are in phase with each other.

equipment and incandescent lighting. Resistive loads are characterized by the facts that

1. they produce heat.
2. the current and voltage are in phase with each other.

Any time that a circuit contains resistance, electrical energy is changed into heat.

When an AC voltage is applied to a resistor, the current flow through the resistor is a copy of the voltage *(Figure 16–19)*. The current rises and falls at the same rate as the voltage and reverses the direction of flow when the voltage reverses polarity. In this condition, the current is said to be **in phase** with the voltage.

16–5 Power in an AC Circuit

True power, or watts, can be produced only when both current and voltage are either positive or negative. When like signs are multiplied, the product is positive (+ × + = +, or − × − = +), and when unlike signs are multiplied the product is negative (+ × − = −). Because the current and voltage are both either positive or negative at the same time, the product, watts, is always positive *(Figure 16–20)*.

16–6 Skin Effect in AC Circuits

When current flows through a conductor connected to a source of DC, the electrons flow through the entire conductor *(Figure 16–21)*. The conductor offers some amount of ohmic resistance to the flow of electrons, depending

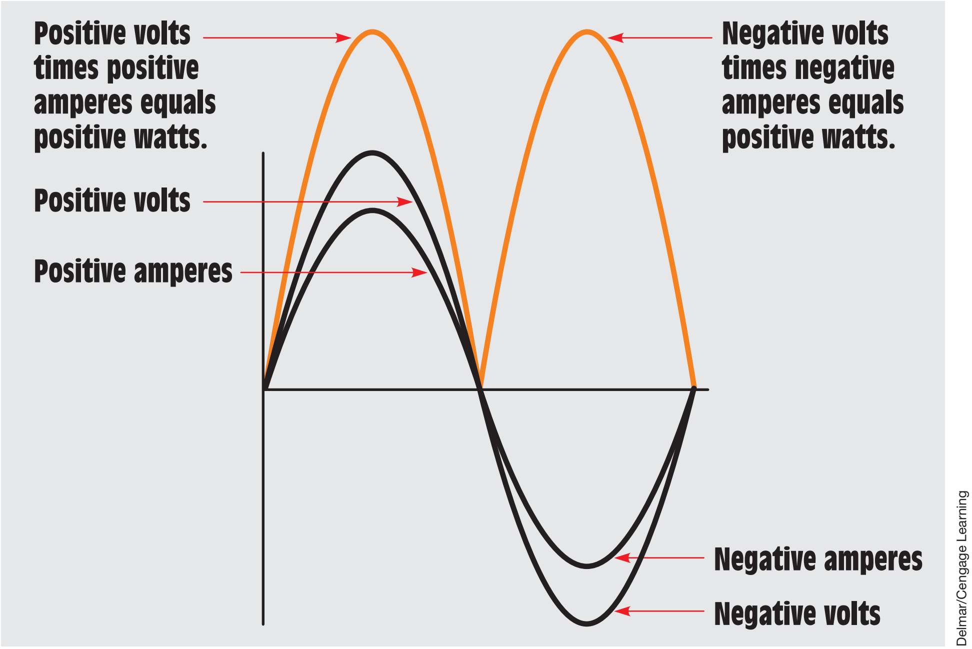

FIGURE 16–20 Power in a pure resistive AC circuit.

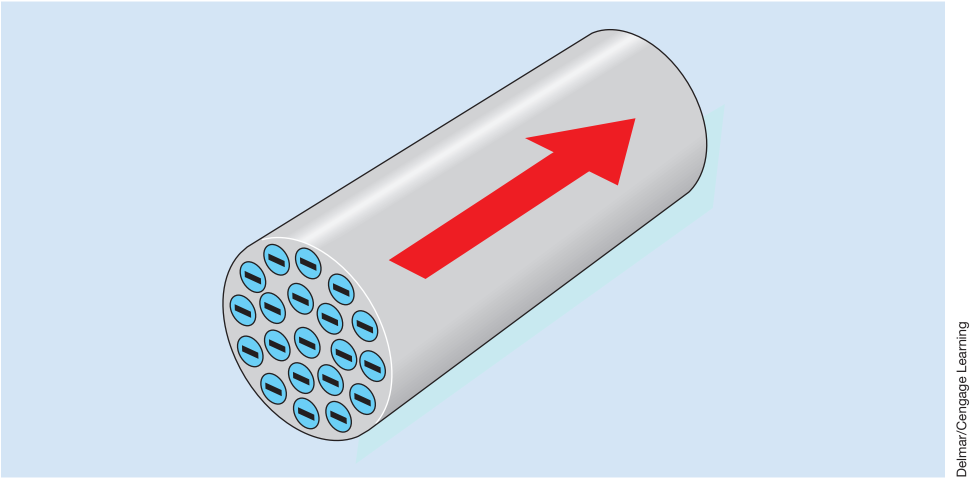

FIGURE 16–21 In a DC circuit, the electrons travel through the entire conductor.

on the type of material from which the conductor is made, its length, and its diameter. If that same conductor were connected to a source of AC, the resistance of the conductor to the flow of current would be slightly higher because of the **skin effect.** The AC induces eddy currents into the

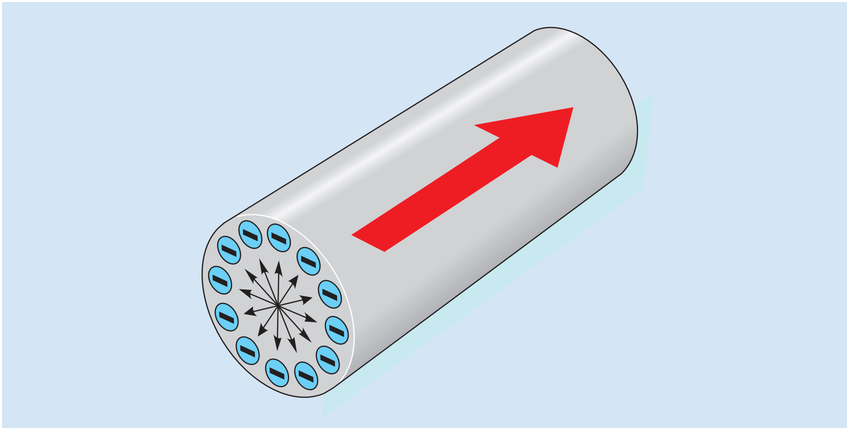

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FIGURE 16–22 In an AC circuit, the electrons are forced to the outside of the conductor. This is called skin effect.

conductor. These eddy currents cause the electrons to be repelled toward the outer surface of the conductor *(Figure 16–22)*. This phenomenon is called the skin effect. Forcing the electrons toward the outer surface of the conductor has the same effect as decreasing the diameter of the conductor, which increases conductor resistance. The skin effect is proportional to the frequency. As the frequency increases, the skin effect increases. At low frequencies, such as 60 hertz, the skin effect has very little effect on the resistance of a conductor and generally is not taken into consideration when computing the size wire needed for a particular circuit. At high frequencies, however, the skin effect can have a great effect on the operation of the circuit.

GREEN TIP: High-frequency circuits should employ conductors that have a very large surface area, such as braided cable, to help reduce the increased conductor resistance due to skin effect. ■

To help overcome the problem of skin effect in high-frequency circuits, conductors with a large amount of surface area must be used. Grounding a piece of equipment operating at 60 hertz, for example, may be as simple as using a grounding rod and a piece of 6 AWG copper conductor. Grounding a piece of equipment operating at 20 megahertz, however, may require the use of wide copper tape or a wide, flat, braided cable. Braided cable is less affected by skin effect because it contains many small conductors, which provide a large amount of surface area.

Summary

- Most of the electric power generated in the world is AC.
- AC can be transformed and DC cannot.
- AC reverses its direction of flow at periodic intervals.
- The most common AC waveform is the sine wave.
- There are 360° in one complete sine wave.
- One complete waveform is called a cycle.
- The number of complete cycles that occur in 1 second is called the frequency.
- Sine waves are produced by rotating machines.
- Frequency is measured in hertz (Hz).
- The instantaneous voltage at any point on a sine wave is equal to the peak, or maximum, voltage times the sine of the angle of rotation.
- The peak-to-peak voltage is the amount of voltage measured from the positive-most peak to the negative-most peak.
- The peak value is the maximum amount of voltage attained by the waveform.
- The RMS value of voltage will produce as much power as a like amount of DC voltage.
- The average value of voltage is used when an AC sine wave is changed into DC.
- The current and voltage in a pure resistive circuit are in phase with each other.
- True power, or watts, can be produced only when current and voltage are both positive or both negative.
- Resistance in AC circuits is characterized by the fact that the resistive part will produce heat.
- There are three basic types of AC loads: resistive, inductive, and capacitive.

- The electrons in an AC circuit are forced toward the outside of the conductor by eddy current induction in the conductor itself.
- Skin effect is proportional to frequency.
- Skin effect can be reduced by using conductors with a large surface area.

Review Questions

1. What is the most common type of AC waveform?
2. How many degrees are there in one complete sine wave?
3. At what angle does the voltage reach its maximum negative value on a sine wave?
4. What is frequency?
5. A sine wave has a maximum value of 230 V. What is the voltage after 38° of rotation?
6. A sine wave has a voltage of 63 V after 22° of rotation. What is the maximum voltage reached by this waveform?
7. A sine wave has a maximum value of 560 V. At what angle of rotation will the voltage reach a value of 123 V?
8. A sine wave has a peak value of 433 V. What is the RMS value?
9. A sine wave has a peak-to-peak value of 88 V. What is the average value?
10. A DC voltage has an average value of 68 V. What is the RMS value?

Practical Applications

You are an electrician working on an overhead crane. The crane uses a large electromagnet to pick up large metal pipes. The magnet must have a minimum of 200 VDC to operate properly. The crane has an AC source of 240 V. You are given four diodes that have a peak voltage rating of 400 V each. These diodes are to be used to form a bridge rectifier to convert the AC voltage into DC voltage. Is the voltage rating of the diodes sufficient? To the nearest volt, what will be the DC output voltage of the bridge rectifier? ■

Practical Applications

You are a journeyman electrician working in a large office building. The fluorescent lighting system is operated at 277 V. You have been instructed to replace the existing light ballasts with a new electronic type that is more efficient. The manufacturer of the ballast states that the maximum peak operating voltage for the ballast is 350 V. Will the new electronic ballast operate on the building's lighting system without harm? ■

Practice Problems

Refer to the AC formulas in Appendix D to answer the following questions.

Sine Wave Values

Fill in all the missing values.

Peak Volts	Inst. Volts	Degrees
347	208	
780		43.5
	24.3	17.6
224	5.65	
48.7		64.6
	240	45
87.2	23.7	
156.9		82.3
	62.7	34.6
1256	400	
15,720		12
	72.4	34.8

$$E_{(INST)} = E_{(MAX)} \times \sin \angle\theta$$

$$E_{(MAX)} = \frac{E_{(INST)}}{\sin \angle\theta}$$

$$\sin \angle\theta = \frac{E_{(INST)}}{E_{(MAX)}}$$

Peak, RMS, and Average Values

Fill in all the missing values.

Peak	RMS	Full-Wave Rectified Average
12.7		
	53.8	
		164.2
1235		
	240	
		16.6
339.7		
	12.6	
		9
123.7		
	74.8	
		108

VI

Alternating Current (AC) Circuits Containing Inductance

Courtesy of Getty Images, Inc.

Unit 17

Inductance in AC Circuits

OUTLINE

KEY TERMS

Current lags voltage
Induced voltage
Inductance (L)
Inductive reactance, (X_L)
Quality (Q)
Reactance
Reactive power ($VARs_L$)

Why You Need to Know

Inductance is one the three major types of loads found in alternating current circuits. Electricians need to understand the impact on a pure inductive circuit and how current lags voltage when the effect is applied in an AC circuit. This unit

- explains how properties other than resistance can limit the flow of current.
- introduces another measurement called impedance. Impedance is the total current-limiting effect in an AC circuit and can be comprised of more than one element, such as resistance and inductance. Without an understanding of inductance, you will never be able to understand many of the concepts to follow in later units.

Courtesy of Niagara Mohawk Power Corporation

Objectives

After studying this unit, you should be able to

- discuss the properties of inductance in an AC circuit.
- discuss inductive reactance.
- calculate values of inductive reactance and inductance.
- discuss the relationship of voltage and current in a pure inductive circuit.
- be able to calculate values for inductors connected in series or parallel.
- discuss reactive power (VARs).
- determine the Q of a coil.

Preview

This unit discusses the effects of inductance on AC circuits. The unit explains how current is limited in an inductive circuit as well as the effect inductance has on the relationship of voltage and current. ■

17–1 Inductance

Inductance (L) is one of the primary types of loads in AC circuits. Some amount of inductance is present in all AC circuits because of the continually changing magnetic field (*Figure 17–1*). The amount of inductance of a single conductor is extremely small, and, in most instances, it is not considered in circuit calculations. Circuits are generally considered to contain inductance when any type of

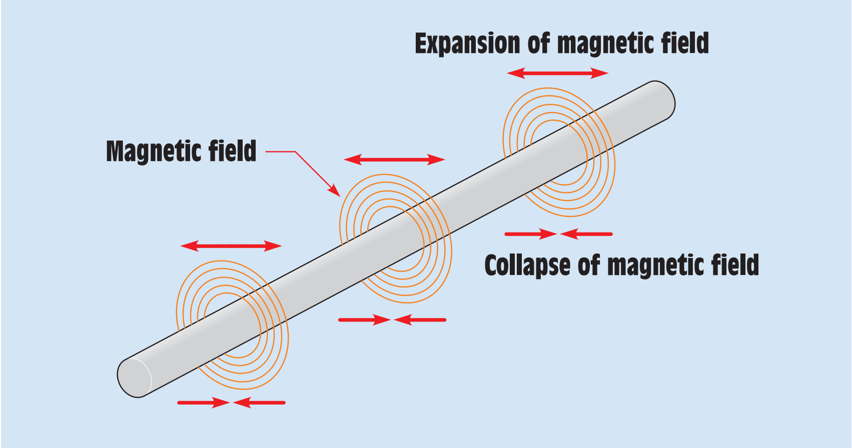

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FIGURE 17–1 A continually changing magnetic field induces a voltage into any conductor.

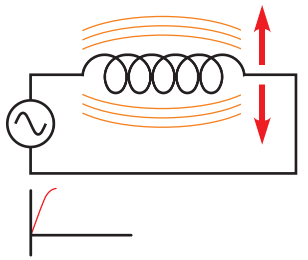


FIGURE 17–2 As current flows through a coil, a magnetic field is created around the coil.

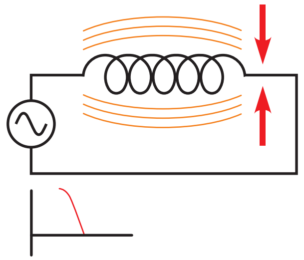


FIGURE 17–3 As current flow decreases, the magnetic field collapses.

load that contains a coil is used. For circuits that contain a coil, inductance *is* considered in circuit calculations. Loads such as motors, transformers, lighting ballast, and chokes all contain coils of wire.

In Unit 14, it was discussed that whenever current flows through a coil of wire, a magnetic field is created around the wire *(Figure 17–2)*. If the amount of current decreases, the magnetic field collapses *(Figure 17–3)*. Recall from Unit 14 several facts concerning inductance:

1. When magnetic lines of flux cut through a coil, a voltage is induced in the coil.
2. An induced voltage is always opposite in polarity to the applied voltage. This is often referred to as counter-electromotive force (CEMF).
3. The amount of induced voltage is proportional to the rate of change of current.
4. An inductor opposes a change of current.

The inductors in *Figure 17–2* and *Figure 17–3* are connected to an alternating voltage. Therefore, the magnetic field continually increases, decreases, and reverses polarity. Because the magnetic field continually changes magnitude and direction, a voltage is continually being induced in the coil. This **induced voltage** is 180° out of phase with the applied voltage and is always in opposition to the applied voltage *(Figure 17–4)*. Because the induced voltage is always in opposition to the applied voltage, the effective applied voltage is reduced by the induced voltage. For example, assume an inductor is connected to a 120-volt AC line. Now assume that the inductor has an induced voltage of 116 volts. Because the induced voltage subtracts from the applied voltage, there are only 4 volts to push current through the wire resistance of the coil (120 V − 116 V = 4).

Calculating the Induced Voltage

The amount of induced voltage in an inductor can be calculated if the resistance of the wire in the coil and the amount of circuit current are known. For example, assume that an ohmmeter is used to measure the actual amount of

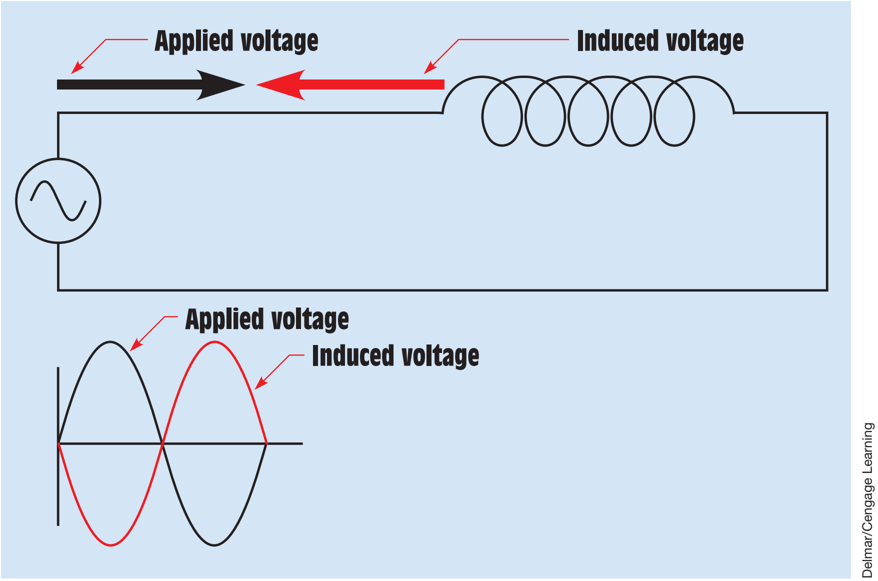


FIGURE 17–4 The applied voltage and induced voltage are 180 degrees out of phase with each other.

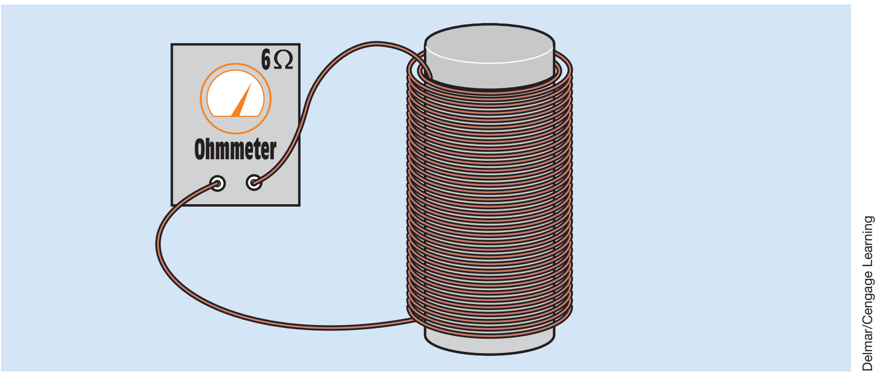


FIGURE 17–5 Measuring the resistance of a coil.

resistance in a coil, and the coil is found to contain 6 ohms of wire resistance *(Figure 17–5)*. Now assume that the coil is connected to a 120-volt AC circuit and an ammeter measures a current flow of 0.8 ampere *(Figure 17–6)*. Ohm's law can now be used to determine the amount of voltage necessary to push 0.8 ampere of current through 6 ohms of resistance:

$$E = I \times R$$
$$E = 0.8\text{ A} \times 6$$
$$E = 4.8\text{ V}$$

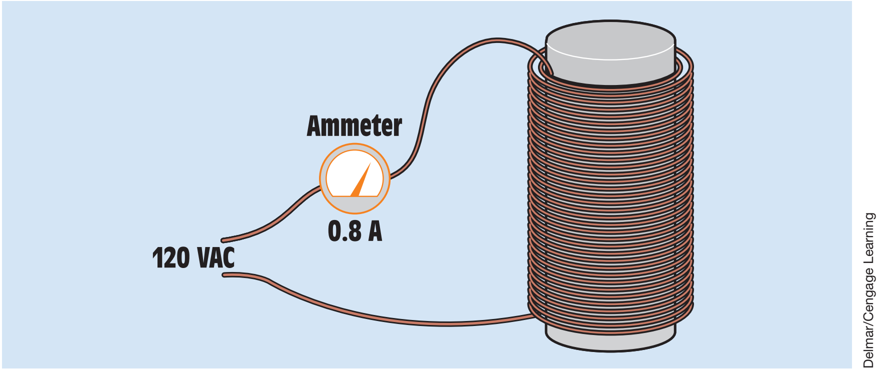


FIGURE 17–6 Measuring circuit current with an ammeter.

Because only 4.8 volts are needed to push the current through the wire resistance of the inductor, the remainder of the 120 volts is used to overcome the coil's induced voltage of 119.904 volts ($\sqrt{(120\text{ V})^2 - (4.8\text{V})^2} = 119.904$ volts).

17–2 Inductive Reactance

Notice that the induced voltage is able to limit the flow of current through the circuit in a manner similar to resistance. This induced voltage is *not* resistance, but it can limit the flow of current just as resistance does. This current-limiting property of the inductor is called **reactance** and is symbolized by the letter *X*. This reactance is caused by inductance, so it is called **inductive reactance** and is symbolized by $\mathbf{X_L}$**,** pronounced "X sub L." Inductive reactance is measured in ohms just as resistance is and can be calculated when the values of inductance and frequency are known. The following formula can be used to find inductive reactance:

$$X_L = 2\,\pi\,fL$$

where

X_L = inductive reactance
2 = a constant
π = 3.1416
f = frequency in hertz (Hz)
L = inductance in henrys (H)

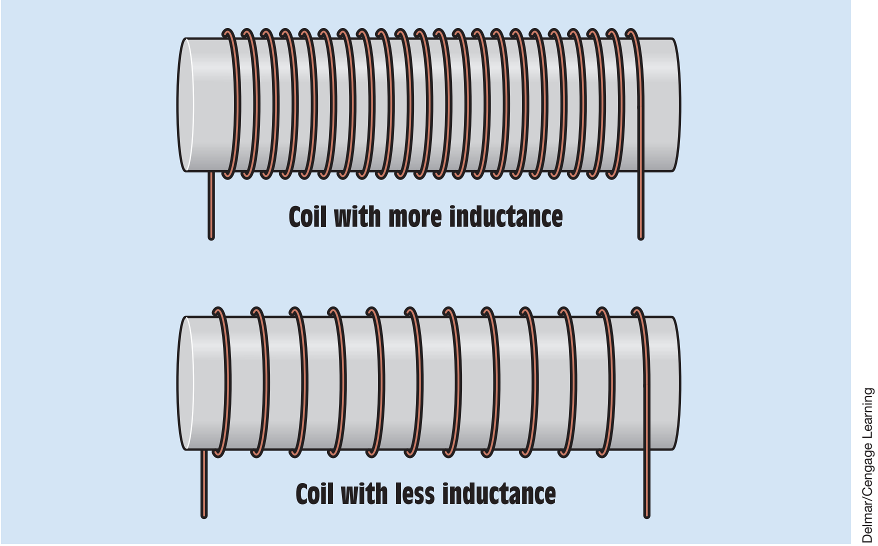


FIGURE 17–7 Coils with turns closer together produce more inductance than coils with turns farther apart.

The inductive reactance, in ohms, is caused by the induced voltage and is therefore proportional to the three factors that determine induced voltage:

1. the *number* of turns of wire;
2. the *strength* of the magnetic field;
3. the *speed* of the cutting action (relative motion between the inductor and the magnetic lines of flux).

The number of turns of wire and the strength of the magnetic field are determined by the physical construction of the inductor. Factors such as the size of wire used, the number of turns, how close the turns are to each other, and the type of core material determine the amount of inductance (in henrys, H) of the coil *(Figure 17–7)*. The speed of the cutting action is proportional to the frequency (hertz). An increase of frequency causes the magnetic lines of flux to cut the conductors at a faster rate and thus produces a higher induced voltage or more inductive reactance.

EXAMPLE 17-1

The inductor shown in *Figure 17–8* has an inductance of 0.8 H and is connected to a 120-V, 60-Hz line. How much current will flow in this circuit if the wire resistance of the inductor is negligible?

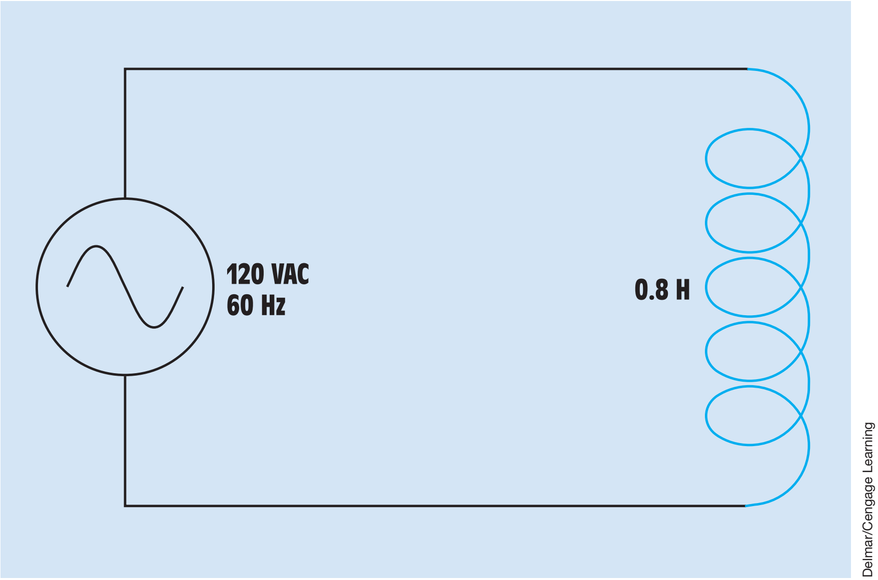


FIGURE 17–8 Circuit current is limited by inductive reactance.

Solution

The first step is to determine the amount of inductive reactance of the inductor:

$$X_L = 2\pi fL$$
$$X_L = 2 \times 3.1416 \times 60 \text{ Hz} \times 0.8$$
$$X_L = 301.594\ \Omega$$

Because inductive reactance is the current-limiting property of this circuit, it can be substituted for the value of R in an Ohm's law formula:

$$I = \frac{E}{X_L}$$
$$I = \frac{120 \text{ V}}{301.594\ \Omega}$$
$$I = 0.398 \text{ A}$$

If the amount of inductive reactance is known, the inductance of the coil can be determined using the formula

$$L = \frac{X_L}{2\pi f}$$

EXAMPLE 17-2

Assume an inductor with a negligible resistance is connected to a 36-V, 400-Hz line. If the circuit has a current flow of 0.2 A, what is the inductance of the inductor?

Solution

The first step is to determine the inductive reactance of the circuit:

$$X_L = \frac{E}{I}$$

$$X_L = \frac{36 \text{ V}}{0.2 \text{ A}}$$

$$X_L = 180 \ \Omega$$

Now that the inductive reactance of the inductor is known, the inductance can be determined:

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{180 \ \Omega}{2 \times 3.1416 \times 400 \text{ Hz}}$$

$$L = 0.0716 \text{ H}$$

EXAMPLE 17-3

An inductor with negligible resistance is connected to a 480-V, 60-Hz line. An ammeter indicates a current flow of 24 A. How much current will flow in this circuit if the frequency is increased to 400 Hz?

Solution

The first step in solving this problem is to determine the amount of inductance of the coil. Because the resistance of the wire used to make the inductor is negligible, the current is limited by inductive reactance. The inductive reactance can be found by substituting X_L for R in an Ohm's law formula:

$$X_L = \frac{E}{I}$$
$$X_L = \frac{480\ V}{24\ A}$$
$$X_L = 20\ \Omega$$

Now that the inductive reactance is known, the inductance of the coil can be found using the formula

$$L = \frac{X_L}{2\pi f}$$

Note: When using a frequency of 60 hertz, $2 \times \pi \times 60 = 376.992$. To simplify calculations, this value is generally rounded to 377. Because 60 hertz is the major frequency used throughout the United States, 377 should be memorized because it is used in many calculations:

$$L = \frac{20\ \Omega}{377\ Hz}$$
$$L = 0.053\ H$$

Because the inductance of the coil is determined by its physical construction, it does not change when connected to a different frequency. Now that the inductance of the coil is known, the inductive reactance at 400 hertz can be calculated:

$$X_L = 2\pi fL$$
$$X_L = 2 \times 3.1416 \times 400\ Hz \times 0.053$$
$$X_L = 133.204\ \Omega$$

The amount of current flow can now be found by substituting the value of inductive reactance for resistance in an Ohm's law formula:

$$I = \frac{E}{X_L}$$
$$I = \frac{480\ V}{133.204\ \Omega}$$
$$I = 3.603\ A$$

17–3 Schematic Symbols

The schematic symbol used to represent an inductor depicts a coil of wire. Several symbols for inductors are shown in *Figure 17–9*. The symbols shown with the two parallel lines represent iron-core inductors, and the symbols without the parallel lines represent air-core inductors.

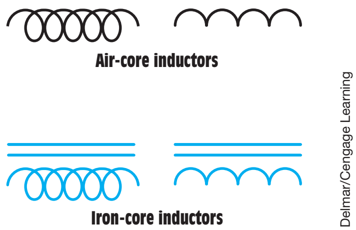


FIGURE 17–9 Schematic symbols for inductors.

17–4 Inductors Connected in Series

When inductors are connected in series *(Figure 17–10),* the total inductance of the circuit (L_T) equals the sum of the inductances of all the inductors:

$$L_T = L_1 + L_2 + L_3$$

The total inductive reactance (X_{LT}) of inductors connected in series equals the sum of the inductive reactances for all the inductors:

$$X_{LT} = X_{L1} + X_{L2} + X_{L3}$$

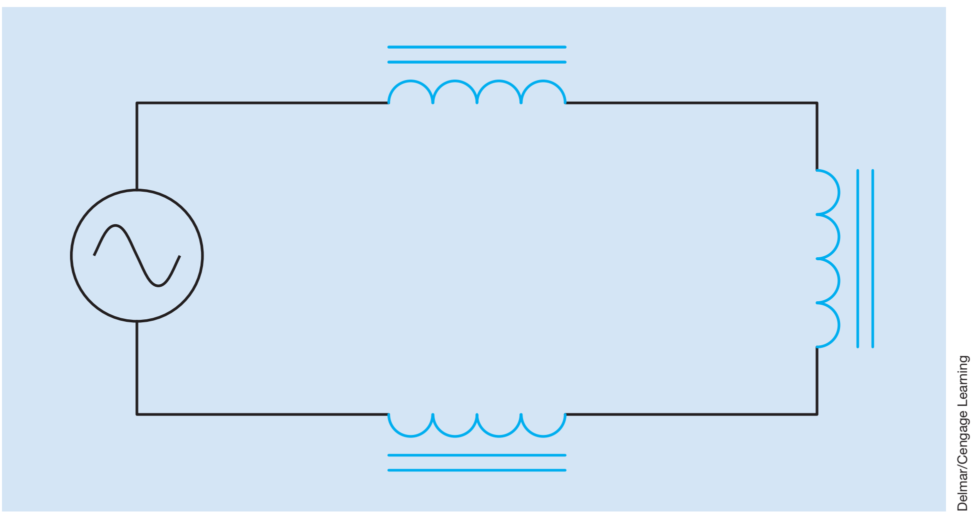


FIGURE 17–10 Inductors connected in series.

■ EXAMPLE 17-4

Three inductors are connected in series. Inductor 1 has an inductance of 0.6 H, Inductor 2 has an inductance of 0.4 H, and Inductor 3 has an inductance of 0.5 H. What is the total inductance of the circuit?

Solution

$$L_T = 0.6\text{ H} + 0.4\text{ H} + 0.5\text{ H}$$
$$L_T = 1.5\text{ H}$$

■ EXAMPLE 17-5

Three inductors are connected in series. Inductor 1 has an inductive reactance of 180 Ω, Inductor 2 has an inductive reactance of 240 Ω, and Inductor 3 has an inductive reactance of 320 Ω. What is the total inductive reactance of the circuit?

Solution

$$X_{LT} = 180\ \Omega + 240\ \Omega + 320\ \Omega$$
$$X_{LT} = 740\ \Omega$$

17–5 Inductors Connected in Parallel

When inductors are connected in parallel *(Figure 17–11),* the total inductance can be found in a manner similar to finding the total resistance of a parallel circuit. The reciprocal of the total inductance is equal to the sum of the reciprocals of all the inductors:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

or

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

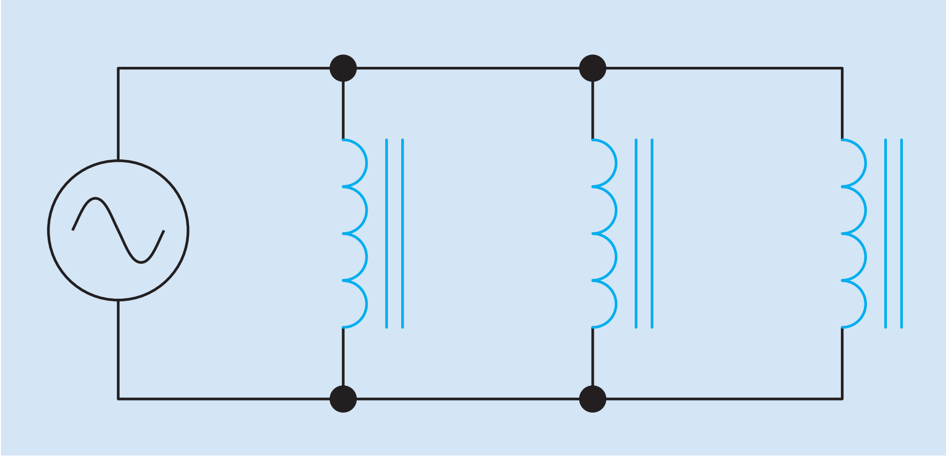


FIGURE 17–11 Inductors connected in parallel.

Another formula that can be used to find the total inductance of parallel inductors is the product-over-sum formula:

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

If the values of all the inductors are the same, total inductance can be found by dividing the inductance of one inductor by the total number of inductors:

$$L_T = \frac{L}{N}$$

Similar formulas can be used to find the total inductive reactance of inductors connected in parallel:

$$\frac{1}{X_{LT}} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}$$

or

$$X_{LT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}}$$

or

$$X_{LT} = \frac{X_{L1} \times X_{L2}}{X_{L1} + X_{L2}}$$

or

$$X_{LT} = \frac{X_L}{N}$$

■ EXAMPLE 17-6

Three inductors are connected in parallel. Inductor 1 has an inductance of 2.5 H, Inductor 2 has an inductance of 1.8 H, and Inductor 3 has an inductance of 1.2 H. What is the total inductance of this circuit?

Solution

$$L_T = \frac{1}{\frac{1}{2.5\text{ H}} + \frac{1}{1.8\text{ H}} + \frac{1}{1.2\text{ H}}}$$

$$L_T = \frac{1}{(1.788)}$$

$$L_T = 0.559\text{ H}$$

17–6 Voltage and Current Relationships in an Inductive Circuit

In Unit 16, it was discussed that when current flows through a pure resistive circuit, the current and voltage are in phase with each other. ***In a pure inductive circuit, the current lags the voltage by 90°.*** At first this may seem to be an impossible condition until the relationship of applied voltage and induced voltage is considered. How the current and applied voltage can become 90° out of phase with each other can best be explained by comparing the relationship of the current and induced voltage *(Figure 17–12)*. Recall that the induced voltage is proportional to the rate of change of the current (speed of cutting action). At the beginning of the waveform, the current is shown at its maximum value in the negative direction. At this time, the current is not changing, so induced voltage is zero. As the current begins to decrease in value, the magnetic field produced by the flow of current decreases or collapses and begins to induce a voltage into the coil as it cuts through the conductors *(Figure 17–3)*.

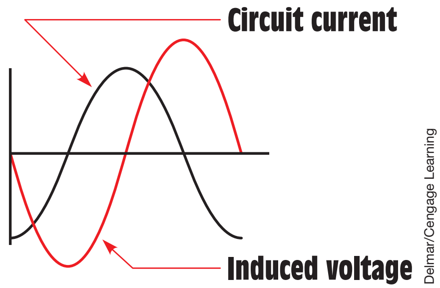


FIGURE 17–12 Induced voltage is proportional to the rate of change of current.

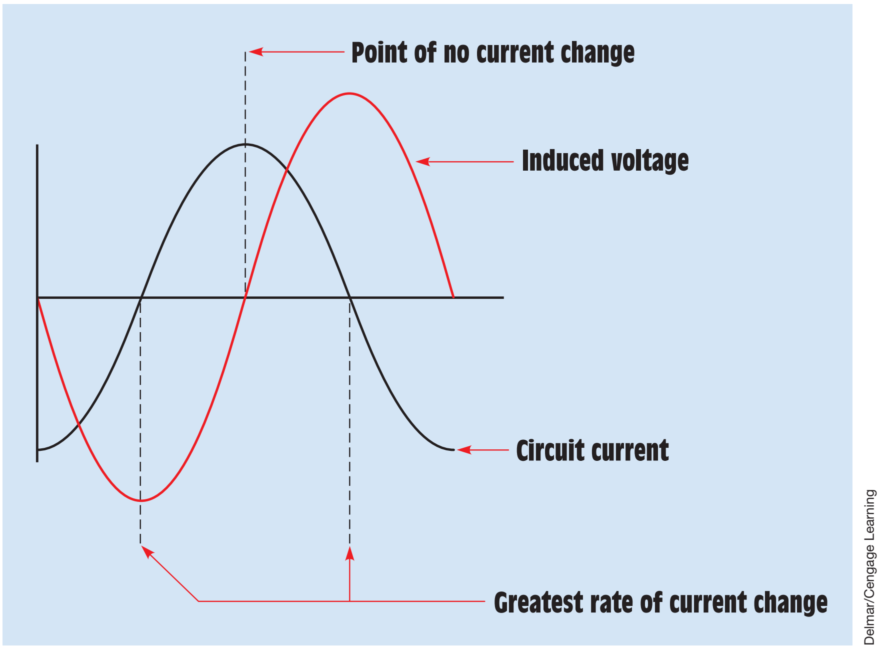


FIGURE 17–13 No voltage is induced when the current does not change.

The greatest rate of current change occurs when the current passes from negative, through zero and begins to increase in the positive direction *(Figure 17–13)*. Because the current is changing at the greatest rate, the induced voltage is maximum. As current approaches its peak value in the positive direction, the rate of change decreases, causing a decrease in the induced voltage. The induced voltage will again be zero when the current reaches its peak value and the magnetic field stops expanding.

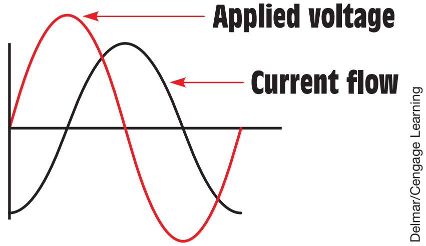


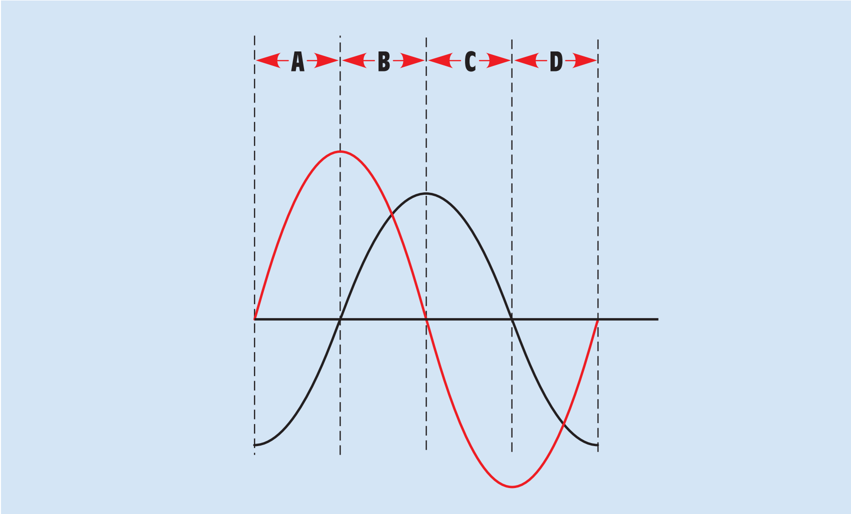
FIGURE 17–14 The current lags the applied voltage by 90°.

It can be seen that the current flowing through the inductor is leading the induced voltage by 90°. Because the induced voltage is 180° out of phase with the applied voltage, the current lags the applied voltage by 90° *(Figure 17–14)*.

17–7 Power in an Inductive Circuit

In a pure resistive circuit, the true power, or watts, is equal to the product of the voltage and current. In a pure inductive circuit, however, no true power, or watts, is produced. Recall that voltage and current must both be either positive or negative before true power can be produced. Because the voltage and current are 90° out of phase with each other in a pure inductive circuit, the current and voltage will be at different polarities 50% of the time and at the same polarity 50% of the time. During the period of time that the current and voltage have the same polarity, power is being given to the circuit in the form of creating a magnetic field. When the current and voltage are opposite in polarity, power is being given back to the circuit as the magnetic field collapses and induces a voltage back into the circuit. Because power is stored in the form of a magnetic field and then given back, no power is used by the inductor. Any power used in an inductor is caused by losses such as the resistance of the wire used to construct the inductor, generally referred to as I^2R losses, eddy current losses, and hysteresis losses.

The current and voltage waveform in *Figure 17–15* has been divided into four sections: A, B, C, and D. During the first time period, indicated by A, the current is negative and the voltage is positive. During this period, energy is being given to the circuit as the magnetic field collapses. During the second time period, B, both the voltage and current are positive. Power is being used to produce the magnetic field. In the third time period, C, the current is positive and the voltage is negative. Power is again being given back to the circuit as the field collapses. During the fourth time period, D, both the voltage and current are negative. Power is again being used to produce the magnetic field. If the amount of power used to produce the magnetic field is subtracted from the power given back, the result will be zero.



Delmar/Cengage Learning

FIGURE 17–15 Voltage and current relationships during different parts of a cycle.

17–8 Reactive Power

Although essentially no true power is being used, except by previously mentioned losses, an electrical measurement called volt-amperes-reactive **(VARs)** is used to measure the **reactive power** in a pure inductive circuit. VARs can be calculated in the same way as watts except that inductive values are substituted for resistive values in the formulas. VARs is equal to the amount of current flowing through an inductive circuit times the voltage applied to the inductive part of the circuit. Several formulas for calculating VARs are

$$\text{VARs} = E_L \times I_L$$

$$\text{VARs} = \frac{E_L^2}{X_L}$$

$$\text{VARs} = I_L^2 \times X_L$$

where

E_L = voltage applied to an inductor
I_L = current flow through an inductor
X_L = inductive reactance

17–9 Q of an Inductor

So far in this unit, it has been generally assumed that an inductor has no resistance and that inductive reactance is the only current-limiting factor. In reality, that is not true. Because inductors are actually coils of wire, they all contain some amount of internal resistance. Inductors actually appear to be a coil connected in series with some amount of resistance *(Figure 17–16)*. The amount of resistance compared with the inductive reactance determines the **quality (Q)** of the coil. Inductors that have a higher ratio of inductive reactance to resistance are considered to be inductors of higher quality. An inductor constructed with a large wire will have a low wire resistance and therefore a higher Q *(Figure 17–17)*. Inductors constructed with many turns of small wire have a much higher resistance and therefore a lower Q. To determine the Q of an inductor, divide the inductive reactance by the resistance:

$$Q = \frac{X_L}{R}$$

Although inductors have some amount of resistance, inductors that have a Q of 10 or greater are generally considered to be pure inductors. Once the ratio of inductive reactance becomes 10 times as great as resistance, the amount of resistance is considered negligible. For example, assume an inductor has an inductive reactance of 100 ohms and a wire resistance of 10 ohms. The

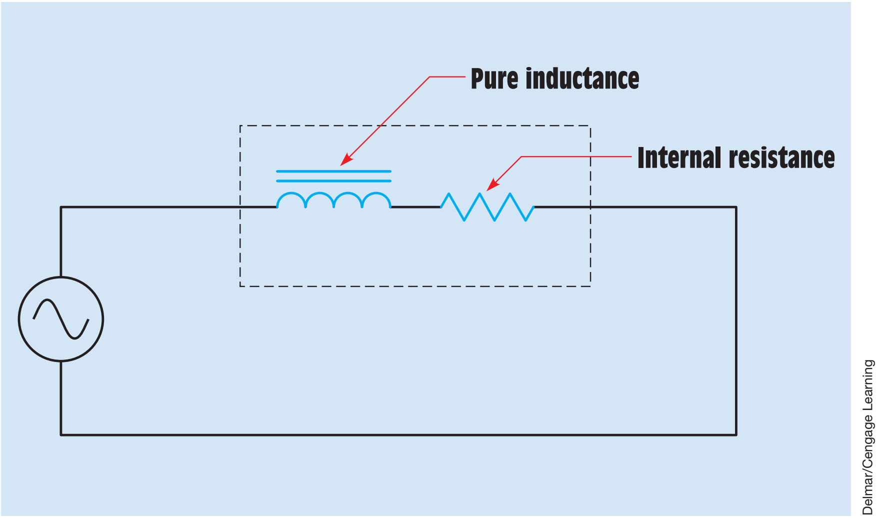


FIGURE 17–16 Inductors contain internal resistance.

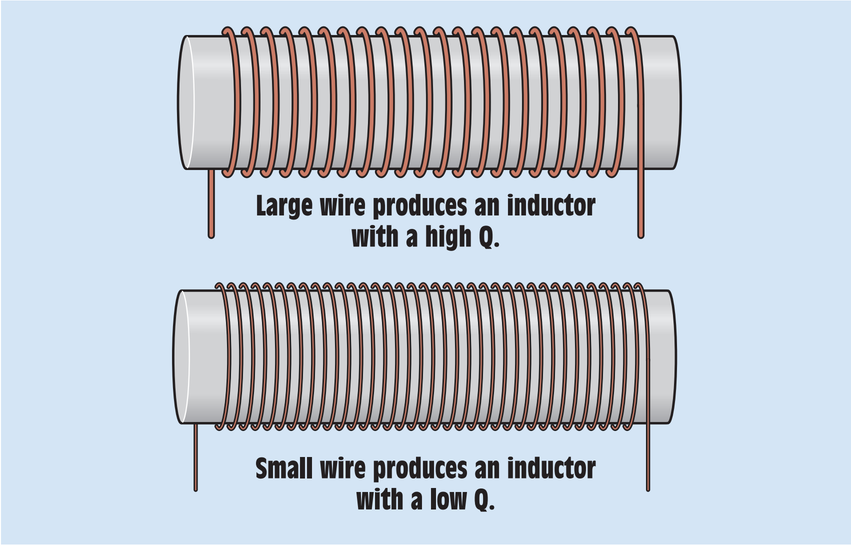


FIGURE 17–17 The Q of an inductor is a ratio of inductive reactance as compared to resistance. The letter Q stands for quality.

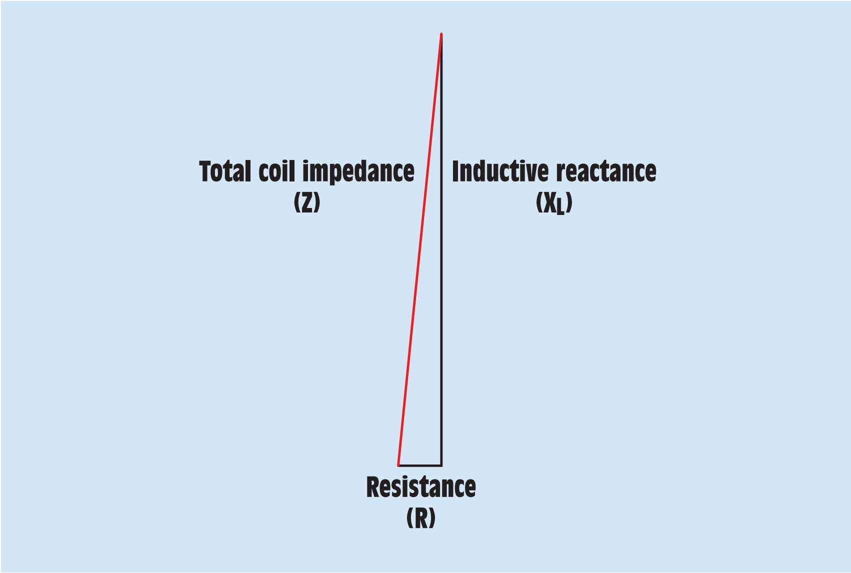


FIGURE 17–18 Coil impedance is a combination of wire resistance and inductive reactance.

inductive reactive component in the circuit is 90° out of phase with the resistive component. This relationship produces a right triangle *(Figure 17–18)*. The total current-limiting effect of the inductor is a combination of the inductive reactance and resistance. This total current-limiting effect is called impedance and is symbolized by the letter *Z*. The impedance of the circuit is represented by the hypotenuse of the right triangle formed by the inductive reactance and the resistance. To calculate the value of impedance for the coil, the inductive reactance and the resistance must be added. Because these two components form the legs of a right triangle and the impedance forms the hypotenuse, the Pythagorean theorem discussed in Unit 15 can be used to calculate the value of impedance:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{10^2 + 100^2}$$

$$Z = \sqrt{10{,}100}$$

$$Z = 100.499\ \Omega$$

Notice that the value of total impedance for the inductor is only 0.5 ohm greater than the value of inductive reactance.

If it should become necessary to determine the true inductance of an inductor, the resistance of the wire must be taken into consideration. Assume that an inductor is connected to a 480-volt, 60-Hz power source and that an ammeter indicates a current flow of 0.6 ampere. Now assume that an ohmmeter measures 150 Ω of wire resistance in the inductor. What is the inductance of the inductor?

To determine the inductance, it will be necessary to first determine the amount of inductive reactance as compared to the wire resistance. The total current-limiting value (impedance) can be found with Ohm's law:

$$Z = \frac{E}{I}$$

$$Z = \frac{480}{0.6}$$

$$Z = 800\ \Omega$$

The total current-limiting effect of the inductor is 800 Ω. This value is a combination of both the inductive reactance of the inductor and the wire resistance. Because the resistive part and the inductive reactance part of the inductor are 90° out of phase with each other, they form the legs of a right triangle with the impedance forming the hypotenuse of the triangle *(Figure 17-19)*. To determine the amount of inductive reactance, use the following formula:

$$X_L = \sqrt{Z^2 - R^2}$$

$$X_L = \sqrt{800^2 - 150^2}$$

$$X_L = 785.812\ \Omega$$

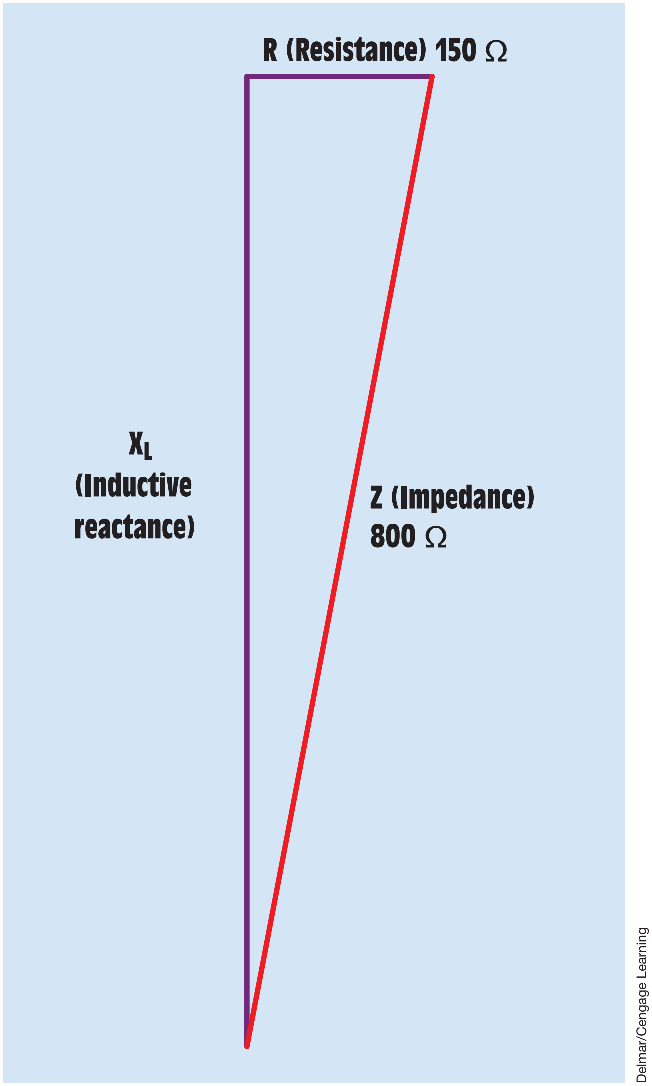


FIGURE 17–19 The inductive reactance forms one leg of a right triangle.

Now that the amount of inductive reactance has been determined, the inductance can be calculated using the formula

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{785.812}{2 \times 3.1416 \times 60}$$

$$L = 2.084 \text{ henrys}$$

Summary

- Induced voltage is proportional to the rate of change of current.
- Induced voltage is always opposite in polarity to the applied voltage.
- Inductive reactance is a countervoltage that limits the flow of current, as does resistance.
- Inductive reactance is measured in ohms.
- Inductive reactance is proportional to the inductance of the coil and the frequency of the line.
- Inductive reactance is symbolized by X_L.
- Inductance is measured in henrys (H) and is symbolized by the letter *L*.
- When inductors are connected in series, the total inductance is equal to the sum of all the inductors.
- When inductors are connected in parallel, the reciprocal of the total inductance is equal to the sum of the reciprocals of all the inductors.
- The current lags the applied voltage by 90° in a pure inductive circuit.
- All inductors contain some amount of resistance.
- The Q of an inductor is the ratio of the inductive reactance to the resistance.
- Inductors with a Q of 10 are generally considered to be "pure" inductors.
- Pure inductive circuits contain no true power or watts.
- Reactive power is measured in VARs.
- VARs is an abbreviation for volt-amperes-reactive.

Review Questions

1. How many degrees are the current and voltage out of phase with each other in a pure resistive circuit?
2. How many degrees are the current and voltage out of phase with each other in a pure inductive circuit?
3. To what is inductive reactance proportional?
4. Four inductors, each having an inductance of 0.6 H, are connected in series. What is the total inductance of the circuit?
5. Three inductors are connected in parallel. Inductor 1 has an inductance of 0.06 H; Inductor 2 has an inductance of 0.05 H; and Inductor 3 has an inductance of 0.1 H. What is the total inductance of this circuit?

6. If the three inductors in Question 5 were connected in series, what would be the inductive reactance of the circuit? Assume the inductors are connected to a 60-Hz line.
7. An inductor is connected to a 240-V, 1000-Hz line. The circuit current is 0.6 A. What is the inductance of the inductor?
8. An inductor with an inductance of 3.6 H is connected to a 480-V, 60-Hz line. How much current will flow in this circuit?
9. If the frequency in Question 8 is reduced to 50 Hz, how much current will flow in the circuit?
10. An inductor has an inductive reactance of 250 Ω when connected to a 60-Hz line. What will be the inductive reactance if the inductor is connected to a 400-Hz line?

Practical Applications

You are working as an electrician installing fluorescent lights. You notice that the lights were made in Europe and that the ballasts are rated for operation on a 50-Hz system. Will these ballasts be harmed by overcurrent if they are connected to 60 Hz? If there is a problem with these lights, what will be the most likely cause of the trouble? ■

Practical Applications

You have the task of ordering a replacement inductor for one that has become defective. The information on the nameplate has been painted over and cannot be read. The machine that contains the inductor operates on 480 V at a frequency of 60 Hz. Another machine has an identical inductor in it, but its nameplate has been painted over also. A clamp-on ammeter indicates a current of 18 A, and a voltmeter indicates a voltage drop across the inductor of 324 V in the machine that is still in operation. After turning off the power and locking out the panel, you disconnect the inductor in the operating machine and measure a wire resistance of 1.2 Ω with an ohmmeter. Using the identical inductor in the operating machine as an example, what inductance value should you order and what would be the minimum VAR rating of the inductor? Should you be concerned with the amount of wire resistance in the inductor when ordering? Explain your answers. ■

Practice Problems

Inductive Circuits

1. Fill in all the missing values. Refer to the following formulas:

$$X_L = 2\pi fL$$

$$L = \frac{X_L}{2\pi f}$$

$$f = \frac{X_L}{2\pi L}$$

Inductance (H)	Frequency (Hz)	Inductive Reactance (Ω)
1.2	60	
0.085		213.628
	1000	4712.389
0.65	600	
3.6		678.584
	25	411.459
0.5	60	
0.85		6408.849
	20	201.062
0.45	400	
4.8		2412.743
	1000	40.841

2. What frequency must be applied to a 33-mH inductor to produce an inductive reactance of 99.526 Ω?
3. An inductor is connected to a 120-volt, 60-Hz line and has a current flow of 4 amperes. An ohmmeter indicates that the inductor has a wire resistance of 12 Ω. What is the inductance of the inductor?
4. A 0.75-henry inductor has a wire resistance of 90 Ω. When connected to a 60-Hz power line, what is the total current-limiting effect of the inductor?
5. An inductor has a current flow of 3 amperes when connected to a 240-volt, 60-Hz power line. The inductor has a wire resistance of 15 Ω. What is the Q of the inductor?

Unit 18

Resistive-Inductive Series Circuits

OUTLINE

KEY TERMS

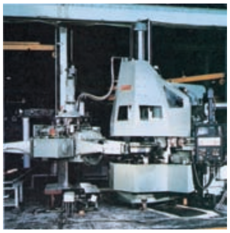
Angle theta (∠θ)
Apparent power (VA)
Power factor (PF)
Quadrature power
Total current (I_T)
Wattless power

Why You Need to Know

In previous units, you learned that current and voltage are in phase with each other in a pure resistive circuit and that current and voltage are 90° out of phase with each other in a pure inductive circuit. This unit

- describes what happens when resistive and inductive elements are combined in the same circuit. Although there are some applications for connecting resistors and inductors in series with each other, more often you will encounter devices that appear to have both elements connected in series with each other. A very good example of this is AC motors and transformers. Motors and transformers are inductive because they contain wound coils. At no load, these devices appear to be very inductive and current is limited by inductive reactance. As load is added, electrical energy is converted to some other form and they appear to become more resistive.
- explains what power factor is and how to correct for its impact. Without a knowledge of what happens when inductance and resistance are connected in the same circuit, you will never be able to understand such concepts as power factor and power factor correction.

Objectives


Courtesy of Simmons Machine Tool Co.

After studying this unit, you should be able to

- discuss the relationship of resistance and inductance in an AC series circuit.
- define power factor.
- calculate values of voltage, current, apparent power, true power, reactive power, impedance, resistance, inductive reactance, and power factor in an RL series circuit.
- calculate the phase angle for current and voltage in an RL series circuit.
- connect an RL series circuit and make measurements using test instruments.
- discuss vectors and be able to plot electrical quantities using vectors.

Preview

This unit covers the relationship of resistance and inductance used in the same circuit. The resistors and inductors are connected in series. Concepts such as circuit impedance, power factor, and vector addition are introduced. Although it is true that some circuits are basically purely resistive or purely inductive, many circuits contain a combination of both resistive and inductive elements. ■

18–1 R-L Series Circuits

When a pure resistive load is connected to an AC circuit, the voltage and current are in phase with each other. When a pure inductive load is connected to an AC circuit, the voltage and current are 90° out of phase with each other *(Figure 18–1)*. When a circuit containing both resistance, R, and inductance, L, is connected to an AC circuit, the voltage and current will be out of phase with each other by some amount between 0° and 90°. ***The exact amount of phase angle difference is determined by the ratio of resistance as compared to inductance.*** In the following example, a series circuit containing 30 ohms of resistance (R) and 40 ohms of inductive reactance (X_L) is connected to a 240-volt, 60-hertz line *(Figure 18–2)*. It is assumed that the inductor has negligible resistance. The following unknown values will be calculated:

Z—total circuit impedance

I—current flow

E_R—voltage drop across the resistor

P—watts (true power)

L—inductance of the inductor

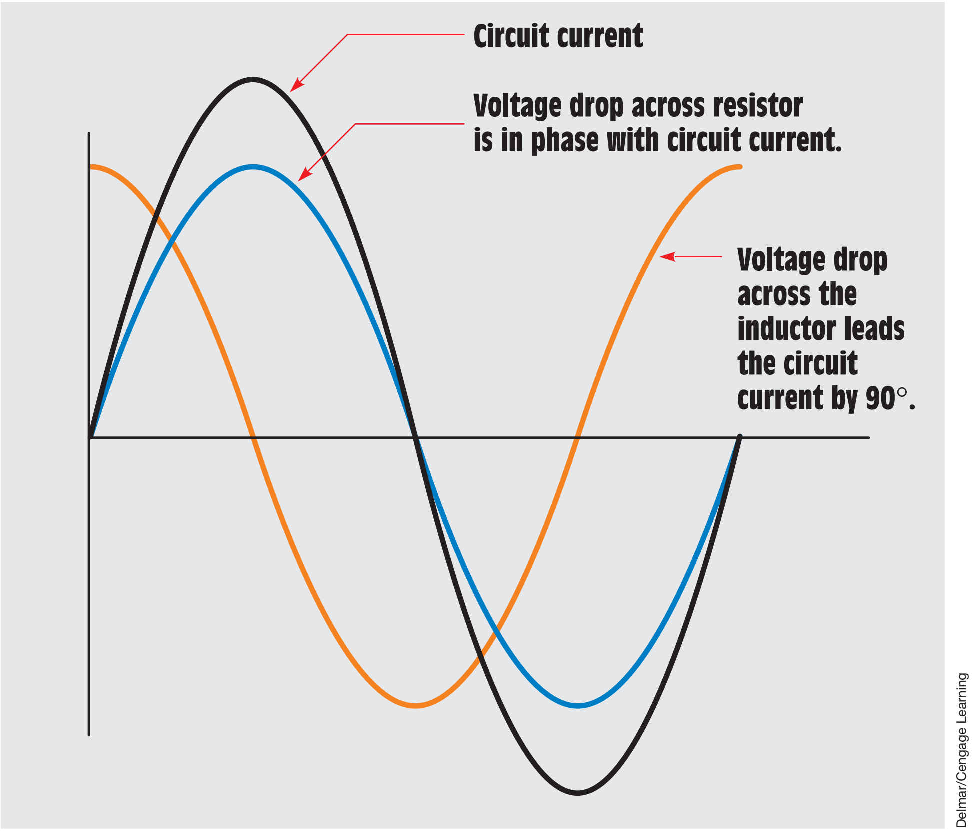


FIGURE 18–1 Relationship of resistive and inductive current with voltage.

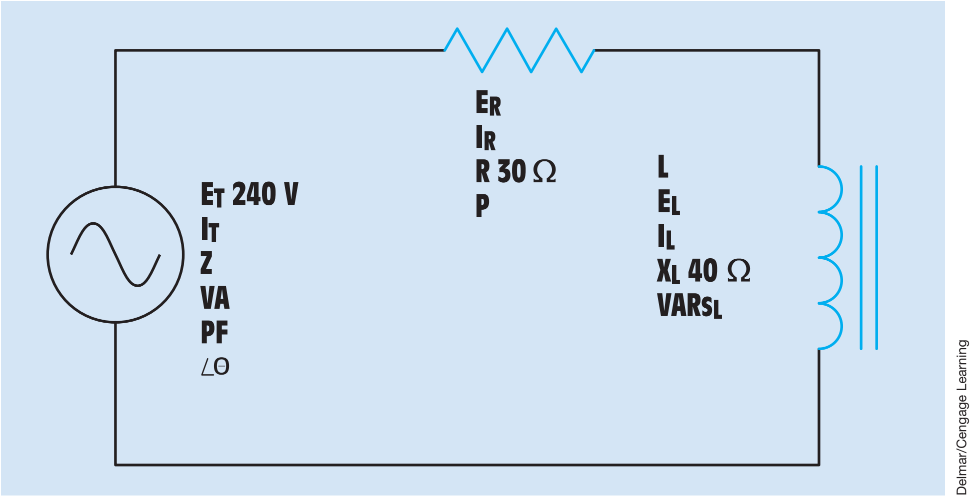


FIGURE 18–2 R-L series circuit.

E_L—voltage drop across the inductor

VARs—reactive power

VA—apparent power

PF—power factor

$\angle\theta$—the angle the voltage and current are out of phase with each other

18–2 Impedance

In Unit 17, impedance was defined as a measure of the part of the circuit that impedes, or hinders, the flow of current. It is measured in ohms and symbolized by the letter *Z*. In this circuit, impedance is a combination of resistance and inductive reactance.

In a series circuit, the total resistance is equal to the sum of the individual resistors. In this instance, however, the total impedance (Z) is the sum of the resistance and the inductive reactance. It would first appear that the sum of these two quantities should be 70 ohms ($30\ \Omega + 40\ \Omega = 70\ \Omega$). In practice, however, the resistive part of the circuit and the reactive part of the circuit are out of phase with each other by 90°. To find the sum of these two quantities, vector addition must be used. Because these two quantities are 90° out of phase with each other, the resistive and inductive reactance form the two legs of a right triangle, and the impedance is the hypotenuse *(Figure 18–3)*.

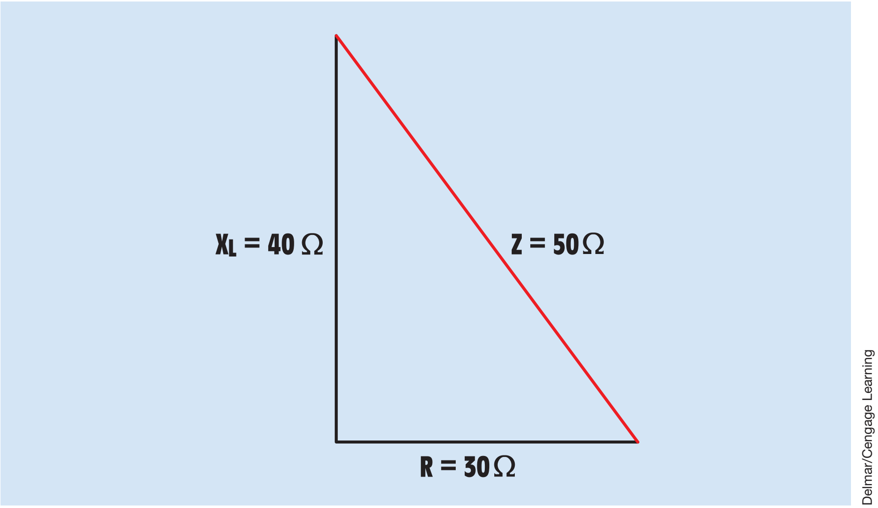


FIGURE 18–3 Impedance is the combination of resistance and inductive reactance.

The total impedance (Z) can be calculated using the formula

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{(30\ \Omega)^2 + (40\ \Omega)^2}$$

$$Z = \sqrt{900\ \Omega^2 + 1600\ \Omega^2}$$

$$Z = \sqrt{2500\ \Omega^2}$$

$$Z = 50\ \Omega$$

To find the impedance of the circuit in *Figure 18–3* using vector addition, connect the starting point of one vector to the ending point of the other. Because resistance and inductive reactance are 90° out of phase with each other, the two vectors must be placed at a 90° angle. If the resistive vector has a magnitude of 30 ohms and the inductive vector has a magnitude of 40 ohms, the resultant (impedance) will have a magnitude of 50 ohms *(Figure 18–4)*. Notice that the result is the same as that found using the right triangle.

The parallelogram method of vector addition can also be used to find the total impedance of the circuit shown in *Figure 18–2*. The resistance forms a vector with a magnitude of 30 ohms and a direction of 0°. The inductive reactance forms a vector with a magnitude of 40 ohms and a direction of 90°. When lines are extended to form a parallelogram and a resultant is drawn, the resultant will have a magnitude of 50 ohms, which is the impedance of the

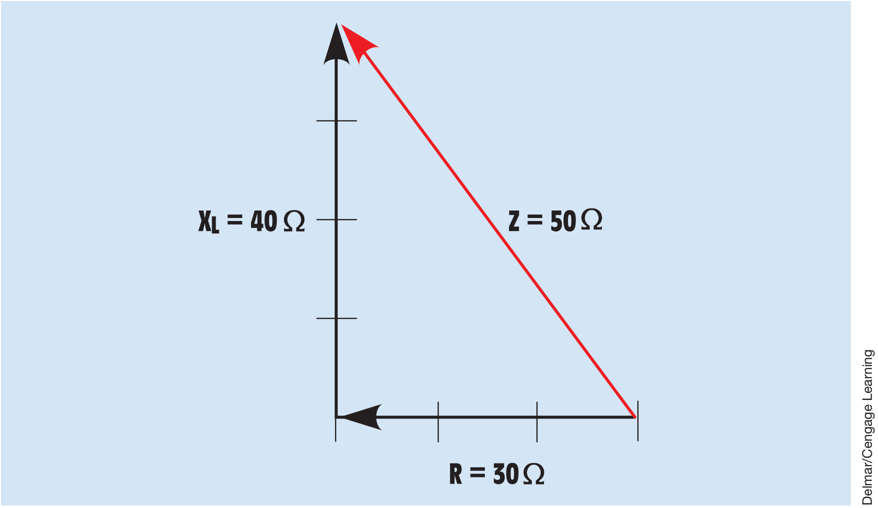


FIGURE 18–4 Determining impedance using vector addition.

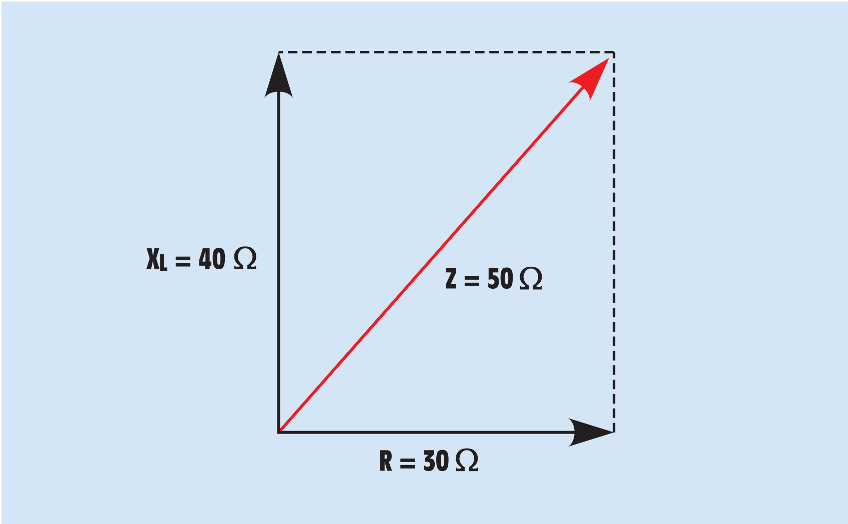


FIGURE 18–5 Finding the impedance of the circuit using the parallelogram method of vector addition.

circuit *(Figure 18–5)*. Some students of electricity find the right triangle concept easier to understand, and others find vectors more helpful. For this reason, this text uses both methods to help explain the relationship of voltage, current, and power in AC circuits.

18–3 Total Current

One of the primary laws for series circuits is that the current must be the same in any part of the circuit. This law holds true of R-L series circuits also. Because the impedance is the total current-limiting component of the circuit, it can be used to replace R in an Ohm's law formula. The **total current (I_T)** flow through the circuit can be calculated by dividing the total applied voltage by the total current-limiting factor. Total current can be found by using the formula

$$I_T = \frac{E_T}{Z}$$

The total current for the circuit in *Figure 18–2,* then, is

$$I_T = \frac{240\ \text{V}}{50\ \Omega}$$

$$I_T = 4.8\ \text{A}$$

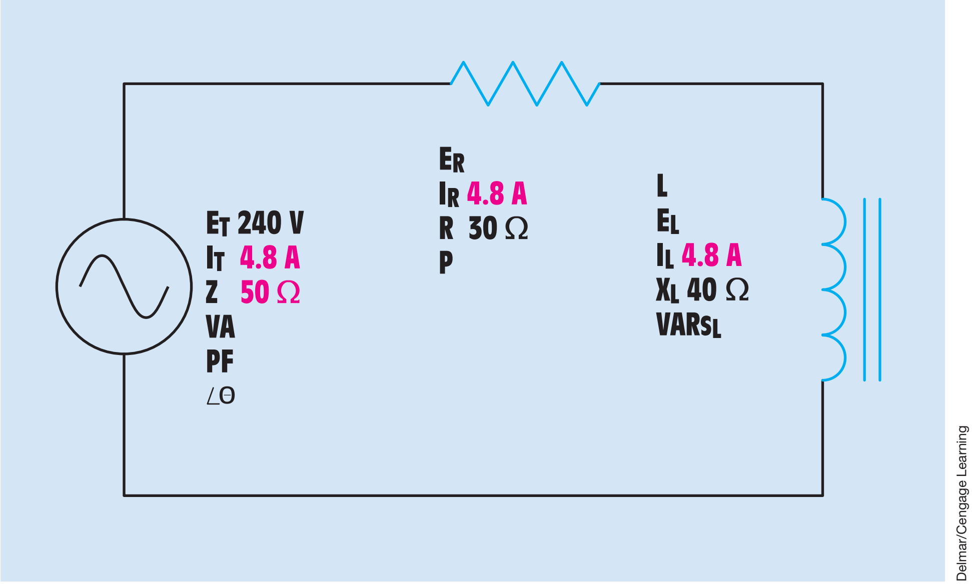


FIGURE 18–6 Total voltage divided by impedance equals total current.

In a series circuit, the current is the same at any point in the circuit. Therefore, 4.8 amperes of current flow through both the resistor and the inductor. These values can be added to the circuit, as shown in *Figure 18–6*.

18–4 Voltage Drop across the Resistor

Now that the amount of current flow through the resistor is known, the voltage drop across the resistor (E_R) can be calculated using the formula:

$$E_R = I_R \times R$$

The voltage drop across the resistor in our circuit is

$$E_R = 4.8\ A \times 30\ \Omega$$
$$E_R = 144\ V$$

Notice that the amount of voltage dropped across the resistor was found using quantities that pertained only to the resistive part of the circuit. The amount of voltage dropped across the resistor could not be found using a formula such as

$$E_R = I_R \times X_L$$

or

$$E_R = I_R \times Z$$

Inductive reactance (X_L) is an inductive quantity, and impedance (Z) is a circuit total quantity. These quantities cannot be used with Ohm's law to find resistive quantities. They can, however, be used with vector addition to find like resistive quantities. For example, both inductive reactance and impedance are measured in ohms. The resistive quantity that is measured in ohms is resistance (R). If the impedance and inductive reactance of a circuit were known, they could be used with the following formula to find the circuit resistance:

$$R = \sqrt{Z^2 - X_L^2}$$

Note: Refer to the Resistive-Inductive Series Circuits section of the AC formulas listed in Appendix B.

18–5 Watts

True power (P) for the circuit can be calculated by using any of the watts formulas with pure resistive parts of the circuit. Watts (W) can be calculated, for example, by multiplying the voltage dropped across the resistor (E_R) by the current flow through the resistor (I_R), or by squaring the voltage dropped across the resistor and dividing by the resistance of the resistor, or by squaring the current flow through the resistor and multiplying by the resistance of the resistor. Watts cannot be calculated by multiplying the total voltage (E_T) by the current flow through the resistor or by multiplying the square of the current by the inductive reactance. Recall that true power, or watts, can be produced only during periods of time when the voltage and current are both positive or both negative.

In an R-L series circuit, the current is the same through both the resistor and the inductor. The voltage dropped across the resistor, however, is in phase with the current, and the voltage dropped across the inductor is 90° out of phase with the current *(Figure 18–7)*. Because true power, or watts, can be produced only when the current and voltage are both positive or both negative, only resistive parts of the circuit can produce watts.

The formula used in this example is

$$P = E_R \times I_R$$

$$P = 144\ \text{V} \times 4.8\ \text{A}$$

$$P = 691.2\ \text{W}$$

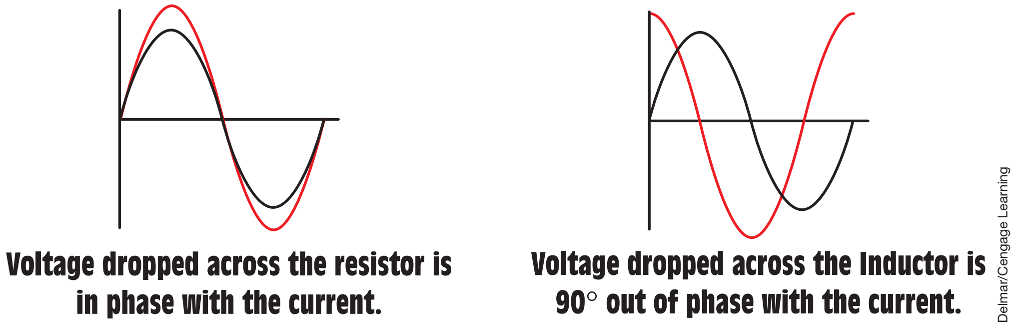


FIGURE 18–7 Relationship of current and voltage in an R-L series circuit.

18–6 Calculating the Inductance

The amount of inductance can be calculated using the formula

$$L = \frac{X_L}{2\pi f}$$
$$L = \frac{40\ \Omega}{377}$$
$$L = 0.106\ H$$

18–7 Voltage Drop across the Inductor

The voltage drop across the inductor (E_L) can be calculated using the formula

$$E_L = I_L \times X_L$$
$$E_L = 4.8\ A \times 40\ \Omega$$
$$E_L = 192\ V$$

Notice that only inductive quantities were used to find the voltage drop across the inductor.

18–8 Total Voltage

Although the total applied voltage in this circuit is known (240 volts), the total voltage is also equal to the sum of the voltage drops, just as it is in any other series circuit. Because the voltage dropped across the resistor is in phase with the current and the voltage dropped across the inductor is 90° out of phase with the current, vector addition must be used. The total voltage will be the hypotenuse of a right triangle, and the resistive and inductive voltage drops will form the legs of the triangle *(Figure 18–8)*. This relationship of voltage drops can also be represented using the parallelogram method of vector addition as shown in *Figure 18–9*.

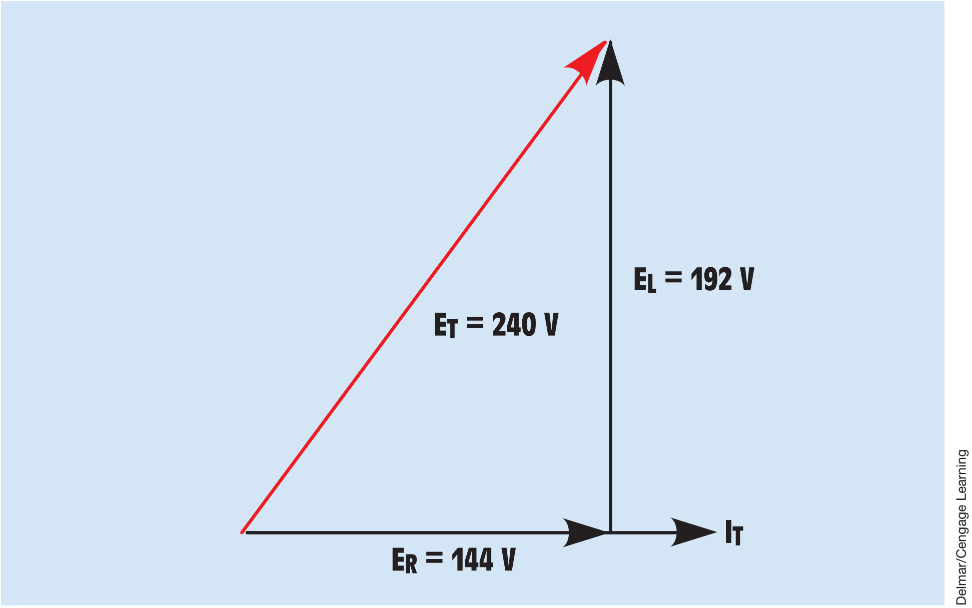


FIGURE 18–8 Relationship of resistive and inductive voltage drops in an R-L series circuit.

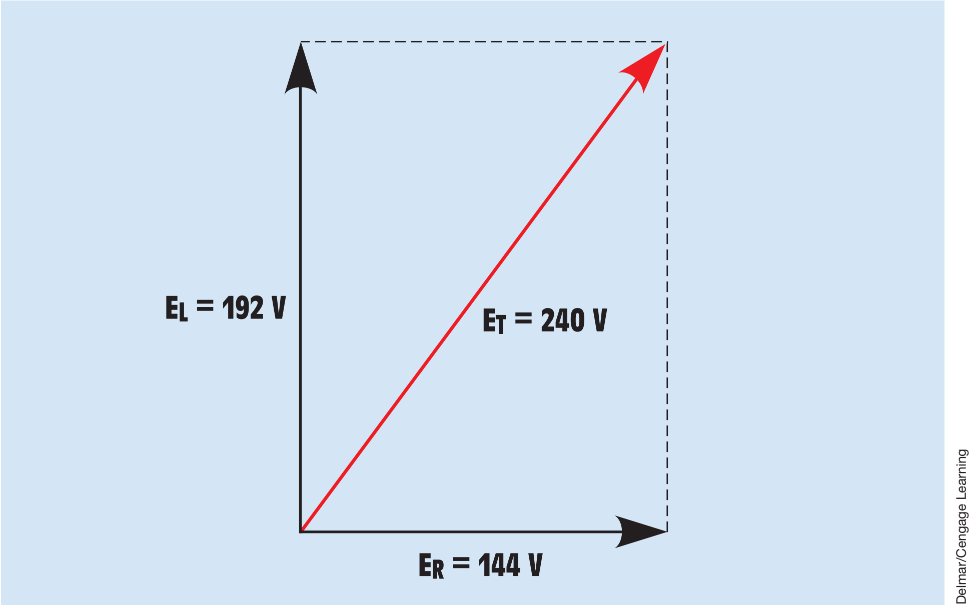


FIGURE 18–9 Graphic representation of voltage drops using the parallelogram method of vector addition.

The following formulas can be used to find total voltage or the voltage drops across the resistor or inductor if the other two voltage values are known:

$$E_T = \sqrt{E_R^2 + E_L^2}$$
$$E_R = \sqrt{E_T^2 - E_L^2}$$
$$E_L = \sqrt{E_T^2 - E_R^2}$$

Note: Refer to the Resistive-Inductive Series Circuits section of the AC formulas listed in Appendix B.

18–9 Calculating the Reactive Power

VARs is an abbreviation for volt-amperes-reactive and is the amount of reactive power (VARs) in the circuit. VARs should not be confused with watts, which is true power. VARs represents the product of the volts and amperes that are 90° out of phase with each other, such as the voltage dropped across the inductor and the current flowing through the inductor. Recall that true power can be produced only during periods of time when the voltage and current are both positive or both negative *(Figure 18–10)*. During these periods, the power is being stored in the form of a magnetic field. During the periods that voltage and current have opposite signs, the power is returned to the circuit. For this reason, VARs is often referred to as **quadrature power,** or **wattless power.** It can be calculated in a manner similar to watts except that reactive values of voltage and current are used instead of resistive values. In this example, the formula used is

$$\text{VARs} = I_L^2 \times X_L$$
$$\text{VARs} = (4.8\ \text{A})^2 \times 40\ \Omega$$
$$\text{VARs} = 921.6$$

18–10 Calculating the Apparent Power

Volt-amperes (VA) is the apparent power of the circuit. It can be calculated in a manner similar to watts or VARs, except that total values of voltage and current are used. It is called **apparent power (VA)** because it is the value that would be found if a voltmeter and ammeter were used to measure the circuit voltage and current and then these measured values were multiplied together *(Figure 18–11)*. In this example, the formula used is

$$\text{VA} = E_T \times I_T$$
$$\text{VA} = 240\ \text{V} \times 4.8\ \text{A}$$
$$\text{VA} = 1152$$

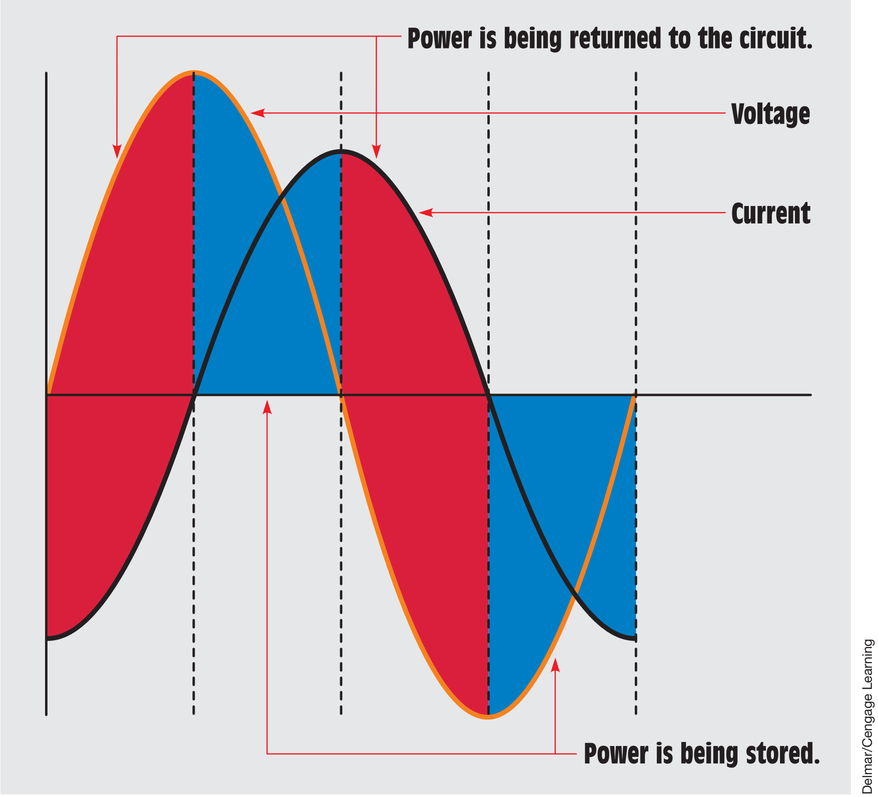


FIGURE 18–10 Power is stored and then returned to the circuit.

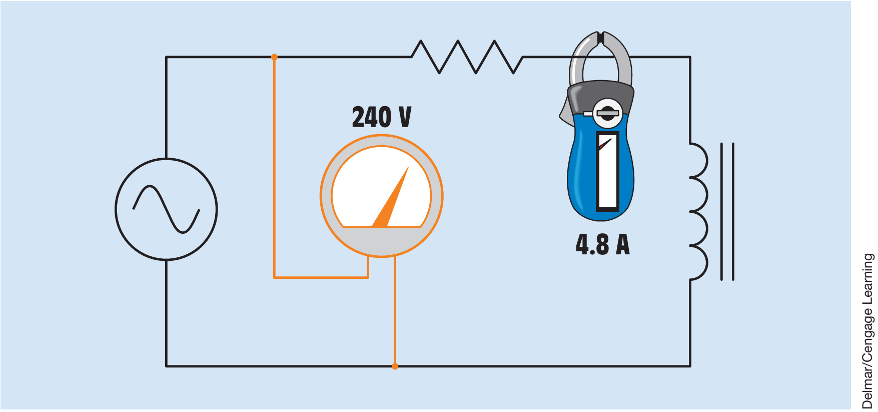


FIGURE 18–11 Apparent power is the product of measured values (240 V × 4.8 A = 1152 VA).

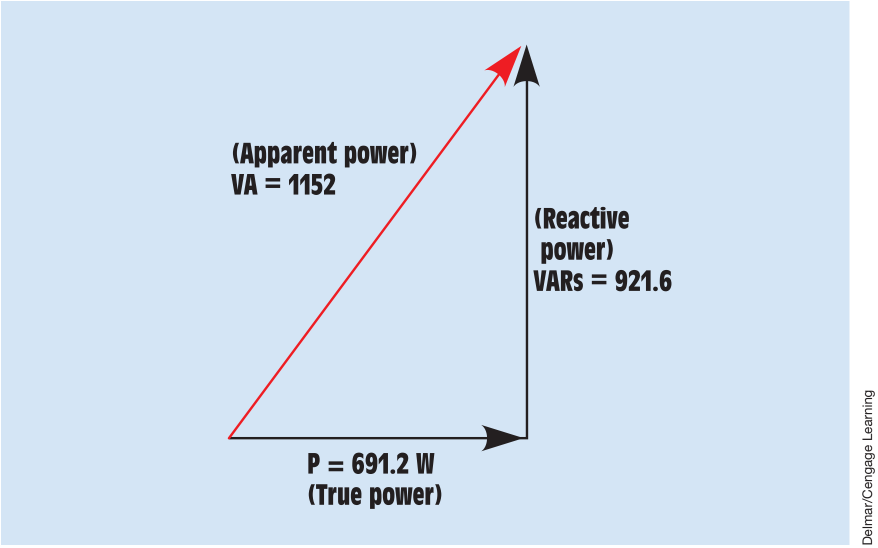


FIGURE 18–12 Relationship of true power (watts), reactive power (VARs), and apparent power (volt-amperes) in an R-L series circuit.

The apparent power can also be found using vector addition in a manner similar to impedance or total voltage. Because true power, or watts, is a pure resistive component and VARs is a pure reactive component, they form the legs of a right triangle. The apparent power is the hypotenuse of this triangle *(Figure 18–12)*. This relationship of the three power components can also be plotted using the parallelogram method *(Figure 18–13)*. The following formulas can be used to calculate the values of apparent power, true power, and reactive power when the other two values are known:

$$VA = \sqrt{P^2 + VARs^2}$$

$$P = \sqrt{VA^2 - VARs^2}$$

$$VARs = \sqrt{VA^2 - P^2}$$

18–11 Power Factor

Power factor (PF) is a ratio of the true power to the apparent power. It can be calculated by dividing any resistive value by its like total value. For example, power factor can be calculated by dividing the voltage drop across the resistor

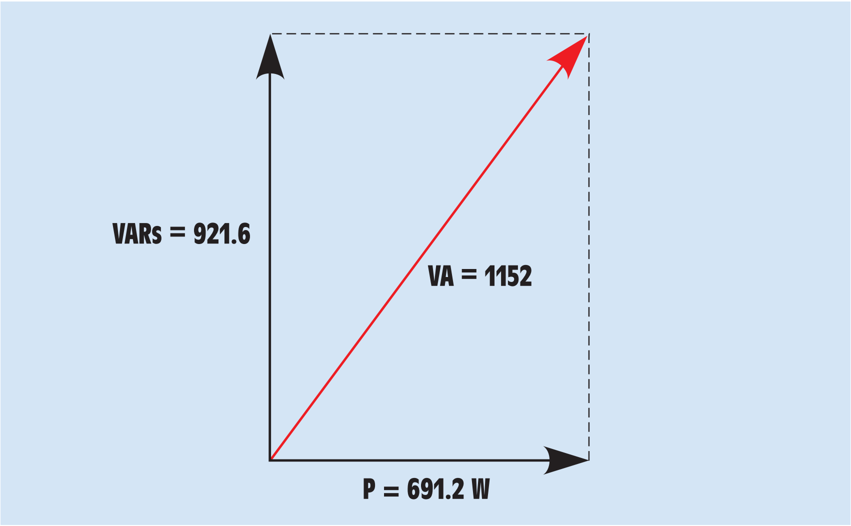


FIGURE 18–13 Using the parallelogram method to plot the relationship of volt-amperes, watts, and VARs.

by the total circuit voltage; or by dividing resistance by impedance; or by dividing watts by volt-amperes:

$$PF = \frac{E_R}{E_T}$$

$$PF = \frac{R}{Z}$$

$$PF = \frac{P}{VA}$$

Power factor is generally expressed as a percentage. The decimal fraction calculated from the division will therefore be changed to a percent by multiplying it by 100. In this circuit, the formula used is

$$PF = \frac{W}{VA}$$

$$PF = \frac{691.2\ W}{1152\ VA}$$

$$PF = 0.6 \times 100, \text{ or } 60\%$$

Note that in a series circuit, the power factor cannot be calculated using current because current is the same in all parts of the circuit.

Power factor can become very important in an industrial application. Most power companies charge a substantial surcharge when the power factor drops below a certain percent. The reason for this is that electric power is sold on the basis of true power, or watt-hours, consumed. The power company, however, must supply the apparent power. Assume that an industrial plant has a power factor of 60% and is consuming 5 megawatts of power. At a power factor of 60%, the power company must actually supply 8.333 megavolt-amperes (5 MW/0.6 = 8.333 MVA). If the power factor were to be corrected to 95%, the power company would have to supply only 5.263 megavolt-amperes to furnish the same amount of power to the plant.

18–12 Angle Theta

The angular displacement by which the voltage and current are out of phase with each other is called **angle theta ($\angle\theta$).** Because the power factor is the ratio of true power to apparent power, the phase angle of voltage and current is formed between the resistive leg of the right triangle and the hypotenuse *(Figure 18–14)*. The resistive leg of the triangle is adjacent to the angle, and the total leg is the hypotenuse. The trigonometric function that corresponds to the adjacent side and the hypotenuse is the cosine. Angle theta is the cosine of watts divided by volt-amperes. Watts divided by volt-amperes is

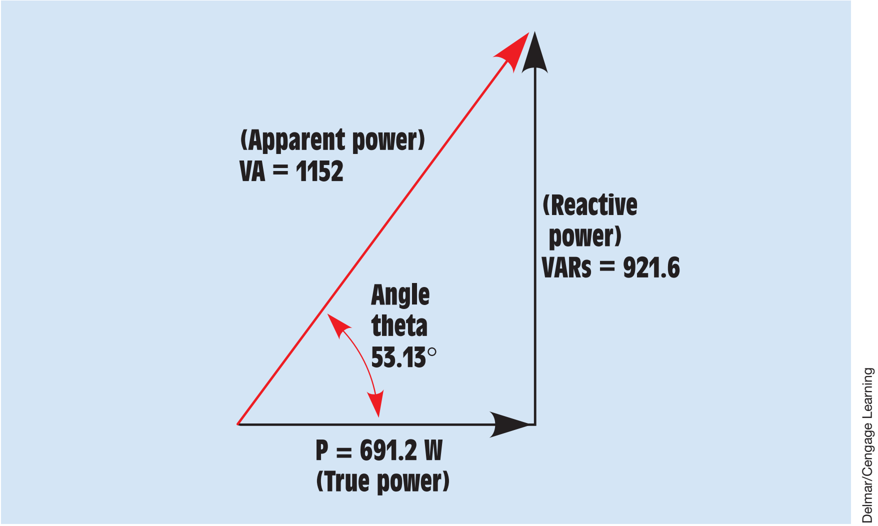


FIGURE 18–14 The angle theta is the relationship of true power to apparent power.

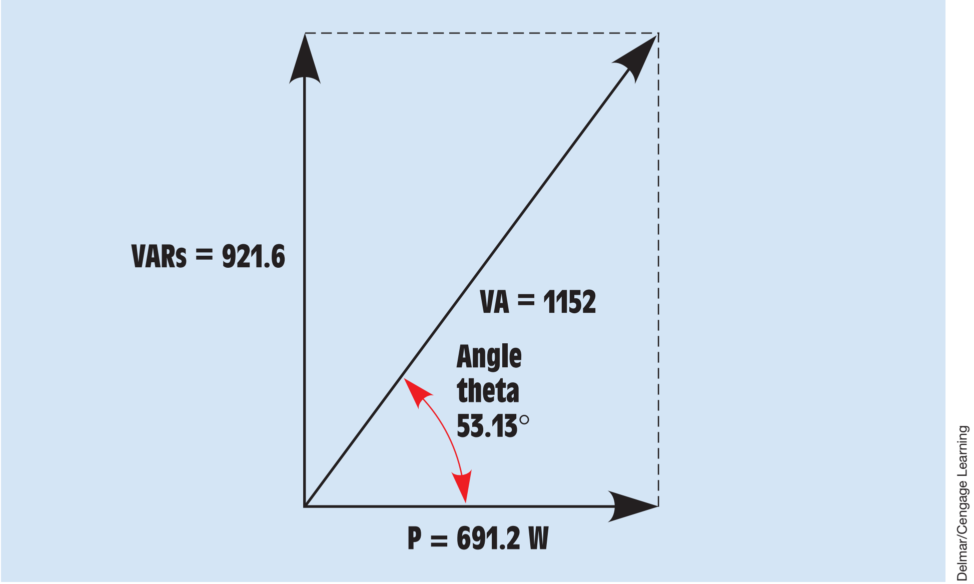


FIGURE 18–15 The angle theta can be found using vectors provided by the parallelogram method.

also the power factor. Therefore, the cosine of angle theta ($\angle\theta$) is the power factor (PF):

$$\cos\angle\theta = \text{PF}$$
$$\cos\angle\theta = 0.6$$
$$\angle\theta = 53.13^\circ$$

The vectors formed using the parallelogram method of vector addition can also be used to find angle theta as shown in *Figure 18–15*. Notice that the total quantity, volt-amperes, and the resistive quantity, watts, are again used to determine angle theta.

Because this circuit contains both resistance and inductance, the current is lagging the voltage by 53.13° *(Figure 18–16)*. Angle theta can also be determined by using any of the other trigonometric functions:

$$\sin\angle\theta = \frac{\text{VARs}}{\text{VA}}$$

$$\tan\angle\theta = \frac{\text{VARs}}{\text{P}}$$

Now that all the unknown values have been calculated, they can be filled in as shown in *Figure 18–17*.

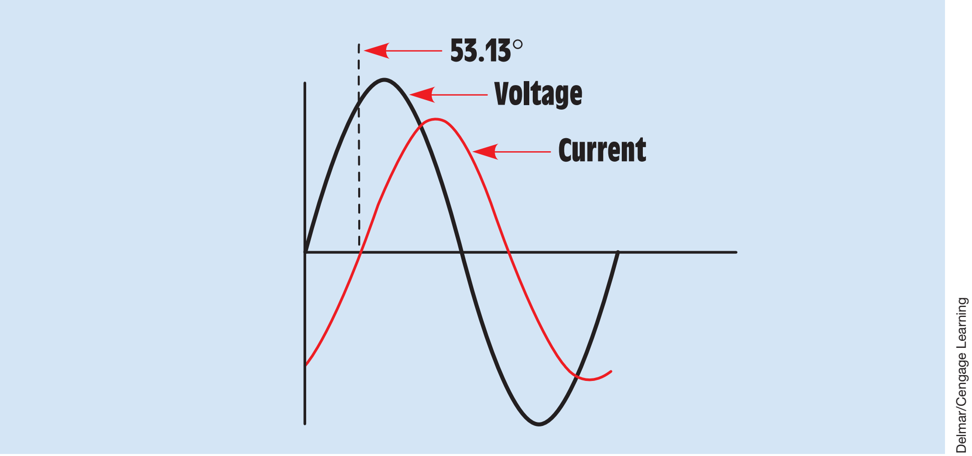


FIGURE 18–16 Current and voltage are 53.13° out of phase with each other.

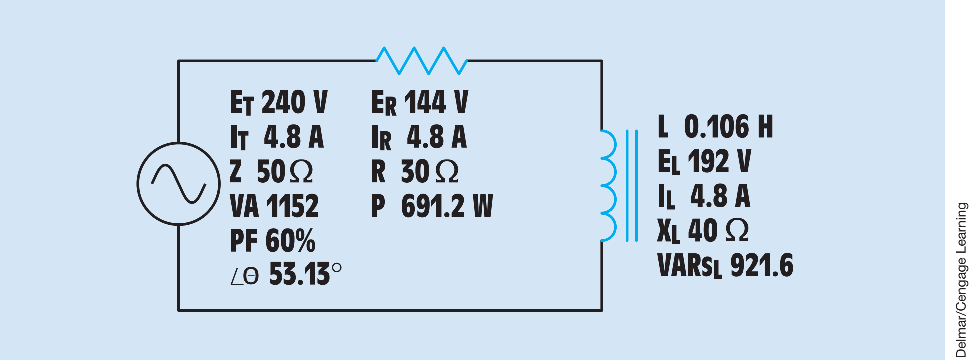


FIGURE 18–17 Filling in all unknown values.

■ EXAMPLE 18–1

Two resistors and two inductors are connected in series *(Figure 18–18)*. The circuit is connected to a 130-V, 60-Hz line. The first resistor has a power dissipation of 56 W, and the second resistor has a power dissipation of 44 W. One inductor has a reactive power of 152 VARs and the second a reactive power of 88 VARs. Find the unknown values in this circuit.

Solution

The first step is to find the total amount of true power and the total amount of reactive power. The total amount of true power can be calculated by adding the

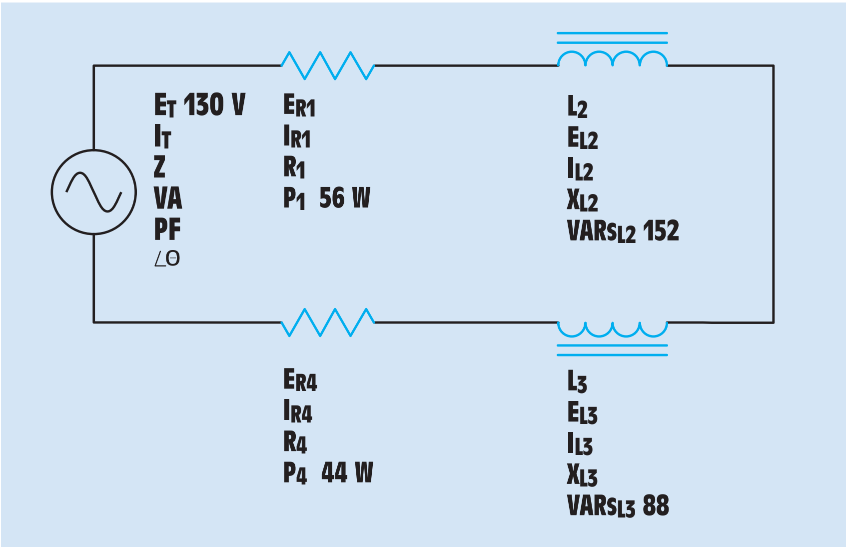


FIGURE 18–18 An R-L series circuit containing two resistors and two inductors.

values of the resistors together. A vector diagram of these two values would reveal that they both have a direction of 0° *(Figure 18–19)*.

$$P_T = P_1 + P_4$$
$$P_T = 56\ W + 44\ W$$
$$P_T = 100\ W$$

The total reactive power in the circuit can be found in the same manner. Like watts, the VARs are both inductive and are therefore in the same direction *(Figure 18–20)*. The total reactive power will be the sum of the two reactive power ratings:

$$VARs_T = VARs_{L2} + VARs_{L3}$$
$$VARs_T = 152 + 88$$
$$VARs_T = 240$$

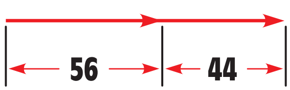


FIGURE 18–19 The two true power (watts) vectors are in the same direction.

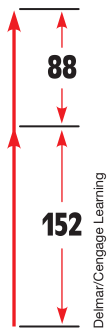


FIGURE 18–20 The two reactive power (VARs) vectors are in the same direction.

Apparent Power

Now that the total amount of true power and the total amount of reactive power are known, the apparent power (VA) can be calculated using vector addition:

$$VA = \sqrt{P_T^2 + VARs_T^2}$$

$$VA = \sqrt{(100\ W)^2 + (240\ VARs)^2}$$

$$VA = 260$$

The parallelogram method of vector addition is shown in *Figure 18–21* for this calculation.

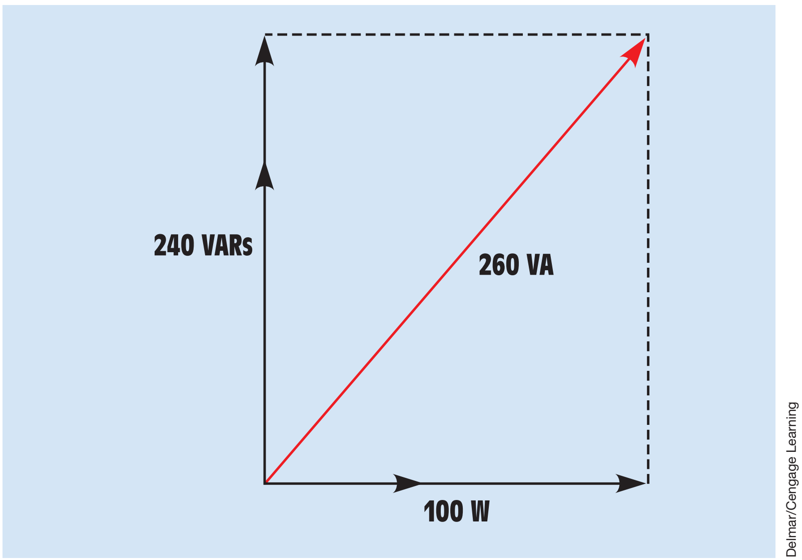


FIGURE 18–21 Power vector for the circuit.

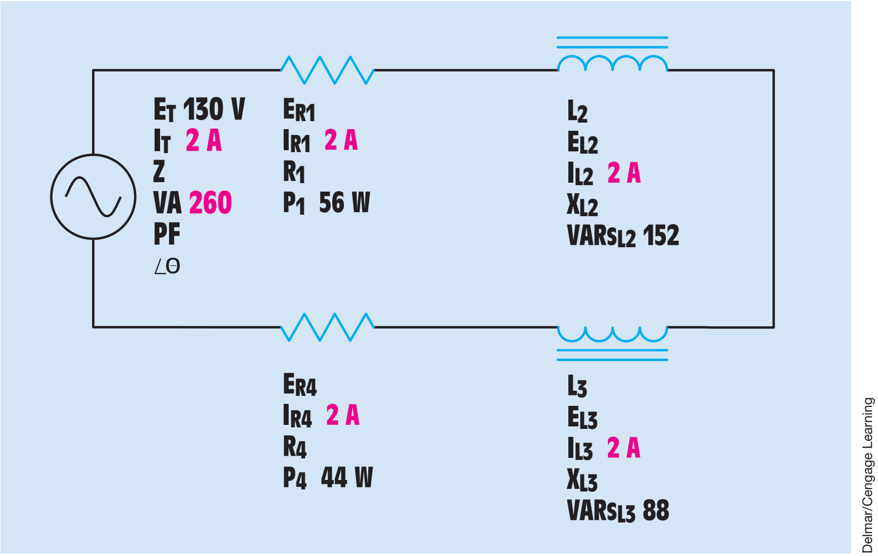


FIGURE 18–22 Adding circuit values.

Total Circuit Current

Now that the apparent power is known, the total circuit current can be found using the applied voltage and Ohm's law:

$$I_T = \frac{VA}{E_T}$$

$$I_T = \frac{260\text{ VA}}{130\text{ V}}$$

$$I_T = 2\text{ A}$$

Because this is a series circuit, the current must be the same at all points in the circuit. The known values added to the circuit are shown in *Figure 18–22*.

Other Circuit Values

Now that the total circuit current has been found, other values can be calculated using Ohm's law.

Impedance

$$Z = \frac{E_T}{I_T}$$

$$Z = \frac{130\text{ V}}{2\text{ A}}$$

$$Z = 65\ \Omega$$

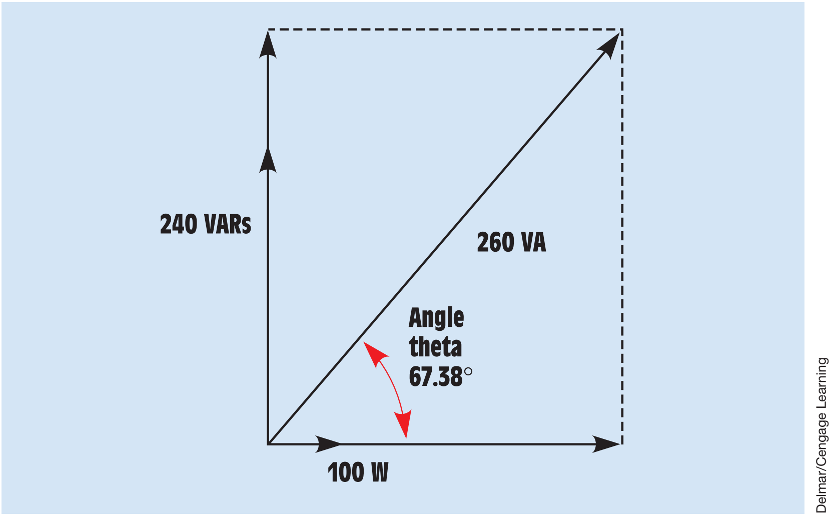


FIGURE 18–23 Angle theta for the circuit.

Power Factor

$$PF = \frac{W_T}{VA}$$

$$PF = \frac{100\ W}{260\ VA}$$

$$PF = 38.462\%$$

Angle Theta

Angle theta is the cosine of the power factor. A vector diagram showing this relationship is shown in *Figure 18–23*.

$$\cos \angle\theta = PF$$

$$\cos \angle\theta = 0.38462$$

$$\angle\theta = 67.38°$$

The relationship of voltage and current for this circuit is shown in *Figure 18–24*.

E_{R1}

$$E_{R1} = \frac{P_1}{I_{R1}}$$

$$E_{R1} = \frac{56\ W}{2\ A}$$

$$E_{R1} = 28\ V$$

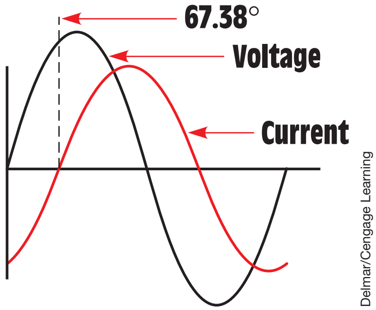


FIGURE 18–24 Voltage and current are 67.38° out of phase with each other.

R_1

$$R_1 = \frac{E_{R1}}{I_{R1}}$$

$$R_1 = \frac{28\ V}{2\ A}$$

$$R_1 = 14\ \Omega$$

E_{L2}

$$E_{L2} = \frac{VARs_{L2}}{I_{L2}}$$

$$E_{L2} = \frac{152\ VARs}{2\ A}$$

$$E_{L2} = 76\ V$$

X_{L2}

$$X_{L2} = \frac{E_{L2}}{I_{L2}}$$

$$X_{L2} = \frac{76\ V}{2\ A}$$

$$X_{L2} = 38\ \Omega$$

L_2

$$L_2 = \frac{X_{L2}}{2\pi f}$$

$$L_2 = \frac{38\ \Omega}{377}$$

$$L_2 = 0.101\ H$$

E_{L3}

$$E_{L3} = \frac{VARs_{L3}}{I_{L3}}$$

$$E_{L3} = \frac{88\ VARs}{2\ A}$$

$$E_{L3} = 44\ V$$

X_{L3}

$$X_{L3} = \frac{E_{L3}}{I_{L3}}$$

$$X_{L3} = \frac{44\ V}{2\ A}$$

$$X_{L3} = 22\ \Omega$$

L_3

$$L_3 = \frac{X_{L3}}{2\pi f}$$

$$L_3 = \frac{22\ \Omega}{377}$$

$$L_3 = 0.0584$$

E_{R4}

$$E_{R4} = \frac{P_4}{I_{R4}}$$

$$E_{R4} = \frac{44\ W}{2\ A}$$

$$E_{R4} = 22\ V$$

R_4

$$R_4 = \frac{E_{R4}}{I_{R4}}$$

$$R_4 = \frac{22\ V}{2\ A}$$

$$R_4 = 11\ \Omega$$

The complete circuit with all values is shown in *Figure 18–25*.

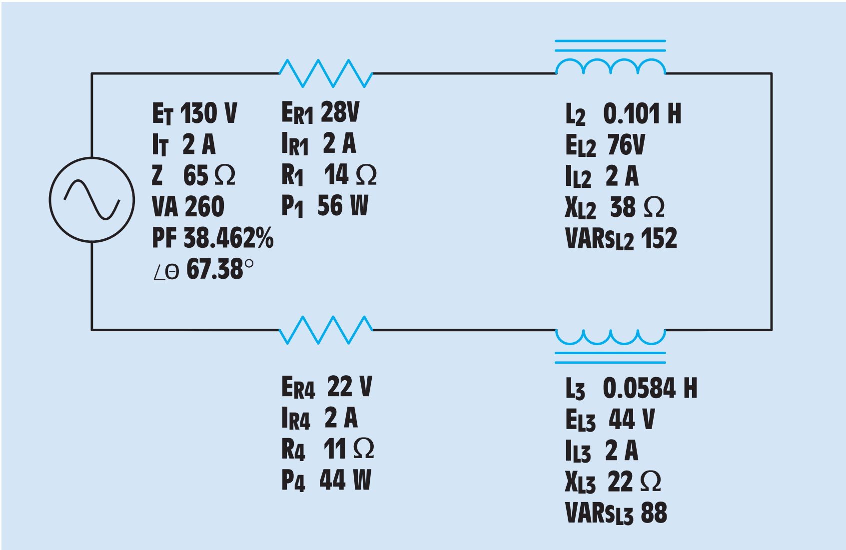


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FIGURE 18–25 All values for the circuit.

Many people working the electrical field encounter R-L series circuits almost every day in ways that they do not realize. A good example of this is an electric motor. As far as the circuit is concerned, a motor is actually an R-L series circuit. The motor winding is basically an inductor. It is a coil of wire surrounded by an iron core. The wire does have resistance, however. Because there is only one path for current flow through the circuit, it is a series circuit *(Figure 18–26)*. When

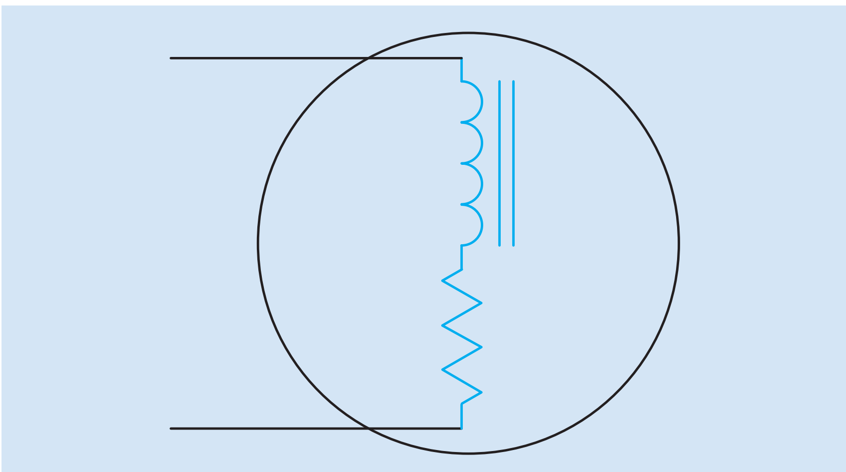

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FIGURE 18–26 A motor winding appears to be an R-L series circuit.

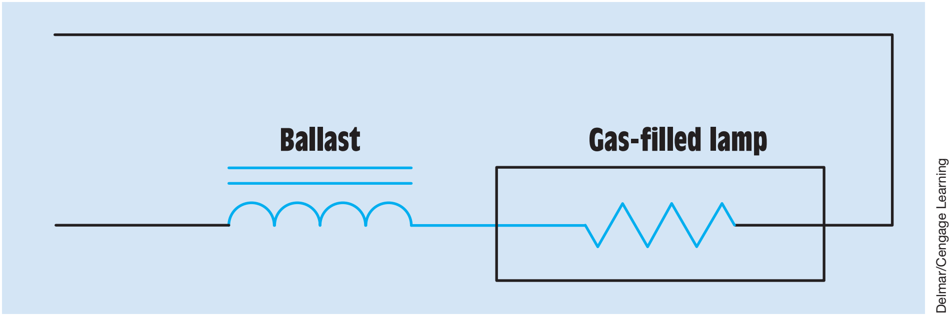


FIGURE 18–27 A ballast is used to prevent excessive current flow when the gas ionizes.

a motor is operated at no load, it will have a large inductive component as compared to resistance. As load is added to the motor, electrical energy is converted into kinetic energy, causing an increase in true power or watts. This has the effect of increasing the amount of circuit resistance. When a motor is operated at full load, the circuit has become an R-L series circuit with more resistance than inductance.

Another example of an RL series circuit is a luminaire (lighting fixture) that depends on the ionization of gas such as fluorescent, mercury vapor, sodium vapor, and so on. When a gas is ionized, it basically becomes a short circuit. A ballast is used to prevent excessive current flow when the gas ionizes. The ballast is connected in series with the lamp *(Figure 18–27)*. When the gas in the lamp ionizes, the inductive reactance of the ballast limits current. The lamp appears as a resistive load after ionization takes place. Without an understanding of the relationship of inductance and resistance in a series circuit, it would be impossible to understand how this everyday electric device actually works.

Summary

- In a pure resistive circuit, the voltage and current are in phase with each other.
- In a pure inductive circuit, the voltage and current are 90° out of phase with each other.
- In an R-L series circuit, the voltage and current will be out of phase with each other by some value between 0° and 90°.
- The amount the voltage and current are out of phase with each other is determined by the ratio of resistance to inductance.

- Total circuit values include total voltage, E_T; total current, I_T; volt-amperes, VA; and impedance, Z.
- Pure resistive values include voltage drop across the resistor, E_R; current flow through the resistor, I_R; resistance, R; and watts, P.
- Pure inductive values include inductance of the inductor, L; voltage drop across the inductor, E_L; current through the inductor, I_L; inductive reactance, X_L; and inductive VARs, $VARs_L$.
- Angle theta measures the phase angle difference between the applied voltage and total circuit current.
- The cosine of angle theta is equal to the power factor.
- Power factor is a ratio of true power to apparent power.

Review Questions

1. What is the relationship of voltage and current (concerning phase angle) in a pure resistive circuit?
2. What is the relationship of voltage and current (concerning phase angle) in a pure inductive circuit?
3. What is power factor?
4. A circuit contains a 20-Ω resistor and an inductor with an inductance of 0.093 H. If the circuit has a frequency of 60 Hz, what is the total impedance of the circuit?
5. An R-L series circuit has a power factor of 86%. How many degrees are the voltage and current out of phase with each other?
6. An R-L series circuit has an apparent power of 230 VA and a true power of 180 W. What is the reactive power?
7. The resistor in an R-L series circuit has a voltage drop of 53 V, and the inductor has a voltage drop of 28 V. What is the applied voltage of the circuit?
8. An R-L series circuit has a reactive power of 1234 VARs and an apparent power of 4329 VA. How many degrees are voltage and current out of phase with each other?
9. An R-L series circuit contains a resistor and an inductor. The resistor has a value of 6.5 Ω. The circuit is connected to 120 V and has a current flow of 12 A. What is the inductive reactance of this circuit?
10. What is the voltage drop across the resistor in the circuit in Question 9?

Practical Applications

An AC electric motor is connected to a 240-V, 60-Hz source. A clamp-on ammeter with a peak hold function reveals that the motor has an inrush current of 34 A when the motor is first started. Your job is to reduce the inrush current to a value of 20 A by connecting a resistor in series with the motor. The resistor will be shunted out of the circuit after the motor is started. Using an ohmmeter, you find that the motor has a wire resistance of 3 Ω. How much resistance should be connected in series with the motor to reduce the starting current to 20 A? ■

Practical Applications

You are a journeyman electrician working in an industrial plant. Your task is to connect an inductor to a 480-V, 60-Hz line. To determine the proper conductor and fuse size for this installation, you need to know the amount of current the inductor will draw from the line. The nameplate on the inductor indicates that it has an inductance of 0.1 H. An ohmmeter reveals that it has a wire resistance of 10 Ω. How much current should this inductor draw when connected to the line? ■

Practice Problems

Refer to the circuit shown in *Figure 18–2* and the Resistive-Inductive Series Circuits section of the AC formulas listed in Appendix B.

1. Assume that the circuit shown in *Figure 18–2* is connected to a 480-V, 60-Hz line. The inductor has an inductance of 0.053 H, and the resistor has a resistance of 12 Ω.

E_T 480V	E_R ______	E_L ______
I_T ______	I_R ______	I_L ______
Z ______	R 12 Ω	X_L ______
VA ______	P ______	$VARs_L$ ______
PF ______	∠θ ______	L 0.053 H

2. Assume that the voltage drop across the resistor, E_R, is 78 V, that the voltage drop across the inductor, E_L, is 104 V, and the circuit has a total impedance, Z, of 20 Ω. The frequency of the AC voltage is 60 Hz.

E_T ________	E_R 78 V	E_L 104 V
I_T ________	I_R ________	I_L ________
Z 20 Ω	R ________	X_L ________
VA ________	P ________	$VARs_L$ ________
PF ________	∠θ ________	L ________

3. Assume the circuit shown in *Figure 18–2* has an apparent power of 144 VA and a true power of 115.2 W. The inductor has an inductance of 0.15915 H, and the frequency is 60 Hz.

E_T ________	E_R ________	E_L ________
I_T ________	I_R ________	I_L ________
Z ________	R ________	X_L ________
VA 144	P 115.2 W	$VARs_L$ ________
PF ________	∠θ ________	L 0.15915 H

4. Assume the circuit shown in *Figure 18–2* has a power factor of 78%, an apparent power of 374.817 VA, and a frequency of 400 Hz. The inductor has an inductance of 0.0382 H.

E_T ________	E_R ________	E_L ________
I_T ________	I_R ________	I_L ________
Z ________	R ________	X_L ________
VA 374.817	P ________	$VARs_L$ ________
PF 78%	∠θ ________	L 0.0382 H

5. In an RL series circuit, E_T = 240 volts, R = 60 Ω, and X_L = 75 Ω. Find E_L.

6. In an RL series circuit, E_T = 208 volts, R = 2.4 kΩ, and X_L = 1.5 kΩ. Find PF.

7. In an RL series circuit, E_T = 120 volts, R = 35 Ω, and X_L = 48 Ω. Find reactive power.

8. In an RL series circuit, the apparent power is 560 VA, PF = 62%. Find reactive power.

9. An RL series circuit is connected to a 60-Hz, 208-volt power line. A clamp-on ammeter indicates a current of 18 amperes. The inductor has a reactive power of 1860 VARs. What is the value of R?
10. In an RL series circuit, $Z = 88\ \Omega$, $R = 32\ \Omega$. Find X_L.
11. In an RL series circuit, apparent power = 450 VA, reactive power = 224 VARs. Find true power.
12. In an RL series circuit, $\angle\theta = 22°$, true power = 94 watts. Find reactive power.
13. An RL series circuit contains two resistors and two inductors. The resistors have values of 120 Ω and 300 Ω. The inductors have reactive values of 220 Ω and 470 Ω. Find impedance.
14. An RL series circuit contains two resistors and two inductors. The resistors dissipate powers of 96 watts and 125 watts. The inductors have reactive powers of 100 VARs and 78 VARs. What is the power factor?
15. An RL series circuit contains two resistors and two inductors. The resistors are 68 Ω and 124 Ω. The inductors have inductive reactances of 44 Ω and 225 Ω. The total voltage is 240 volts. Find the voltage drop across the 124-Ω resistor.
16. An RL series circuit contains two resistors and two inductors. The resistors are 86 kΩ and 68 kΩ. The inductors have inductive reactances of 24 kΩ and 56 kΩ. The total voltage is 480 volts. Find the voltage drop across the 56-kΩ inductor.

Unit 19

Resistive-Inductive Parallel Circuits

OUTLINE

KEY TERMS

Current flow through the inductor (I_L)

Current flow through the resistor (I_R)

Why You Need to Know

Many times, resistive and inductive loads are connected in parallel with each other. This can be seen in every kind of electrical environment. Incandescent lights in a home are resistive loads, but they are often connected in parallel with a motor or transformer. A common heat-pump system in a home is a perfect example of this type circuit. The compressor and blower motors are inductive loads, but the electric heat strips are resistive loads. To understand how these different loads affect the circuit, you must understand resistive-inductive parallel circuits. This unit

- illustrates how to calculate the effect on voltage, current, and impedance when a parallel circuit contains both resistance and inductance.
- explains how to apply the relationship of power factor to true power in a parallel circuit containing resistive-inductive factors.

Courtesy of Toyota Motor Manufacturing, Kentucky, Inc.

Objectives

After studying this unit, you should be able to

- discuss the operation of a parallel circuit containing resistance and inductance.
- calculate circuit values of an RL parallel circuit.
- connect an RL parallel circuit and measure circuit values with test instruments.

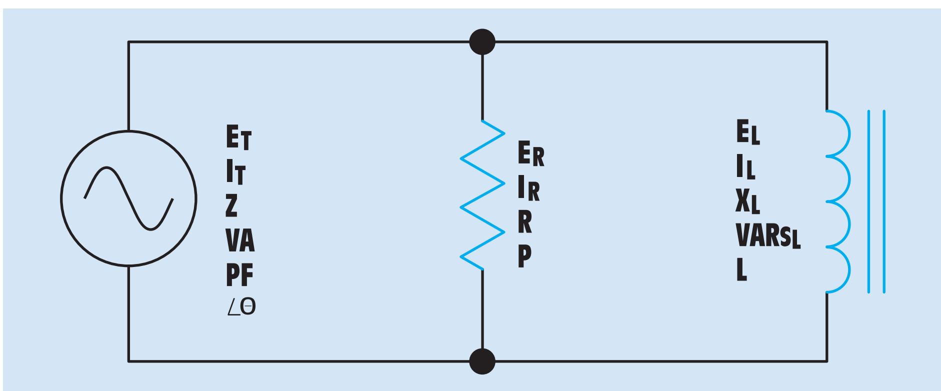
Preview

This unit discusses circuits that contain resistance and inductance connected in parallel with each other. Mathematical calculations are used to show the relationship of current and voltage on the entire circuit and the relationship of current through different branches of the circuit. ■

19–1 Resistive-Inductive Parallel Circuits

A circuit containing a resistor and an inductor connected in parallel is shown in *Figure 19–1*. Because the voltage applied to any device in parallel must be the same, the voltage applied to the resistor and inductor must be in phase and have the same value. The current flow through the inductor will be 90° out of phase with the voltage, and the current flow through the resistor will be in phase with the voltage *(Figure 19–2)*. This configuration produces a phase angle difference of 90° between the current flow through a pure inductive load and a pure resistive load *(Figure 19–3)*.

The amount of phase angle shift between the total circuit current and voltage is determined by the ratio of the amount of resistance to the amount of inductance. The circuit power factor is still determined by the ratio of true power to apparent power.



Delmar/Cengage Learning

FIGURE 19–1 A resistive-inductive parallel circuit.

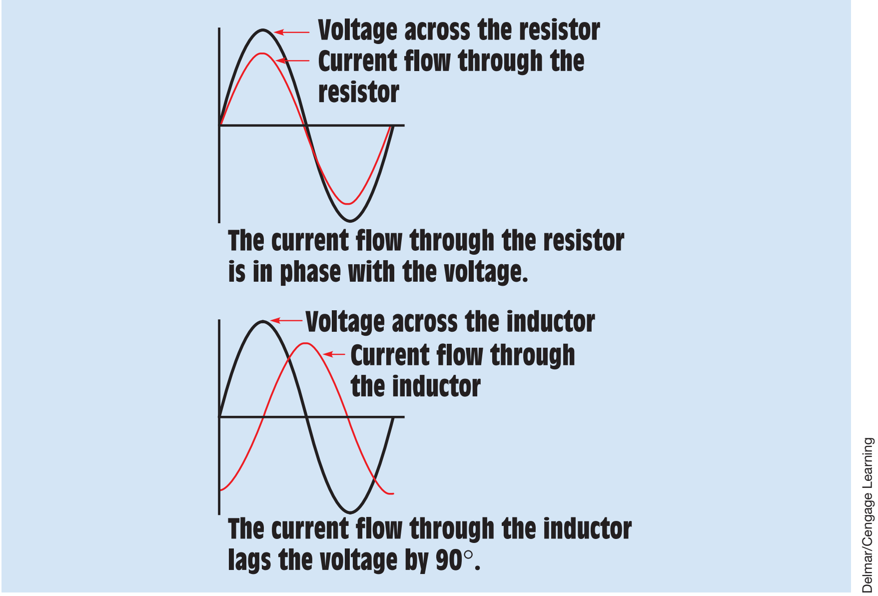


FIGURE 19–2 Relationship of voltage and current in an RL parallel circuit.

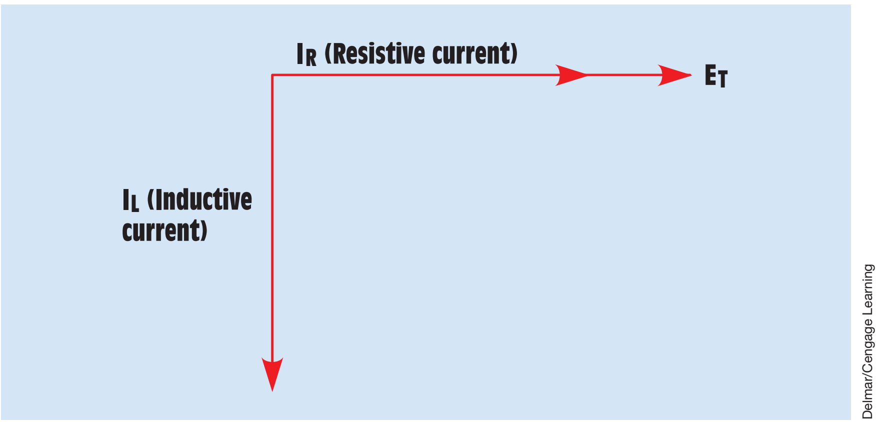


FIGURE 19–3 Resistive and inductive currents are 90° out of phase with each other in an RL parallel circuit.

19–2 Calculating Circuit Values

In the circuit shown in *Figure 19–4*, a resistance of 15 ohms is connected in parallel with an inductive reactance of 20 ohms. The circuit is connected to a voltage of 240 volts AC and a frequency of 60 hertz. In this example problem,

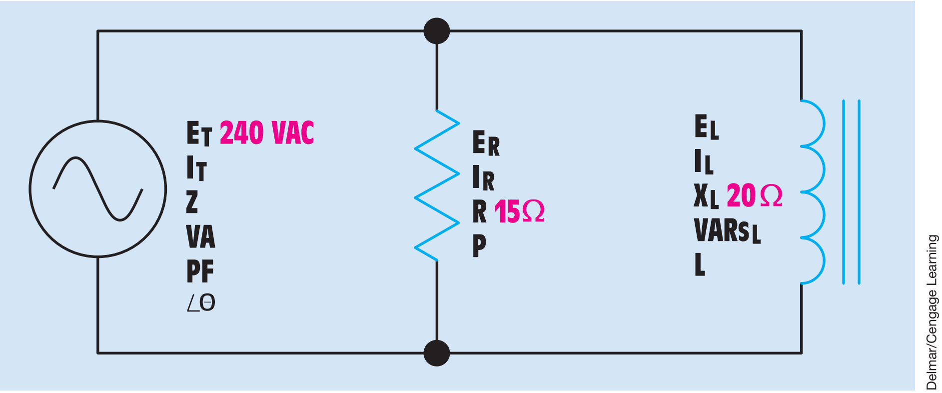


FIGURE 19–4 Typical RL parallel circuit.

the following circuit values will be calculated:

I_R—current flow through the resistor

P—watts (true power)

I_L—current flow through the inductor

VARs—reactive power

I_T—total circuit current

Z—total circuit impedance

VA—apparent power

PF—power factor

$\angle\theta$—the angle the voltage and current are out of phase with each other

Resistive Current

In any parallel circuit, the voltage is the same across each component in the circuit. Therefore, 240 volts are applied across both the resistor and the inductor. Because the amount of voltage applied to the resistor is known, the amount of **current flow through the resistor (I_R)** can be calculated by using the formula:

$$I_R = \frac{E}{R}$$

$$I_R = \frac{240\text{ V}}{15\ \Omega}$$

$$I_R = 16\text{ A}$$

Watts

True power (P), or watts (W), can be calculated using any of the watts formulas and pure resistive values. The amount of true power in this circuit is calculated using the formula:

$$P = E_R \times I_R$$
$$P = 240\ V \times 16\ A$$
$$P = 3840\ W$$

Inductive Current

Because the voltage applied to the inductor is known, the current flow can be found by dividing the voltage by the inductive reactance. The amount of **current flow through the inductor (I_L)** is calculated using the formula:

$$I_L = \frac{E}{X_L}$$
$$I_L = \frac{240\ V}{20\ \Omega}$$
$$I_L = 12\ A$$

VARs

The amount of reactive power (VARs) is calculated using the formula:

$$VARs = E_L \times I_L$$
$$VARs = 240\ V \times 12\ A$$
$$VARs = 2880$$

Inductance

Because the frequency and the inductive reactance are known, the inductance of the coil can be found using the formula:

$$L = \frac{X_L}{2\pi f}$$
$$L = \frac{20\ \Omega}{377}$$
$$L = 0.0531\ H$$

Total Current

The total current (I_T) flow through the circuit can be calculated by adding the current flow through the resistor and the inductor. Because these two currents

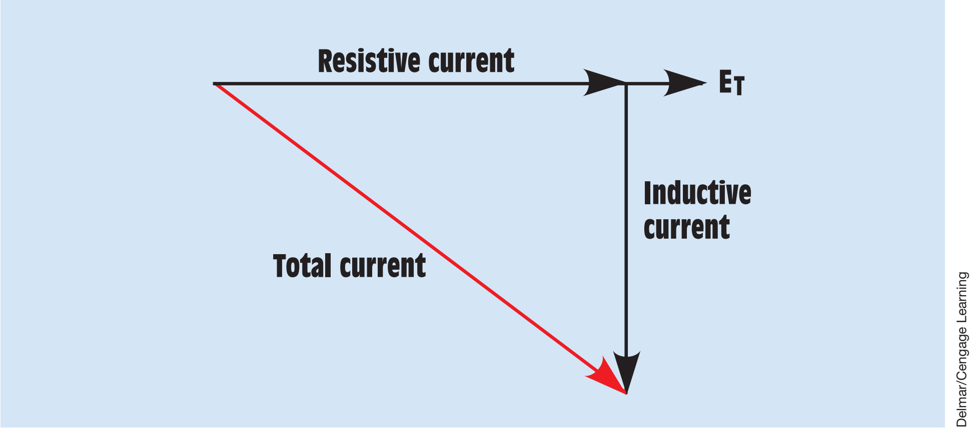


FIGURE 19–5 Relationship of resistive, inductive, and total current in an RL parallel circuit.

are 90° out of phase with each other, vector addition is used. If these current values were plotted, they would form a right triangle similar to the one shown in *Figure 19–5*. Notice that the current flow through the resistor and inductor forms the legs of a right triangle and the total current is the hypotenuse Because the resistive and inductive currents form the legs of a right triangle and the total current forms the hypotenuse, the Pythagorean theorem can be used to add these currents together:

$$I_T = \sqrt{I_R^2 + I_L^2}$$
$$I_T = \sqrt{(16\ A)^2 + (12\ A)^2}$$
$$I_T = \sqrt{256\ A^2 + 144\ A^2}$$
$$I_T = \sqrt{400\ A^2}$$
$$I_T = 20\ A$$

The parallelogram method for plotting the total current is shown in *Figure 19–6*.

Impedance

Now that the total current and total voltage are known, the total impedance (Z) can be calculated by substituting Z for R in an Ohm's law formula. The total impedance of the circuit can be calculated using the formula:

$$Z = \frac{E}{I_T}$$
$$Z = \frac{240\ V}{20\ A}$$
$$Z = 12\ \Omega$$

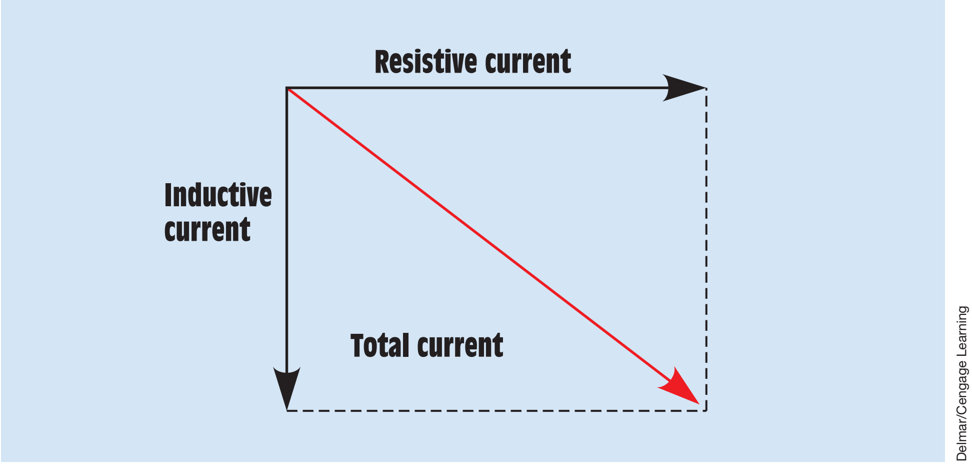


FIGURE 19–6 Plotting total current using the parallelogram method.

The value of impedance can also be found if total current and voltage are not known. In a parallel circuit, the reciprocal of the total resistance is equal to the sum of the reciprocals of each resistor. This same rule can be amended to permit a similar formula to be used in an RL parallel circuit. Because resistance and inductive reactance are 90° out of phase with each other, vector addition must be used when the reciprocals are added. The initial formula is:

$$\left(\frac{1}{Z}\right)^2 = \left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2$$

This formula states that the square of the reciprocal of the impedance is equal to the sum of the squares of the reciprocals of resistance and inductive reactance. To remove the square from the reciprocal of the impedance, take the square root of both sides of the equation:

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}$$

Notice that the formula can now be used to find the reciprocal of the impedance, not the impedance. To change the formula so that it is equal to the impedance, take the reciprocal of both sides of the equation:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}}$$

Numeric values can now be substituted in the formula to find the impedance of the circuit:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{15\ \Omega}\right)^2 + \left(\frac{1}{20\ \Omega}\right)^2}}$$

$$Z = \frac{1}{\sqrt{(0.004444 + 0.0025)\frac{1}{\Omega^2}}}$$

$$Z = \frac{1}{\sqrt{0.006944\frac{1}{\Omega^2}}}$$

$$Z = \frac{1}{0.08333\frac{1}{\Omega}}$$

$$Z = 12\ \Omega$$

Another formula that can be used to determine the impedance of resistance and inductive reactance connected in parallel is:

$$Z = \frac{R \times X_L}{\sqrt{R^2 + X_L{}^2}}$$

Substituting the same values for resistance and inductive reactance in this formula will result in the same answer:

$$Z = \frac{15\ \Omega \times 20\ \Omega}{\sqrt{(15\ \Omega)^2 + (20\ \Omega)^2}}$$

$$Z = \frac{300\ \Omega}{\sqrt{625\ \Omega^2}}$$

$$Z = \frac{300\ \Omega}{25\ \Omega}$$

$$Z = 12\ \Omega$$

Apparent Power

The apparent power (VA) can be calculated by multiplying the circuit voltage by the total current flow. The relationship of volt-amperes, watts, and VARs is the same for an RL parallel circuit as it is for an RL series circuit. The reason is that power adds in any type of circuit. Because the true power and reactive power are 90° out of phase with each other, they form a right triangle with apparent power as the hypotenuse *(Figure 19–7)*.

$$VA = E_T \times I_T$$

$$VA = 240\ V \times 20\ A$$

$$VA = 4800$$

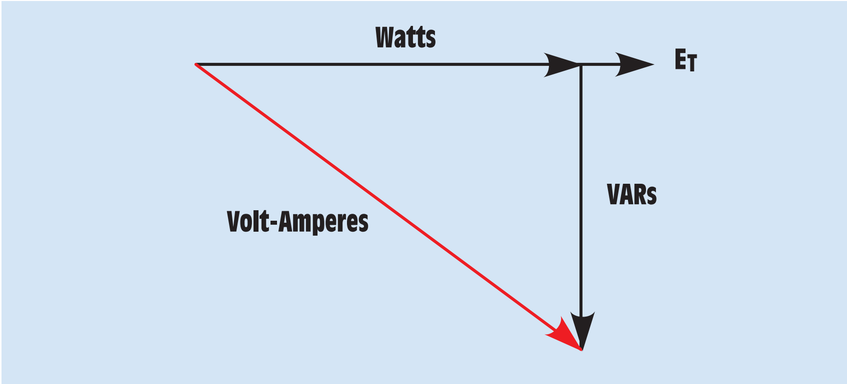


FIGURE 19–7 Relationship of apparent power (volt-amperes), true power (watts), and reactive power (VARs) in an RL parallel circuit.

Power Factor

Power factor (PF) in an RL parallel circuit is the relationship of apparent power to the true power just as it was in the RL series circuit. There are some differences in the formulas used to calculate power factor in a parallel circuit, however. In an RL series circuit, power factor could be calculated by dividing the voltage dropped across the resistor by the total, or applied, voltage. In a parallel circuit, the voltage is the same, but the currents are different. Therefore, power factor can be calculated by dividing the current flow through the resistive parts of the circuit by the total circuit current:

$$PF = \frac{I_R}{I_T}$$

Another formula that changes involves resistance and impedance. In a parallel circuit, the total circuit impedance will be less than the resistance. Therefore, if power factor is to be calculated using impedance and resistance, the impedance must be divided by the resistance:

$$PF = \frac{Z}{R}$$

The circuit power factor in this example will be calculated using the formula:

$$PF = \frac{P}{VA} \times 100$$

$$PF = \frac{3840\ W}{4800\ VA} \times 100$$

$$PF = 0.80, \quad \text{or} \quad 80\%$$

Angle Theta

The cosine of angle theta ($\angle\theta$) is equal to the power factor:

$$\cos \angle\theta = 0.80$$
$$\angle\theta = 36.87°$$

A vector diagram using apparent power, true power, and reactive power is shown in *Figure 19–8*. Notice that angle theta is the angle produced by the apparent power and the true power. The relationship of current and voltage for this circuit is shown in *Figure 19–9*. The circuit with all values is shown in Figure *19–10*.

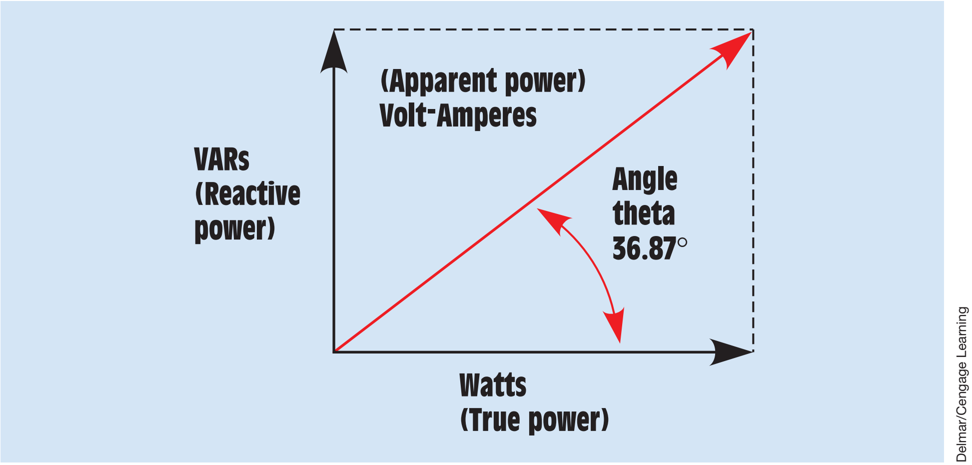


FIGURE 19–8 Angle theta.

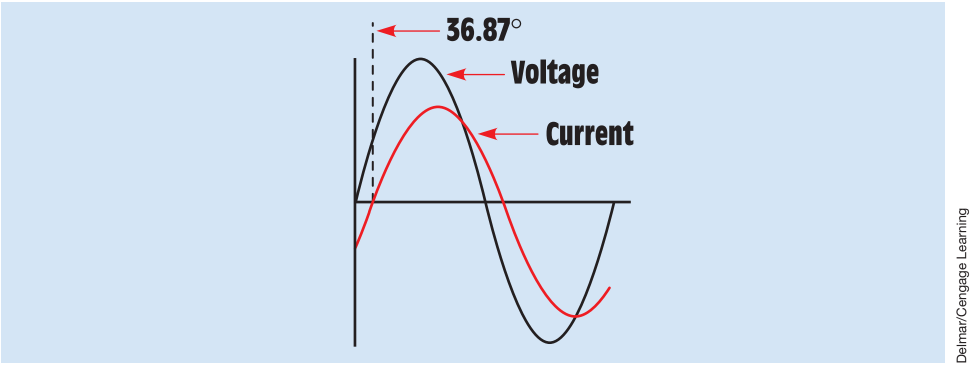


FIGURE 19–9 The current is 36.87° out of phase with the voltage.

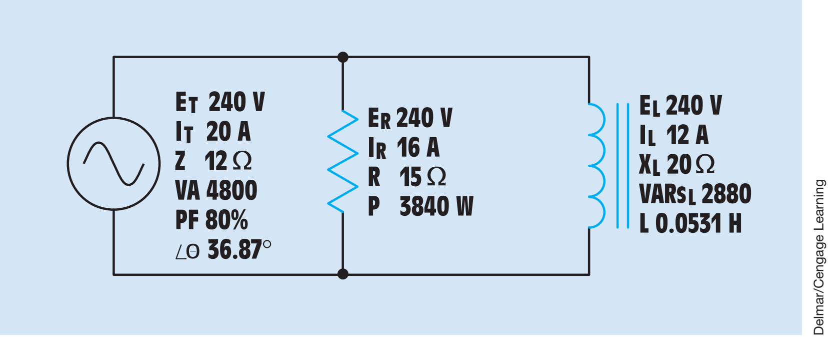


FIGURE 19–10 All values have been found.

■ EXAMPLE 19–1

In this circuit, one resistor is connected in parallel with two inductors *(Figure 19–11)*. The frequency is 60 Hz. The circuit has an apparent power of 6120 VA, the resistor has a resistance of 45 Ω, the first inductor has an inductive reactance of 40 Ω, and the second inductor has an inductive reactance of 60 Ω. It is assumed that both inductors have a Q greater than 10 and their resistance is negligible. Find the following missing values:

Z—total circuit impedance

I_T—total circuit current

E_T—applied voltage

E_R—voltage drop across the resistor

I_R—current flow through the resistor

P—watts (true power)

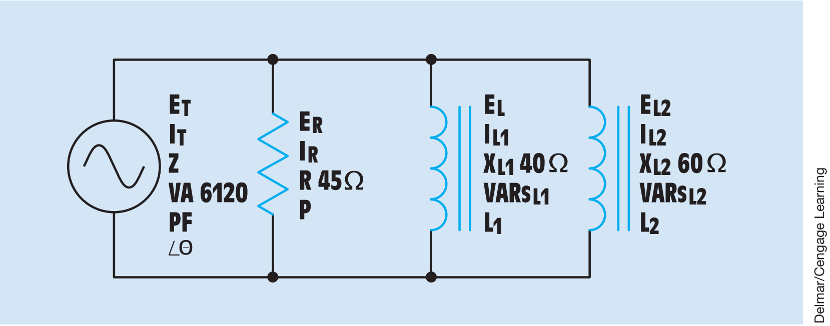


FIGURE 19–11 Example Circuit 2.

E_{L1}—voltage drop across the first inductor

I_{L1}—current flow through the first inductor

$VARs_{L1}$—reactive power of the first inductor

L_1—inductance of the first inductor

E_{L2}—voltage drop across the second inductor

I_{L2}—current flow through the second inductor

$VARs_{L2}$—reactive power of the second inductor

L_2—inductance of the second inductor

$\angle\theta$—the angle that voltage and current are out of phase with each other

Solution

Impedance

Before it is possible to calculate the impedance of the circuit, the total amount of inductive reactance for the circuit must be found. Because these two inductors are connected in parallel, the reciprocal of their inductive reactances must be added. This will give the reciprocal of the total inductive reactance:

$$\frac{1}{X_{LT}} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}}$$

To find the total inductive reactance, take the reciprocal of both sides of the equation:

$$X_{LT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}}}$$

Refer to the formulas for pure inductive circuits shown in the AC formulas section of the Appendix B. Numeric values can now be substituted in the formula to find the total inductive reactance:

$$X_{LT} = \frac{1}{\frac{1}{40\ \Omega} + \frac{1}{60\ \Omega}}$$

$$X_{LT} = \frac{1}{(0.025 + 0.01667)\frac{1}{\Omega}}$$

$$X_{LT} = 24\ \Omega$$

Now that the total amount of inductive reactance for the circuit is known, the impedance can be calculated using the formula:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_{LT}}\right)^2}}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{45\ \Omega}\right)^2 + \left(\frac{1}{24\ \Omega}\right)^2}}$$

$$Z = 21.176\ \Omega$$

A diagram showing the relationship of resistance, inductive reactance, and impedance is shown in *Figure 19–12*.

E_T

Now that the circuit impedance and the apparent power are known, the applied voltage can be calculated using the formula:

$$E_T = \sqrt{VA \times Z}$$

$$E_T = \sqrt{6120\ VA \times 21.176\ \Omega}$$

$$E_T = 359.996\ V$$

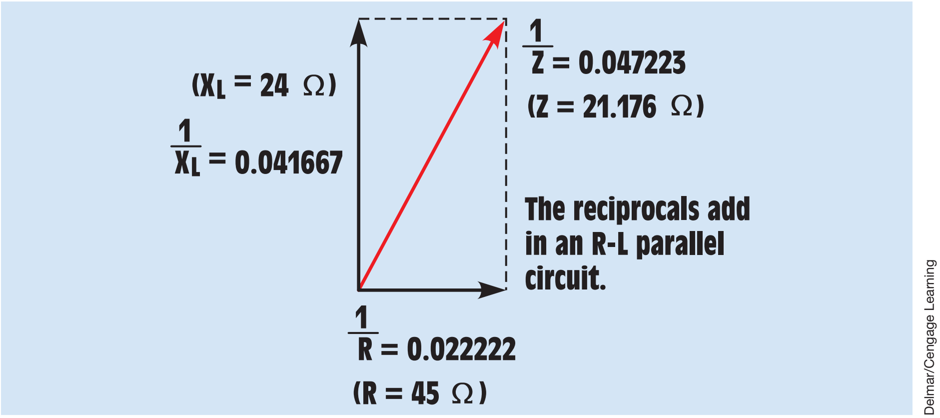


FIGURE 19–12 Relationship of resistance, inductive reactance, and impedance for Circuit 2.

E_R, E_{L1}, E_{L2}

In a parallel circuit, the voltage must be the same across any leg or branch. Therefore, 360 V is dropped across the resistor, the first inductor, and the second inductor:

$$E_R = 359.996 \text{ V}$$
$$E_{L1} = 359.996 \text{ V}$$
$$E_{L2} = 359.996 \text{ V}$$

I_T

The total current of the circuit can now be calculated using the formula:

$$I_T = \frac{E_T}{Z}$$
$$I_T = \frac{359.996 \text{ V}}{21.176\ \Omega}$$
$$I_T = 17 \text{ A}$$

The remaining values of the circuit can be found using Ohm's law. Refer to the Resistive-Inductive Parallel Circuits listed in the AC formula section in Appendix B.

I_R

$$I_R = \frac{E_R}{R}$$
$$I_R = \frac{359.996 \text{ V}}{45\ \Omega}$$
$$I_R = 8 \text{ A}$$

P

$$P = E_R \times I_R$$
$$P = 359.996 \text{ V} \times 8\ \Omega$$
$$P = 2879.968 \text{ W}$$

I_{L1}

$$I_{L1} = \frac{E_{L1}}{X_{L1}}$$
$$I_{L1} = \frac{359.996 \text{ V}}{40\ \Omega}$$
$$I_{L1} = 9 \text{ A}$$

$VARs_{L1}$

$$VARs_{L1} = E_{L1} \times I_{L1}$$
$$VARs_{L1} = 359.996\ V \times 9\ A$$
$$VARs_{L1} = 3239.964$$

L_1

$$L_1 = \frac{X_{L1}}{2\pi f}$$
$$L_1 = \frac{40\ \Omega}{377}$$
$$L_1 = 0.106\ H$$

I_{L2}

$$I_{L2} = \frac{E_{L2}}{X_{L2}}$$
$$I_{L2} = \frac{359.996\ V}{60\ \Omega}$$
$$I_{L2} = 6\ A$$

$VARs_{L2}$

$$VARs_{L2} = E_{L2} \times I_{L2}$$
$$VARs_{L2} = 359.996 \times 6$$
$$VARs_{L2} = 2159.976$$

L_2

$$L_2 = \frac{X_{L2}}{2\pi f}$$
$$L_2 = \frac{60\ \Omega}{377}$$
$$L_2 = 0.159\ H$$

PF

$$PF = \frac{W}{VA}$$

$$PF = \frac{2879.968\ W}{6120\ VA}$$

$$PF = 47.06\%$$

$\angle\theta$

$$\cos \angle\theta = PF$$

$$\cos \angle\theta = 0.4706$$

$$\angle\theta = 61.93°$$

A vector diagram showing angle theta is shown in *Figure 19–13*. The vectors used are those for apparent power, true power, and reactive power. The phase relationship of voltage and current for this circuit is shown in *Figure 19–14*, and the circuit with all completed values is shown in *Figure 19–15*.

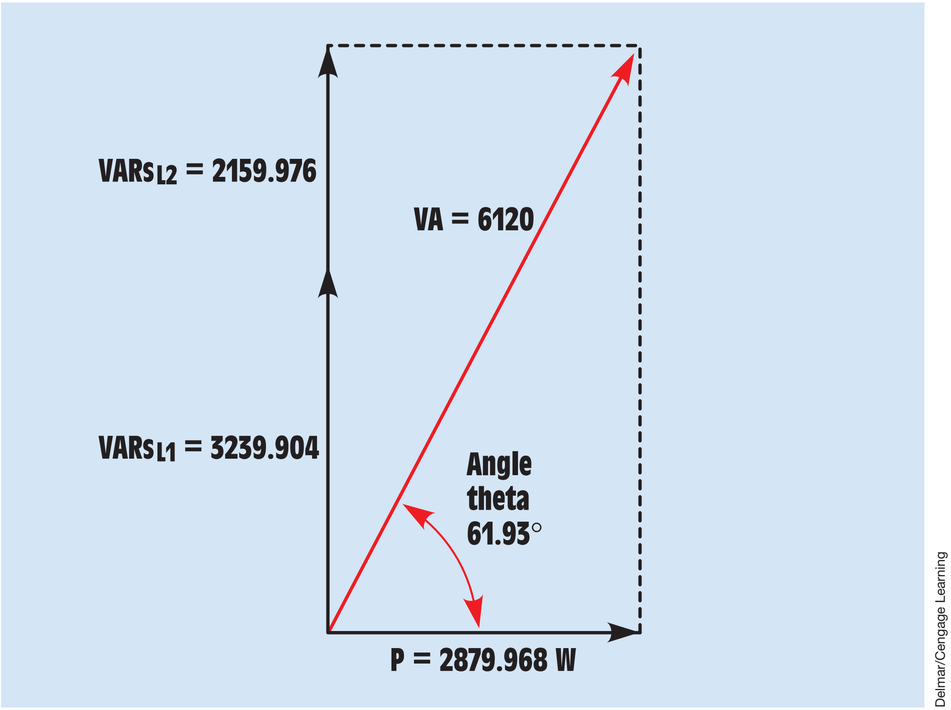


FIGURE 19–13 Angle theta determined by power vectors.

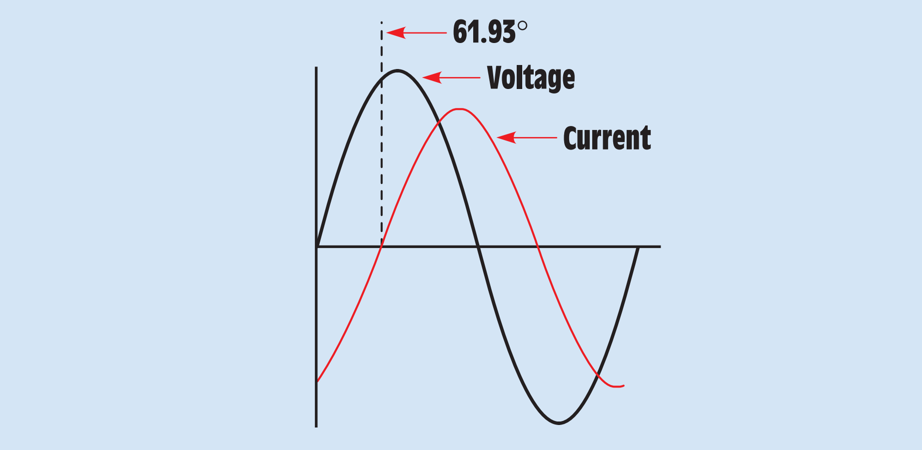


FIGURE 19–14 Voltage and current are 61.93° out of phase with each other.

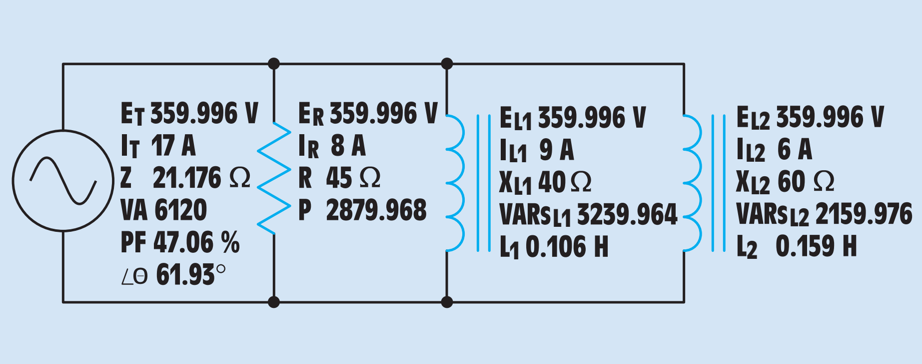


FIGURE 19–15 Completed values for Circuit 2.

Practical Applications

RL parallel circuits exist throughout the electrical field. Many circuits contain both inductive and resistive loads connected to the same branch circuit *(Figure 19–16)*. A ceiling fan, for example, often has a light kit attached to the fan. The fan is an inductive load, and the incandescent lamps are a resistive load. Branch circuits can also contain incandescent lamps, fluorescent lights, and motors connected on the same circuit. All these loads are connected in parallel. ■

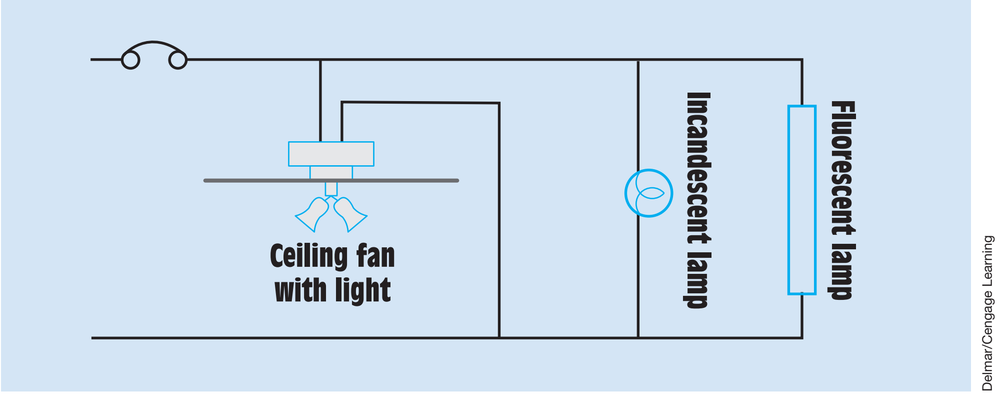


FIGURE 19–16 Branch circuits often contain resistive and inductive loads connected in parallel.

Summary

- The voltage applied across components in a parallel circuit must be the same.
- The current flowing through resistive parts of the circuit will be in phase with the voltage.
- The current flowing through inductive parts of the circuit will lag the voltage by 90°.
- The total current in a parallel circuit is equal to the sum of the individual currents. Vector addition must be used because the current through the resistive parts of the circuit is 90° out of phase with the current flowing through the inductive parts.
- The impedance of an RL parallel circuit can be calculated by using vector addition to add the reciprocals of the resistance and inductive reactance.
- Apparent power, true power, and reactive power add in any kind of a circuit. Vector addition must be used, however, because true power and reactive power are 90° out of phase with each other.

Review Questions

1. When an inductor and a resistor are connected in parallel, how many degrees out of phase are the current flow through the resistor and the current flow through the inductor?
2. An inductor and resistor are connected in parallel to a 120-V, 60-Hz line. The resistor has a resistance of 50 ohms, and the inductor has an inductance of 0.2 H. What is the total current flow through the circuit?
3. What is the impedance of the circuit in Question 2?

4. What is the power factor of the circuit in Question 2?
5. How many degrees out of phase are the current and voltage in Question 2?
6. In the circuit shown in *Figure 19–1*, the resistor has a current flow of 6.5 A and the inductor has a current flow of 8 A. What is the total current in this circuit?
7. A resistor and an inductor are connected in parallel. The resistor has a resistance of 24 ohms, and the inductor has an inductive reactance of 20 ohms. What is the impedance of this circuit?
8. The RL parallel circuit shown in *Figure 19–1* has an apparent power of 325 VA. The circuit power factor is 66%. What is the true power in this circuit?
9. The RL parallel circuit shown in *Figure 19–1* has an apparent power of 465 VA and a true power of 320 W. What is the reactive power?
10. How many degrees out of phase are the total current and voltage in Question 9?

Practical Applications

Incandescent lighting of 500 W is connected in parallel with an inductive load. A clamp-on ammeter reveals a total circuit current of 7 A. What is the inductance of the load connected in parallel with the incandescent lights? Assume a voltage of 120 V and a frequency of 60 Hz. ■

Practical Applications

You are working on a residential heat pump. The heat pump is connected to a 240-V, 60-Hz powerline. The compressor has a current draw of 34 amperes when operating. The compressor has a power factor of 70%. The back-up strip heat is rated at 10 kW. You need to know the amount of total current draw that will occur if the strip heat comes on while the compressor is operating. ■

Practice Problems

Refer to the circuit shown in *Figure 19–1*. Use the AC formulas in the Resistive-Inductive Parallel Circuits section of Appendix B.

1. Assume that the circuit shown in *Figure 19–1* is connected to a 60-Hz line and has a total current flow of 34.553 A. The inductor has an inductance of 0.02122 H, and the resistor has a resistance of 14 Ω.

E_T ______	E_R ______	E_L ______
I_T 34.553A ______	I_R ______	I_L ______
Z ______	R 14 Ω ______	X_L ______
VA ______	P ______	$VARs_L$ ______
PF ______	∠θ ______	L 0.02122 H

2. Assume that the current flow through the resistor, I_R, is 15 A; the current flow through the inductor, I_L, is 36 A; and the circuit has an apparent power of 10,803 VA. The frequency of the AC voltage is 60 Hz.

E_T ______	E_R ______	E_L ______
I_T ______	I_R 15 A ______	I_L 36 A
Z ______	R ______	X_L ______
VA 10,803	P ______	$VARs_L$ ______
PF ______	∠θ ______	L ______

3. Assume that the circuit in *Figure 19–1* has an apparent power of 144 VA and a true power of 115.2 W. The inductor has an inductance of 0.15915 H, and the frequency is 60 Hz.

E_T ______	E_R ______	E_L ______
I_T ______	I_R ______	I_L ______
Z ______	R ______	X_L ______
VA 144 ______	P 115.2 ______	$VARs_L$ ______
PF ______	∠θ ______	L 0.15915 H ______

4. Assume that the circuit in *Figure 19–1* has a power factor of 78%, an apparent power of 374.817 VA, and a frequency of 400 Hz. The inductor has an inductance of 0.0382 H.

E_T ______	E_R ______	E_L ______
I_T ______	I_R ______	I_L ______

Z ______	R ______	X_L ______
VA 374.817	P ______	$VARs_L$ ______
PF 78%	∠θ ______	L 0.0382 H

5. In an RL parallel circuit, R = 240 Ω and X_L = 360 Ω. Find impedance.
6. In an RL parallel circuit, I_T = 0.25 amps, I_R = 0.125 amps. The inductor has a reactive power of 75 VARs. What is E_T?
7. In an RL parallel circuit, E_T = 120 volts, R = 120 Ω, X_L = 150 Ω. Find I_L.
8. In an RL parallel circuit, E_T = 48 volts, I_T = 0.25 amps, R = 320 Ω. Find X_L.
9. In an RL parallel circuit, E_T = 240 volts, R = 560 Ω, and X_L = 330 Ω. Find reactive power.
10. In an RL parallel circuit, E_T = 240 volts, R = 560 Ω, and X_L = 330 Ω. Find apparent power.
11. In an RL parallel circuit, E_T = 208 volts, R = 2.4 kΩ, and X_L = 1.8 kΩ. Find I_T.
12. In an RL parallel circuit, E_T = 480 volts, R = 16 Ω, and X_L = 24 Ω. Find PF.
13. In an RL parallel circuit, I_T = 1.25 amps, R = 1.2 kΩ, and X_L = 1 kΩ. Find I_R.
14. In an RL parallel circuit, true power = 4.6 watts and reactive power = 5.4 VARs. What is the apparent power?
15. An RL parallel circuit is connected to 240 volts at 60 Hz. The resistor has a resistance of 68 Ω, and the inductor has an inductive reactance of 48 Ω. What is the reactance of the inductor?
16. An RL parallel circuit has an applied voltage of 208 volts and a total current of 2 amperes. The resistor has a value 180 Ω. Find I_L.

VII AC Circuits Containing Capacitors

Courtesy of Getty Images, Inc.

Unit 20

Capacitors

OUTLINE

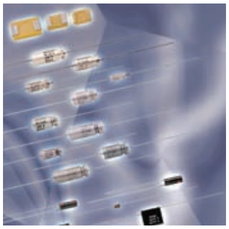
KEY TERMS

Capacitor
Dielectric
Dielectric constant
Dielectric stress
Electrolytic
Exponential
Farad
HIPOT
JAN (Joint Army-Navy) standard
Leakage current
Nonpolarized capacitors
Plates
Polarized capacitors
RC time constant
Surface area
Variable capacitors

Why You Need to Know

Capacitors are one of the major electric devices. This unit

- explains how capacitors are constructed, how they are charged and discharged, the differences between different types of capacitors, and their markings.
- describes how capacitance is measured and the importance of the voltage rating.
- explains how capacitors store energy in an electrostatic field and how current can flow only when the capacitors are charging or discharging.



Courtesy of Vishay Intertechnology.

Objectives

After studying this unit, you should be able to

- list the three factors that determine the capacitance of a capacitor.
- discuss the electrostatic charge.
- discuss the differences between nonpolarized and polarized capacitors.
- calculate values for series and parallel connections of capacitors.
- calculate an RC time constant.

Preview

Capacitors perform a variety of jobs such as power factor correction, storing an electric charge to produce a large current pulse, timing circuits, and electronic filters. Capacitors can be nonpolarized or polarized depending on the application. Nonpolarized capacitors can be used in both AC and DC circuits, whereas polarized capacitors can be used in DC circuits only. Both types are discussed in this unit. ■

20–1 Capacitors

CAUTION: *It is the habit of some people to charge a capacitor to high voltage and then hand it to another person. Although some people think this is comical, it is an extremely dangerous practice. Capacitors have the ability to supply an almost infinite amount of current. Under some conditions, a capacitor can have enough energy to cause a person's heart to go into fibrillation.* ■

This statement is not intended to strike fear into the heart of anyone working in the electrical field. It is intended to make you realize the danger that capacitors can pose under certain conditions.

Capacitors *are devices that oppose a change of voltage.* The simplest type of capacitor is constructed by separating two metal **plates** by some type of insulating material called the **dielectric** (Figure 20–1). Figure 20–2 shows the capacitor symbol. Three factors determine the capacitance of a capacitor:

1. the surface area of the plates
2. the distance between the plates
3. the type of dielectric used

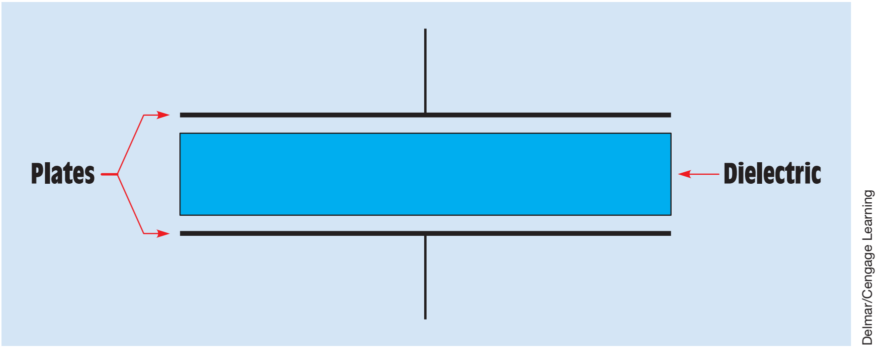


FIGURE 20–1 A capacitor is made by separating two metal plates with a dielectric.

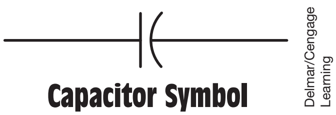


FIGURE 20–2 Symbol generally used to indicate a capacitor.

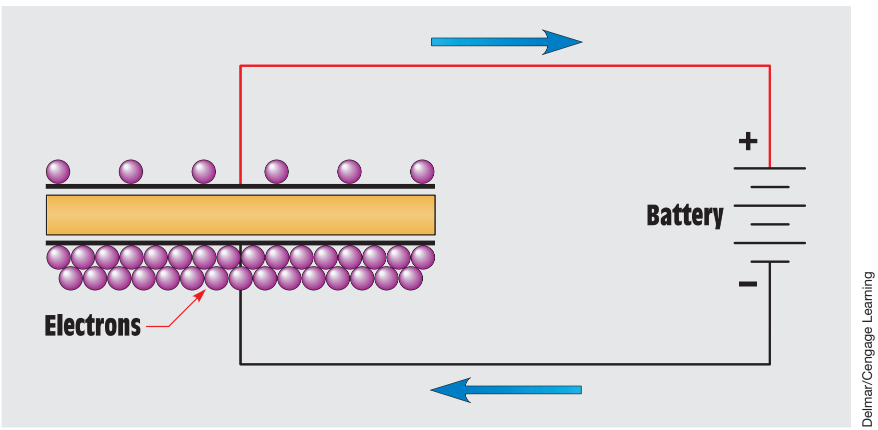


FIGURE 20–3 A capacitor can be charged by removing electrons from one plate and depositing electrons on the other plate.

The greater the **surface area** of the plates, the more capacitance a capacitor will have. If a capacitor is charged by connecting it to a DC source *(Figure 20–3)*, electrons are removed from the plate connected to the positive battery terminal and are deposited on the plate connected to the negative terminal.

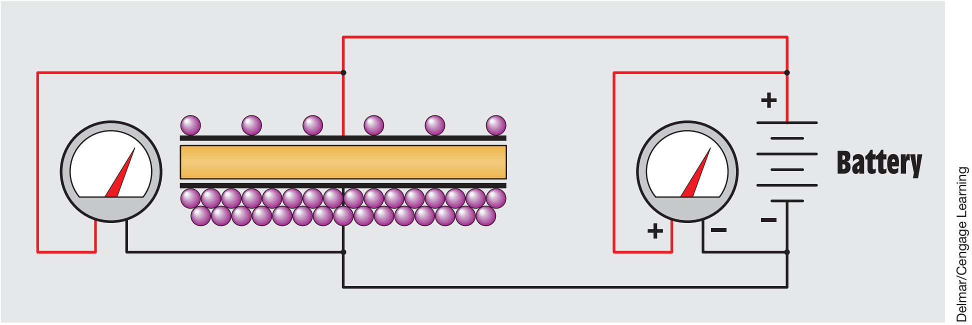


FIGURE 20–4 Current flows until the voltage across the capacitor is equal to the voltage of the battery.

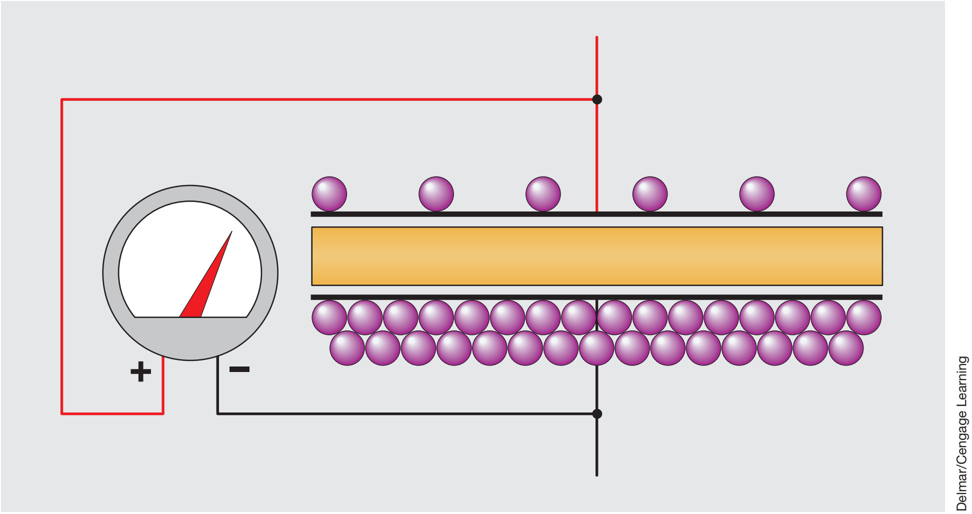


FIGURE 20–5 The capacitor remains charged after the battery is removed from the circuit.

This flow of current continues until a voltage equal to the battery voltage is established across the plates of the capacitor *(Figure 20–4)*. When these two voltages become equal, the flow of electrons stops. The capacitor is now charged. If the battery is disconnected from the capacitor, the capacitor will remain charged as long as there is no path by which the electrons can move from one plate to the other *(Figure 20–5)*. A good rule to remember concerning a capacitor and current flow is that ***current can flow only during the period of time that a capacitor is either charging or discharging.***

In theory, it should be possible for a capacitor to remain in a charged condition forever. In actual practice, however, it cannot. No dielectric is a perfect

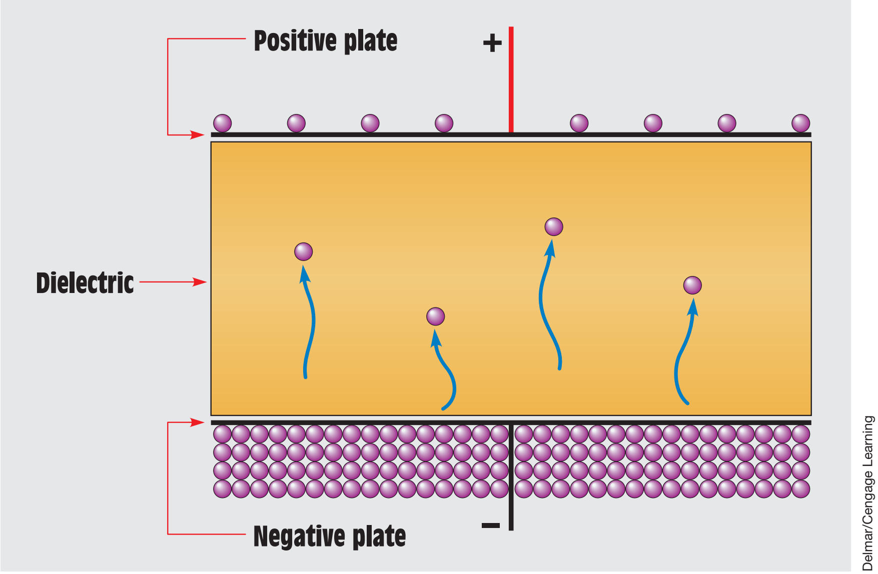


FIGURE 20–6 Electrons eventually leak through the dielectric. This flow of electrons is known as leakage current.

insulator, and electrons eventually move through the dielectric from the negative plate to the positive, causing the capacitor to discharge *(Figure 20–6)*. This current flow through the dielectric is called **leakage current** and is proportional to the resistance of the dielectric and the charge across the plates. If the dielectric of a capacitor becomes weak, it will permit an excessive amount of leakage current to flow. A capacitor in this condition is often referred to as a *leaky capacitor*.

20–2 Electrostatic Charge

Two other factors that determine capacitance are the type of dielectric used and the distance between the plates. To understand these concepts, it is necessary to understand how a capacitor stores energy. In previous units, it was discussed that an inductor stores energy in the form of a magnetic field. A capacitor stores energy in an electrostatic field.

The term *electrostatic* refers to electric charges that are stationary, or not moving. They are very similar to the static electric charges that form on objects that are good insulators, as discussed in Unit 3. The electrostatic field is formed when electrons are removed from one plate and deposited on the other.

Dielectric Stress

When a capacitor is not charged, the atoms of the dielectric are uniform as shown in *Figure 20–7*. The valence electrons orbit the nucleus in a circular pattern. When the capacitor becomes charged, however, a potential exists between the plates of the capacitor. The plate with the lack of electrons has a positive charge, and the plate with the excess of electrons has a negative charge. Because electrons are negative particles, they are repelled away from the negative plate and attracted to the positive plate. This attraction causes the electron orbit to become stretched as shown in *Figure 20–8*. This stretching of the atoms of the dielectric is called **dielectric stress.** Placing the atoms of the dielectric under stress has the same effect as drawing back a bowstring with an arrow and holding it *(Figure 20–9);* that is, it stores energy.

The amount of dielectric stress is proportional to the voltage difference between the plates. The greater the voltage, the greater the dielectric stress. If the voltage becomes too great, the dielectric will break down and permit current to flow between the plates. At this point the capacitor becomes shorted. Capacitors have a voltage rating that should not be exceeded. The voltage rating indicates the maximum amount of voltage the dielectric is intended to withstand without breaking down. The amount of voltage

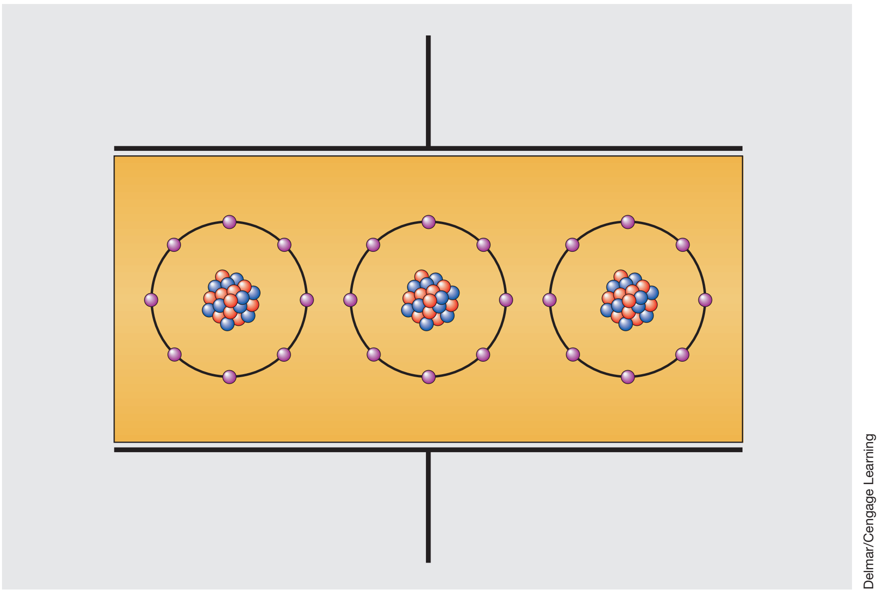


FIGURE 20–7 Atoms of the dielectric in an uncharged capacitor.

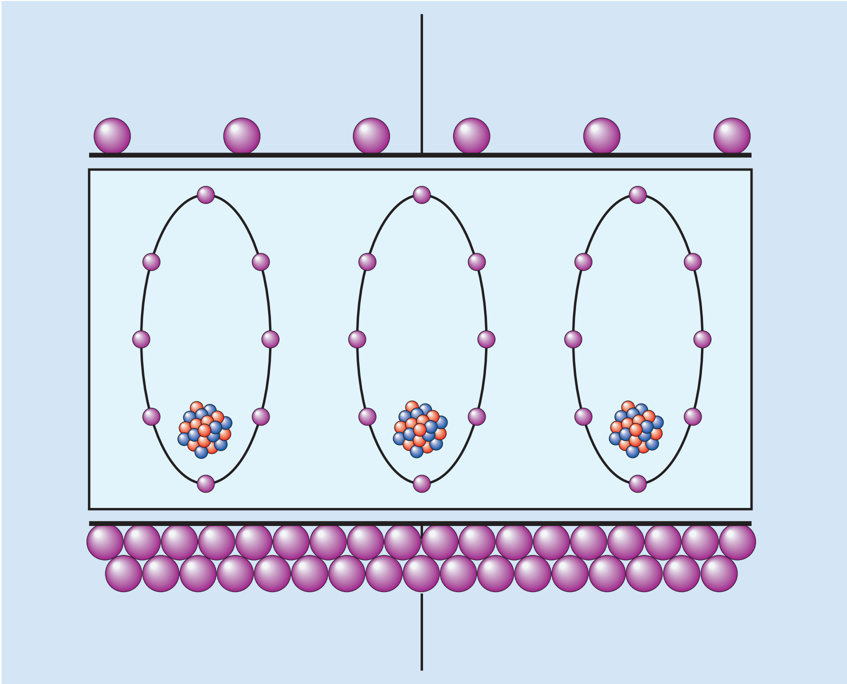


FIGURE 20–8 Atoms of the dielectric in a charged capacitor.

applied to a capacitor is critical to its life span. Capacitors operated above their voltage rating will fail relatively quickly. Many years ago, the U.S. military made a study of the voltage rating of a capacitor relative to its life span. The results showed that a capacitor operated at one half its rated voltage will have a life span approximately eight times longer than a capacitor operated at the rated voltage.

The energy of the capacitor is stored in the dielectric in the form of an electrostatic charge. It is this electrostatic charge that permits the capacitor to produce extremely high currents under certain conditions. If the leads of a capacitor are shorted together, it has the effect of releasing the drawn-back bowstring *(Figure 20–9)*. When the bowstring is released, the arrow is propelled forward at a high rate of speed. The same is true for the capacitor. When the leads are shorted, the atoms of the dielectric snap back to their normal position. Shorting causes the electrons on the negative plate to be literally blown off and attracted to the positive plate. Capacitors can produce currents of thousands of amperes for short periods of time.

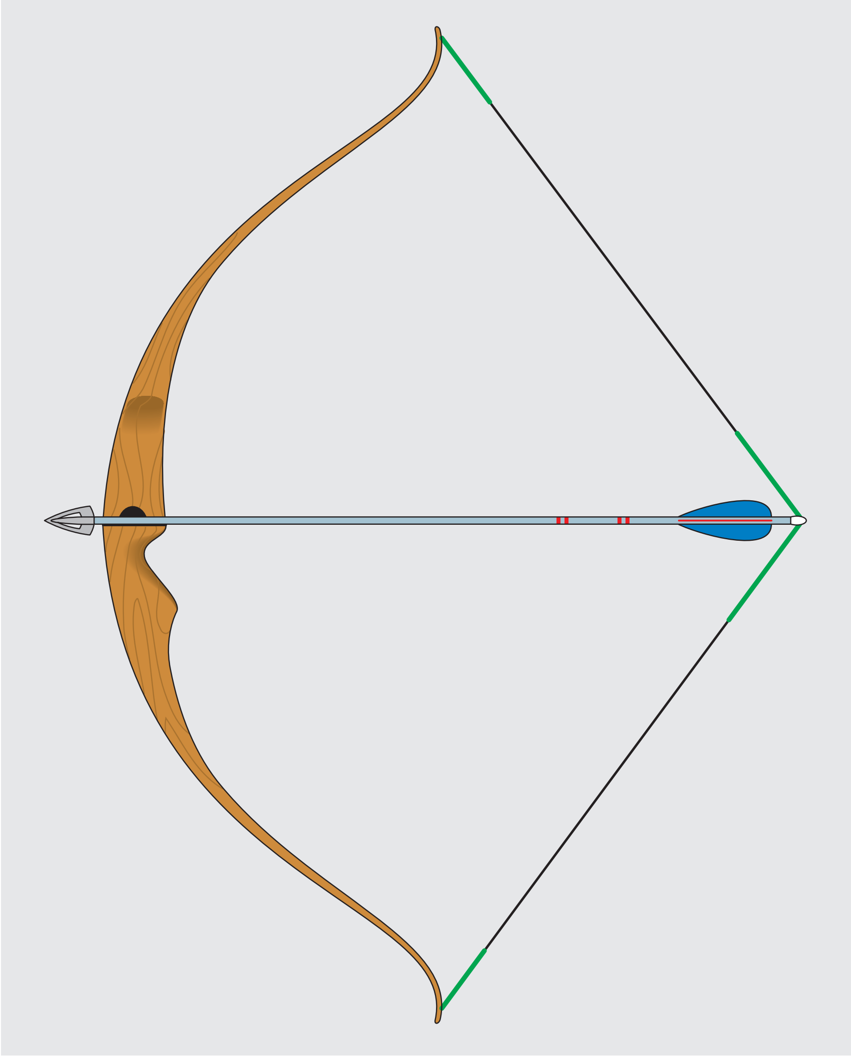


FIGURE 20–9 Dielectric stress is similar to drawing back a bowstring with an arrow and holding it.

This principle is used to operate the electronic flash of many cameras. Electronic flash attachments contain a small glass tube filled with a gas called xenon. Xenon produces a very bright white light similar to sunlight when the gas is ionized. A large amount of power is required, however, to produce a bright flash. A battery capable of directly ionizing the xenon would be very large and expensive and would have a potential of about 500 volts. The simple circuit shown in *Figure 20–10* can be used to overcome the problem. In this circuit, two small 1.5-volt batteries are connected to an oscillator. The oscillator

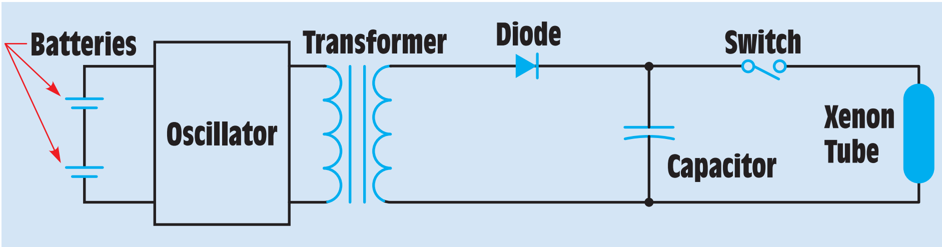


FIGURE 20–10 Energy is stored in a capacitor.

changes the DC of the batteries into square wave AC. The AC is then connected to a transformer, and the voltage is increased to about 500 volts peak. A diode changes the AC voltage back into DC and charges the capacitor. The capacitor charges to the peak value of the voltage waveform. When the switch is closed, the capacitor suddenly discharges through the xenon tube and supplies the power needed to ionize the gas. It may take several seconds to store enough energy in the capacitor to ionize the gas in the tube, but the capacitor can release the stored energy in a fraction of a second.

To understand how the capacitor can supply the energy needed, consider the amount of gunpowder contained in a 0.357 cartridge. If the powder were to be removed from the cartridge and burned in the open air, it would be found that the actual amount of energy contained in the powder is very small. This amount of energy would not even be able to raise the temperature by a noticeable amount in a small enclosed room. If this same amount of energy is converted into heat in a fraction of a second, however, enough force is developed to propel a heavy projectile with great force. This same principle is at work when a capacitor is charged over some period of time and then discharged in a fraction of a second.

20–3 Dielectric Constant

Because much of the capacitor's energy is stored in the dielectric, the type of dielectric used is extremely important in determining the amount of capacitance a capacitor will have. Different materials are assigned a number called the **dielectric constant.** Vacuum is assigned the number 1 and is used as a reference. Air has a dielectric constant of approximately 1.0006. For example, assume that a capacitor uses vacuum as the dielectric and is found to have a capacitance of 1 microfarad (1 μF). Now assume that some material is placed between the plates without changing the spacing and the capacitance value becomes 5 microfarad. This material has a dielectric constant of 5. A chart showing the dielectric constant of different materials is shown in *Figure 20–11*.

Material	Dielectric constant
Air	1.006
Bakelite	4.0 –10.0
Castor oil	4.3 – 4.7
Cellulose acetate	7.0
Ceramic	1200
Dry paper	3.5
Hard rubber	2.8
Insulating oils	2.2 – 4.6
Lucite	2.4 – 3.0
Mica	6.4 – 7.0
Mycalex	8.0
Paraffin	1.9 – 2.2
Porcelain	5.5
Pure water	81
Pyrex glass	4.1 – 4.9
Rubber compounds	3.0 – 7.0
Teflon	2
Titanium dioxide compounds	90 – 170

Delmar/Cengage Learning

FIGURE 20–11 Dielectric constant of different materials.

20–4 Capacitor Ratings

The basic unit of capacitance is the **farad** and is symbolized by the letter *F*. It receives its name from a famous scientist named Michael Faraday. ***A capacitor has a capacitance of one farad when a change of 1 volt across its plates results in a movement of 1 coulomb:***

$$Q = C \times V$$

where

Q = charge in coulombs

C = capacitance in farads

V = charging voltage

Although the farad is the basic unit of capacitance, it is seldom used because it is an extremely large amount of capacitance. The following formula can be used to determine the capacitance of a capacitor when the area of the plates, the dielectric constant, and the distance between the plates are known:

$$C = \frac{K \times A}{4.45\ D}$$

where

$$C = \text{capacitance in pF (picofarads)}$$
$$K = \text{dielectric constant (F/in.)}$$
$$A = \text{area of one plate in sq. in.}$$
$$D = \text{distance between the plates in in.}$$

■ EXAMPLE 20-1

What would be the plate area of a 1-F (farad) capacitor if air is used as the dielectric and the plates are separated by a distance of 1 in.?

Solution

The first step is to convert the preceding formula to solve for area:

$$A = \frac{C \times 4.45 \times D}{K}$$

$$A = \frac{1{,}000{,}000{,}000{,}000 \times 4.45 \times 1}{1.006}$$

$$A = 4{,}447{,}000,\ 000{,}000 \text{ sq. in.}$$

$$A = 1107.7 \text{ sq. miles}$$

Because the basic unit of capacitance is so large, other units such as the microfarad (μF), nanofarad (nF), and picofarad (pF) are generally used:

$$\mu F = \frac{1}{1{,}000{,}000}\ (1 \times 10^{-6}) \text{ of a farad}$$

$$nF = \frac{1}{1{,}000{,}000{,}000}\ (1 \times 10^{-9}) \text{ of a farad}$$

$$pF = \frac{1}{1{,}000{,}000{,}000{,}000}\ (1 \times 10^{-12}) \text{ of a farad}$$

The picofarad is sometimes referred to as a micro-microfarad and is symbolized by μμF.

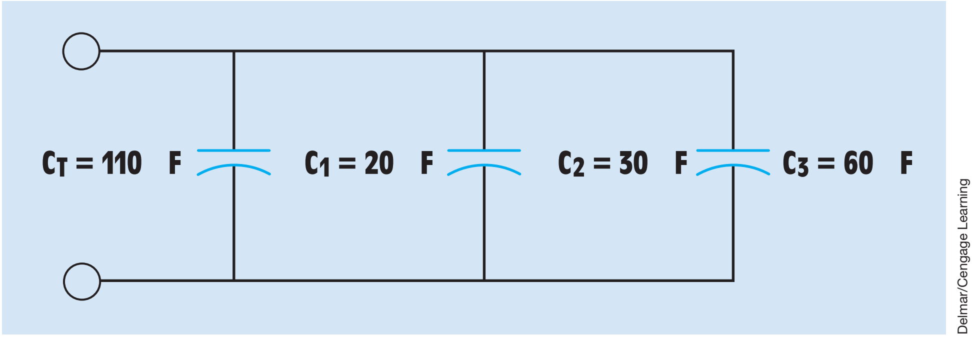


FIGURE 20–12 Capacitors connected in parallel.

20–5 Capacitors Connected in Parallel

Connecting capacitors in parallel *(Figure 20–12)* has the same effect as increasing the plate area of one capacitor. In the example shown, three capacitors having a capacitance of 20 microfarads, 30 microfarads, and 60 microfarads are connected in parallel. The total capacitance of this connection is

$$C_T = C_1 + C_2 + C_3$$
$$C_T = 20\ \mu F + 30\ \mu F + 60\ \mu F$$
$$C_T = 110\ \mu F$$

20–6 Capacitors Connected in Series

Connecting capacitors in series *(Figure 20–13)* has the effect of increasing the distance between the plates, thus reducing the total capacitance of the circuit. The total capacitance can be calculated in a manner similar to calculating

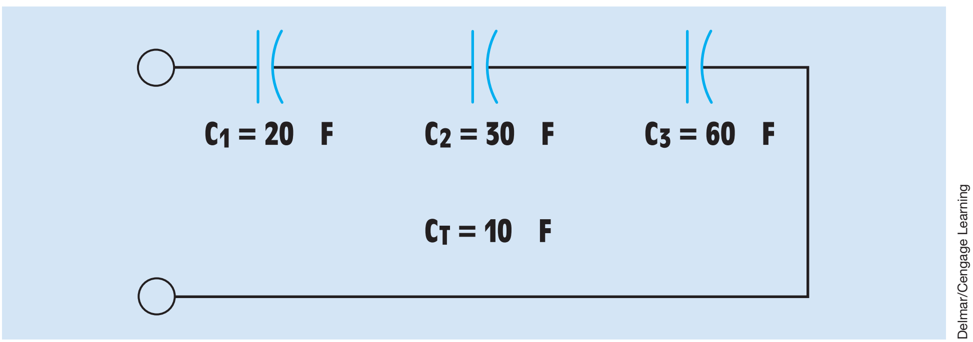


FIGURE 20–13 Capacitors connected in series.

parallel resistance. The following formulas can be used to find the total capacitance when capacitors are connected in series:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

or

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

or

$$C_T = \frac{C}{N}$$

where

C = capacitance of one capacitor

N = number of capacitors connected in series

Note: The last formula can be used only when all the capacitors connected in series are of the same value.

EXAMPLE 20-2

What is the total capacitance of three capacitors connected in series if C_1 has a capacitance of 20 μF, C_2 has a capacitance of 30 μF, and C_3 has a capacitance of 60 μF?

Solution

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

$$C_T = \frac{1}{\frac{1}{20\ \mu F} + \frac{1}{30\ \mu F} + \frac{1}{60\ \mu F}}$$

$$C_T = 10\ \mu F$$

20–7 Capacitive Charge and Discharge Rates

Capacitors charge and discharge at an **exponential** rate. A charge curve for a capacitor is shown in *Figure 20–14*. The curve is divided into five time constants, and during each time constant the voltage changes by an amount equal to 63.2% of the maximum amount that it can change. In *Figure 20–14,* it is assumed that a capacitor is to be charged to a total of 100 volts. At the end of the first time constant, the voltage has reached 63.2% of 100, or 63.2 volts. At the end of the second time constant, the voltage reaches 63.2% of the remaining voltage, or 86.4 volts. This pattern continues until the capacitor has been charged to 100 volts.

The capacitor discharges in the same manner *(Figure 20–15)*. At the end of the first time constant, the voltage will decrease by 63.2% of its charged value. In this example, the voltage decreases from 100 volts to 36.8 volts in the first time constant. At the end of the second time constant, the voltage will drop to 13.6 volts; and by the end of the third time constant, the voltage will drop to 5 volts. The voltage will continue to drop at this rate until it reaches approximately 0 after five time constants.

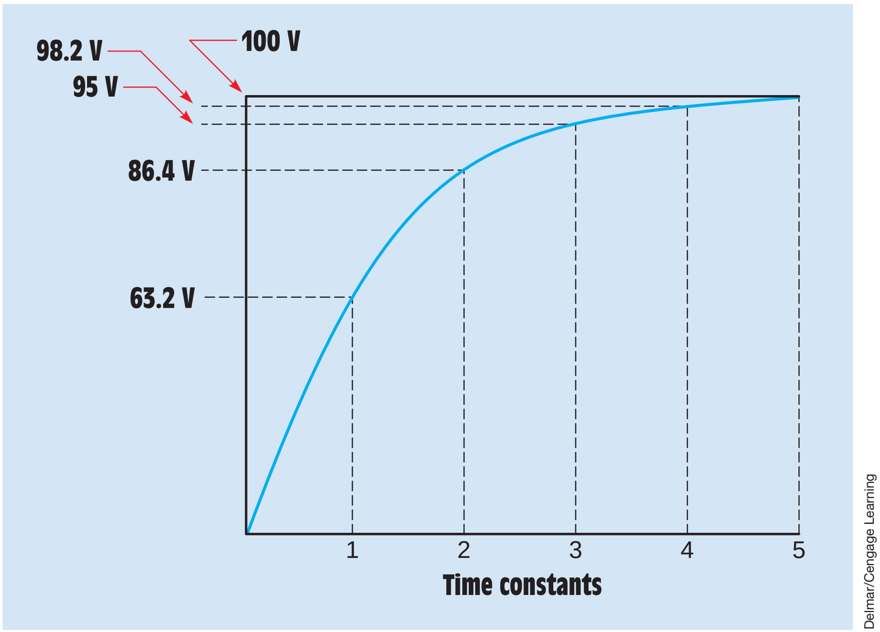


FIGURE 20–14 Capacitors charge at an exponential rate.

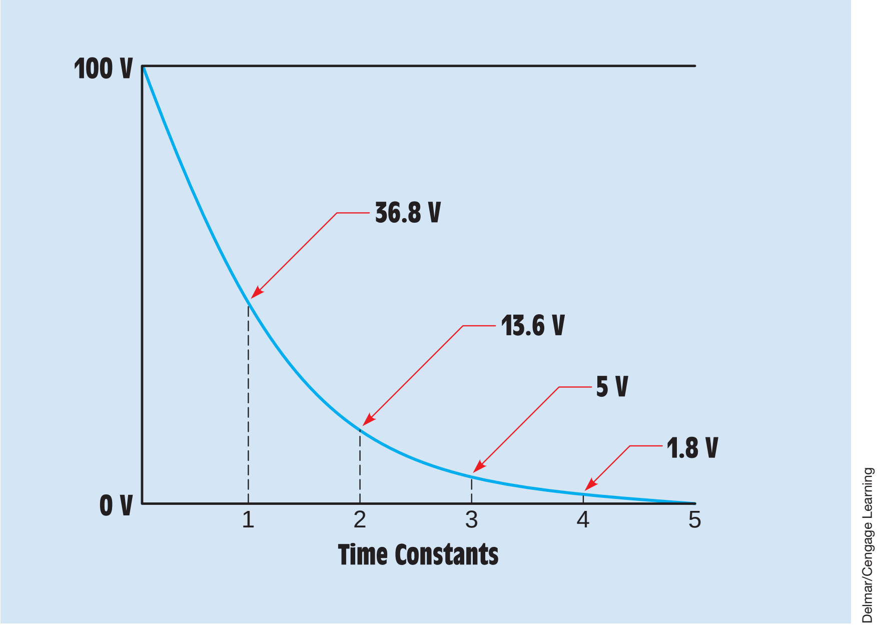


FIGURE 20–15 Capacitor discharge curve.

20–8 RC Time Constants

When a capacitor is connected in a circuit with a resistor, the amount of time needed to charge the capacitor—that is, the **RC time constant**—can be determined very accurately *(Figure 20–16)*. The formula for determining charge time is

$$\tau = R \times C$$

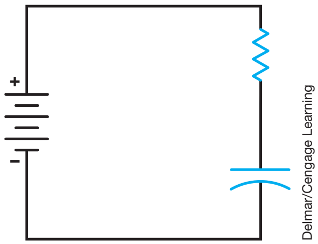


FIGURE 20–16 The charge time of the capacitor can be determined very accurately.

where

τ = the time for one time constant in seconds

R = resistance in ohms

C = capacitance in farads

The Greek letter τ (tau) is used to represent the time for one time constant. It is not unusual, however, for the letter *t* to be used to represent time.

EXAMPLE 20-3

How long will it take the capacitor shown in *Figure 20–15* to charge if it has a value of 50 μF and the resistor has a value of 100 kΩ?

Solution

$$\tau = R \times C$$

$$\tau = 0.000050\ F \times 100{,}000\ \Omega$$

$$\tau = 5\ s$$

The formula is used to find the time for one time constant. Five time constants are required to charge the capacitor:

$$\text{Total time} = 5\ s \times 5\ \text{time constants}$$

$$\text{Total time} = 25\ s$$

EXAMPLE 20-4

How much resistance should be connected in series with a 100-pF capacitor to give it a total charge time of 0.2 s?

Solution

Change the preceding formula to solve for resistance:

$$R = \frac{\tau}{C}$$

The total charge time is to be 0.2 s. The value of τ is therefore 0.2/5 = 0.04 s. Substitute these values in the formula:

$$R = \frac{0.04\ s}{100^{\times 10^{-12}}\ F}$$

$$R = 400\ M\Omega$$

■ EXAMPLE 20-5

A 500-kΩ resistor is connected in series with a capacitor. The total charge time of the capacitor is 15 s. What is the capacitance of the capacitor?

Solution

Change the base formula to solve for the value of capacitance:

$$C = \frac{\tau}{R}$$

Because the total charge time is 15 s, the time of one time constant will be 3 s (15 s/5 = 3 s):

$$C = \frac{3\ s}{500{,}000\ \Omega}$$

$$C = 0.000006F$$

or

$$C = 6\ \mu F$$

20–9 Applications for Capacitors

Capacitors are among the most used of electric components. They are used for power factor correction in industrial applications; in the start windings of many single-phase AC motors; to produce phase shifts for SCR and Triac circuits; to filter pulsating DC; and in RC timing circuits. (SCRs and Triacs are solid-state electronic devices used throughout industry to control high-current circuits.) Capacitors are used extensively in electronic circuits for control of frequency and pulse generation. The type of capacitor used is dictated by the circuit application.

20–10 Nonpolarized Capacitors

Capacitors can be divided into two basic groups, nonpolarized and polarized. **Nonpolarized capacitors** are often referred to as *AC capacitors* because they are not sensitive to polarity connection. Nonpolarized capacitors can be connected to either DC or AC circuits without harm to the capacitor. Nonpolarized capacitors are constructed by separating metal plates by some type of dielectric *(Figure 20–1)*. These capacitors can be obtained in many different styles and case types *(Figure 20–17)*.

A common type of AC capacitor called the paper capacitor or oil-filled paper capacitor is often used in motor circuits and for power factor correction *(Figure 20–18)*. It derives its name from the type of dielectric used. This capacitor is constructed by separating plates made of metal foil with thin sheets

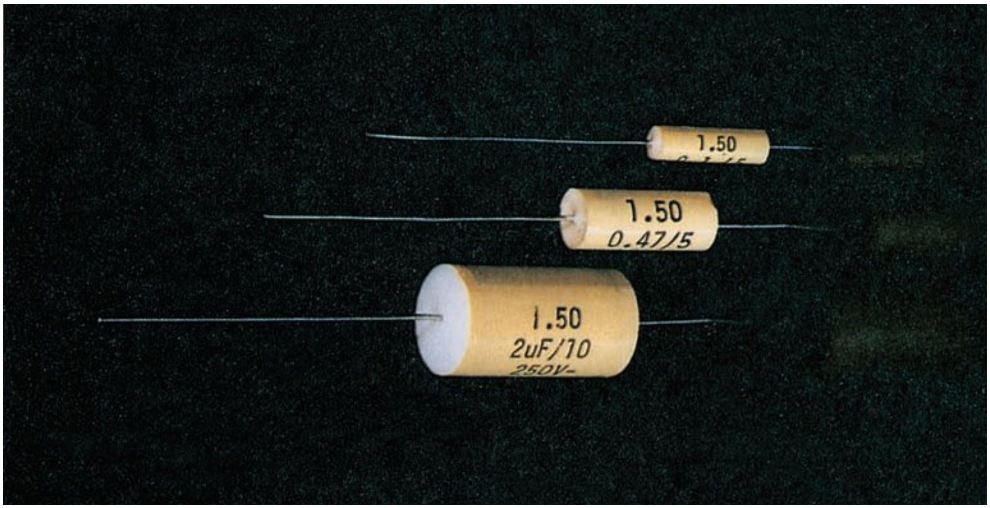


FIGURE 20–17 Nonpolarized capacitors. *(Courtesy of Vishay Intertechnology)*

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FIGURE 20–18 Oil-filled paper capacitor.

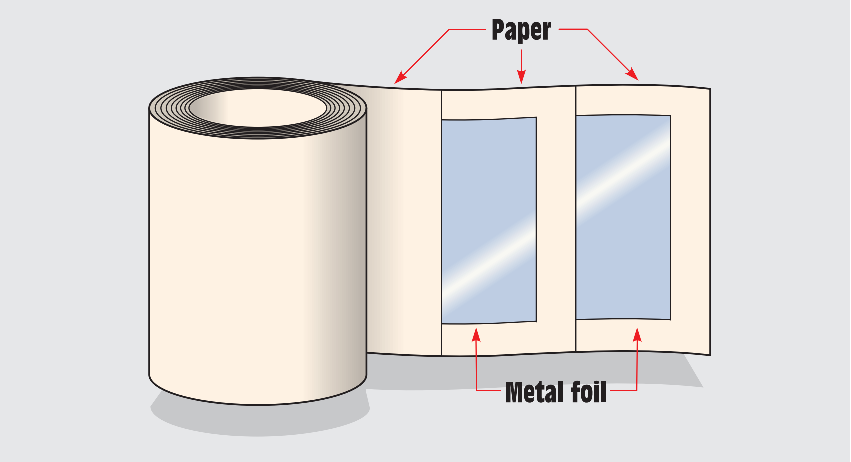

FIGURE 20–19 Oil-filled paper capacitor.

of paper soaked in a dielectric oil *(Figure 20–19)*. These capacitors are often used as the run or starting capacitors for single-phase motors. Many manufacturers of oil-filled capacitors identify one terminal with an arrow, a painted dot, or a stamped dash in the capacitor can *(Figure 20–20)*. This identified terminal marks the connection to the plate that is located nearer to the metal container or can. It has long been known that when a capacitor's dielectric breaks down and permits a short circuit to ground, the plate nearer to the outside case most

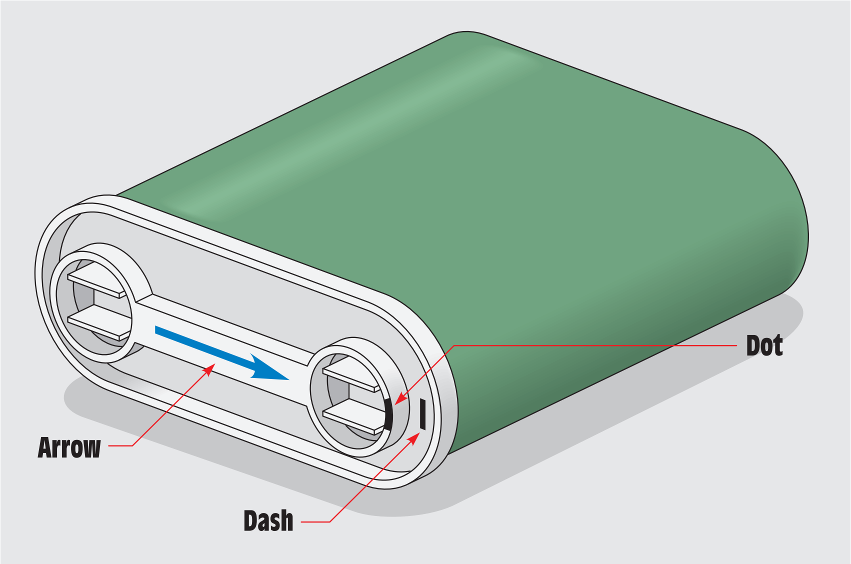

FIGURE 20–20 Marks indicate plate nearest capacitor case.

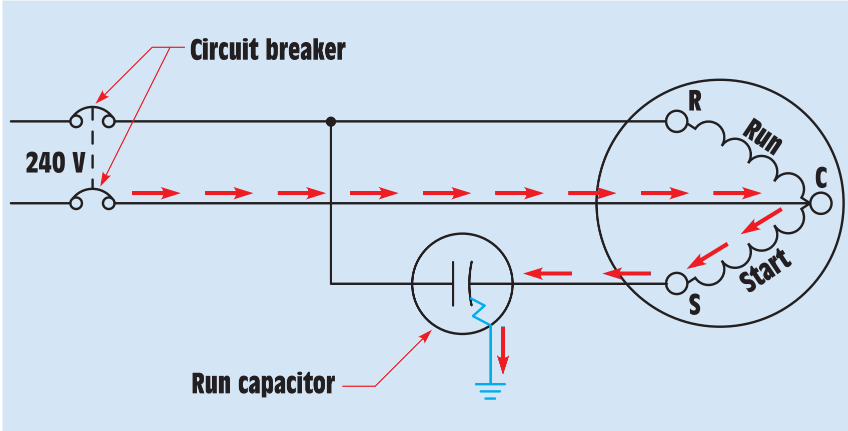

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FIGURE 20–21 Identified capacitor terminal connected to motor start winding (incorrect connection).

often becomes grounded. For this reason, it is generally desirable to connect the identified capacitor terminal to the line side instead of to the motor start winding.

In *Figure 20–21,* the run capacitor has been connected in such a manner that the identified terminal is connected to the start winding of a single-phase motor. If the capacitor should become shorted to ground, a current path exists through the motor start winding. The start winding is an inductive-type load, and inductive reactance will limit the value of current flow to ground. Because the flow of current is limited, it will take the circuit breaker or fuse some time to open the circuit and disconnect the motor from the power line. This time delay can permit the start winding to overheat and become damaged.

In *Figure 20–22,* the run capacitor has been connected in the circuit in such a manner that the identified terminal is connected to the line side. If the

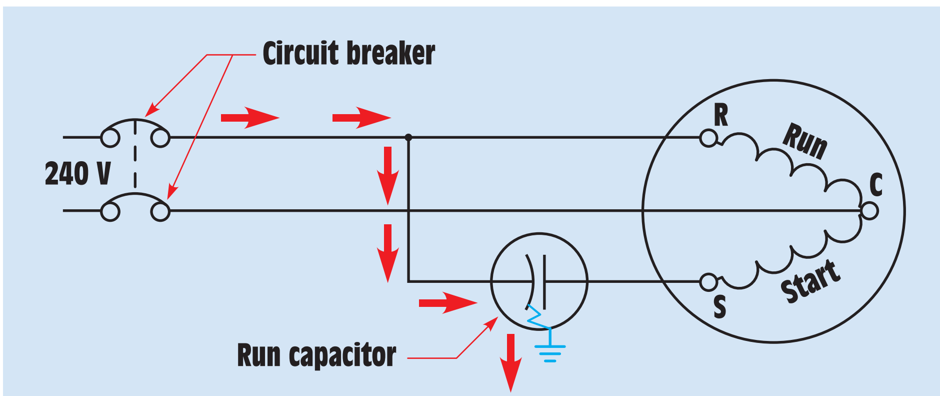

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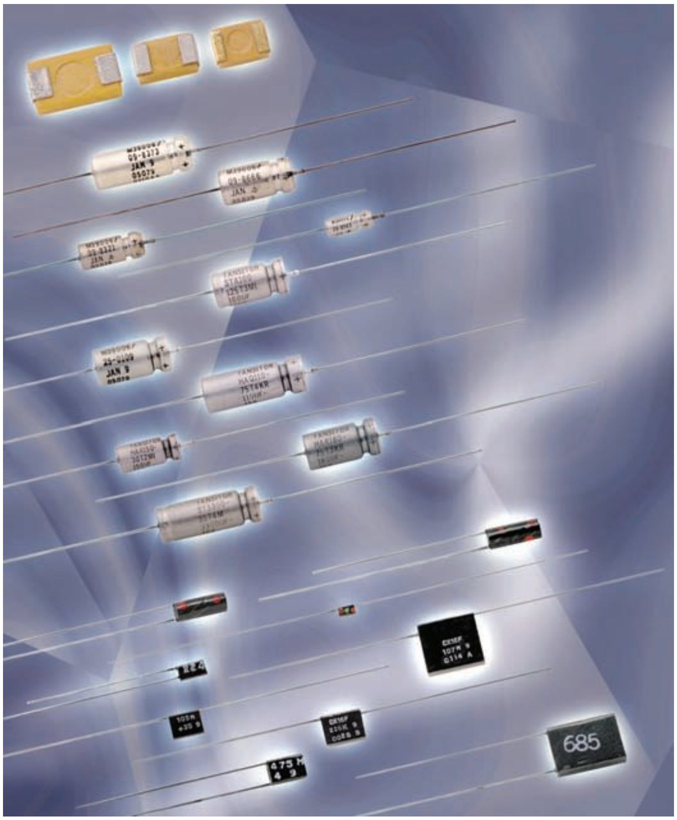
FIGURE 20–22 Identified terminal connected to the line (correct connections).

capacitor should become shorted to ground, a current path exists directly to ground, bypassing the motor start winding. When the capacitor is connected in this manner, the start winding does not limit current flow and permits the fuse or circuit breaker to open the circuit almost immediately.

20–11 Polarized Capacitors

Polarized capacitors are generally referred to as **electrolytic** capacitors. These capacitors are sensitive to the polarity they are connected to and have one terminal identified as positive or negative *(Figure 20–23)*. Polarized capacitors can be used in DC circuits only. If their polarity connection is reversed, the capacitor can be damaged and will sometimes explode. The advantage of electrolytic capacitors is that they can have very high capacitance in a small case.



Courtesy of Vishay Intertechnology

FIGURE 20–23 Polarized capacitors.

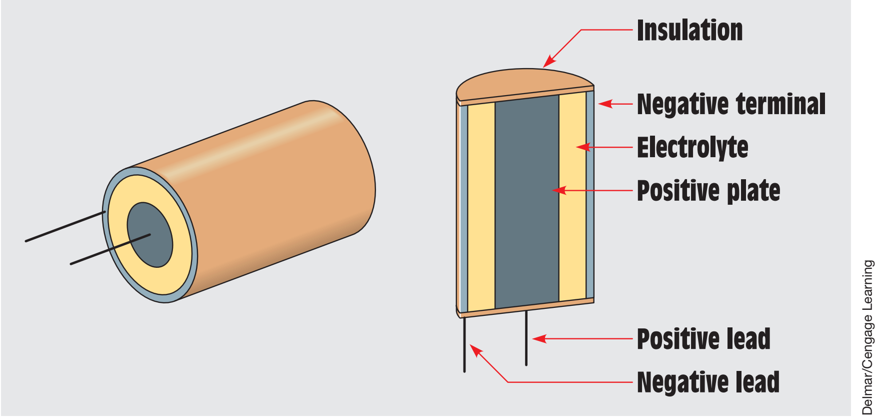


FIGURE 20–24 Wet-type electrolytic capacitor.

The two basic types of electrolytic capacitors are the wet type and the dry type. The wet-type electrolytic capacitor *(Figure 20–24)* has a positive plate made of aluminum foil. The negative plate is actually an electrolyte made from a borax solution. A second piece of aluminum foil is placed in contact with the electrolyte and becomes the negative terminal. When a source of DC is connected to the capacitor, the borax solution forms an insulating oxide film on the positive plate. This film is only a few molecules thick and acts as the insulator to separate the plates. The capacitance is very high because the distance between the plates is so small.

If the polarity of the wet-type electrolytic capacitor becomes reversed, the oxide insulating film dissolves and the capacitor becomes shorted. If the polarity connection is corrected, the film reforms and restores the capacitor.

AC Electrolytic Capacitors

This ability of the wet-type electrolytic capacitor to be shorted and then reformed is the basis for a special type of nonpolarized electrolytic capacitor called the AC electrolytic capacitor. This capacitor is used as the starting capacitor for many small single-phase motors, as the run capacitor in many ceiling fan motors, and for low-power electronic circuits when a nonpolarized capacitor with a high capacitance is required. The AC electrolytic capacitor is made by connecting two wet-type electrolytic capacitors together inside the same case *(Figure 20–25)*. In the example shown, the two wet-type electrolytic capacitors have their negative terminals connected. When AC is applied to the leads, one capacitor will be connected to reverse polarity and become shorted. The other capacitor will be connected to the correct polarity and will form. During the next half cycle, the polarity changes and forms the capacitor that was shorted and shorts the other capacitor. An AC electrolytic capacitor is shown in *Figure 20–26.*

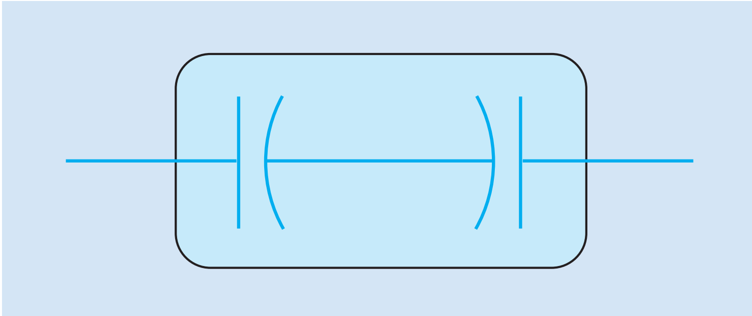


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FIGURE 20–25 Two wet-type electrolytic capacitors connect to form an AC electrolytic capacitor.

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FIGURE 20–26 An AC electrolytic capacitor.

Dry-Type Electrolytic Capacitors

The dry-type electrolytic capacitor is very similar to the wet type except that gauze is used to hold the borax solution. This prevents the capacitor from leaking. Although the dry-type electrolytic capacitor has the advantage of being relatively leak proof, it does have one disadvantage. If the polarity connection should become reversed and the oxide film is broken down, it will not reform when connected to the proper polarity. Reversing the polarity of a dry-type electrolytic capacitor permanently damages the capacitor.

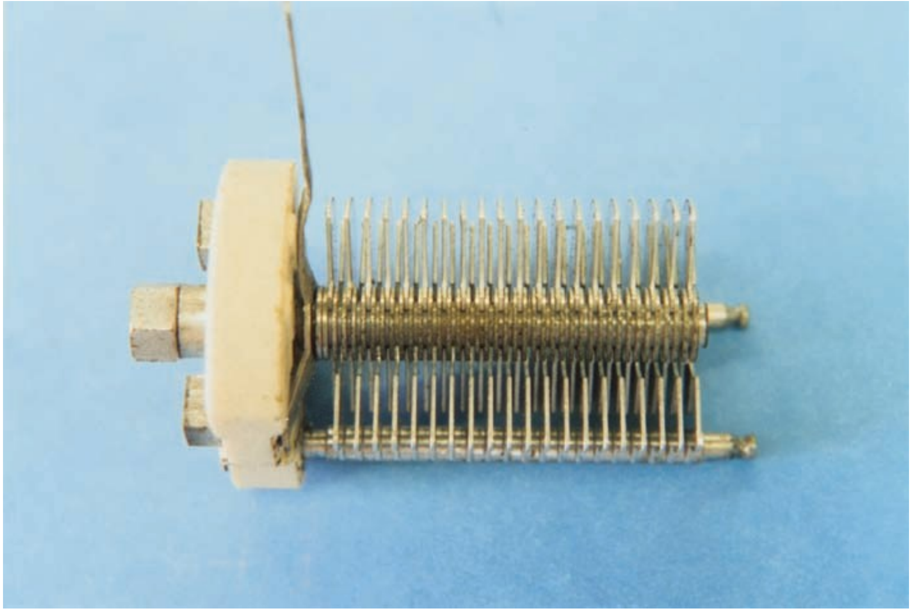


FIGURE 20–27 A variable capacitor.

20–12 Variable Capacitors

Variable capacitors are constructed in such a manner that their capacitance value can be changed over a certain range. They generally contain a set of movable plates, which are connected to a shaft, and a set of stationary plates *(Figure 20–27)*. The movable plates can be interleaved with the stationary plates to increase or decrease the capacitance value. Because air is used as the dielectric and the plate area is relatively small, variable capacitors are generally rated in picofarads. Another type of small variable capacitor is called the trimmer capacitor *(Figure 20–28)*. This capacitor has one movable plate and one stationary plate. The capacitance value is changed by turning

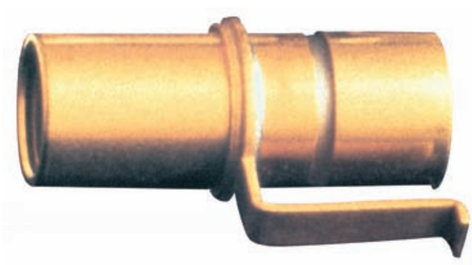


FIGURE 20–28 A trimmer capacitor.

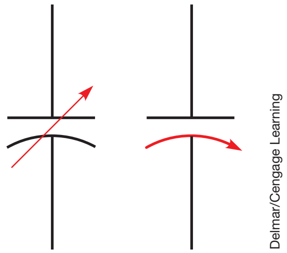


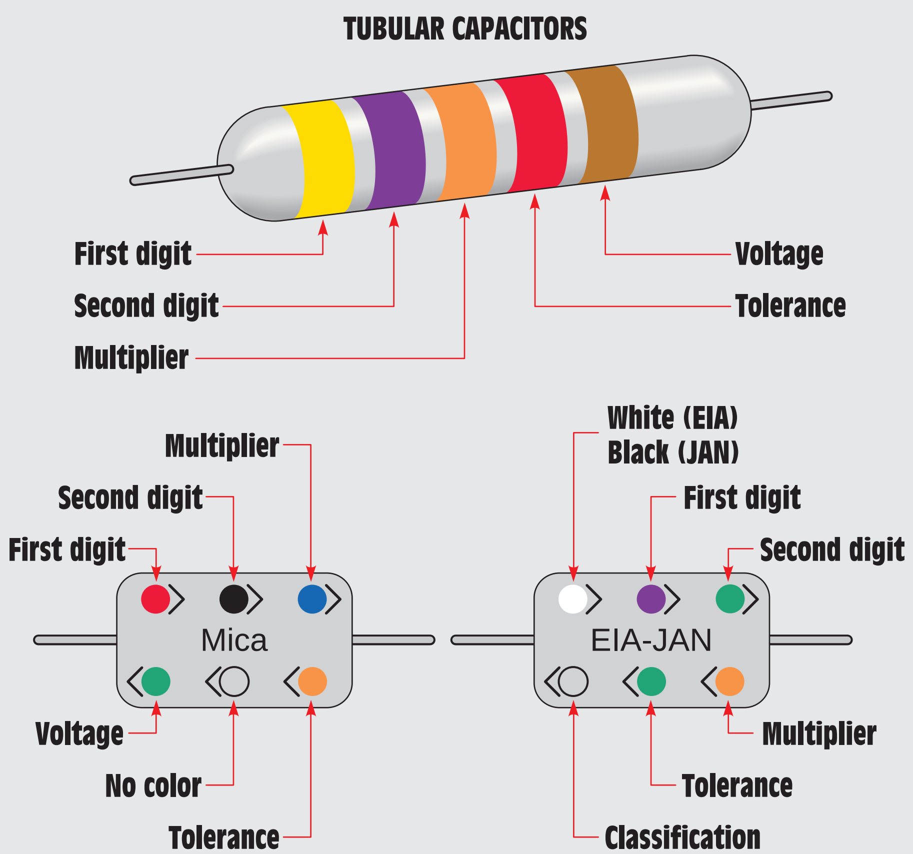
FIGURE 20–29 Variable capacitor symbols.

an adjustment screw that moves the movable plate closer to or farther away from the stationary plate. *Figure 20–29* shows schematic symbols used to represent variable capacitors.

20–13 Capacitor Markings

Different types of capacitors are marked in different ways. Large AC oil-filled paper capacitors generally have their capacitance and voltage values written on the capacitor. The same is true for most electrolytic and small nonpolarized capacitors. Other types of capacitors, however, depend on color codes or code numbers and letters to indicate the capacitance value, tolerance, and voltage rating. Although color coding for capacitors has been abandoned in favor of direct marking by most manufacturers, it is still used by some. Also, many older capacitors with color codes are still in use. For this reason, we discuss color coding for several types of capacitors. Unfortunately, there is no actual set standard used by all manufacturers. The color codes presented are probably the most common. An identification chart for postage stamp (so called because of their size and shape) mica capacitors and tubular paper or tubular mica capacitors is shown in *Figure 20–30*. Note that most postage stamp mica capacitors use a five-dot color code. There are six-dot color codes, however. When a six-dot color code is used, the third dot represents a third digit and the rest of the code is the same as a five-dot code. The capacitance values given are in picofarads. Although these markings are typical, there is no actual standard and it may be necessary to use the manufacturer's literature to determine the true values.

A second method for color coding mica capacitors is called the EIA (Electronic Industries Association) standard, or the **JAN (Joint Army-Navy) standard.** The JAN standard is used for electronic components intended for military use. When the EIA standard is employed, the first dot is white. In some instances, the first dot may be silver instead of white. This indicates that the capacitor's dielectric is paper instead of mica. When the JAN standard is used, the first dot is black. The second and third dots represent digits, the fourth dot is the multiplier, the fifth dot is the tolerance, and the sixth dot indicates classes A to E of temperature and leakage coefficients.



COLOR	NUMBER	MULTIPLIER	TOLERANCE (%)	VOLTAGE
No color			20	500
Black	0	1		
Brown	1	10	1	100
Red	2	100	2	200
Orange	3	1000	3	300
Yellow	4	10,000	4	400
Green	5	100,000	5 (EIA)	500
Blue	6	1,000,000	6	600
Violet	7	10,000,000	7	700
Gray	8	100,000,000	8	800
White	9	1,000,000,000	9	900
Gold		0.1	5 (JAN)	1000
Silver		0.01	10	2000

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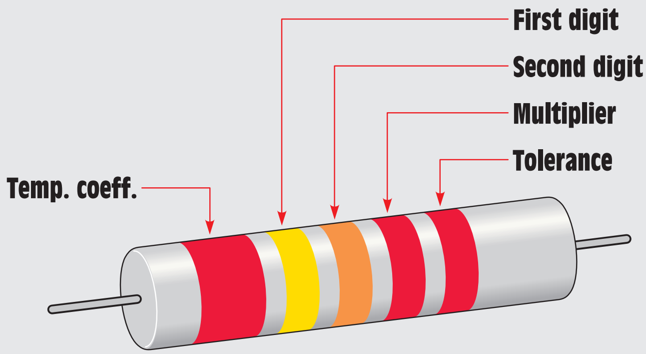
FIGURE 20–30 Identification of mica and tubular capacitors.

20–14 Temperature Coefficients

The temperature coefficient indicates the amount of capacitance change with temperature. Temperature coefficients are listed in parts per million (ppm) per degree Celsius. A positive temperature coefficient indicates that the capacitor will increase its capacitance with an increase in temperature. A negative temperature coefficient indicates that the capacitance will decrease with an increase in temperature.

20–15 Ceramic Capacitors

Another capacitor that often uses color codes is the ceramic capacitor *(Figure 20–31)*. This capacitor generally has one band that is wider than the others. The wide band indicates the temperature coefficient, and the other bands are first and second digits, multiplier, and tolerance.



COLOR	NUMBER	MULTIPLIER	TOLERANCE OVER 10 pF	TOLERANCE 10 pF OR LESS	TEMP. COEFF.
Black	0	1	20%	2.0 pF	0
Brown	1	10	1%		N30
Red	2	100	2%		N80
Orange	3	1000			N150
Yellow	4				N220
Green	5				N330
Blue	6		5%	0.5 pF	N470
Violet	7				N750
Gray	8	0.01		0.25 pF	P30
White	9	0.1	10%	1.0 pF	P500

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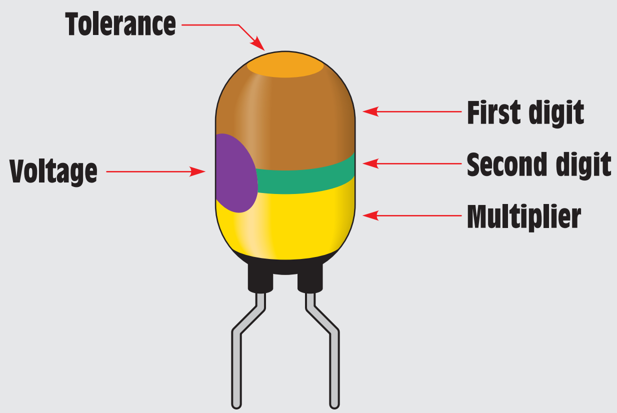
FIGURE 20–31 Color codes for ceramic capacitors.

20–16 Dipped Tantalum Capacitors

A dipped tantalum capacitor is shown in *Figure 20–32*. This capacitor has the general shape of a match head but is somewhat larger. Color bands and dots determine the value, tolerance, and voltage. The capacitance value is given in picofarads.



COLOR	NUMBER	MULTIPLIER	TOLERANCE (%)	VOLTAGE
			No dot 20	
Black	0			4
Brown	1			6
Red	2			10
Orange	3			15
Yellow	4	10,000		20
Green	5	100,000		25
Blue	6	1,000,000		35
Violet	7	10,000,000		50
Gray	8			
White	9			3
Gold			5	
Silver			10	

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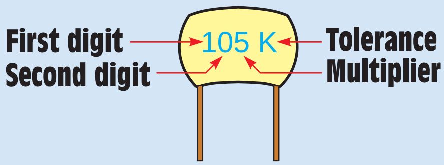
FIGURE 20–32 Dipped tantalum capacitors.

20–17 Film Capacitors

Not all capacitors use color codes to indicate values. Some capacitors use numbers and letters. A film-type capacitor is shown in *Figure 20–33*. This capacitor is marked 105 K. The value can be read as follows:

1. The first two numbers indicate the first two digits of the value.
2. The third number is the multiplier. Add the number of zeros to the first two numbers indicated by the multiplier. In this example, add five zeros to 10. The value is given in picofarads (pF). This capacitor has a value of 1,000,000 pF or 1 μF.
3. The K is the tolerance. In this example, K indicates a tolerance of ±10%.



NUMBER	MULTIPLIER	TOLERANCE		
			10 pF or less	Over 10 pF
0	1	B	0.1 pF	
1	10	C	0.25 pF	
2	100	D	0.5 pF	
3	1000	F	1.0 pF	1%
4	10,000	G	2.0 pF	2%
5	100,000	H		3%
6		J		5%
7		K		10%
8	0.01	M		20%
9	0.1			

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FIGURE 20–33 Film-type capacitors.

20–18 Testing Capacitors

Testing capacitors is difficult at best. Small electrolytic capacitors are generally tested for shorts with an ohmmeter. If the capacitor is not shorted, it should be tested for leakage using a variable DC power supply and a microammeter *(Figure 20–34)*. When rated voltage is applied to the capacitor, the microammeter should indicate zero current flow.

Large AC oil-filled capacitors can be tested in a similar manner. To test the capacitor accurately, two measurements must be made. One is to measure the capacitance value of the capacitor to determine if it is the same or approximately the same as the rated value. The other is to test the strength of the dielectric.

The first test should be made with an ohmmeter. With the power disconnected, connect the terminals of an ohmmeter directly across the capacitor terminals *(Figure 20–35)*. This test determines if the dielectric is shorted. When the ohmmeter is connected, the needle should swing up scale and return to infinity. The amount of needle swing is determined by the capacitance of the capacitor. Then reverse the ohmmeter connection, and the needle should move twice as far up scale and return to the infinity setting.

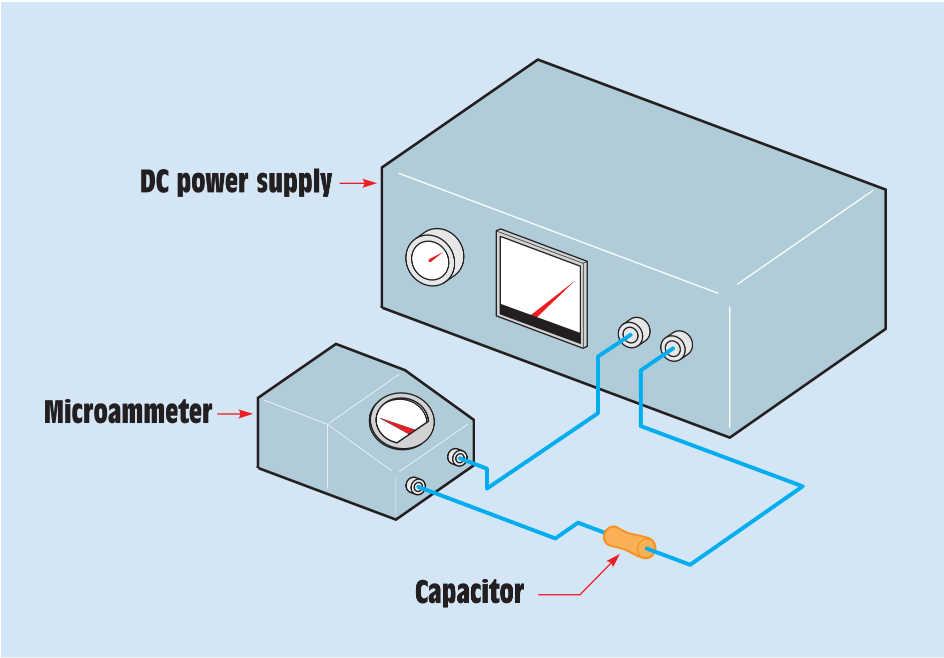

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FIGURE 20–34 Testing a capacitor for leakage.

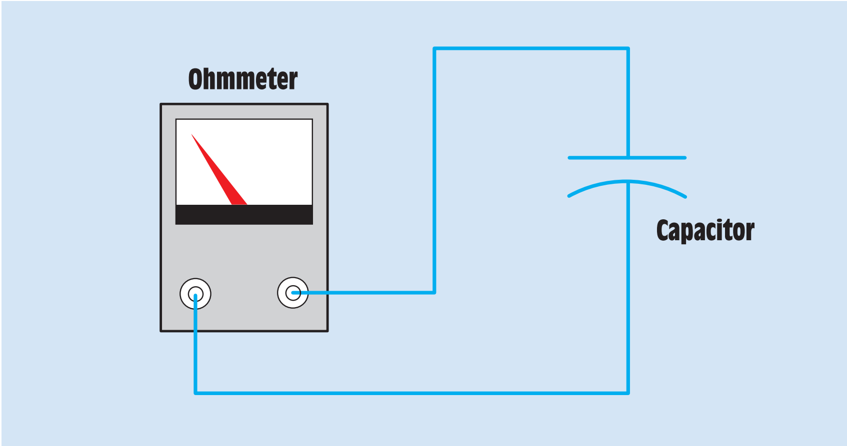

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FIGURE 20–35 Testing the capacitor with an ohmmeter.

If the ohmmeter test is successful, the dielectric must be tested at its rated voltage. This is called a dielectric strength test. To make this test, a dielectric test set must be used *(Figure 20–36)*. This device is often referred to as a **HIPOT** because of its ability to produce a high voltage or high potential.

Courtesy of Megger®

FIGURE 20–36 A dielectric test set.

The dielectric test set contains a variable voltage control, a voltmeter, and a microammeter. To use the HIPOT, connect its terminal leads to the capacitor terminals. Increase the output voltage until rated voltage is applied to the capacitor. The microammeter indicates any current flow between the plates of the dielectric. If the capacitor is good, the microammeter should indicate zero current flow.

The capacitance value must be measured to determine if there are any open plates in the capacitor. To measure the capacitance value of the capacitor, connect some value of AC voltage across the plates of the capacitor *(Figure 20–37)*. This voltage must not be greater than the rated capacitor voltage. Then measure the amount of current flow in the circuit. Now that the voltage and current flow are known, the capacitive reactance of the capacitor can be calculated using the formula:

$$X_C = \frac{E}{I}$$

After the capacitive reactance has been determined, the capacitance can be calculated using the formula:

$$C = \frac{1}{2\pi f X_C}$$

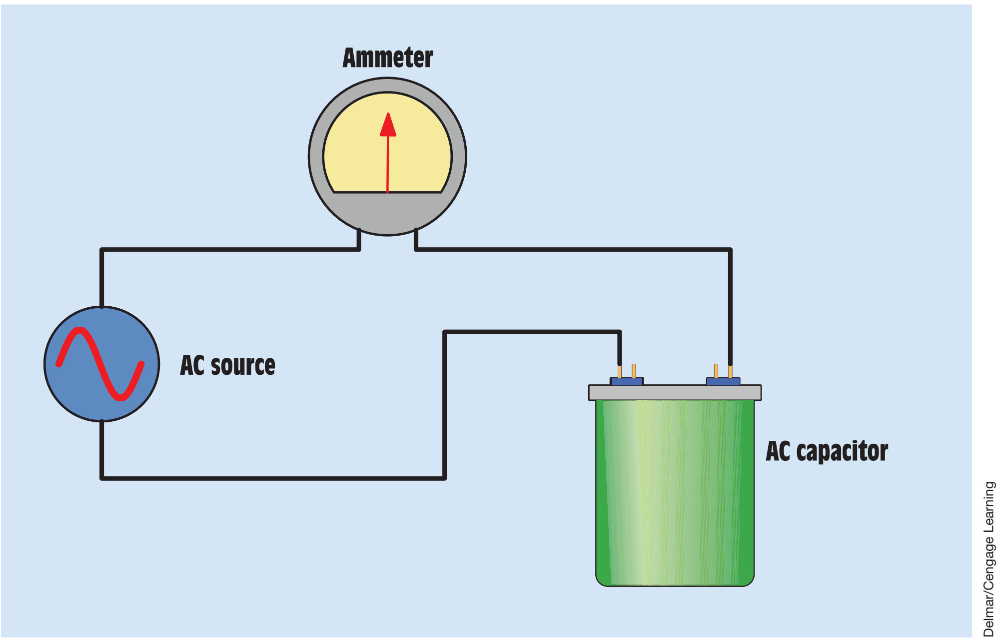

FIGURE 20–37 Determining the capacitance value.

Note: Capacitive reactance is measured in ohms and limits current flow in a manner similar to inductive reactance. Capacitive reactance is covered fully in Unit 21.

Summary

- Capacitors are devices that oppose a change of voltage.
- Three factors that determine the capacitance of a capacitor are
  a. the surface area of the plates.
  b. the distance between the plates.
  c. the type of dielectric used.
- A capacitor stores energy in an electrostatic field.
- Current can flow only during the time a capacitor is charging or discharging.
- Capacitors charge and discharge at an exponential rate.
- The basic unit of capacitance is the farad (F).
- Capacitors are generally rated in microfarads (μF), nanofarads (nF), or picofarads (pF).
- When capacitors are connected in parallel, their capacitance values add.
- When capacitors are connected in series, the reciprocal of the total capacitance is equal to the sum of the reciprocals of all the capacitors.
- The charge and discharge times of a capacitor are proportional to the amount of capacitance and resistance in the circuit.
- Five time constants are required to charge or discharge a capacitor.
- Nonpolarized capacitors are often called AC capacitors.
- Nonpolarized capacitors can be connected to DC or AC circuits.
- Polarized capacitors are often referred to as electrolytic capacitors.
- Polarized capacitors can be connected to DC circuits only.
- There are two basic types of electrolytic capacitors, the wet type and the dry type.
- Wet-type electrolytic capacitors can be re-formed if reconnected to the correct polarity.
- Dry-type electrolytic capacitors will be permanently damaged if connected to the incorrect polarity.

- Capacitors are often marked with color codes or with numbers and letters.
- To test a capacitor for leakage, a microammeter should be connected in series with the capacitor and rated voltage applied to the circuit.

Review Questions

1. What is the dielectric?
2. List three factors that determine the capacitance of a capacitor.
3. A capacitor uses air as a dielectric and has a capacitance of 3 μF. A dielectric material is inserted between the plates without changing the spacing, and the capacitance becomes 15 μF. What is the dielectric constant of this material?
4. In what form is the energy of a capacitor stored?
5. Four capacitors having values of 20 μF, 50 μF, 40 μF, and 60 μF are connected in parallel. What is the total capacitance of this circuit?
6. If the four capacitors in Question 5 were to be connected in series, what would be the total capacitance of the circuit?
7. A 22-μ capacitor is connected in series with a 90-kΩ resistor. How long will it take this capacitor to charge?
8. A 450-pF capacitor has a total charge time of 0.5 second. How much resistance is connected in series with the capacitor?
9. Can a nonpolarized capacitor be connected to a DC circuit?
10. Explain how an AC electrolytic capacitor is constructed.
11. What type of electrolytic capacitor will be permanently damaged if connected to the incorrect polarity?
12. A 500-nF capacitor is connected to a 300-kΩ resistor. What is the total charge time of this capacitor?
13. A film-type capacitor is marked 253 H. What are the capacitance value and tolerance of this capacitor?
14. A postage stamp mica capacitor has the following color marks starting at the upper left dot: yellow, violet, brown, green, no color, and blue. What are the capacitance value, tolerance, and voltage rating of this capacitor?
15. A postage stamp capacitor has the following color marks starting at the upper-left dot: black, orange, orange, black, silver, and white. What are the capacitance value and tolerance of this capacitor?

Practical Applications

You are changing the starting relay on a central air-conditioning unit when you notice that the identifying mark on the compressor-run capacitor is connected to the run winding of the compressor. Should you change the capacitor connection so that the identifying mark is facing the line side or is it correct as connected? Explain your answer. ■

Practical Applications

You are an electrician working in an industrial plant. You discover the problem with a certain machine is a defective capacitor. The capacitor is connected to a 240-volt AC circuit. The information on the capacitor reveals that it has a capacitance value of 10 μF and a voltage rating of 240 VAC. The only 10-μF AC capacitor in the storeroom is marked with a voltage rating of 350 WVDC. Can this capacitor be used to replace the defective capacitor? Explain your answer. ■

Practical Applications

You find that a 25-μF capacitor connected to 480 VAC is defective. The storeroom has no capacitors with a 480-VAC rating. However, you find two capacitors rated at 50 μF and 370 VAC. Can these two capacitors be connected in such a manner that they can replace the defective capacitor? If yes, explain how they are connected and why the capacitors will not be damaged by the lower voltage rating. If no, explain why they cannot be used without damage to the capacitor. ■

Practice Problems

RC Time Constants

1. Fill in all the missing values. Refer to the formulas that follow.

Resistance	Capacitance	Time constant	Total time
150 kΩ	100 μF		
350 kΩ			35 s
	350 pF	0.05 s	
	0.05 μF		10 s
1.2 MΩ	0.47 μF		
	12 μF	0.05 s	
86 kΩ			1.5 s
120 kΩ	470 pF		
	250 nF		100 ms
	8 μF		150 μs
100 kΩ		150 ms	
33 kΩ	4 μF		

$$\tau = RC$$

$$R = \frac{\tau}{C}$$

$$C = \frac{\tau}{R}$$

$$\text{Total time} = \tau \times 5$$

2. Two capacitors having values of 80 μF and 60 μF are connected in series. What is the total capacitance?
3. Three capacitors having values of 120 μF, 20 μF, and 60 μF are connected in parallel. What is the total capacitance?
4. Three capacitors having values of 2.2 μF, 280 nF, and 470 pF are connected in parallel. What is the total capacitance?
5. A 470-μF capacitor is connected in series with a 120-kΩ resistor. How long will it take the capacitor to charge completely?

Unit 21

Capacitance in AC Circuits

OUTLINE

KEY TERMS

Appears to flow
Capacitive reactance (X_C)
Out of phase
Voltage rating

Why You Need to Know

Capacitors are one of the three major types of AC loads and are the exact opposite of inductors in almost every respect. Although a capacitor is an open circuit, you will see how current can appear to flow through it. This unit

- illustrates how to calculate the current-limiting effect of a capacitor.
- discusses the different voltage ratings that are listed on nonpolarized capacitors.
- illustrates how to connect the capacitor into an AC circuit and calculate capacitance charge and discharge rates.
- discusses the effects of frequency in a capacitance circuit.

Courtesy of Niagara Mohawk Power Corporation.

Objectives

After studying this unit, you should be able to

- explain why current appears to flow through a capacitor when it is connected to an AC circuit.
- discuss capacitive reactance.
- calculate the value of capacitive reactance in an AC circuit.
- calculate the value of capacitance in an AC circuit.
- discuss the relationship of voltage and current in a pure capacitive circuit.

Preview

In Unit 20, it was discussed that a capacitor is composed of two metal plates separated by an insulating material called the dielectric. Because there is no complete circuit between the plates, current cannot flow through the capacitor. The only time that current can flow is during the period of time that the capacitor is being charged or discharged. ■

21–1 Connecting the Capacitor into an AC Circuit

When a capacitor *(Figure 21–1)* is connected to an AC circuit, current **appears to flow** through the capacitor. The reason is that in an AC circuit, the current continually changes direction and polarity. To understand this concept, consider the hydraulic circuit shown in *Figure 21–2*. Two tanks are connected to a common pump. Assume Tank A to be full and Tank B to be empty. Now assume that the pump pumps water from Tank A to Tank B. When Tank B

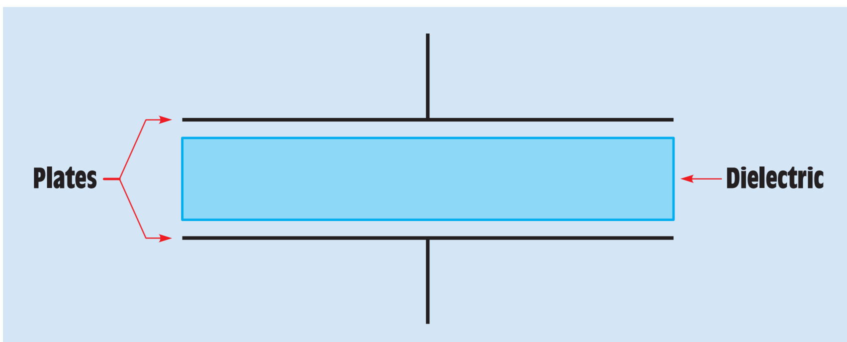

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FIGURE 21–1 A basic capacitor.

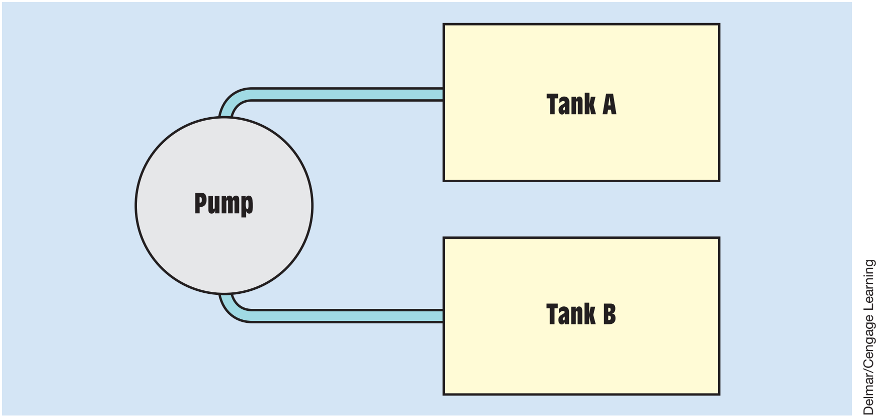

FIGURE 21–2 Water can flow continuously, but not between the two tanks.

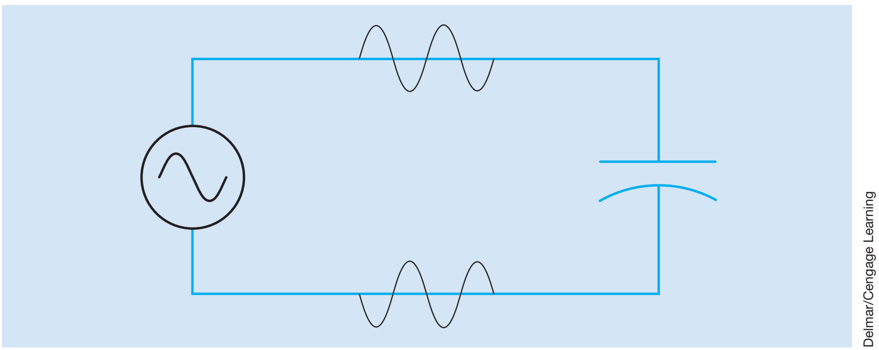

FIGURE 21–3 A capacitor connected to an AC circuit.

becomes full, the pump reverses and pumps the water from Tank B back into Tank A. Each time a tank becomes filled, the pump reverses and pumps water back into the other tank. Notice that water is continually flowing in this circuit, but there is no direct connection between the two tanks.

A similar action takes place when a capacitor is connected to an AC circuit *(Figure 21–3)*. In this circuit, the AC generator or alternator charges one plate of the capacitor positive and the other plate negative. During the next half cycle, the voltage changes polarity and the capacitor discharges and recharges to the opposite polarity also. As long as the voltage continues to increase, decrease, and change polarity, current flows from one plate of the capacitor to the other. If an ammeter were placed in the circuit, it would indicate a continuous flow of current, giving the appearance that current is flowing through the capacitor.

21–2 Capacitive Reactance

As the capacitor is charged, an impressed voltage is developed across its plates as an electrostatic charge is built up *(Figure 21–4)*. The impressed voltage is the voltage provided by the electrostatic charge. This impressed voltage opposes the applied voltage and limits the flow of current in the circuit. This countervoltage is similar to the countervoltage produced by an inductor. The countervoltage developed by the capacitor is called *reactance* also. Because this countervoltage is caused by capacitance, it is called **capacitive reactance (X_C)** and is measured in ohms. The formula for finding capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

where

X_C = capacitive reactance

π = 3.1416

f = frequency in hertz

C = capacitance in farads

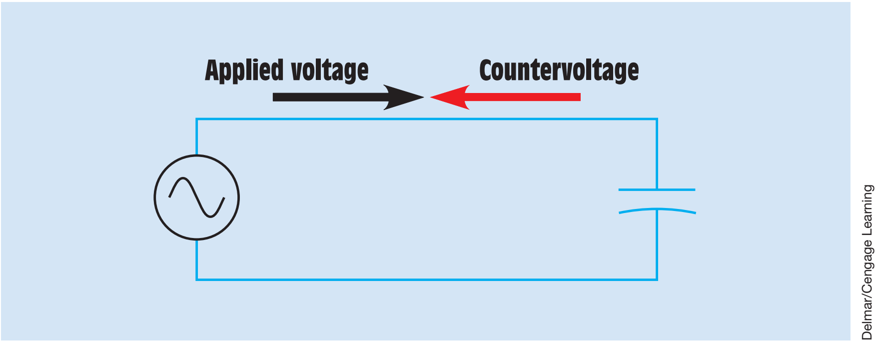

FIGURE 21–4 Countervoltage limits the flow of current.

■ EXAMPLE 21-1

A 35-μF capacitor is connected to a 120-V, 60-Hz line. How much current will flow in this circuit?

Solution

The first step is to calculate the capacitive reactance. Recall that the value of C in the formula is given in F. This must be changed to the capacitive units being used—in this case, μF:

$$X_C = \frac{1}{2 \times 3.1416 \times 60 \times (35 \times 10^{-6})}$$

$$X_C = 75.788\ \Omega$$

Now that the value of capacitive reactance is known, it can be used like resistance in an Ohm's law formula. Because capacitive reactance is the current-limiting factor, it will replace the value of R:

$$I = \frac{E}{X_C}$$

$$I = \frac{120\ V}{75.788\ \Omega}$$

$$I = 1.583\ A$$

21–3 Calculating Capacitance

If the value of capacitive reactance is known, the capacitance of the capacitor can be found using the formula

$$C = \frac{1}{2\pi f X_C}$$

■ EXAMPLE 21-2

A capacitor is connected into a 480-V, 60-Hz circuit. An ammeter indicates a current flow of 2.6 A. What is the capacitance value of the capacitor?

Solution

The first step is to calculate the value of capacitive reactance. Because capacitive reactance, like resistance, limits current flow, it can be substituted for R in an Ohm's law formula:

$$X_C = \frac{E}{I}$$

$$X_C = \frac{480\ V}{2.6\ A}$$

$$X_C = 184.615\ \Omega$$

Now that the capacitive reactance of the circuit is known, the value of capacitance can be found:

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{2 \times 3.1416 \times 60\ Hz \times 184.615\ \Omega}$$

$$C = \frac{1}{69{,}598.378}$$

$$C = 0.000014368\ F = 14.368\ \mu F$$

21–4 Voltage and Current Relationships in a Pure Capacitive Circuit

Earlier in this text, it was shown that the current in a pure resistive circuit is in phase with the applied voltage and that current in a pure inductive circuit lags the applied voltage by 90°. In this unit, it will be shown that in a pure capacitive circuit the current will *lead* the applied voltage by 90°.

When a capacitor is connected to an AC, the capacitor charges and discharges at the same rate and time as the applied voltage. The charge in

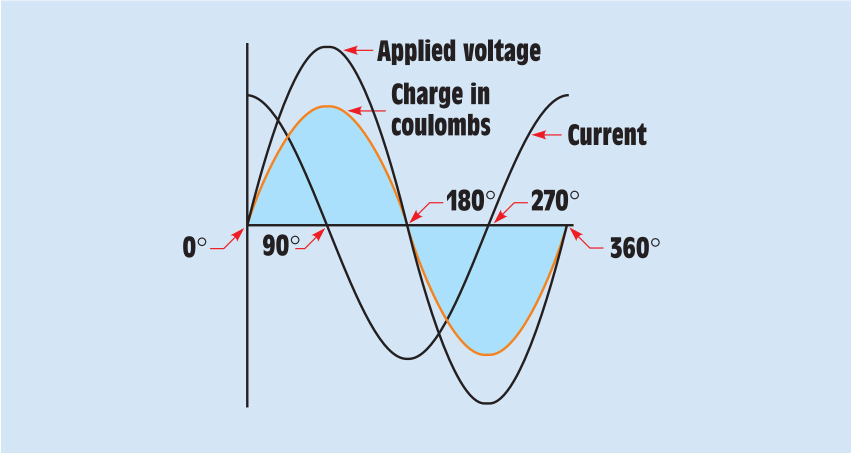

FIGURE 21–5 Capacitive current leads the applied voltage by 90°.

coulombs is equal to the capacitance of the capacitor times the applied voltage ($Q = C \times V$). When the applied voltage is zero, the charge in coulombs and impressed voltage is also zero. When the applied voltage reaches its maximum value, positive or negative, the charge in coulombs and impressed voltage also reaches maximum *(Figure 21–5)*. The impressed voltage follows the same curve as the applied voltage.

In the waveform shown, voltage and charge are both zero at 0°. Because there is no charge on the capacitor, there is no opposition to current flow, which is shown to be maximum. As the applied voltage increases from zero toward its positive peak at 90°, the capacitor begins to charge at the same time. The charge produces an impressed voltage across the plates of the capacitor that opposes the flow of current. The impressed voltage is 180° **out of phase** with the applied voltage *(Figure 21–6)*. When the applied voltage reaches 90° in the positive direction, the charge reaches maximum, the impressed voltage reaches peak in the negative direction, and the current flow is zero.

As the applied voltage begins to decrease, the capacitor begins to discharge, causing the current to flow in the opposite or negative direction. When the applied voltage and charge reach zero at 180°, the impressed voltage is zero also and the current flow is maximum in the negative direction. As the applied voltage and charge increase in the negative direction, the increase of the impressed voltage across the capacitor again causes the current to decrease. The applied voltage and charge reach maximum negative after 270° of rotation. The impressed voltage reaches maximum positive and the current has decreased to zero *(Figure 21–7)*. As the applied voltage decreases

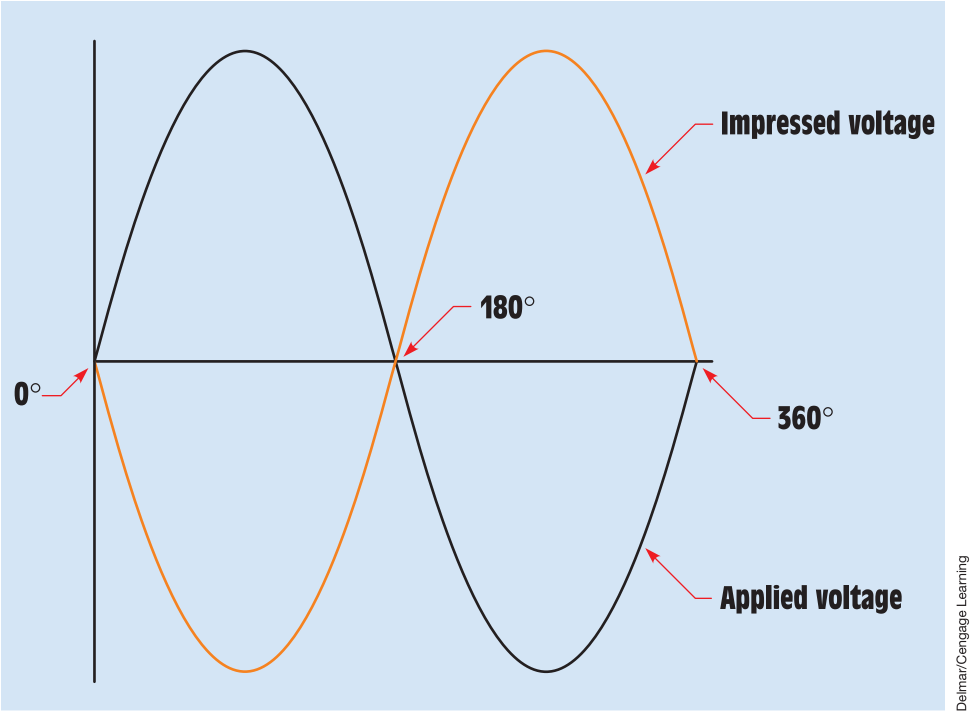

FIGURE 21–6 The impressed voltage is 180° out of phase with applied voltage.

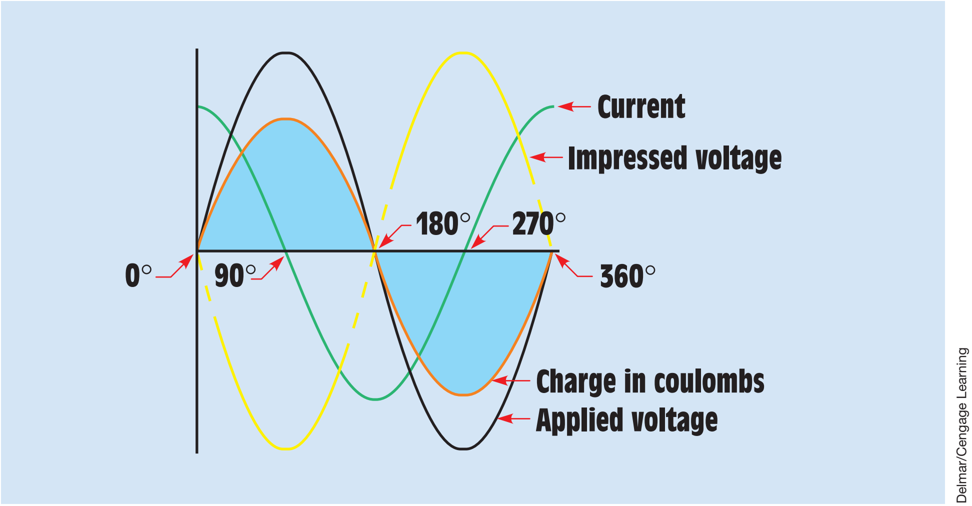

FIGURE 21–7 Voltage, current, and charge relationships for a capacitive circuit.

from its maximum negative value, the capacitor again begins to discharge. This causes the current to flow in the positive direction. The current again reaches its maximum positive value when the applied voltage and charge reach zero after 360° of rotation.

21–5 Power in a Pure Capacitive Circuit

Because the current flow in a pure capacitive circuit leads the applied voltage by 90°, the voltage and current have the same polarity for half the time during one cycle and have opposite polarities the other half of the time *(Figure 21–8)*. During the period of time that the voltage and current have the same polarity, energy is being stored in the capacitor in the form of an electrostatic field. When the voltage and current have opposite polarities, the capacitor is discharging and the energy is returned to the circuit. When the values of current and voltage for one full cycle are added, the sum equals zero just as it does with pure inductive circuits. Therefore, there is no true power, or watts, produced in a pure capacitive circuit.

The power value for a capacitor is reactive power and is measured in VARs, just as it is for an inductor. Inductive VARs and capacitive VARs are 180° out of phase with each other, however *(Figure 21–9)*. To distinguish between inductive and capacitive VARs, inductive VARs are shown as $VARs_L$ and capacitive VARs are shown as $VARs_C$.

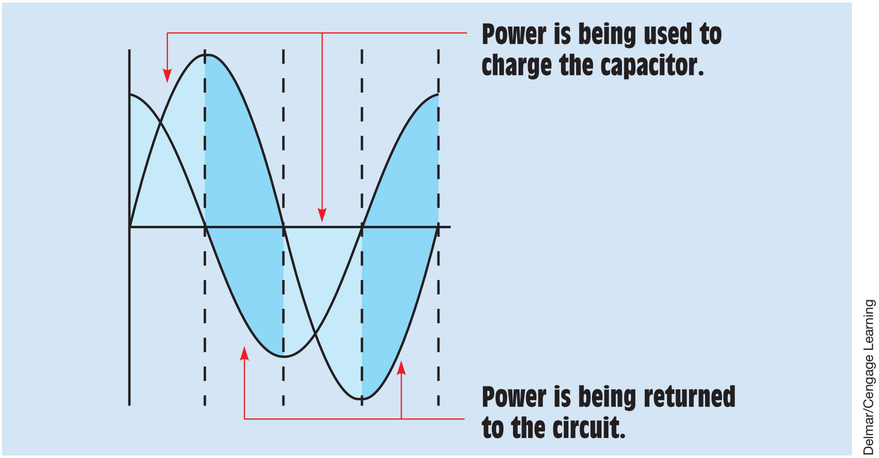

FIGURE 21–8 A pure capacitive circuit has no true power (watts). The power required to charge the capacitor is returned to the circuit when the capacitor discharges.

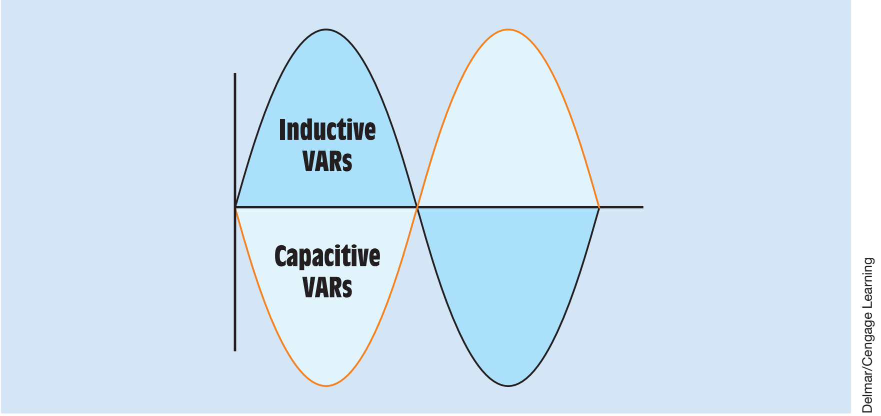

FIGURE 21–9 Inductive VARs and capacitive VARs are 180° out of phase with each other.

21–6 Quality of a Capacitor

The quality (Q) of a capacitor is generally very high. As with inductors, it is a ratio of the resistance to capacitive reactance:

$$Q = \frac{R}{X_C}$$

The R value for a capacitor is generally very high because it is the equivalent resistance of the dielectric between the plates of the capacitor. If a capacitor is leaky, however, the dielectric will appear to be a much lower resistance and the Q rating will decrease.

Q for a capacitor can also be found by using other formulas. One of these formulas follows:

$$Q = \frac{VARs_C}{W}$$

where the reactive power is represented by VARs. Another formula that can be used sets Q equal to the reciprocal of the power factor:

$$Q = \frac{1}{PF}$$

21–7 Capacitor Voltage Rating

The **voltage rating** of a capacitor is actually the voltage rating of the dielectric. ***Voltage rating is extremely important concerning the life of the capacitor and should never be exceeded.*** Unfortunately, there are no set standards concerning how voltage ratings are marked. It is not unusual to see capacitors marked VOLTS AC, VOLTS DC, PEAK VOLTS, and WVDC

(WORKING VOLTS DC). The voltage rating of electrolytic or polarized capacitors is always given in DC volts. The voltage rating of nonpolarized capacitors, however, can be given as AC or DC volts.

If a nonpolarized capacitor has a voltage rating given in AC volts, the voltage indicated is the RMS value. If the voltage rating is given as PEAK or as DC volts, it indicates the peak value of AC volts. If a capacitor is to be connected to an AC circuit, it is necessary to calculate the peak value if the voltage rating is given as DC volts.

EXAMPLE 21-3

An AC oil-filled capacitor has a voltage rating of 300 WVDC. Will the voltage rating of the capacitor be exceeded if the capacitor is connected to a 240-V, 60-Hz line?

Solution

The DC voltage rating of the capacitor indicates the peak value of voltage. To determine whether the voltage rating will be exceeded, find the peak value of 240 V by multiplying by 1.414:

$$\text{Peak} = 240\text{ V} \times 1.414$$

$$\text{Peak} = 339.36\text{ V}$$

The answer is that the capacitor voltage rating will be exceeded.

21–8 Effects of Frequency in a Capacitive Circuit

One of the factors that determines the capacitive reactance of a capacitor is the frequency. Capacitive reactance is inversely proportional to frequency. As the frequency increases, the capacitive reactance decreases. The chart in *Table 21–1* shows the capacitive reactance for different values of capacitance at different frequencies. Frequency has an effect on capacitive reactance because the capacitor charges and discharges faster at a higher frequency. Recall that current is a rate of electron flow. A current of 1 A is 1 coulomb per second:

$$I = \frac{C}{t}$$

where

I = current

C = charge in coulombs

t = time in seconds

Capacitance	Capacitive reactance 30 Hz	60 Hz	400 Hz	1000 Hz
10 pF	530.515 MΩ	265.258 MΩ	39.789 MΩ	15.915 MΩ
350 pF	15.156 MΩ	7.579 MΩ	1.137 MΩ	454.727 k Ω
470 nF	11.286 k Ω	5.644 k Ω	846.567 k Ω	338.627 k Ω
750 nF	7.074 k Ω	3.537 k Ω	530.515 k Ω	212.206 Ω
1 F	5.305 k Ω	2.653 k Ω	397.886 Ω	159.155 Ω
25 F	212.206 Ω	106.103 Ω	15.915 Ω	6.366 Ω

TABLE 21–1 Capacitive Reactance Is Inversely Proportional to Frequency

Assume that a capacitor is connected to a 30-hertz line, and 1 coulomb of charge flows each second. If the frequency is doubled to 60 hertz, 1 coulomb of charge will flow in 0.5 second because the capacitor is being charged and discharged twice as fast *(Figure 21–10)*. This means that in a period of 1 second, 2 coulombs of charge will flow. Because the capacitor is being charged and discharged at a faster rate, the opposition to current flow is decreased.

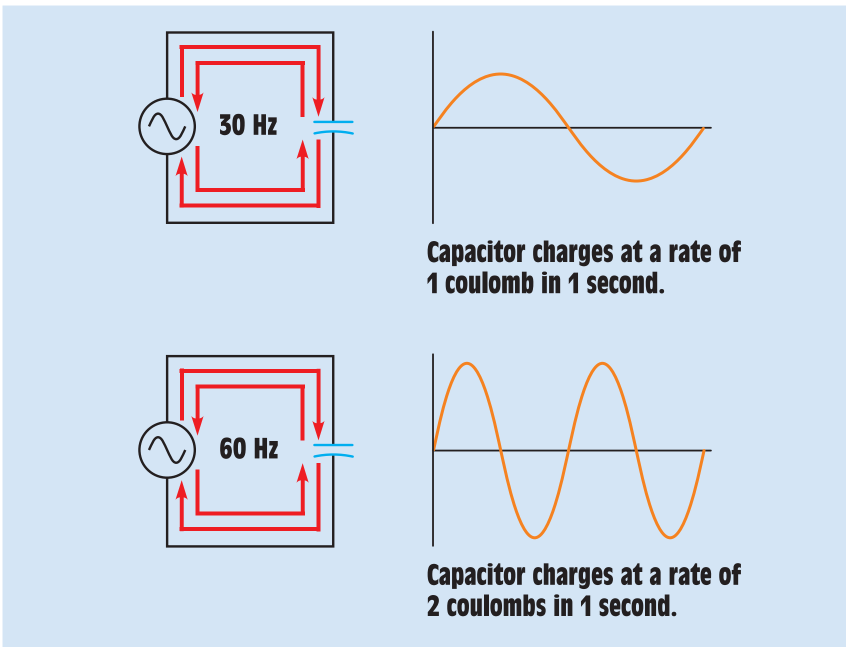

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FIGURE 21–10 The rate of charge increases with frequency.

21–9 Series Capacitors

■ EXAMPLE 21-4

Three capacitors with values of 10 μF, 30 μF, and 15 μF are connected in series to a 480-V, 60-Hz line *(Figure 21–11)*. Find the following circuit values:

X_{C1}—capacitive reactance of the first capacitor

X_{C2}—capacitive reactance of the second capacitor

X_{C3}—capacitive reactance of the third capacitor

X_{CT}—total capacitive reactance for the circuit

C_T—total capacitance for the circuit

I_T—total circuit current

E_{C1}—voltage drop across the first capacitor

$VARs_{C1}$—reactive power of the first capacitor

E_{C2}—voltage drop across the second capacitor

$VARs_{C2}$—reactive power of the second capacitor

E_{C3}—voltage drop across the third capacitor

$VARs_{C3}$—reactive power of the third capacitor

$VARs_{CT}$—total reactive power for the circuit

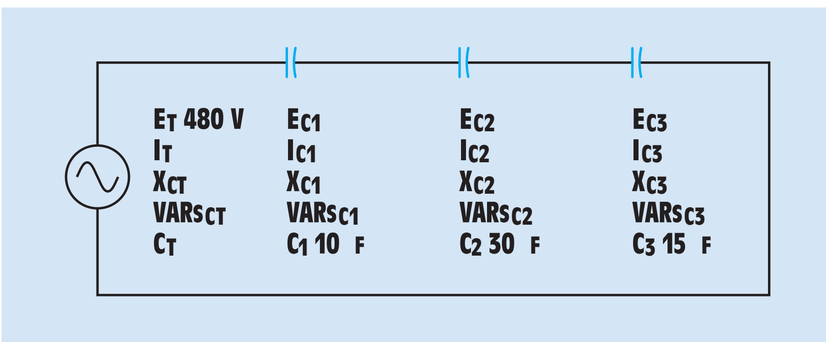

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FIGURE 21–11 Capacitors connected in series.

Solution

Because the frequency and the capacitance of each capacitor are known, the capacitive reactance for each capacitor can be found using the formula

$$X_C = \frac{1}{2\pi fC}$$

Recall that the value for C in the formula is in farads and the capacitors in this problem are rated in microfarads.

$$X_{C1} = \frac{1}{2\pi fC}$$

$$X_{C1} = \frac{1}{377 \times 0.000010}$$

$$X_{C1} = 265.252\ \Omega$$

$$X_{C2} = \frac{1}{2\pi fC}$$

$$X_{C2} = \frac{1}{377 \times 0.000030}$$

$$X_{C2} = 88.417\ \Omega$$

$$X_{C3} = \frac{1}{2\pi fC}$$

$$X_{C3} = \frac{1}{377 \times 0.000015}$$

$$X_{C3} = 176.835\ \Omega$$

Because there is no phase angle shift among the three capacitive reactances, the total capacitive reactance is the sum of the three reactances *(Figure 21–12):*

$$X_{CT} = X_{C1} + X_{C2} + X_{C3}$$

$$X_{CT} = 265.252\ \Omega + 88.417\ \Omega + 176.835\ \Omega$$

$$X_{CT} = 530.504\ \Omega$$

The total capacitance of a series circuit can be calculated in a manner similar to that used for calculating parallel resistance. Refer to the Pure Capacitive Circuits Formula section of Appendix B. Total capacitance in this circuit is calculated using the formula

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

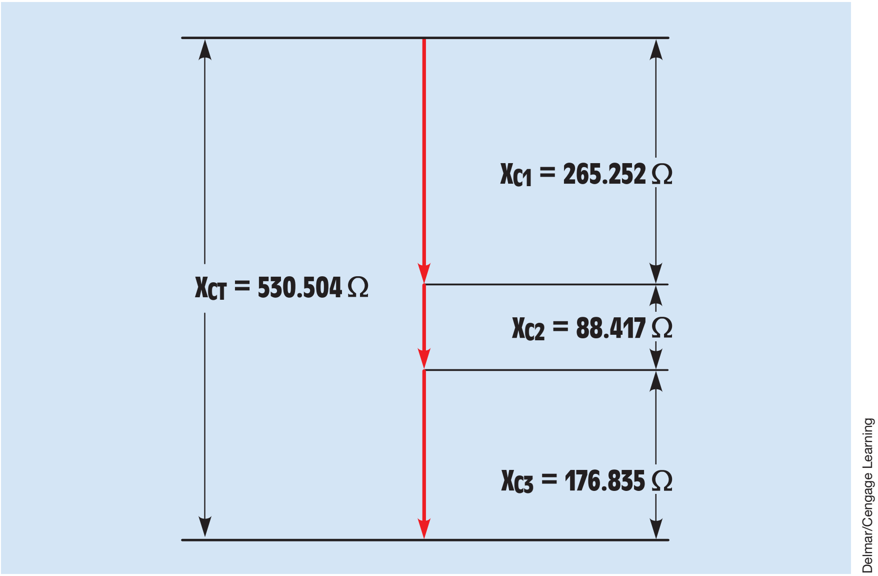

FIGURE 21–12 Vector sum for capacitive reactance.

$$C_T = \frac{1}{\frac{1}{10\ \mu F} + \frac{1}{30\ \mu f} + \frac{1}{15\ \mu F}}$$

$$C_T = \frac{1}{0.2\ \frac{1}{\mu F}}$$

$$C_T = 5\ \mu F$$

The total current can be found by using the total capacitive reactance to substitute for R in an Ohm's law formula:

$$I_T = \frac{E_{CT}}{X_{CT}}$$

$$I_T = \frac{480\ V}{530.504\ \Omega}$$

$$I_T = 0.905\ A$$

Because the current is the same at any point in a series circuit, the voltage drop across each capacitor can now be calculated using the capacitive reactance of each capacitor and the current flowing through it.

$$E_{C1} = I_{C1} \times X_{C1}$$
$$E_{C1} = 0.905 \times 265.25$$
$$E_{C1} = 240.051 \text{ V}$$

$$E_{C2} = I_{C2} \times X_{C2}$$
$$E_{C2} = 0.905 \times 88.417$$
$$E_{C2} = 80.017 \text{ V}$$

$$E_{C3} = I_{C3} \times X_{C3}$$
$$E_{C3} = 0.905 \times 176.83$$
$$E_{C3} = 160.031 \text{ V}$$

Now that the voltage drops of the capacitors are known, the reactive power of each capacitor can be found.

$$\text{VARs}_{C1} = E_{C1} \times I_{C1}$$
$$\text{VARs}_{C1} = 240.051 \times 0.905$$
$$\text{VARs}_{C1} = 217.246$$

$$\text{VARs}_{C2} = E_{C2} \times I_{C2}$$
$$\text{VARs}_{C2} = 80.017 \times 0.905$$
$$\text{VARs}_{C2} = 72.415$$

$$\text{VARs}_{C3} = E_{C3} \times I_{C3}$$
$$\text{VARs}_{C3} = 160.031 \times 0.905$$
$$\text{VARs}_{C3} = 144.828$$

Power, whether true power, apparent power, or reactive, will add in any type of circuit. The total reactive power in this circuit can be found by taking the sum of all the VARs for the capacitors or by using total values of voltage and current and Ohm's law:

$$\text{VARs}_{CT} = \text{VARs}_{C1} + \text{VARs}_{C2} + \text{VARs}_{C3}$$
$$\text{VARs}_{CT} = 217.248 + 72.415 + 144.828$$
$$\text{VARs}_{CT} = 434.491$$

The circuit with all calculated values is shown in *Figure 21–13*.

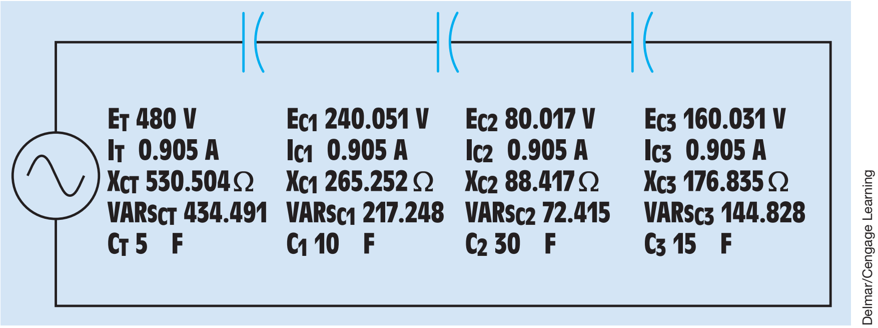

FIGURE 21–13 Series circuit 1 with all values.

21–10 Parallel Capacitors

EXAMPLE 21-5

Three capacitors having values of 50 μF, 75 μF, and 20 μF are connected in parallel to a 60-Hz line. The circuit has a total reactive power of 787.08 VARs *(Figure 21–14)*. Find the following unknown values:

X_{C1}—capacitive reactance of the first capacitor

X_{C2}—capacitive reactance of the second capacitor

X_{C3}—capacitive reactance of the third capacitor

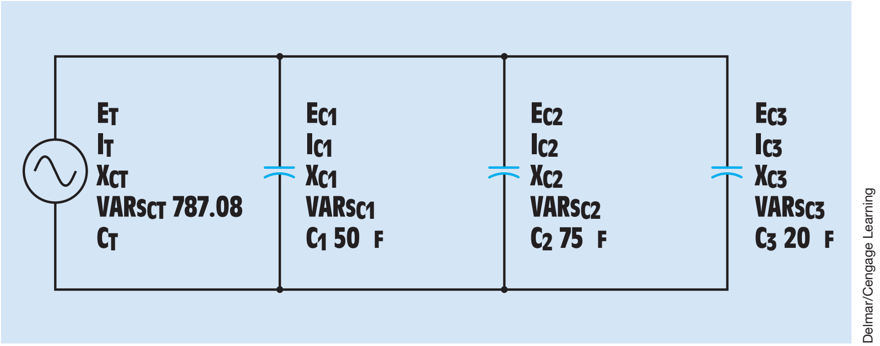

FIGURE 21–14 Capacitors connected in parallel.

X_{CT}—total capacitive reactance for the circuit

E_T—total applied voltage

I_{C1}—current flow through the first capacitor

$VARs_{C1}$—reactive power of the first capacitor

I_{C2}—current flow through the second capacitor

$VARs_{C2}$—reactive power of the second capacitor

I_{C3}—current flow through the third capacitor

$VARs_{C3}$—reactive power of the third capacitor

I_T—total circuit current

Because the frequency of the circuit and the capacitance of each capacitor are known, the capacitive reactance of each capacitor can be calculated using the formula:

$$X_C = \frac{1}{2\pi fC}$$

Note: Refer to the Pure Capacitive Circuits Formula section of Appendix B.

$$X_{C1} = \frac{1}{377 \times 0.000050\text{ F}}$$

$$X_{C1} = 53.05\ \Omega$$

$$X_{C2} = \frac{1}{377 \times 0.000075\text{ F}}$$

$$X_{C2} = 35.367\ \Omega$$

$$X_{C3} = \frac{1}{377 \times 0.000020\text{ F}}$$

$$X_{C3} = 132.626\ \Omega$$

The total capacitive reactance can be found in a manner similar to finding the resistance of parallel resistors:

$$X_{CT} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}}}$$

$$X_{CT} = \frac{1}{\frac{1}{53.05\ \Omega} + \frac{1}{35.367\ \Omega} + \frac{1}{132.626\ \Omega}}$$

$$X_{CT} = \frac{1}{0.05467 \frac{1}{\Omega}}$$

$$X_{CT} = 18.292\ \Omega$$

Now that the total capacitive reactance of the circuit is known and the total reactive power is known, the voltage applied to the circuit can be found using the formula

$$E_T = \sqrt{VARs_{CT} \times X_{CT}}$$

$$E_T = \sqrt{787.08\ VARs \times 18.292\ \Omega}$$

$$E_T = 119.989\ V$$

In a parallel circuit, the voltage must be the same across each branch of the circuit. Therefore, 120 V is applied across each capacitor.

Now that the circuit voltage is known, the amount of total current for the circuit and the amount of current in each branch can be found using Ohm's law:

$$I_{CT} = \frac{E_{CT}}{X_{CT}}$$

$$I_{CT} = \frac{119.989\ V}{18.292\ \Omega}$$

$$I_{CT} = 6.56\ A$$

$$I_{C1} = \frac{E_{C1}}{X_{C1}}$$

$$I_{C1} = \frac{119.989\ V}{53.05\ \Omega}$$

$$I_{C1} = 2.262\ A$$

$$I_{C2} = \frac{E_{C2}}{X_{C2}}$$

$$I_{C2} = \frac{119.989\ V}{35.367\ \Omega}$$

$$I_{C2} = 3.393\ A$$

$$I_{C3} = \frac{E_{C3}}{X_{C3}}$$

$$I_{C3} = \frac{119.989\ V}{132.626\ \Omega}$$

$$I_{C3} = 0.905\ A$$

The amount of reactive power for each capacitor can now be calculated using Ohm's law:

$$VARs_{C1} = E_{C1} \times I_{C1}$$
$$VARs_{C1} = 119.989\text{ V} \times 2.262\text{ A}$$
$$VARs_{C1} = 271.415$$

$$VARs_{C2} = E_{C2} \times I_{C2}$$
$$VARs_{C2} = 119.989\text{ V} \times 3.393\text{ A}$$
$$VARs_{C2} = 407.123$$

$$VARs_{C3} = E_{C3} \times I_{C3}$$
$$VARs_{C3} = 119.987\text{ V} \times 0.905\text{ A}$$
$$VARs_{C3} = 108.590$$

To make a quick check of the circuit values, add the VARs for all the capacitors and see if they equal the total circuit VARs:

$$VARs_{CT} = VARs_{C1} + VARs_{C2} + VARs_{C3}$$
$$VARs_{CT} = 271.415 + 407.123 + 108.590$$
$$VARs_{CT} = 787.128$$

The slight difference in answers is caused by the rounding off of values. The circuit with all values is shown in *Figure 21–15.*

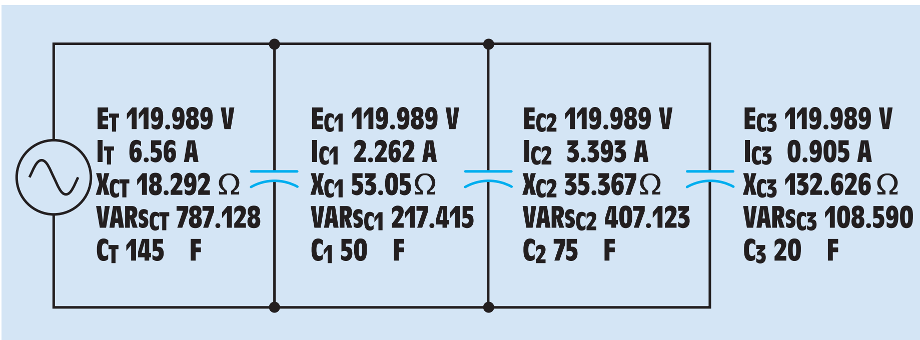

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FIGURE 21–15 Parallel circuit with completed values.

Summary

- When a capacitor is connected to an AC circuit, current appears to flow through the capacitor.
- Current appears to flow through a capacitor because of the continuous increase and decrease of voltage and because of the continuous change of polarity in an AC circuit.
- The current flow in a pure capacitive circuit is limited by capacitive reactance.
- Capacitive reactance is inversely proportional to the capacitance of the capacitor and the frequency of the AC line.
- Capacitive reactance is measured in ohms.
- In a pure capacitive circuit, the current leads the applied voltage by 90°.
- There is no true power, or watts, in a pure capacitive circuit.
- Capacitive power is reactive and is measured in VARs, as is inductance.
- Capacitive and inductive VARs are 180° out of phase with each other.
- The Q of a capacitor is the ratio of the resistance to the capacitive reactance.
- Capacitor voltage ratings are given as volts AC, peak volts, and volts DC.
- A DC voltage rating for an AC capacitor indicates the peak value of voltage.

Review Questions

1. Can current flow through a capacitor?
2. What two factors determine the capacitive reactance of a capacitor?
3. How many degrees are the current and voltage out of phase in a pure capacitive circuit?
4. Does the current in a pure capacitive circuit lead or lag the applied voltage?
5. A 30-μF capacitor is connected into a 240-V, 60-Hz circuit. What is the current flow in this circuit?
6. A capacitor is connected into a 1250-V, 1000-Hz circuit. The current flow is 80 A. What is the capacitance of the capacitor?

7. A capacitor is to be connected into a 480-V, 60-Hz line. If the capacitor has a voltage rating of 600 VDC, will the voltage rating of the capacitor be exceeded?
8. On the average, by what factor is the life expectancy of a capacitor increased if the capacitor is operated at half its voltage rating?
9. A capacitor is connected into a 277-V, 400-Hz circuit. The circuit current is 12 A. What is the capacitance of the capacitor?
10. A capacitor has a voltage rating of 350 VAC. Can this capacitor be connected into a 450-VDC circuit without exceeding the voltage rating of the capacitor?

Practical Applications

You are working as an electrician in an industrial plant. You are given an AC oil-filled capacitor to install on a 480-V, 60-Hz AC line. The capacitor has the following marking: (15 μF 600 VDC). Will this capacitor be damaged if it is installed? Explain your answer. ■

Practical Applications

You are working in an industrial plant. You have been instructed to double the capacitance connected to a machine. The markings on the capacitor, however, are not visible. The capacitor is connected to 560 volts and an ammeter indicates a current of 6 amperes flowing to the capacitor. What size capacitor should be connected in parallel with the existing capacitor? What is the minimum AC voltage rating of the new capacitor? What is the minimum DC voltage rating of the new capacitor? What is the minimum kVAR size that can be used in this installation? ■

Practice Problems

Capacitive Circuits

1. Fill in all the missing values. Refer to the formulas that follow.

$$X_C = \frac{1}{2\pi fC}$$

$$C = \frac{1}{2\pi fX_C}$$

$$f = \frac{1}{2\pi CX_C}$$

Capacitance	X_C	Frequency
38 μF		60 Hz
	78.8 Ω	400 Hz
250 pF	4.5 kΩ	
234 μF		10 kHz
	240 Ω	50 Hz
10 μF	36.8 Ω	
560 nF		2 MHz
	15 kΩ	60 Hz
75 μF	560 Ω	
470 pF		200 kHz
	6.8 kΩ	400 Hz
34 μF	450 Ω	

2. A 4.7-μF capacitor is connected to a 60-Hz power source. What is the capacitive reactance of the capacitor?
3. A capacitor is connected to a 208-volt, 60-Hz power source. An ammeter indicates a current flow of 0.28 amperes. What is the capacitance of the capacitor?
4. A 0.47-μF capacitor is connected to a 240-volt power source. An ammeter indicates a current of 0.2 ampere. What is the frequency of the power source?

5. Three capacitors having capacitance values of 20 μF, 40 μF, and 50 μF are connected in parallel to a 60-Hz power line. An ammeter indicates a circuit current of 8.6 amperes. How much current is flowing through the 40-μF capacitor?

6. A capacitor has a capacitive reactance of 300 Ω when connected to a 60-Hz power line. What is the capacitive reactance if the frequency is increased to 100 Hz?

7. A pure capacitive circuit is connected to a 480-volt, 60-Hz power source. An ammeter indicates a current flow of 24 amperes. The circuit current must be reduced to 16 amperes by connecting a second capacitor in series with the first. What is the value of the existing capacitor? What value capacitor should be connected in series with the original capacitor to limit the circuit current to 16 amperes?

Unit 22

Resistive-Capacitive Series Circuits

OUTLINE

KEY TERMS

Capacitance (C)
Total voltage (E_T)
Voltage drop across the capacitor (E_C)
Voltage drop across the resistor (E_R)

Why You Need to Know

The relationship of voltage, current, impedance, and power when resistance and capacitance are connected in series with each other is not unlike that of resistive-inductive series circuits. This unit

- describes the effect of voltage, current, power, and impedance in series circuits that contain both resistance and capacitance.
- illustrates how to calculate voltage drop across a resistor and how voltage and current are out of phase in an amount less than 90°.

Courtesy of Rockwell Automation

Objectives

After studying this unit, you should be able to

- discuss the relationship of resistance and capacitance in an AC series circuit.
- calculate values of voltage, current, apparent power, true power, reactive power, impedance, resistance, inductive reactance, and power factor in an RC series circuit.
- calculate the phase angle for current and voltage in an RC series circuit.
- connect an RC series circuit and make measurements using test instruments.

Preview

In this unit, the relationship of voltage, current, impedance, and power in a resistive-capacitive series circuit is discussed. As with any other type of series circuit, the current flow must be the same through all parts of the circuit. This unit explores the effect of voltage drop across each component; the relationship of resistance, reactance, and impedance; and the differences between true power, reactive power, and apparent power. ■

22–1 Resistive-Capacitive Series Circuits

When a pure capacitive load is connected to an AC circuit, the voltage and current are 90° out of phase with each other. In a capacitive circuit, the current leads the voltage by 90 electric degrees. When a circuit containing both resistance and capacitance is connected to an AC circuit, the voltage and current will be out of phase with each other by some amount between 0° and 90°. The exact amount of phase angle difference is determined by the ratio of resistance to capacitance. Resistive-capacitive series circuits are similar to resistive-inductive series circuits, covered in Unit 18. Other than changing a few formulas, the procedure for solving circuit values is the same.

In the following example, a series circuit containing 12 ohms of resistance and 16 ohms of capacitive reactance is connected to a 240-volts, 60-hertz line *(Figure 22–1)*. The following unknown values are calculated:

Z—total circuit impedance

I—total current

E_R—voltage drop across the resistor

P—watts (true power)

C—capacitance

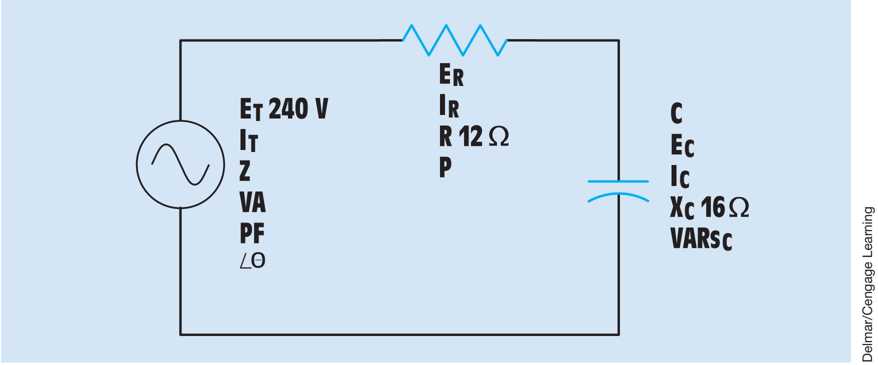


FIGURE 22–1 Resistive-capacitive series circuit.

E_C—voltage drop across the capacitor

$VARs_C$—volt-amperes-reactive (reactive power)

VA—volt-amperes (apparent power)

PF—power factor

∠θ—angle theta (the angle the voltage and current are out of phase with each other)

22–2 Impedance

The total impedance (Z) is the total current-limiting element in the circuit. It is a combination of both resistance and capacitive reactance. Because this is a series circuit, the current-limiting elements must be added. Resistance and capacitive reactance are 90° out of phase with each other, forming a right triangle with impedance being the hypotenuse *(Figure 22–2)*. A vector diagram illustrating this relationship is shown in *Figure 22–3*. Impedance can be calculated using the formula

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{(12\ \Omega)^2 + (16\ \Omega)^2}$$

$$Z = \sqrt{144\ \Omega^2 + 256\ \Omega^2}$$

$$Z = \sqrt{400\ \Omega^2}$$

$$Z = 20\ \Omega$$

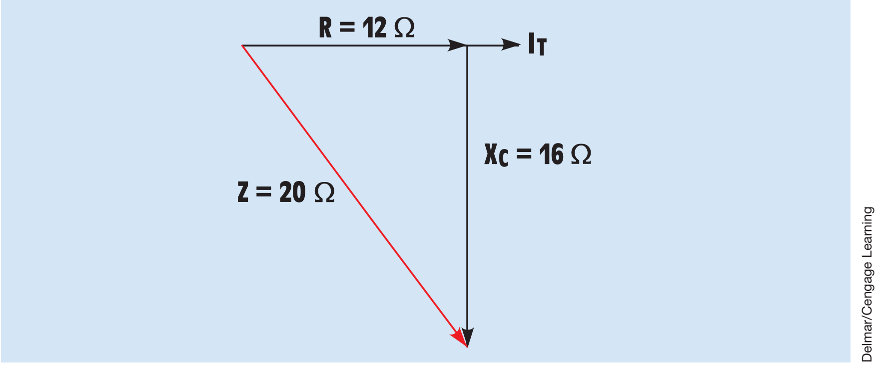


FIGURE 22–2 Resistance and capacitive reactance are 90° out of phase with each other.

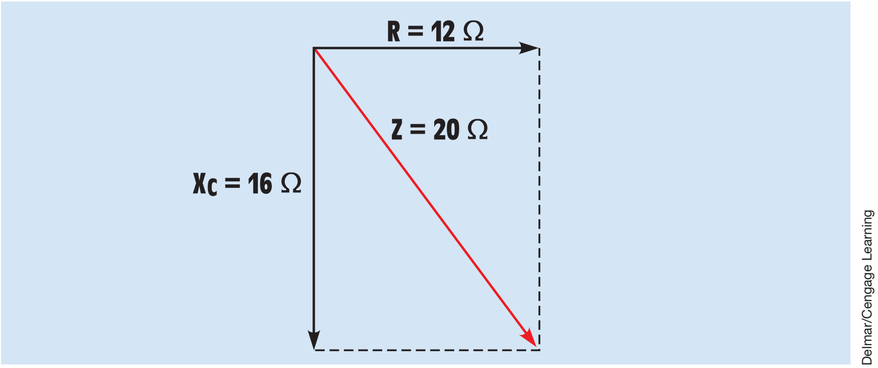


FIGURE 22–3 Impedance vector for example circuit 1.

22–3 Total Current

Now that the total impedance of the circuit is known, the total current flow (I_T) can be calculated using the formula

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{240\ V}{20\ \Omega}$$

$$I_T = 12\ A$$

22–4 Voltage Drop Across the Resistor

In a series circuit, the current is the same at any point in the circuit. Therefore, 12 amperes of current flow through both the resistor and the capacitor. The **voltage drop across the resistor (E_R)** can be calculated by using the formula

$$E_R = I \times R$$
$$E_R = 12\ A \times 12\ \Omega$$
$$E_R = 144\ V$$

22–5 True Power

True power (P) for the circuit can be calculated by using any of the watts formulas as long as values that apply only to the resistive part of the circuit are used. Recall that current and voltage must be in phase with each other for true power to be produced. The formula used in this example is

$$P = E_R \times I$$
$$P = 144\ V \times 12\ A$$
$$P = 1728\ W$$

22–6 Capacitance

The amount of **capacitance (C)** can be calculated using the formula

$$C = \frac{1}{2\pi f X_C}$$
$$C = \frac{1}{377 \times 16\ \Omega}$$
$$C = \frac{1}{6032}$$
$$C = 0.0001658\ F = 165.8\ \mu F$$

22–7 Voltage Drop Across the Capacitor

The **voltage drop across the capacitor (E_C)** can be calculated using the formula

$$E_C = I \times X_C$$
$$E_C = 12\ A \times 16\ \Omega$$
$$E_C = 192\ V$$

22–8 Total Voltage

Although the amount of **total voltage (E_T)** applied to the circuit is given as 240 volt in this circuit, it is possible to calculate the total voltage if it is not known by adding together the voltage drop across the resistor and the voltage drop across the capacitor. In a series circuit, the voltage drops across the resistor and capacitor are 90° out of phase with each other and vector addition must be used. These two voltage drops form the legs of a right triangle, and the total voltage forms the hypotenuse *(Figure 22–4)*. The total voltage can be calculated using the following formula

$$E_T = \sqrt{E_R^2 + E_C^2}$$
$$E_T = \sqrt{(144\ V)^2 + (192\ V)^2}$$
$$E_T = 240\ V$$

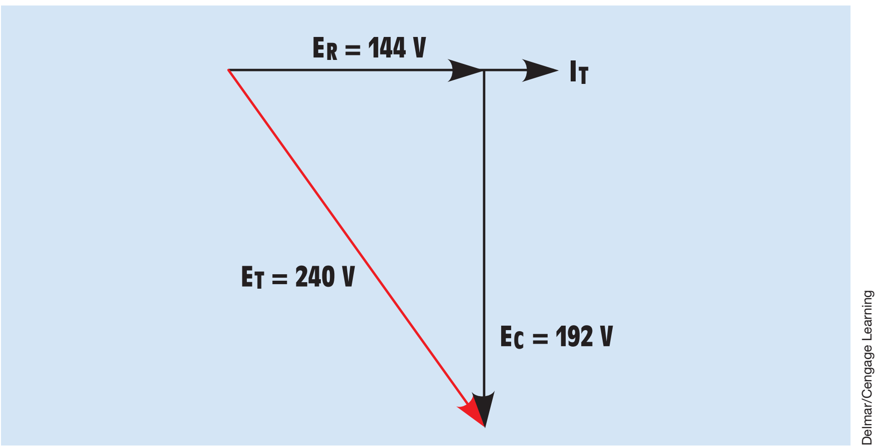


FIGURE 22–4 The voltage drops across the resistor and capacitor are 90° out of phase with each other.

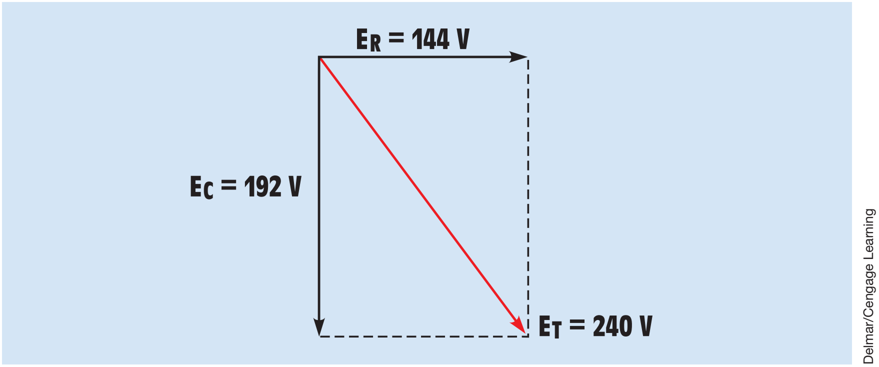


FIGURE 22–5 Voltage vector for example circuit.

A vector diagram illustrating the voltage relationships for this circuit is shown in *Figure 22–5*.

22–9 Reactive Power

The **reactive power ($VARs_C$)** in the circuit can be calculated in a manner similar to that used for watts except that reactive values of voltage and current are used instead of resistive values. In this example, the formula used is

$$VARs_C = E_C \times I$$
$$VARs_C = 192\ V \times 12\ A$$
$$VARs_C = 2304$$

22–10 Apparent Power

The apparent power (VA) of the circuit can be calculated in a manner similar to that used for watts or $VARs_C$, except that total values of voltage and current are used. In this example, the formula used is

$$VA = E_T \times I$$
$$VA = 240\ V \times 12\ A$$
$$VA = 2880$$

The apparent power can also be determined by vector addition of the true power and reactive power *(Figure 22–6)*.

$$VA = \sqrt{P^2 + VARs_C^{\ 2}}$$

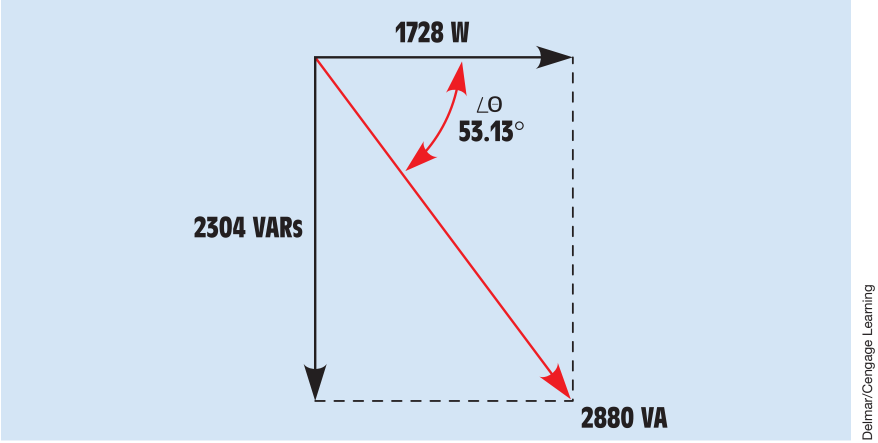


FIGURE 22–6 Apparent power vector for example circuit.

22–11 Power Factor

Power factor (PF) is a ratio of the true power to the apparent power. It can be calculated by dividing any resistive value by its like total value. In this circuit, the formula used is

$$PF = \frac{P}{VA}$$

$$PF = \frac{1728\ W}{2880\ VA}$$

$$PF = 0.6 \times 100, \text{ or } 60\%$$

22–12 Angle Theta

The power factor of a circuit is the cosine of the phase angle. Because the power factor of this circuit is 0.6, angle theta ($\angle\theta$) is

$$\cos \angle\theta = PF$$

$$\cos \angle\theta = 0.6$$

$$\angle\theta = 53.13°$$

In this circuit, the current leads the applied voltage by 53.13° *(Figure 22–7)*.

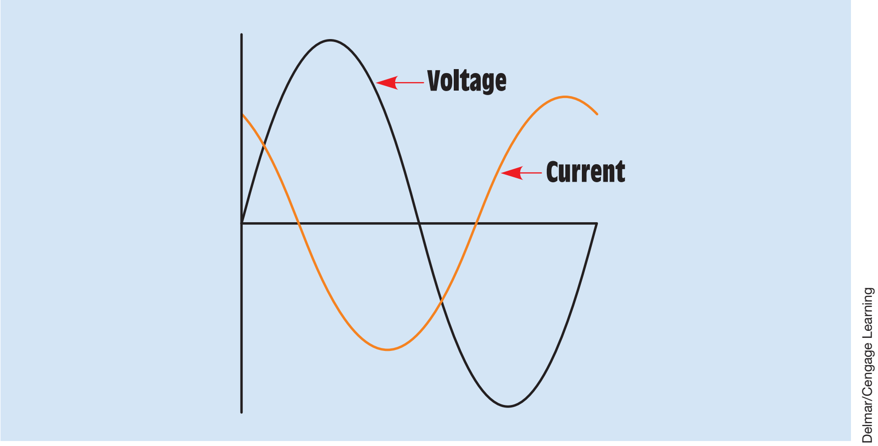


FIGURE 22–7 The current leads the voltage by 53.13°.

EXAMPLE 22-1

One resistor and two capacitors are connected in series to a 42.5-V, 60-Hz line *(Figure 22–8)*. Capacitor 1 has a reactive power of 3.75 VARs, the resistor has a true power of 5 W, and the second capacitor has a reactive power of 5.625 VARs. Find the following values:

VA—apparent power

I_T—total circuit current

Z—impedance of the circuit

PF—power factor

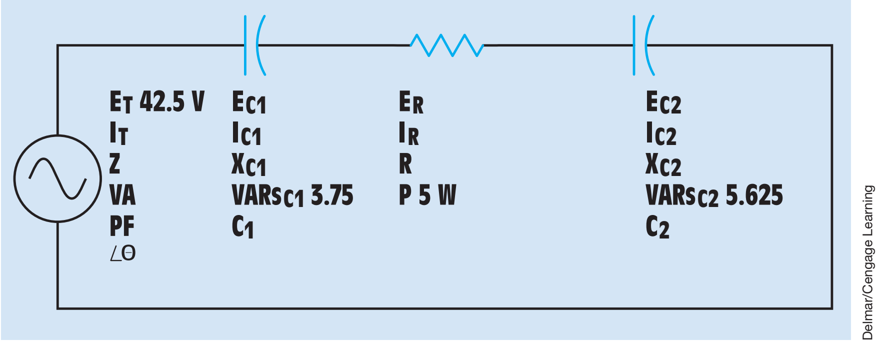


FIGURE 22–8 Example circuit.

$\angle\theta$—angle theta

E_{C1}—voltage drop across the first capacitor

X_{C1}—capacitive reactance of the first capacitor

C_1—capacitance of the first capacitor

E_R—voltage drop across the resistor

R—resistance of the resistor

E_{C2}—voltage drop across the second capacitor

X_{C2}—capacitive reactance of the second capacitor

C_2—capacitance of the second capacitor

Solution

Because the reactive power of the two capacitors is known and the true power of the resistor is known, the apparent power can be found using the formula

$$VA = \sqrt{P^2 + VARs_C^{\,2}}$$

In this circuit, $VARs_C$ is the sum of the VARs of the two capacitors. A power triangle for this circuit is shown in *Figure 22–9*.

$$VA = \sqrt{(5\ W)^2 + (3.75\ VARs + 5.625\ VARs)^2}$$

$$VA = \sqrt{25\ W^2 + 87.891\ VARs^2}$$

$$VA = 10.625$$

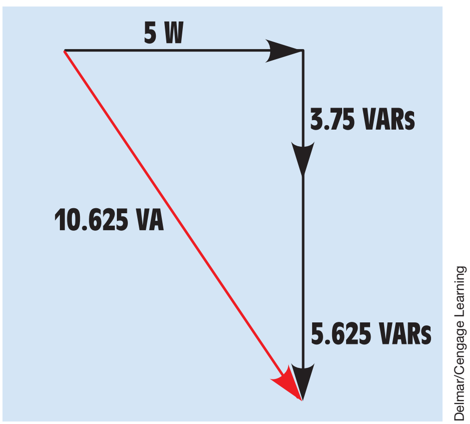


FIGURE 22–9 Power triangle for example circuit.

Now that the apparent power and applied voltage are known, the total circuit current can be calculated using the formula

$$I_T = \frac{VA}{E_T}$$

$$I_T = \frac{10.625\ VA}{42.5\ V}$$

$$I_T = 0.25\ A$$

In a series circuit, the current must be the same at any point in the circuit. Therefore, I_{C1}, I_R, and I_{C2} will all have a value of 0.25 A.

The impedance of the circuit can now be calculated using the formula

$$Z = \frac{E_T}{I_T}$$

$$Z = \frac{42.5\ V}{0.25\ A}$$

$$Z = 170\ \Omega$$

The power factor is calculated using the formula

$$PF = \frac{P}{VA}$$

$$PF = \frac{5\ W}{10.625\ VA}$$

$$PF = 0.4706, \text{ or } 47.06\%$$

The cosine of angle theta is the power factor:

$$\cos \angle\theta = 0.4706$$

$$\angle\theta = 61.93°$$

A vector diagram is shown in *Figure 22–10* illustrating the relationship of angle theta to the reactive power, true power, and apparent power.

Now that the current through each circuit element is known and the power of each element is known, the voltage drop across each element can be calculated:

$$E_{C1} = \frac{VARs_{C1}}{I_{C1}}$$

$$E_{C1} = \frac{3.75\ VARs}{0.25\ A}$$

$$E_{C1} = 15\ V$$

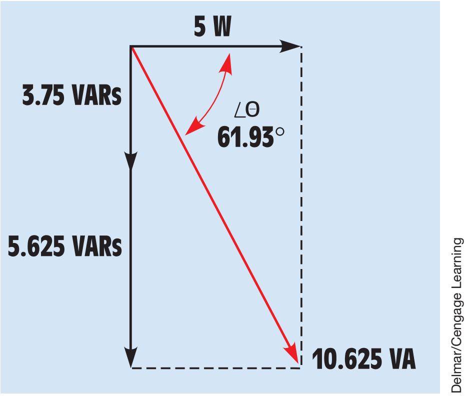


FIGURE 22–10 Vector relationship of reactive, true, and apparent power.

$$E_R = \frac{P}{I_R}$$

$$E_R = \frac{5\ \text{W}}{0.25\ \text{A}}$$

$$E_R = 20\ \text{V}$$

$$E_{C2} = \frac{\text{VARs}_{C2}}{I_{C2}}$$

$$E_{C2} = \frac{5.625\ \text{VARs}}{0.25\ \text{A}}$$

$$E_{C2} = 22.5\ \text{V}$$

The capacitive reactance of the first capacitor is

$$X_{C1} = \frac{E_{C1}}{I_{C1}}$$

$$X_{C1} = \frac{15\ \text{V}}{0.25\ \text{A}}$$

$$X_{C1} = 60\ \Omega$$

The capacitance of the first capacitor is

$$C_1 = \frac{1}{2\pi f X_{C1}}$$

$$C_1 = \frac{1}{377 \times 30\ \Omega}$$

$$C_1 = 0.0000442\ \text{F, or } 44.2\ \mu\text{F}$$

The resistance of the resistor is

$$R = \frac{E_R}{I_R}$$

$$R = \frac{20\ \text{V}}{0.25\ \text{A}}$$

$$R = 80\ \Omega$$

The capacitive reactance of the second capacitor is

$$X_{C2} = \frac{E_{C2}}{I_{C2}}$$

$$X_{C2} = \frac{22.5\ \text{V}}{0.25\ \text{A}}$$

$$X_{C2} = 90\ \Omega$$

The capacitance of the second capacitor is

$$C_2 = \frac{1}{2\pi f X_{C2}}$$

$$C_2 = \frac{1}{377 \times 90\ \Omega}$$

$$C_2 = 0.0000295\ \text{F, or } 29.5\ \mu\text{F}$$

The completed circuit with all values is shown in *Figure 22–11*.

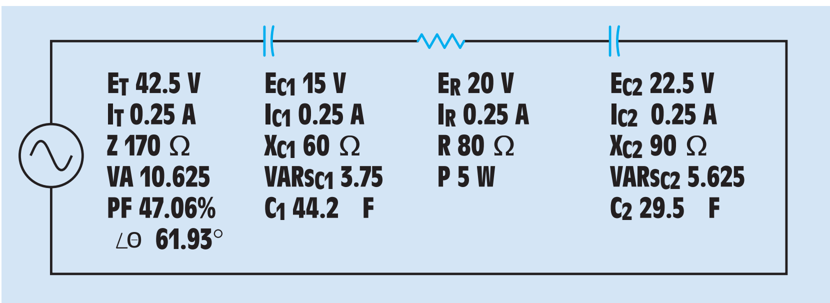


FIGURE 22–11 Example circuit with completed values.

EXAMPLE 22-2

A small indicating lamp has a rating of 2 W when connected to 120 V. The lamp must be connected to a voltage of 480 V at 60 Hz. A capacitor will be connected in series with the lamp to reduce the circuit current to the proper value. What value of capacitor will be needed to perform this job?

Solution

The first step is to determine the amount of current the lamp will normally draw when connected to a 120-V line:

$$I_{LAMP} = \frac{P}{E}$$

$$I_{LAMP} = \frac{2\ W}{120\ V}$$

$$I_{LAMP} = 0.0167\ A$$

The next step is to determine the amount of voltage that must be dropped across the capacitor when a current of 0.01667 A flows through it. Because the voltage dropped across the resistor and the voltage dropped across the capacitor are 90° out of phase with each other, vectors must be used to determine the voltage drop across the capacitor *(Figure 22–12)*. The voltage drop across the capacitor can be calculated using the formula

$$E_C = \sqrt{E_T^2 - E_R^2}$$

$$E_C = \sqrt{(480\ V)^2 - (120\ V)^2}$$

$$E_C = \sqrt{216{,}000\ V^2}$$

$$E_C = 464.758\ V$$

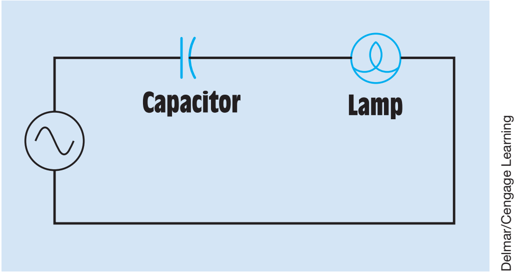


FIGURE 22–12 Determining voltage drop across the capacitor.

Now that the voltage drop across the capacitor and the amount of current flow are known, the capacitive reactance can be calculated:

$$X_C = \frac{E_C}{I}$$

$$X_C = \frac{464.758\ V}{0.0167\ A}$$

$$X_C = 27{,}829.82\ \Omega$$

The amount of capacitance needed to produce this capacitive reactance can now be calculated using the formula

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{377 \times 27{,}829.82\ \Omega}$$

$$C = 0.0000000953\ F, \text{ or } 95.3\ nF$$

The circuit containing the lamp and capacitor is shown in *Figure 22–13*.

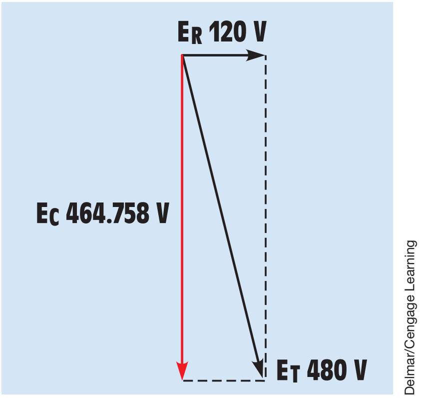


FIGURE 22–13 The capacitor reduces the current to the lamp.

Summary

- In a pure capacitive circuit, the voltage and current are 90° out of phase with each other.
- In a pure resistive circuit, the voltage and current are in phase with each other.

- In a circuit containing resistance and capacitance, the voltage and current will be out of phase with each other by some amount between 0° and 90°.
- The amount of phase angle difference between voltage and current in an RC series circuit is the ratio of resistance to capacitance.
- In a series circuit, the current flow through all components is the same. Therefore, the voltage drops across the resistive and capacitive parts become out of phase with each other.
- True power can be produced by resistive parts of the circuit only.
- Power factor is the ratio of true power to apparent power.

Review Questions

Refer to the formulas in the Resistive-Capacitive Series Circuits Formula section of Appendix B.

1. In a pure capacitive circuit, does the current lead or lag the voltage?
2. A series circuit contains a 20-Ω resistor and a capacitor with a capacitance of 110.5 μF. If the circuit has a frequency of 60 Hz, what is the total impedance of the circuit?
3. An RC series circuit has a power factor of 76%. How many degrees are the voltage and current out of phase with each other?
4. An RC series circuit has a total impedance of 84 Ω. The resistor has a value of 32 Ω. What is the capacitive reactance of the capacitor?

$$X_C = \sqrt{Z^2 - R^2}$$

5. A capacitor has a capacitive reactance of 50 Ω when connected to a 60-Hz line. What will be the capacitive reactance if the capacitor is connected to a 1000-Hz line?

Practice Problems

Refer to the formulas in the Resistive-Capacitive Series Circuits Formula section of Appendix B and to *Figure 22–1*.

1. Assume that the circuit shown in *Figure 22–1* is connected to a 480-V, 60-Hz line. The capacitor has a capacitance of 165.782 μF, and the resistor has a resistance of 12 Ω. Find the missing values.

E_T 480 V ______	E_R ______	E_C ______
I_T ______	I_R ______	I_C ______
Z ______	R 12 Ω ______	X_C ______
VA ______	P ______	$VARs_C$ ______
PF ______	∠θ ______	C 165.782 μF ______

2. Assume that the voltage drop across the resistor, E_R, is 78 V; the voltage drop across the capacitor, E_C, is 104 V; and the circuit has a total impedance, Z, of 20 Ω. The frequency of the AC voltage is 60 Hz. Find the missing values.

E_T ______	E_R 78 V ______	E_C 104 V ______
I_T ______	I_R ______	I_C ______
Z 20 Ω ______	R ______	X_C ______
VA ______	P ______	$VARs_C$ ______
PF ______	∠θ ______	C ______

3. Assume the circuit shown in *Figure 22–1* has an apparent power of 432 VA and a true power of 345.6 W. The capacitor has a capacitance of 15.8919 μF, and the frequency is 60 Hz. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T ______	I_R ______	I_C ______
Z ______	R ______	X_C ______
VA 432 ______	P 345.6 W ______	$VARs_C$ ______
PF ______	∠θ ______	C 15.8919 μF ______

4. Assume the circuit in *Figure 22–1* has a power factor of 68%, an apparent power of 300 VA, and a frequency of 400 Hz. The capacitor has a capacitance of 4.7125 μF. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T ______	I_R ______	I_C ______
Z ______	R ______	X_C ______
VA 300 ______	P ______	$VARs_C$ ______
PF 68% ______	∠θ ______	C 4.7125 μF ______

5. In a series RC circuit, E_T = 240 volts, R = 60 Ω, and X_C = 85 Ω. Find E_C.

6. In a series RC circuit, $E_T = 120$ volts, $R = 124\ \Omega$, and $X_C = 64\ \Omega$. Find reactive power.
7. In a series RC circuit, $E_T = 208$ volts, $I_T = 2.4$ amperes, and $R = 45\ \Omega$. Find the power factor.
8. In a series RC circuit, $E_T = 460$ volts and $\angle\theta = 44°$. Find E_C.
9. In a series RC circuit, $E_T = 240$ volts at 60 Hz. An ammeter indicates a total current of 0.75 amperes. The resistor has a value of 140 Ω. What is the capacitance of the capacitor?
10. In a series RC circuit, the apparent power is 4,250 VA and the reactive power is 2125 VARs. What is the true power?

Unit 23
Resistive-Capacitive Parallel Circuits

OUTLINE

KEY TERMS

Circuit impedance (Z)

Current flow through the capacitor (I_C)

Phase angle shift

Total circuit current (I_T)

Why You Need to Know

The relationship of voltage, current, impedance, and power when resistance and capacitance are connected in parallel with each other is very similar to resistive-inductive parallel circuits. Although it may seem that the units on resistive-capacitive series circuits and resistive-capacitive parallel circuits are a repeat of the information covered previously, they are an important step toward understanding what happens when elements of resistance, inductance, and capacitance are combined into the same circuit. This unit

- discusses parallel circuits that contain both resistance and capacitance and the effect on voltage, current, power, and impedance.
- illustrates how to calculate circuit current and voltage and their relationship in a resistive-capacitive parallel circuit.


Courtesy of FAA

Objectives

After studying this unit, you should be able to

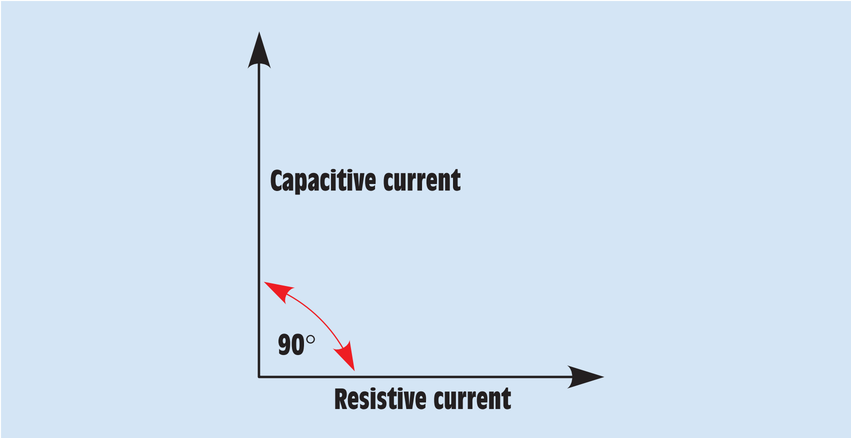
- discuss the operation of a parallel circuit containing resistance and capacitance.
- calculate circuit values of an RC parallel circuit.
- connect an RC parallel circuit and measure circuit values with test instruments.

Preview

This unit discusses the relationship of different electrical quantities such as voltage, current, impedance, and power in a circuit that contains both resistance and capacitance connected in parallel. Because all components connected in parallel must share the same voltage, the current flow through different components will be out of phase with each other. The effect this condition has on other circuit quantities is explored. ■

23–1 Operation of RC Parallel Circuits

When resistance and capacitance are connected in parallel, the voltage across all the devices will be in phase and will have the same value. The current flow through the capacitor, however, will be 90° out of phase with the current flow through the resistor *(Figure 23–1)*. The amount of **phase angle shift** between the total circuit current and voltage is determined by the ratio of the amount



Delmar/Cengage Learning

FIGURE 23–1 Current flow through the capacitor is 90° out of phase with current flow through the resistor.

of resistance to the amount of capacitance. The circuit power factor is still determined by the ratio of resistance and capacitance.

23–2 Calculating Circuit Values

■ EXAMPLE 23-1

In the RC parallel circuit shown in *Figure 23–2*, assume that a resistance of 30 Ω is connected in parallel with a capacitive reactance of 20 Ω. The circuit is connected to a voltage of 240 VAC and a frequency of 60 Hz. Calculate the following circuit values:

I_R—current flow through the resistor

P—watts (true power)

I_C—current flow through the capacitor

$VARs_C$—volt-amperes reactive (reactive power)

C—capacitance of the capacitor

I_T—total circuit current

Z—total impedance of the circuit

VA—volt-amperes (apparent power)

PF—power factor

$\angle\theta$—angle theta (phase angle of voltage and current)

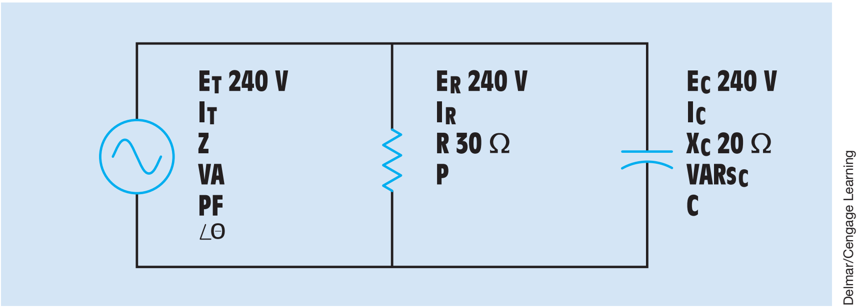


FIGURE 23–2 Resistive-capacitive parallel circuit.

Solution

Resistive Current

The amount of current flow through the resistor (I_R) can be calculated by using the formula

$$I_R = \frac{E}{R}$$

$$I_R = \frac{240\ V}{30\ \Omega}$$

$$I_R = 8\ A$$

True Power

The amount of total true power (P) in the circuit can be determined by using any of the values associated with the pure resistive part of the circuit. In this example, true power is found using the formula

$$P = E \times I_R$$

$$P = 240\ V \times 8\ A$$

$$P = 1920\ W$$

Capacitive Current

The amount of **current flow through the capacitor (I_C)** is calculated using the formula

$$I_C = \frac{E}{X_C}$$

$$I_C = \frac{240\ V}{20\ \Omega}$$

$$I_C = 12\ A$$

Reactive Power

The amount of reactive power ($VARs_C$) can be found using any of the total capacitive values. In this example, $VARs_C$ is calculated using the formula

$$VARs_C = E \times I_C$$

$$VARs_C = 240\ V \times 12\ A$$

$$VARs_C = 2880$$

Capacitance

The capacitance of the capacitor can be calculated using the formula

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{377 \times 20\ \Omega}$$

$$C = \frac{1}{7540}$$

$$C = 0.0001326\ \text{F} = 132.6\ \mu\text{F}$$

Total Current

The voltage is the same across all legs of a parallel circuit. The current flow through the resistor is in phase with the voltage, and the current flow through the capacitor is leading the voltage by 90° *(Figure 23–3)*. The 90° difference in capacitive and resistive current forms a right triangle as shown in *Figure 23–4*. Because these two currents are connected in parallel, vector addition can be used to find the total current flow in the circuit

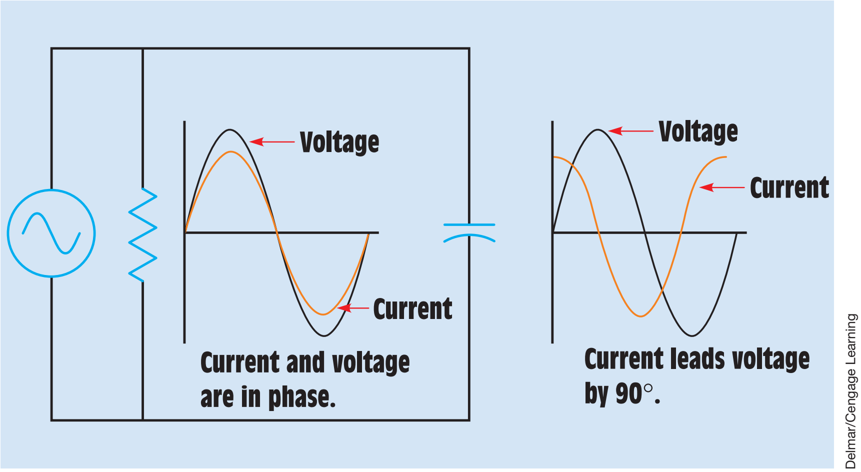


FIGURE 23–3 Phase relationship of current and voltage in an RC parallel circuit.

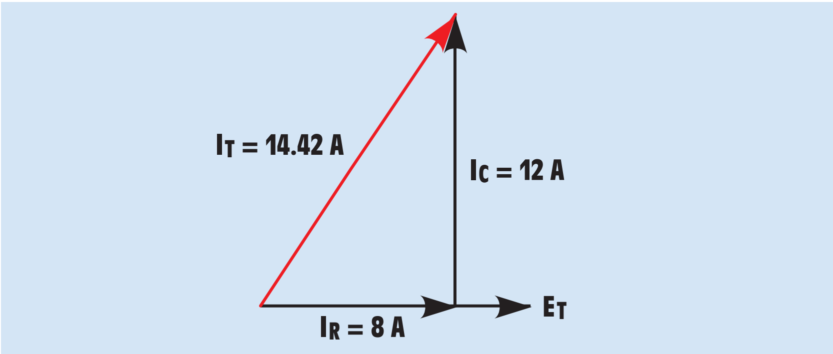


FIGURE 23–4 Resistance current and capacitive current are 90° out of phase with each other.

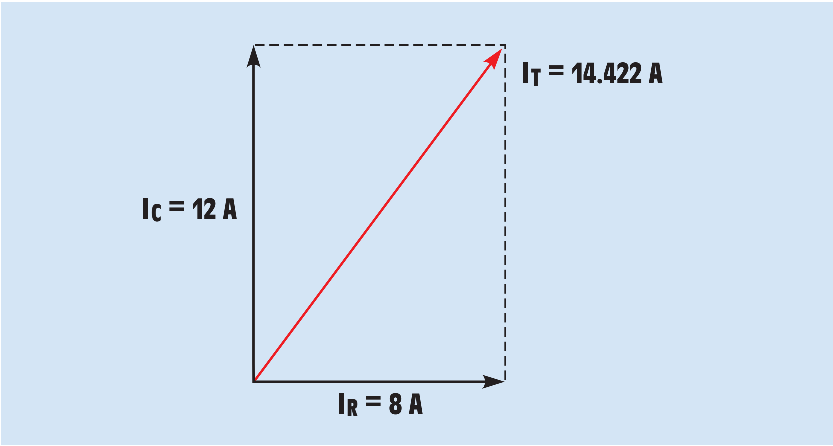


FIGURE 23–5 Vector addition can be used to find total current.

(Figure 23–5). The **total circuit current (I_T)** flow can be calculated by using the formula:

$$I_T = \sqrt{I_R^2 + I_C^2}$$

$$I_T = \sqrt{(8A)^2 + (12\ A)^2}$$

$$I_T = \sqrt{64\ A^2 + 144\ A^2}$$

$$I_T = \sqrt{208\ A^2}$$

$$I_T = 14.422\ A$$

Impedance

The total **circuit impedance (Z)** can be found by using any of the total values and substituting Z for R in an Ohm's law formula. The total impedance of this circuit is calculated using the formula

$$Z = \frac{E}{I_T}$$

$$Z = \frac{240\text{ V}}{14.422\text{ A}}$$

$$Z = 16.641\ \Omega$$

The impedance can also be found by adding the reciprocals of the resistance and capacitive reactance. Because the resistance and capacitive reactance are 90° out of phase with each other, vector addition must be used:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2}}$$

Another formula that can be used to determine the impedance in a circuit that contains both resistance and capacitive reactance is

$$Z = \frac{R \times X_C}{\sqrt{R^2 + X_C^2}}$$

Apparent Power

The apparent power (VA) can be calculated by multiplying the circuit voltage by the total current flow:

$$VA = E \times I_T$$

$$VA = 240\text{ V} \times 14.422\text{ A}$$

$$VA = 3461.28$$

Power Factor

The power factor (PF) is the ratio of true power to apparent power. The circuit power factor can be calculated using the formula

$$PF = \frac{W}{VA} \times 100$$

$$PF = \frac{1920}{3461.28}$$

$$PF = 0.5547\text{, or }55.47\%$$

Angle Theta

The cosine of angle theta ($\angle\theta$) is equal to the power factor:

$$\cos \angle\theta = 0.5547$$
$$\angle\theta = 56.31°$$

A vector diagram of apparent, true, and reactive power is shown in *Figure 23–6*. Angle theta is the angle developed between the apparent and true power. The complete circuit with all values is shown in *Figure 23–7*.

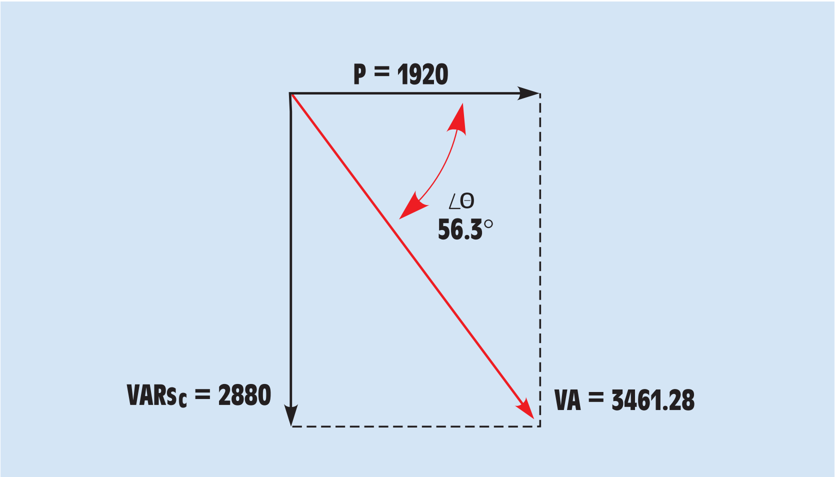


FIGURE 23–6 Vector relationship of apparent, true, and reactive power.

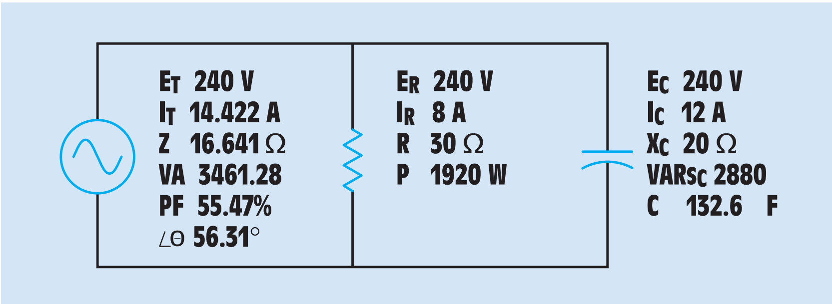


FIGURE 23–7 Example circuit with all calculated values.

EXAMPLE 23-2

In this circuit, a resistor and a capacitor are connected in parallel to a 400-Hz line. The power factor is 47.1%, the apparent power is 4086.13 VA, and the capacitance of the capacitor is 33.15 μF *(Figure 23–8)*. Find the following unknown values:

$\angle\theta$—angle theta

P—true power

$VARs_C$—capacitive VARs

X_C—capacitive reactance

E_C—voltage drop across the capacitor

I_C—capacitive current

E_R—voltage drop across the resistor

I_R—resistive current

R—resistance of the resistor

E_T—applied voltage

I_T—total circuit current

Z—impedance of the circuit

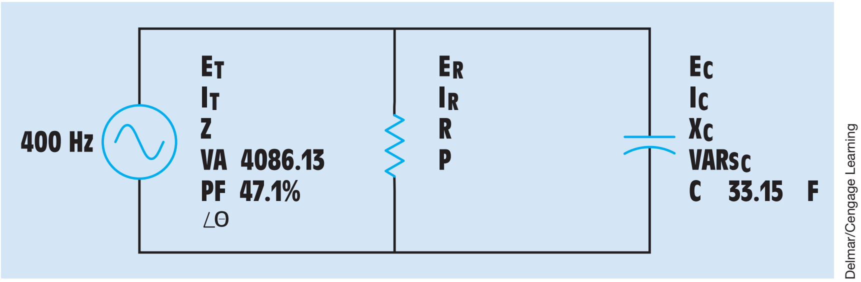


FIGURE 23–8 Example circuit.

Solution

Angle Theta

The power factor is the cosine of angle theta. To find angle theta, change the power factor from a percentage into a decimal fraction by dividing by 100:

$$PF = \frac{47.1}{100}$$

$$PF = 0.471$$

$$\cos \angle\theta = 0.471$$

$$\angle\theta = 61.9°$$

True Power

The power factor is determined by the ratio of true power to apparent power:

$$PF = \frac{P}{VA}$$

This formula can be changed to calculated the true power when the power factor and apparent power are known (refer to the Resistive-Capacitive Parallel Circuits Formula Section of Appendix B).

$$P = VA \times PF$$

$$P = 4086.13 \times 0.471$$

$$P = 1924.47\text{ W}$$

Reactive Power

The apparent power, true power, and reactive power form a right triangle as shown in *Figure 23–9*. Because these powers form a right triangle, the Pythagorean theorem can be used to find the leg of the triangle represented by the reactive power:

$$VARs_C = \sqrt{VA^2 - P^2}$$

$$VARs_C = \sqrt{4086.13^2 - 1924.47^2}$$

$$VARs_C = \sqrt{12{,}992{,}873.6}$$

$$VARs_C = 3604.56$$

A vector diagram showing the relationship of apparent power, true power, reactive power, and angle theta is shown in *Figure 23–10*.

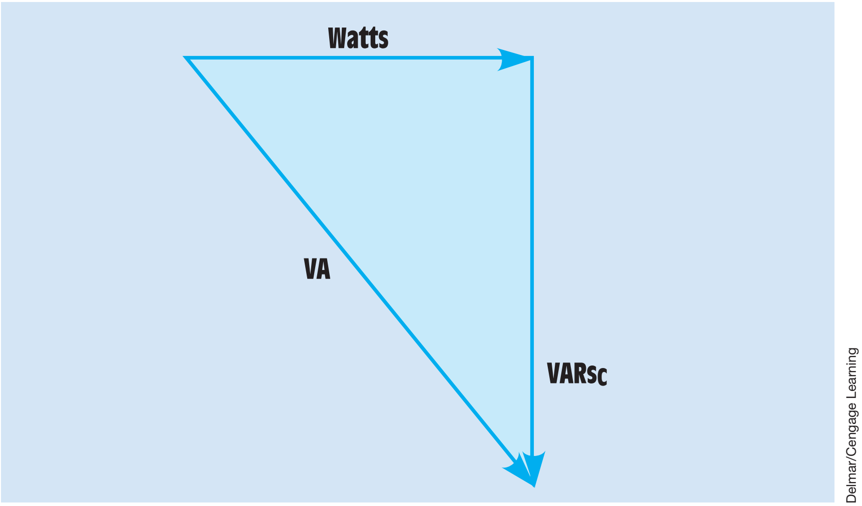


FIGURE 23–9 Right triangle formed by the apparent, true, and reactive powers.

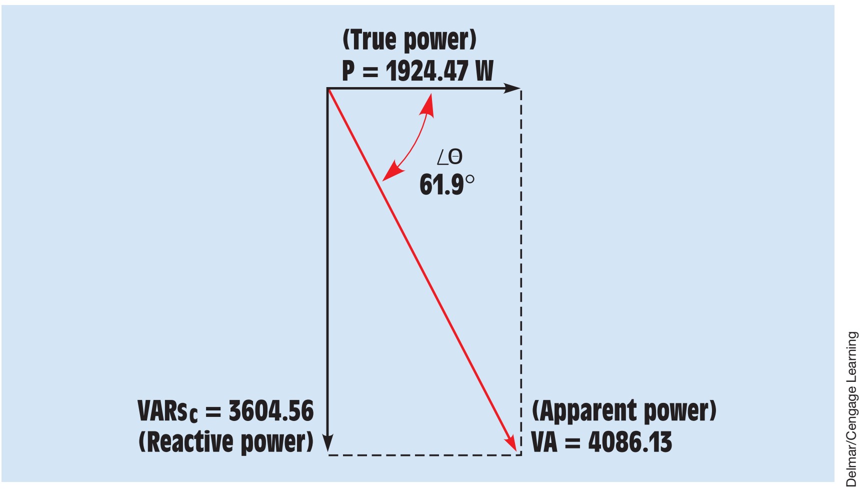


FIGURE 23–10 Vector diagram of apparent power, true power, reactive power, and angle theta.

Capacitive Reactance

Because the capacitance of the capacitor and the frequency are known, the capacitive reactance can be found using the formula

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1 \text{ Hz}}{2 \times 3.1416 \times 400 \text{ Hz} \times 0.00003315 \text{ F}}$$

$$X_C = 12.003\ \Omega$$

Voltage Drop Across the Capacitor

$$E_C = \sqrt{VARs_C \times X_C}$$
$$E_C = \sqrt{3604.56\ VARs \times 12.003\ \Omega}$$
$$E_C = \sqrt{43{,}265.53}$$
$$E_C = 208\ V$$

E_R and E_T

The voltage must be the same across all branches of a parallel circuit. Therefore, if 208 V are applied across the capacitive branch, 208 V must be the total voltage of the circuit as well as the voltage applied across the resistive branch:

$$E_T = 208\ V$$
$$E_R = 208\ V$$

I_C

The amount of current flowing in the capacitive branch can be calculated using the formula

$$I_C = \frac{E_C}{X_C}$$
$$I_C = \frac{208\ V}{12\ \Omega}$$
$$I_C = 17.331$$

I_R

The amount of current flowing through the resistor can be calculated using the formula

$$I_R = \frac{P}{E_R}$$
$$I_R = \frac{1924.47\ W}{208}$$
$$I_R = 9.25\ A$$

Resistance

The amount of resistance can be calculated using the formula

$$R = \frac{E_R}{I_R}$$

$$R = \frac{208\ V}{9.25\ A}$$

$$R = 22.49\ \Omega$$

Total Current

The total current can be calculated using Ohm's law or by vector addition because both the resistive and capacitive currents are known. Vector addition is used in this example:

$$I_T = \sqrt{I_R{}^2 + I_C{}^2}$$

$$I_T = \sqrt{(9.25\ A)^2 + (17.33\ A)^2}$$

$$I_T = \sqrt{385.89\ A^2}$$

$$I_T = 19.64\ A$$

Impedance

The impedance of the circuit is calculated using the formula

$$Z = \frac{R \times X_C}{\sqrt{R^2 + X_C{}^2}}$$

$$Z = \frac{22.479\ \Omega \times 12.003\ \Omega}{\sqrt{(22.479\ \Omega)^2 + (12.003\ \Omega)^2}}$$

$$Z = \frac{269.815\ \Omega}{\sqrt{649.377\ \Omega^2}}$$

$$Z = \frac{269.815\ \Omega}{25.483\ \Omega}$$

$$Z = 10.588\ \Omega$$

The complete circuit with all values is shown in *Figure 23–11*.

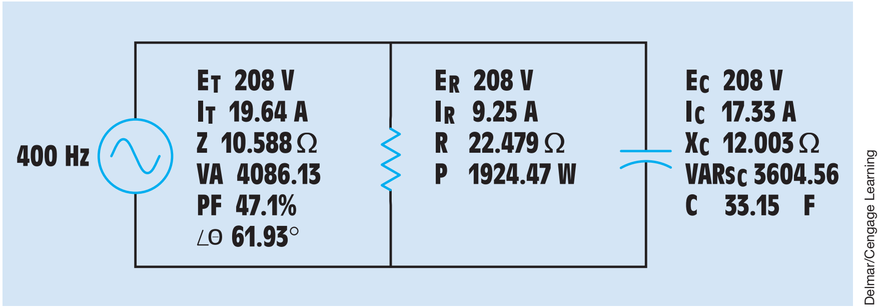


FIGURE 23–11 Example Circuit 2 with completed values.

Summary

- The current flow in the resistive part of the circuit is in phase with the voltage.
- The current flow in the capacitive part of the circuit leads the voltage by 90°.
- The amount the current and voltage are out of phase with each other is determined by the ratio of resistance to capacitance.
- The voltage is the same across any leg of a parallel circuit.
- The circuit power factor is the ratio of true power to apparent power.

Review Questions

1. When a capacitor and a resistor are connected in parallel, how many degrees out of phase are the current flow through the resistor and the current flow through the capacitor?
2. A capacitor and a resistor are connected in parallel to a 120-V, 60-Hz line. The resistor has a resistance of 40 Ω, and the capacitor has a capacitance of 132.6 μF. What is the total current flow through the circuit?
3. What is the impedance of the circuit in Question 2?
4. What is the power factor of the circuit in Question 2?
5. How many degrees out of phase are the current and voltage in Question 2?

Practice Problems

Refer to the formulas in the Resistive-Capacitive Parallel Circuits section of Appendix B and to *Figure 23–2*.

1. Assume that the circuit shown in *Figure 23–2* is connected to a 60-Hz line and has a total current flow of 10.463 A. The capacitor has a capacitance of 123.626 μF, and the resistor has a resistance of 14 Ω. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T 10.463 A	I_R ______	I_C ______
Z ______	R 14 Ω	X_C ______
VA ______	P ______	$VARs_C$ ______
PF ______	∠θ ______	C 132.626 μF

2. Assume that the circuit is connected to a 400-Hz line and has a total impedance of 21.6 Ω. The resistor has a resistance of 36 Ω, and the capacitor has a current flow of 2 A through it. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T ______	I_R ______	I_C 2 A
Z 21.6 Ω	R 36 Ω	X_C ______
VA ______	P ______	$VARs_C$ ______
PF ______	∠θ ______	C ______

3. Assume that the circuit shown in *Figure 23–2* is connected to a 600-Hz line and has a current flow through the resistor of 65.6 A and a current flow through the capacitor of 124.8 A. The total impedance of the circuit is 2.17888 Ω. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T ______	I_R 65.6 A	I_C 124.8 A
Z 2.17888 Ω	R ______	X_C ______
VA ______	P ______	$VARs_C$ ______
PF ______	∠θ ______	C ______

4. Assume that the circuit shown in *Figure 23–2* is connected to a 1000-Hz line and has a true power of 486.75 W and a reactive power of

187.5 VARs. The total current flow in the circuit is 7.5 A. Find the missing values.

E_T ______	E_R ______	E_C ______
I_T 7.5 A	I_R ______	I_C ______
Z ______	R ______	X_C ______
VA ______	P 486.75 W	$VARs_C$ 187.5
PF ______	$\angle\theta$ ______	C ______

5. In an RC parallel circuit, R = 3.6 kΩ and X_C = 4.7 kΩ. Find Z.

6. In an RC parallel circuit, I_R = 0.6 amperes, R = 24 Ω, and X_C = 33 Ω. Find I_C.

7. In an RC parallel circuit, E_T = 120 volts, I_T = 1.2 amperes, and R = 240 Ω. Find X_C.

8. In an RC parallel circuit, the apparent power is 3400 VA and $\angle\theta = 58°$. Find reactive power.

9. In an RC parallel circuit, the true power is 780 watts and the reactive power is 560 VARs. Find the power factor.

10. In an RC parallel circuit, E_T = 7.5 volts at 1 kHz. The circuit current is 2.214 amperes. R = 4 Ω. What is the value of the capacitor connected in the circuit?

VIII

AC Circuits Containing Resistance-Inductance-Capacitance

Courtesy of Getty Images, Inc.

Unit 24

Resistive-Inductive-Capacitive Series Circuits

OUTLINE

KEY TERMS

Bandwidth
Lagging power factor
Leading power factor
Resonance

Why You Need to Know

This unit combines the elements of resistance, inductance, and capacitance in the same circuit. RLC series circuits are generally employed in a particular application. An RLC series resonant circuit, for example, can produce a very large increase in the voltage across a particular component. This unit

- discusses the values of voltage, current, power, and impedance in series circuits containing resistance, inductance, and capacitance.
- determines the voltage and current phase relationship in this circuit when applied to the resistor, capacitor, and inductor.
- illustrates how to calculate the values needed to produce a resonant circuit at a particular frequency.
- presents another important concept when dealing with resonance, called bandwidth.

Courtesy of Motoman, Inc.

Objectives

After studying this unit, you should be able to

- discuss AC circuits that contain resistance, inductance, and capacitance connected in series.
- connect an RLC series circuit.
- calculate values of impedance, inductance, capacitance, power, VARs, reactive power, voltage drop across individual components, power factor, and phase angle of voltage and current.
- discuss series resonant circuits.

Preview

Circuits containing resistance, inductance, and capacitance connected in series are presented in this unit. Electrical quantities for voltage drop, impedance, and power are calculated for the total circuit values and for individual components. Circuits that become resonant at a certain frequency are presented as well as the effect a resonant circuit has on electrical quantities such as voltage, current, and impedance. ■

24–1 RLC Series Circuits

When an AC circuit contains elements of resistance, inductance, and capacitance connected in series, the ***current is the same*** through all components, but the ***voltages dropped across the elements are out of phase*** with each other. The voltage dropped across the resistance is in phase with the current; the voltage dropped across the inductor leads the current by 90°; and the voltage dropped across the capacitor lags the current by 90° *(Figure 24–1)*. An RLC series circuit is shown in *Figure 24–2*. The ratio of resistance, inductance, and capacitance determines how much the applied voltage leads or lags the circuit current. If the circuit contains more inductive VARs than capacitive VARs, the current lags the applied voltage and the power factor is a **lagging power factor.** If there are more capacitive VARs than inductive VARs, the current leads the voltage and the power factor is a **leading power factor.**

Because inductive reactance and capacitive reactance are 180° out of phase with each other, they cancel each other in an AC circuit. This cancellation can permit the impedance of the circuit to become less than either or both of the reactances, producing a high amount of current flow through the circuit. When Ohm's law is applied to the circuit values, note that the voltage drops developed across these components can be higher than the applied voltage.

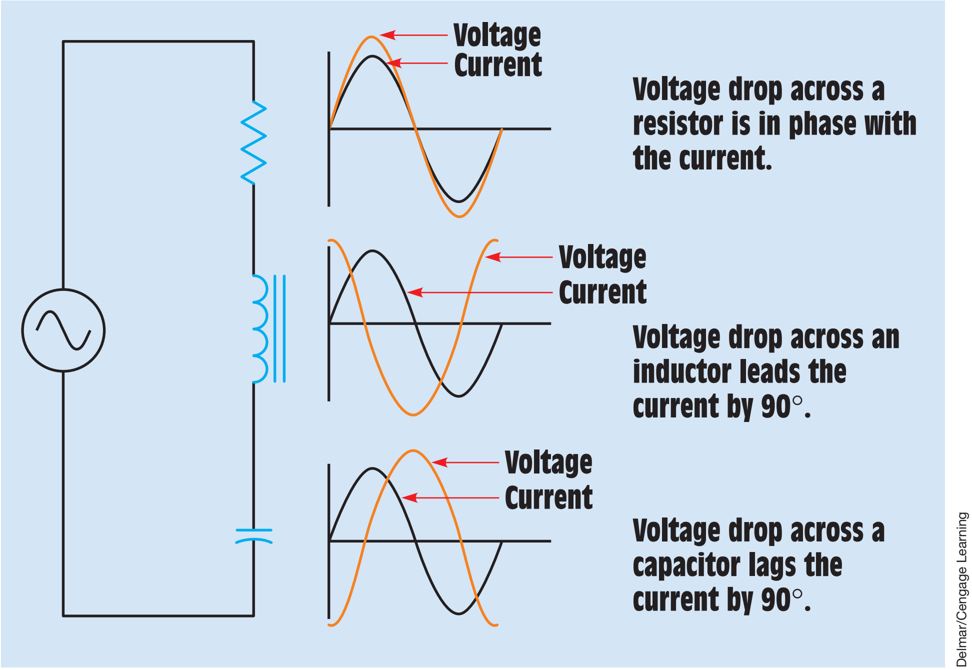


FIGURE 24–1 Voltage and current relationship in an RLC series circuit.

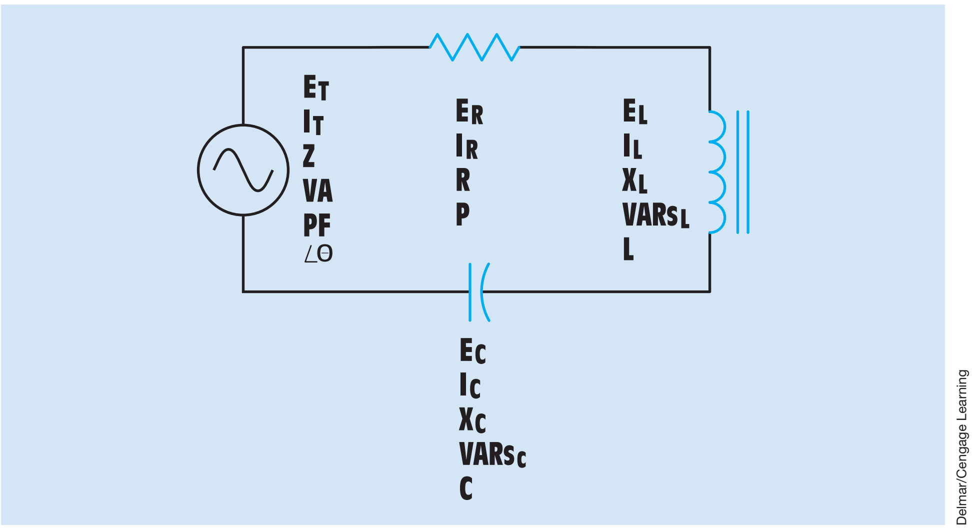


FIGURE 24–2 Resistive-inductive-capacitive series circuit.

EXAMPLE 24–1

Assume that the circuit shown in *Figure 24–2* has an applied voltage of 240 V at 60 Hz and that the resistor has a value of 12 Ω, the inductor has an inductive reactance of 24 Ω, and the capacitor has a capacitive reactance of 8 Ω. Find the following unknown values:

Z—impedance of the circuit

I_T—circuit current

E_R—voltage drop across the resistor

P—true power (watts)

L—inductance of the inductor

E_L—voltage drop across the inductor

$VARs_L$—reactive power of the inductor

C—capacitance

E_C—voltage drop across the capacitor

$VARs_C$—reactive power of the capacitor

VA—volt-amperes (apparent power)

PF—power factor

$\angle\theta$—angle theta

Solution

Total Impedance

The impedance of the circuit is the sum of resistance, inductive reactance, and capacitive reactance. Because inductive reactance and capacitive reactance are 180° out of phase with each other, vector addition must be used to find their sum. This method results in the smaller of the two reactive values being subtracted from the larger *(Figure 24–3)*. The smaller value is eliminated, and the larger value is reduced by the amount of the smaller value. The total impedance is the hypotenuse formed by the resulting right triangle *(Figure 24–4)*.

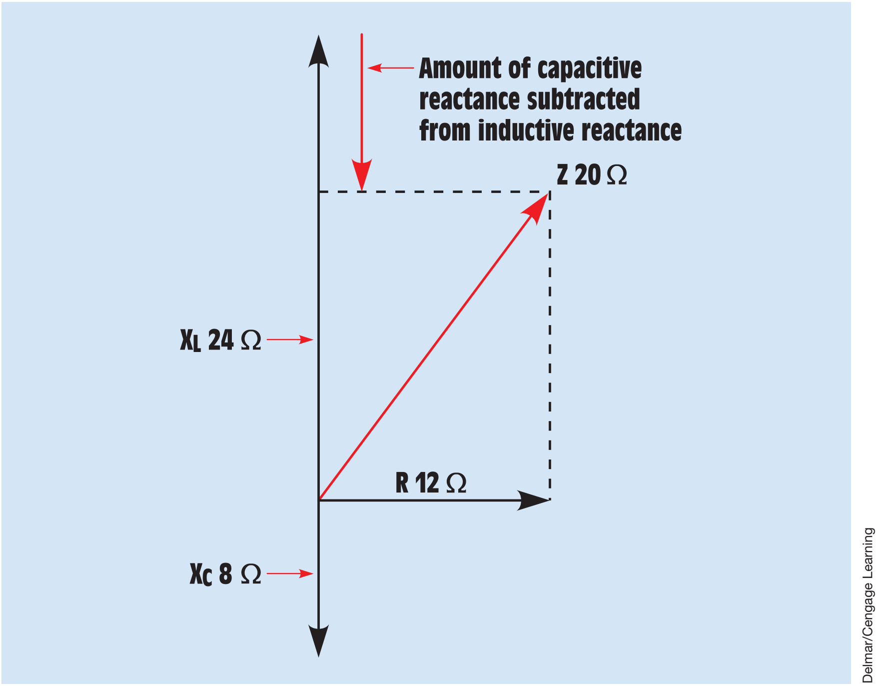


FIGURE 24–3 Vector addition is used to determine impedance.

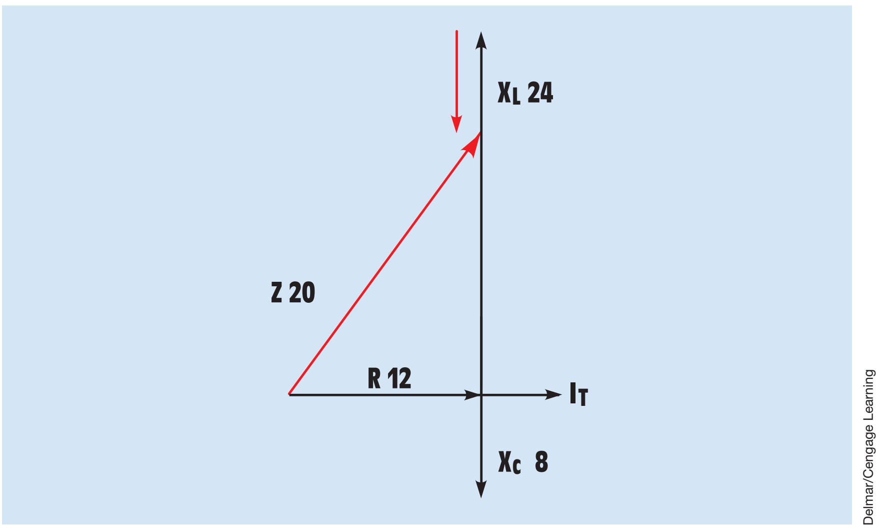


FIGURE 24–4 Right triangle formed by circuit impedance.

The impedance is calculated by using the formula

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{(12\ \Omega)^2 + (24\ \Omega - 8\ \Omega)^2}$$

$$Z = \sqrt{(12\ \Omega)^2 + (16\ \Omega)^2}$$

$$Z = \sqrt{144\ \Omega + 256\ \Omega}$$

$$Z = \sqrt{400\ \Omega}$$

$$Z = 20\ \Omega$$

In the preceding formula, the capacitive reactance is subtracted from the inductive reactance and then the difference is squared. If the capacitive reactance is a larger value than the inductive reactance, the difference is a negative number. The sign of the difference has no effect on the answer, however, because the square of a negative or positive number is always positive. For example, assume that an RLC series circuit contains a resistor with a value of 10 Ω, an inductor with an inductive reactance of 30 Ω, and a capacitor with a capacitive reactance of 54 Ω. When these values are substituted in the previous formula, the difference between the inductive and capacitive reactances is a negative number:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{(10\ \Omega)^2 + (30\ \Omega - 54\ \Omega)^2}$$

$$Z = \sqrt{(10\ \Omega)^2 + (-24\ \Omega)^2}$$

$$Z = \sqrt{(100 + 576\ \Omega)^2}$$

$$Z = \sqrt{676\ \Omega}$$

$$Z = 26\ \Omega$$

Current

The total current flow through the circuit can now be calculated using the formula

$$I_T = \frac{E_T}{Z}$$

$$I_T = \frac{240\ V}{20\ \Omega}$$

$$I_T = 12\ A$$

In a series circuit, the current flow is the same at any point in the circuit. Therefore, 12 A flow through each of the circuit components.

Resistive Voltage Drop

The voltage drop across the resistor can be calculated using the formula

$$E_R = I_R \times R$$
$$E_R = 12\text{ A} \times 12\ \Omega$$
$$E_R = 144\text{ V}$$

Watts

The true power of the circuit can be calculated using any of the pure resistive values. In this example, true power is found using the formula

$$P = E_R \times I$$
$$P = 144\text{ V} \times 12\text{ A}$$
$$P = 1728\text{ W}$$

Inductance

The amount of inductance in the circuit can be calculated using the formula

$$L = \frac{X_L}{2\pi f}$$
$$L = \frac{24\ \Omega}{377}$$
$$L = 0.0637\text{H}$$

Voltage Drop Across the Inductor

The amount of voltage drop across the inductor can be calculated using the formula

$$E_L = I \times X_L$$
$$E_L = 12\text{ A} \times 24\ \Omega$$
$$E_L = 288\text{ V}$$

Notice that the voltage drop across the inductor is greater than the applied voltage.

Inductive VARs

The amount of reactive power of the inductor can be calculated by using inductive values:

$$VARs_L = E_L \times I$$
$$VARs_L = 288\text{ V} \times 12\text{ A}$$
$$VARs_L = 3456$$

Capacitance

The amount of capacitance in the circuit can be calculated by using the formula

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{377 \times 8\ \Omega}$$

$$C = \frac{1}{3016}$$

$$C = 0.000331565\ \text{F, or } 331.565\ \mu\text{F}$$

Voltage Drop Across the Capacitor

The voltage dropped across the capacitor can be calculated using the formula

$$E_C = I \times X_C$$

$$E_C = 12\ \text{A} \times 8\ \Omega$$

$$E_C = 96\ \text{V}$$

Capacitive VARs

The amount of capacitive VARs can be calculated using the formula

$$VARs_C = E_C \times I$$

$$VARs_C = 96\ \text{V} \times 12\ \text{A}$$

$$VARs_C = 1152$$

Apparent Power

The VAs (apparent power) can be calculated by multiplying the applied voltage and the circuit current:

$$VA = E_T \times I$$

$$VA = 240\ \text{V} \times 12\ \text{A}$$

$$VA = 2880$$

The apparent power can also be found by vector addition of true power, inductive VARs, and capacitive VARs *(Figure 24–5)*. As with the addition of resistance, inductive reactance, and capacitive reactance, inductive VARs, $VARs_L$, and capacitive VARs, $VARs_C$ are 180° out of phase with each other. The result is the elimination

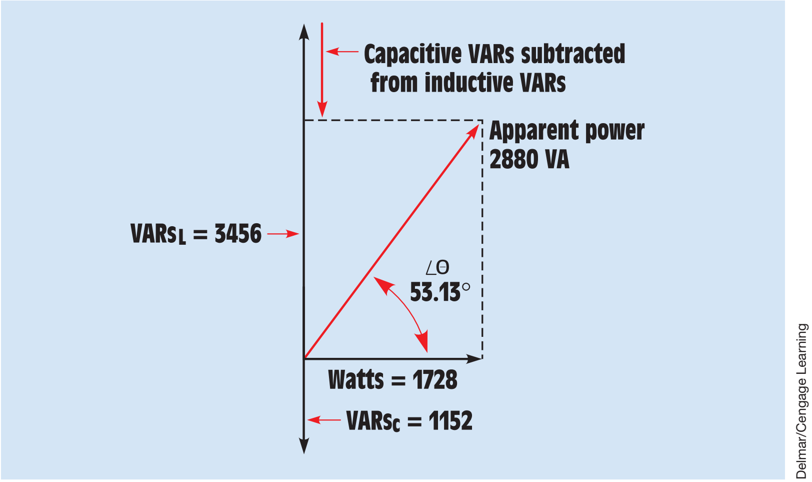


FIGURE 24–5 Vector addition of apparent power, true power, and reactive power.

of the smaller and a reduction of the larger. The following formula can be used to determine apparent power:

$$VA = \sqrt{P^2 + (VARs_L - VARs_C)^2}$$

$$VA = \sqrt{(1728\ W)^2 + (3456\ VARs_L - 1152\ VARs_C)^2}$$

$$VA = \sqrt{(1728\ W)^2 + (2304\ VARs)^2}$$

$$VA = \sqrt{8{,}294{,}400}$$

$$VA = 2880$$

Power Factor

The power factor can be calculated by dividing the true power of the circuit by the apparent power. The answer is multiplied by 100 to change the decimal into a percent:

$$PF = \frac{W}{VA} \times 100$$

$$PF = \frac{1728\ W}{2880\ VA} \times 100$$

$$PF = 0.06 \times 100$$

$$PF = 60\%$$

Angle Theta

The power factor is the cosine of angle theta:

$$\cos \angle\theta = 0.60$$

$$\angle\theta = 53.13°$$

The circuit with all calculated values is shown in *Figure 24–6*.

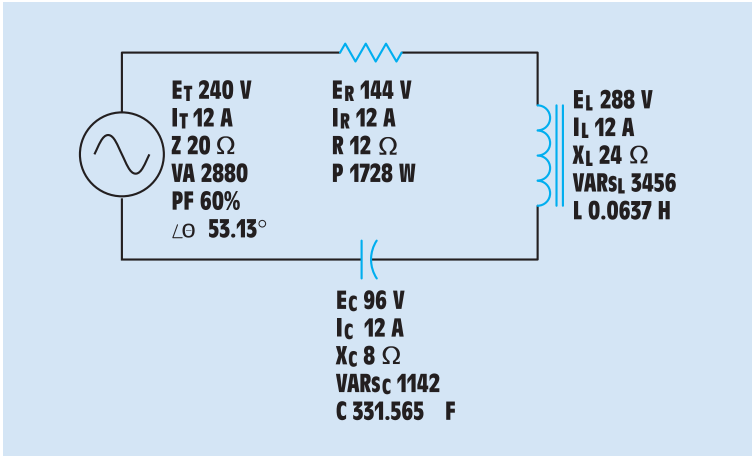


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FIGURE 24–6 Example circuit with calculated values.

■ EXAMPLE 24-2

An RLC series circuit contains a capacitor with a capacitance of 66.3 μF, an inductor with an inductance of 0.0663 H, and a resistor with a value of 8 Ω connected to a 120-V, 60-Hz line *(Figure 24–7)*. How much current will flow in this circuit?

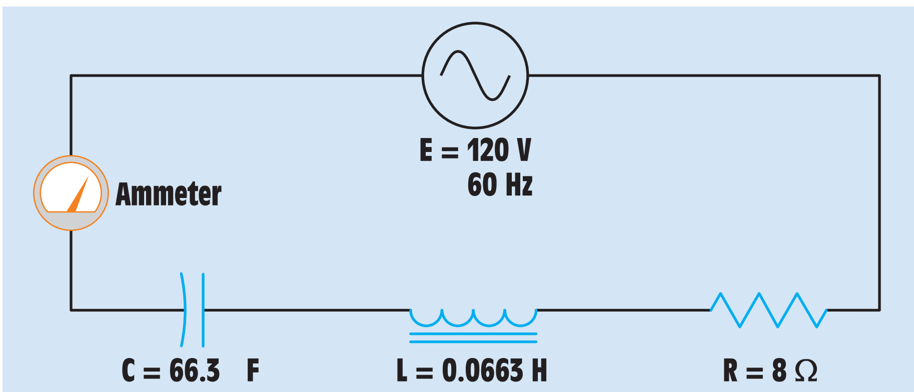

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FIGURE 24–7 Example circuit.

Solution

The first step in solving this problem is to find the values of capacitive and inductive reactance:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{377 \times 0.0000663\ \text{F}}$$

$$X_C = 40.008\ \Omega$$

$$X_L = 2\pi fL$$

$$X_L = 377 \times 0.0663\ \text{H}$$

$$X_L = 24.995\ \Omega$$

Now that the capacitive and inductive reactance values are known, the circuit impedance can be found using the formula

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{(8\ \Omega)^2 + (24.995\ \Omega - 40.008\ \Omega)^2}$$

$$Z = \sqrt{64\ \Omega + 225.39\ \Omega}$$

$$Z = 17.011\ \Omega$$

Now that the circuit impedance is known, the current flow can be found using Ohm's law

$$I_T = \frac{E_T}{Z}$$

$$I_T = \frac{120\ \text{V}}{17.011\ \Omega}$$

$$I_T = 7.054\ \text{A}$$

■ EXAMPLE 24-3

The RLC series circuit shown in *Figure 24–8* contains an inductor with an inductive reactance of 62 Ω and a capacitor with a capacitive reactance of 38 Ω. The circuit is connected to a 208-V, 60-Hz line. How much resistance should be connected in the circuit to limit the circuit current to a value of 8 A?

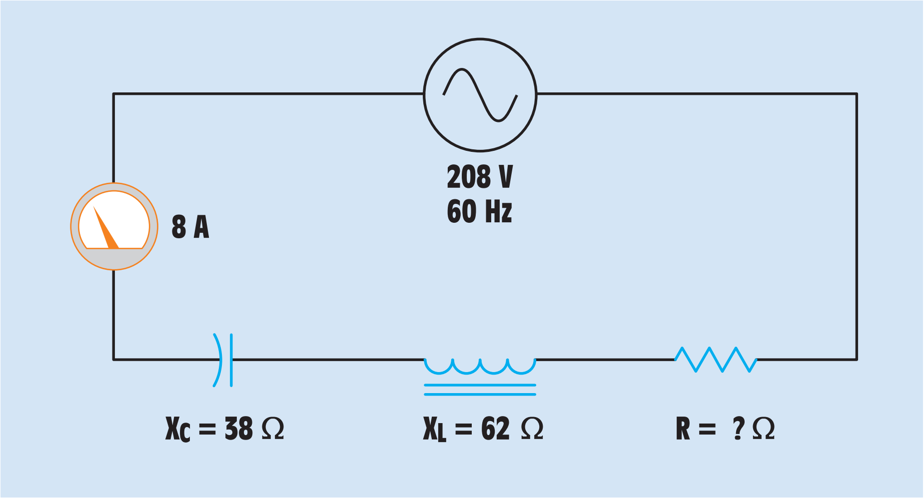

FIGURE 24–8 Example circuit.

Solution

The first step is to determine the total impedance necessary to limit the circuit current to a value of 8 A:

$$Z = \frac{E_T}{I_T}$$

$$Z = \frac{208\ \text{V}}{8\ \text{A}}$$

$$Z = 26\ \Omega$$

The formula for finding impedance in an RLC series circuit can now be adjusted to find the missing resistance value (refer to the Resistive-Inductive-Capacitive Series Circuits section in Appendix B):

$$R = \sqrt{Z^2 - (X_L - X_C)^2}$$

$$R = \sqrt{(26\ \Omega)^2 - (62\ \Omega - 38\ \Omega)^2}$$

$$R = \sqrt{(26\ \Omega)^2 - (24\ \Omega)^2}$$

$$R = \sqrt{100\ \Omega^2}$$

$$R = 10\ \Omega$$

24–2 Series Resonant Circuits

When an inductor and capacitor are connected in series *(Figure 24–9),* there is one frequency at which the inductive reactance and capacitive reactance become equal. The reason for this is that, as frequency increases, inductive reactance increases and capacitive reactance decreases. The point at which the two reactances become equal is called **resonance.** Resonant circuits are used to provide great increases of current and voltage at the resonant frequency. The following formula can be used to determine the resonant frequency when the values of inductance (I) and capacitance (C) are known:

$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

where

f_R = frequency at resonance
L = inductance in henrys
C = capacitance in farads

In the circuit shown in *Figure 24–9,* an inductor has an inductance of 0.0159 henry and a wire resistance in the coil of 5 ohms. The capacitor connected in series with the inductor has a capacitance of 1.59 microfarads. This circuit reaches resonance at 1000 hertz, when both the inductor and capacitor produce reactances of 100 ohms. At this point, the two reactances are equal and opposite in direction and the only current-limiting factor in the circuit is the 5 ohms of wire resistance in the coil *(Figure 24–10).*

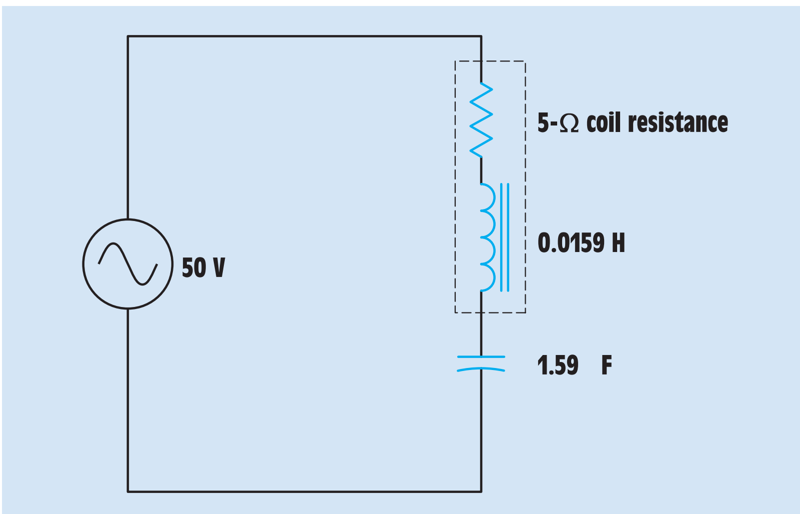

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FIGURE 24–9 LC series circuit.

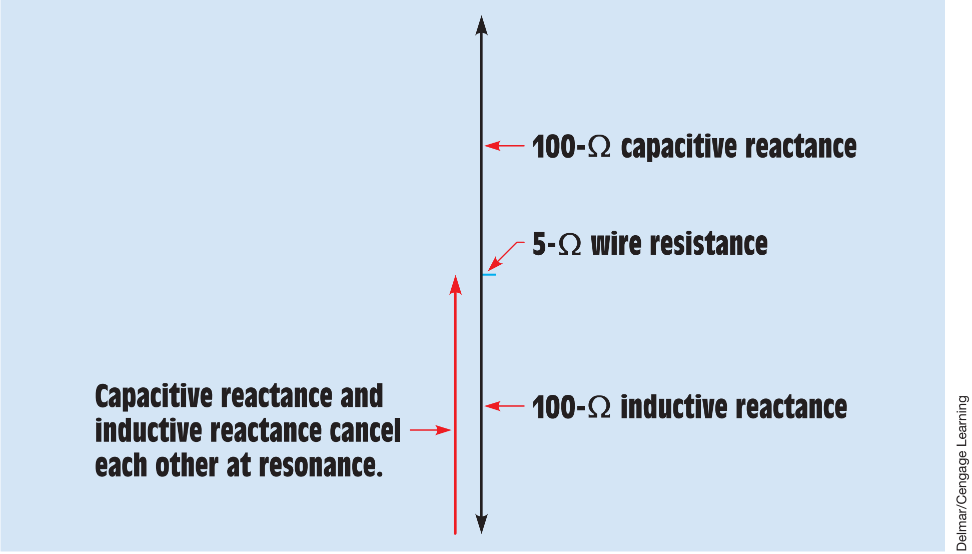


FIGURE 24–10 Inductive reactance and capacitive reactance become equal at resonance.

During the period of time that the circuit is not at resonance, current flow is limited by the combination of inductive reactance and capacitive reactance. At 600 hertz, the inductive reactance is 59.942 ohms and the capacitive reactance is 166.829 ohms. The total circuit impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{(5\ \Omega)^2 + (59.942\ \Omega - 166.829\ \Omega)^2}$$

$$Z = 107.004\ \Omega$$

If 50 volts are applied to the circuit, the current flow will be 0.467 ampere (50 V/107.004 Ω).

If the frequency is greater than 1000 hertz, the inductive reactance increases and the capacitive reactance decreases. At a frequency of 1400 hertz, for example, the inductive reactance has become 139.864 ohms and the capacitive reactance has become 71.498 Ω. The total impedance of the circuit at this point is 68.549 ohms. The circuit current is 0.729 ampere (50 V/68.549 Ω).

When the circuit reaches resonance, the current suddenly increases to 10 amperes because the only current-limiting factor is the 5 ohms of wire resistance (50 V/5 Ω = 10 A). A graph illustrating the effect of current in a resonant circuit is shown in *Figure 24–11*.

Although inductive and capacitive reactance cancel each other at resonance, each is still a real value. In this example, both the inductive reactance and capacitive reactance have an ohmic value of 100 ohms at the resonant frequency.

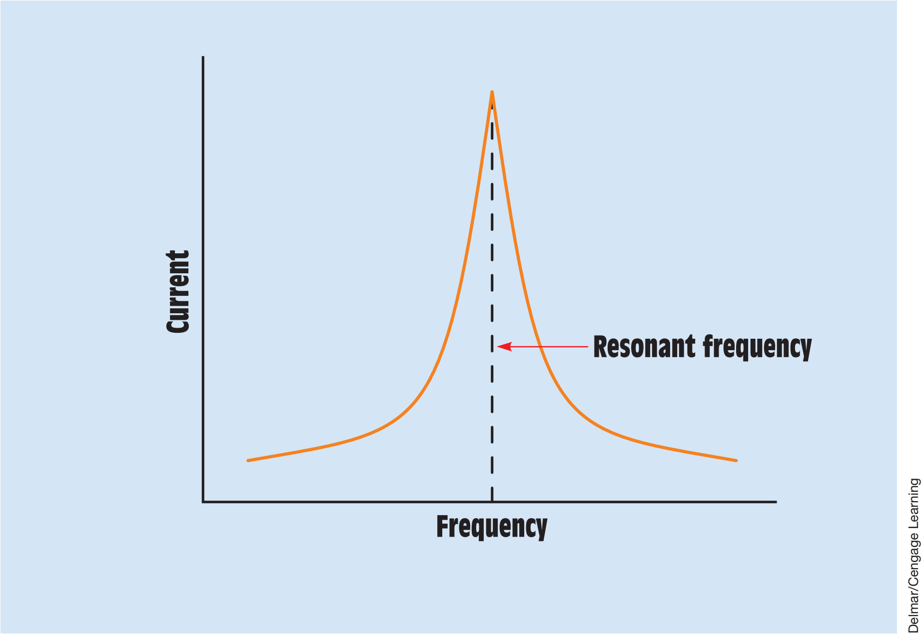


FIGURE 24–11 The current increases sharply at the resonant frequency.

The voltage drop across each component is proportional to the reactance and the amount of current flow. If voltmeters were connected across each component, a voltage of 1000 volts would be seen (10 A × 100 Ω = 1000 V) *(Figure 24–12)*.

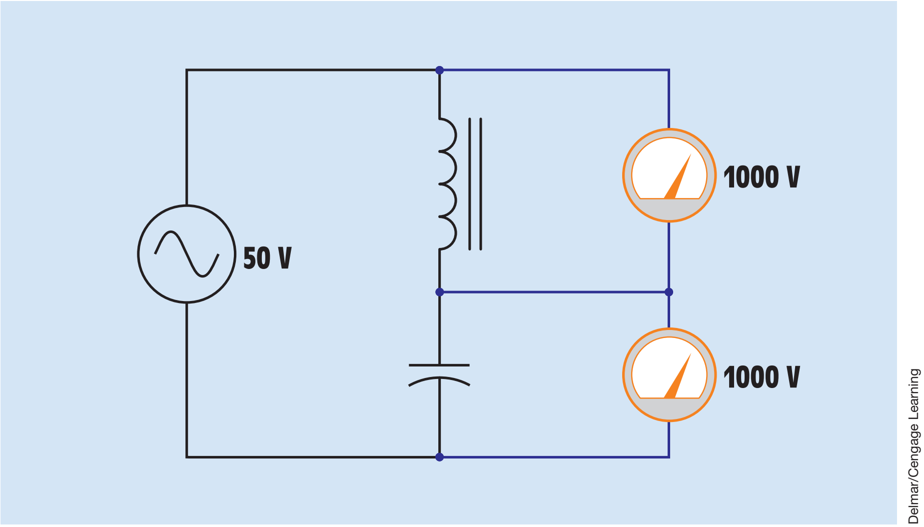


FIGURE 24–12 The voltage drops across the inductor and capacitor increase at resonance.

Bandwidth

The rate of current increase and decrease is proportional to the quality (Q) of the components in the circuit:

$$B = \frac{f_R}{Q}$$

where

B = bandwidth
Q = quality of circuit components
f_R = frequency at resonance

High-Q components result in a sharp increase of current as illustrated by the curve of *Figure 24–11*. Not all series resonant circuits produce as sharp an increase or decrease of current as illustrated in *Figure 24–11*. The term used to describe this rate of increase or decrease is **bandwidth.** Bandwidth is a frequency measurement. It is the difference between the two frequencies at which the current is at a value of 0.707 of the maximum current value *(Figure 24–13)*:

$$B = f_2 - f_1$$

Assume the circuit producing the curve in *Figure 24–13* reaches resonance at a frequency of 1000 hertz. Also assume that the circuit reaches a maximum value of 1 ampere at resonance. The bandwidth of this circuit can be determined by

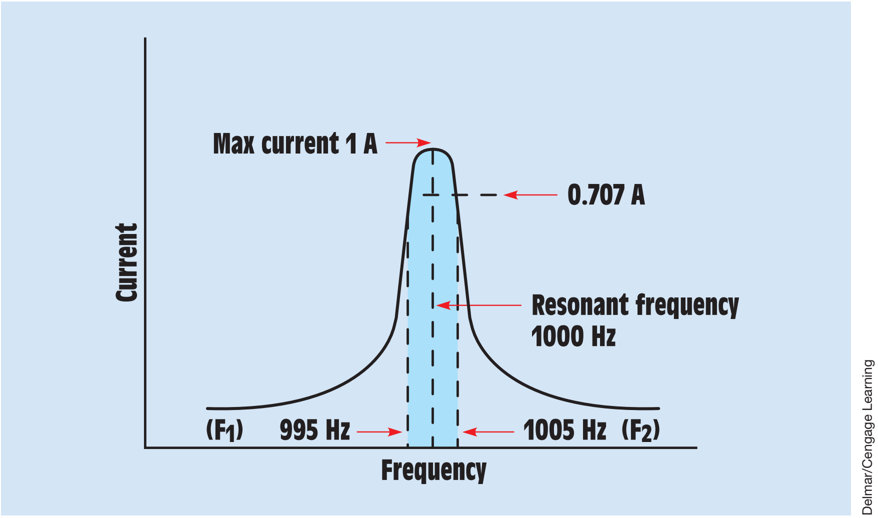


FIGURE 24–13 A narrow-band resonant circuit is produced by high-Q inductors and capacitors.

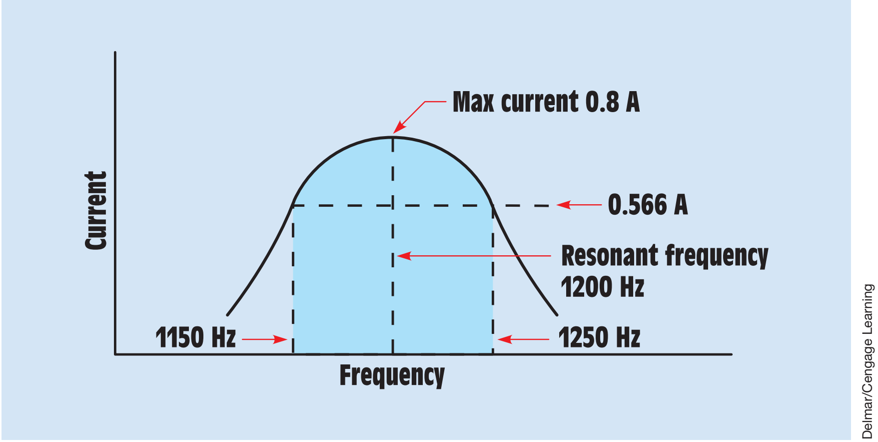


FIGURE 24–14 A wide-band resonant circuit is produced by low-Q inductors and capacitors.

finding the lower and upper frequencies on either side of 1000 hertz at which the current reaches a value of 0.707 of the maximum value. In this illustration that is 0.707 ampere (1 A × 0.707 B = 0.707 A). Assume the lower frequency value to be 995 hertz and the upper value to be 1005 hertz. This circuit has a bandwidth of 10 hertz (1005 Hz − 995 Hz = 10 Hz). When resonant circuits are constructed with components that have a relatively high Q, the difference between the two frequencies is small. These circuits are said to have a *narrow* bandwidth.

In a resonant circuit using components with a lower Q rating, the current does not increase as sharply, as shown in *Figure 24–14*. In this circuit, it is assumed that resonance is reached at a frequency of 1200 hertz and the maximum current flow at resonance is 0.8 ampere. The bandwidth is determined by the difference between the two frequencies at which the current is at a value of 0.566 ampere (0.8 A × 0.707 = 0.566 A). Assume the lower frequency to be 1150 hertz and the upper frequency to be 1250 hertz. This circuit has a bandwidth of 100 hertz (1250 Hz − 1150 Hz = 100 Hz). This circuit is said to have a *wide* bandwidth.

Determining Resonant Values of L and C

There are times when it is necessary to determine what value of inductance or capacitance is needed to resonate with an existing value for inductance or capacitance. The two formulas shown can be used to determine these values for a series or parallel resonant circuit:

$$L = \frac{1}{4\pi^2 f_R^2 C} \quad \text{or} \quad C = \frac{1}{4\pi^2 f_R^2 L}$$

where

$$\pi = 3.1416$$
$$f_R = \text{resonant frequency}$$
$$C = \text{capacitance in farads}$$
$$L = \text{inductance in henrys}$$

What value of capacitance would be needed to resonate at a frequency of 1200 Hz with a 0.2-henry inductor?

$$C = \frac{1}{4\pi^2 f_R{}^2 L}$$

$$C = \frac{1}{4 \times 3.1416^2 \times (1200\ \text{Hz})^2 \times 0.2\ \text{H}}$$

$$C = \frac{1}{4 \times 9.869 \times 1{,}440{,}000\ \text{Hz}^2 \times 0.2\ \text{H}}$$

$$C = \frac{1}{11{,}369{,}088}$$

$$C = 0.000{,}000{,}088 \text{ farads or } 0.088\ \mu\text{F or } 88\ \text{nF}$$

What value of inductance is needed to resonate with a 50-microfarad capacitor at 400 hertz?

$$L = \frac{1}{4\pi^2 f_R{}^2 C}$$

$$L = \frac{1}{4 \times 3.1416^2 \times (400\ \text{Hz})^2 \times 0.000{,}050\ \text{F}}$$

$$L = \frac{1}{4 \times 9.869 \times 160{,}000\ \text{Hz}^2 \times 0.000{,}050\ \text{F}}$$

$$L = \frac{1}{315.808}$$

$$L = 0.003166 \text{ henry, or } 3.166\ \text{mH}$$

Summary

- The voltage dropped across the resistor in an RLC series circuit will be in phase with the current.
- The voltage dropped across the inductor in an RLC series circuit will lead the current by 90°.

- The voltage dropped across the capacitor in an RLC series circuit will lag the current by 90°.
- Vector addition can be used in an RLC series circuit to find values of total voltage, impedance, and apparent power.
- In an RLC circuit, inductive and capacitive values are 180° out of phase with each other. Adding them results in the elimination of the smaller value and a reduction of the larger value.
- LC resonant circuits increase the current and voltage drop at the resonant frequency.
- Resonance occurs when inductive reactance and capacitive reactance become equal.
- The rate the current increases is proportional to the Q of the circuit components.
- Bandwidth is determined by calculating the upper and lower frequencies at which the current reaches a value of 0.707 of the maximum value.
- Bandwidth is inversely proportional to the Q of the components in the circuit.

Review Questions

1. What is the phase angle relationship of current and the voltage dropped across a pure resistance?
2. What is the phase angle relationship of current and the voltage dropped across an inductor?
3. What is the phase angle relationship of current and the voltage dropped across a capacitor?
4. An AC circuit has a frequency of 400 Hz. A 16-Ω resistor, a 0.0119-H inductor, and a 16.6-μF capacitor are connected in series. What is the total impedance of the circuit?
5. If 440 V are connected to the circuit, how much current will flow?
6. How much voltage would be dropped across the resistor, inductor, and capacitor in this circuit?

   E_R = ________________ V

   E_L = ________________ V

   E_C = ________________ V
7. What is the true power of the circuit in Question 6?
8. What is the apparent power of the circuit in Question 6?

9. What is the power factor of the circuit in Question 6?
10. How many degrees are the voltage and current out of phase with each other in the circuit in Question 6?

Practical Applications

You are an electrician working in a plant. A series resonant circuit is to be used to produce a high voltage at a frequency of 400 Hz. The inductor has an inductance of 15 mH and a wire resistance of 2 Ω. How much capacitance should be connected in series with the inductor to produce a resonant circuit? The voltage supplied to the circuit is 240 V at 400 Hz. What is the minimum voltage rating of the capacitor? ■

Practice Problems

Refer to the Resistive-Inductive-Capacitive Series Circuits Formula section of Appendix B and to *Figure 24–2*.

Find all the missing values in the following problems.

1. The circuit shown in *Figure 24–2* is connected to a 120-V, 60-Hz line. The resistor has a resistance of 36 Ω, the inductor has an inductive reactance of 100 Ω, and the capacitor has a capacitive reactance of 52 Ω.

E_T 120 V	E_R ______	E_L ______	E_C ______
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R 36 Ω	X_L 100 Ω	X_C 52 Ω
VA ______	P ______	$VARs_L$ ______	$VARs_C$ ______
PF ______	$\angle\theta$ ______	L ______	C ______

2. The circuit is connected to a 400-Hz line with an applied voltage of 35.678 V. The resistor has a true power of 14.4 W, and there are 12.96 inductive VARs and 28.8 capacitive VARs.

E_T 35.678 Ω	E_R ______	E_L ______	E_C ______
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R ______	X_L ______	X_C ______
VA ______	P 14.4 W	$VARs_L$ 12.96	$VARs_C$ 28.8
PF ______	$\angle\theta$ ______	L ______	C ______

3. The circuit is connected to a 60-Hz line. The apparent power in the circuit is 29.985 VA, and the power factor is 62.5%. The resistor has a voltage drop of 14.993 V, the inductor has an inductive reactance of 60 Ω, and the capacitor has a capacitive reactance of 45 Ω.

E_T ______	E_R 14.993 V	E_L ______	E_C ______
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R ______	X_L 60 Ω	X_C 45 Ω
VA 29.985	P ______	$VARs_L$ ______	$VARs_C$ ______
PF 62.5%	∠θ ______	L ______	C ______

4. This circuit is connected to a 1000-Hz line. The resistor has a voltage drop of 185 V, the inductor has a voltage drop of 740 V, and the capacitor has a voltage drop of 444 V. The circuit has an apparent power of 51.8 VA.

E_T ______	E_R 185 V	E_L 740 V	E_C 444 V
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R ______	X_L ______	X_C ______
VA 51.8	P ______	$VARs_L$ ______	$VARs_C$ ______
PF ______	∠θ ______	L ______	C ______

5. A series RLC circuit contains a 4-kΩ resistor, an inductor with an inductive reactance of 3.5 kΩ, and a capacitor with a capacitive reactance of 2.4 kΩ. A 120-VAC, 60-Hz power source is connected to the circuit. How much voltage is dropped across the inductor?

6. A series RLC circuit contains a resistor with a true power of 18 watts, an inductor with a reactive power of 24 VARs, and a capacitor with a reactive power of 34 VARs. What is the circuit power factor?

7. Is the power factor in Question 6 a leading or lagging power factor? Explain your answer.

8. A series RLC circuit contains a resistor with a resistance of 8 Ω, an inductor with a reactance of 12 Ω, and a capacitor with a reactance of 16 Ω. E_R = 17.8 volts. Find E_C.

9. A series RLC circuit has an applied voltage of 240 volts and an apparent power of 600 VA. The circuit power factor is 62%. Find the value of the resistor.

10. A series RLC circuit is connected to a 60-Hz power line. The resistor has a value of 240 Ω. The inductor has an inductance of 0.796 henrys and the capacitor has a capacitance of 5.89 μF. Find Z.

Unit 25

Resistive-Inductive-Capacitive Parallel Circuits

Why You Need to Know

RLC parallel circuits are used throughout the electrical field. They are employed in electronic equipment as filters to separate one frequency from another. They are used in industry to produce large increases in current flow for induction heating applications and to correct the power factor of inductive loads in an effort to reduce the amperage supplied to a particular load. RLC parallel resonant circuits are often referred to as "tank" circuits. Tank circuits are the principle used in many motor-control applications as proximity sensors that detect the presence or absence of metal. This unit

- discusses the values and how to calculate voltage, current, power, and impedance in parallel circuits that contain resistance, capacitance, and inductance.
- gives a step-by-step procedure for determining and correcting power factor to the desired percentage.

OUTLINE

KEY TERMS

Power factor correction

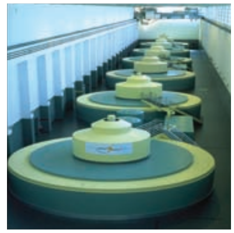
Tank circuits

Unity

Objectives

After studying this unit, you should be able to

- discuss parallel circuits that contain resistance, inductance, and capacitance.
- calculate the values of an RLC parallel circuit.
- calculate values of impedance, inductance, capacitance, power, reactive power, current flow through individual components, power factor, and phase angle from measurements taken.
- discuss the operation of a parallel resonant circuit.
- calculate the power factor correction for an AC motor.



Courtesy of Tennessee Valley Authority

Preview

Circuits containing elements of resistance, inductance, and capacitance connected in parallel are discussed in this unit. Electrical quantities of current, impedance, and power are calculated for the entire circuit as well as for individual components. Parallel resonant circuits, or tank circuits, and their effect on voltage, current, and impedance are also presented. ■

25–1 RLC Parallel Circuits

When an AC circuit contains elements of resistance, inductance, and capacitance connected in parallel, the ***voltage dropped across each element is the same. The currents flowing through each branch, however, will be out of phase with each other*** *(Figure 25–1)*. The current flowing through a pure

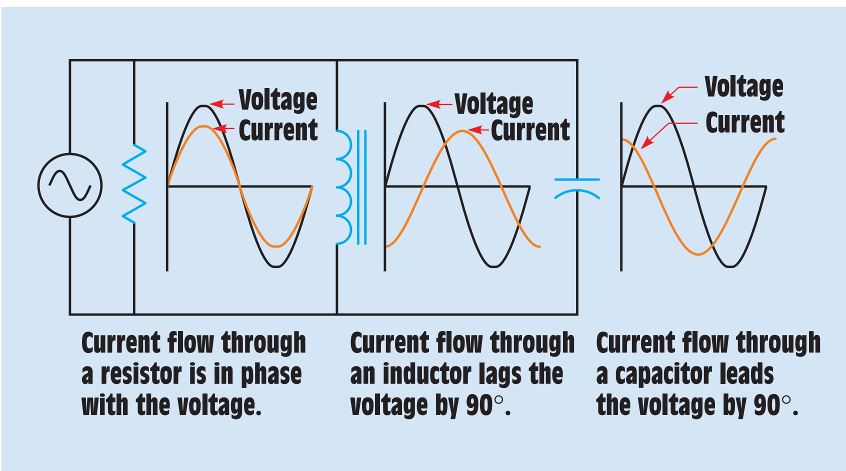


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FIGURE 25–1 Voltage and current relationship in an RLC parallel circuit. The voltage is the same across each branch, but the currents are out of phase.

resistive element will be in phase with the applied voltage. The current flowing through a pure inductive element lags the applied voltage by 90 electrical degrees, and the current flowing through a pure capacitive element will lead the voltage by 90 electrical degrees. The phase angle difference between the applied voltage and the total current is determined by the ratio of resistance, inductance, and capacitance connected in parallel. As with an RLC series circuit, if the inductive VARs is greater than the capacitive VARs, the current will lag the voltage and the power factor will be lagging. If the capacitive VARs is greater, the current will lead the voltage and the power factor will be leading.

EXAMPLE 25-1

Assume that the RLC parallel circuit shown in *Figure 25–2* is connected to a 240-V, 60-Hz line. The resistor has a resistance of 12 Ω, the inductor has an inductive reactance of 8 Ω, and the capacitor has a capacitive reactance of 16 Ω. Complete the following unknown values:

Z—impedance of the circuit

I_T—total circuit current

I_R—current flow through the resistor

P—true power (watts)

L—inductance of the inductor

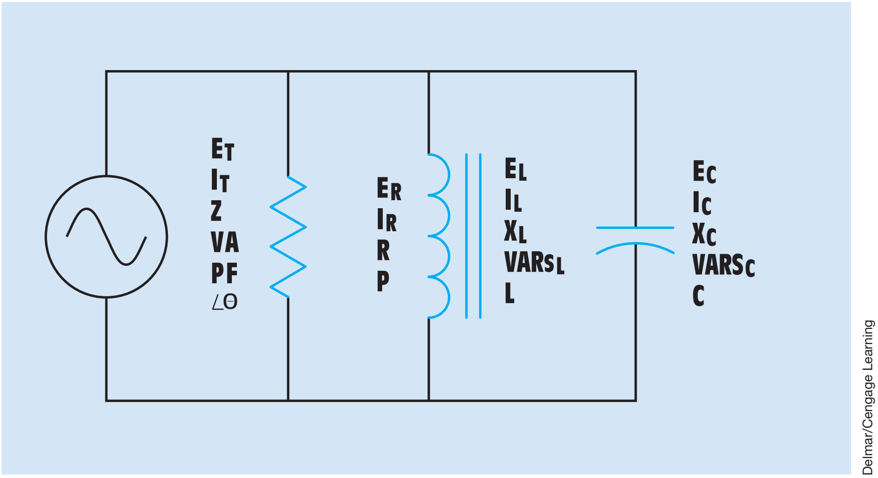

FIGURE 25–2 RLC parallel circuit.

I_L—current flow through the inductor

$VARs_L$—reactive power of the inductor

C—capacitance

I_C—current flow through the capacitor

$VARs_C$—reactive power of the capacitor

VA—volt-amperes (apparent power)

PF—power factor

$\angle\theta$—angle theta

Solution

Impedance

The impedance of the circuit is the reciprocal of the sum of the reciprocals of the legs. Because these values are out of phase with each other, vector addition must be used:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{12\Omega}\right)^2 + \left(\frac{1}{8\Omega} - \frac{1}{16\Omega}\right)^2}}$$

$$Z = \frac{1}{\sqrt{(0.006944 + 0.003906)\frac{1}{\Omega}}}$$

$$Z = \frac{1}{\sqrt{(0.01085)\frac{1}{\Omega}}}$$

$$Z = \frac{1}{(0.10416)\frac{1}{\Omega}}$$

$$Z = 9.601\Omega$$

To find the total impedance of the previous example using a scientific calculator, press the following keys. Note that the calculator automatically carries each answer to the maximum number of decimal places. This increases the accuracy of the answer.

1 2 1/x x² + (8 1/x − 1 6 1/x) x² = √ 1/x

Note that this is intended to illustrate how total parallel resistance can be determined using many scientific calculators. Some calculators may require a different key entry or pressing the equal key at the end.

Another formula that can be used to determine the total impedance of a circuit containing resistance, inductive reactance, and capacitive reactance is

$$Z = \frac{R \times X}{\sqrt{R^2 + X^2}}$$

where

$$X = \frac{X_L \times X_C}{X_L + X_C}$$

In this formula, X_L is a positive number and X_C is a negative number. Therefore, Z will be either positive or negative depending on whether the circuit is more inductive (positive) or capacitive (negative). To find the total impedance of this circuit using this formula, first determine the value of X:

$$X = \frac{X_L \times X_C}{X_L + X_C}$$

$$X = \frac{8\ \Omega \times (-16\ \Omega)}{8\ \Omega + (-16\ \Omega)}$$

$$X = \frac{-128\ \Omega^2}{-8\Omega}$$

$$X = 16\ \Omega$$

Now that the value of X has been determined, the impedance can be calculated using the formula

$$Z = \frac{R \times X}{\sqrt{R^2 + X^2}}$$

$$Z = \frac{12\ \Omega \times 16\ \Omega}{\sqrt{(12\ \Omega)^2 + (16\ \Omega)^2}}$$

$$Z = \frac{192\ \Omega}{\sqrt{400\ \Omega}}$$

$$Z = \frac{192\ \Omega}{20\ \Omega}$$

$$Z = 9.6\ \Omega$$

Resistive Current

The next unknown value to be found is the current flow through the resistor. This can be calculated by using the formula

$$I_R = \frac{E}{R}$$

$$I_R = \frac{240\ V}{12\ \Omega}$$

$$I_R = 20\ A$$

True Power

The true power, or watts (W), can be calculated using the formula

$$P = E \times I_R$$

$$P = 240\ V \times 20\ A$$

$$P = 4800\ W$$

Inductive Current

The amount of current flow through the inductor can be calculated using the formula

$$I_L = \frac{E}{R}$$

$$I_L = \frac{240\ V}{12\ \Omega}$$

$$I_L = 30\ A$$

Inductive VARs

The amount of reactive power, or VARs, produced by the inductor can be calculated using the formula

$$VARs_L = E \times I_L$$

$$VARs_L = 240\ V \times 30\ A$$

$$VARs_L = 7200$$

Inductance

The amount of inductance in the circuit can be calculated using the formula

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{8\ \Omega}{377}$$

$$L = 0.0212\ \text{H}$$

Capacitive Current

The current flow through the capacitor can be calculated using the formula

$$I_C = \frac{E}{X_C}$$

$$I_C = \frac{240\ \text{V}}{16\ \Omega}$$

$$I_C = 15\ \text{A}$$

Capacitance

The amount of circuit capacitance can be calculated using the formula

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{377 \times 16\ \Omega}$$

$$C = 0.000165782\ \text{F} = 165.782\ \mu\text{F}$$

Capacitive VARs

The capacitive VARs can be calculated using the formula

$$VARs_C = E \times I_C$$

$$VARs_C = 240 \times 15$$

$$VARs_C = 3600$$

Total Circuit Current

The amount of total current flow in the circuit can be calculated by vector addition of the current flowing through each leg of the circuit *(Figure 25–3)*. The inductive current is 180° out of phase with the capacitive current. These two currents tend to cancel each other, resulting in the elimination of the smaller and reduction

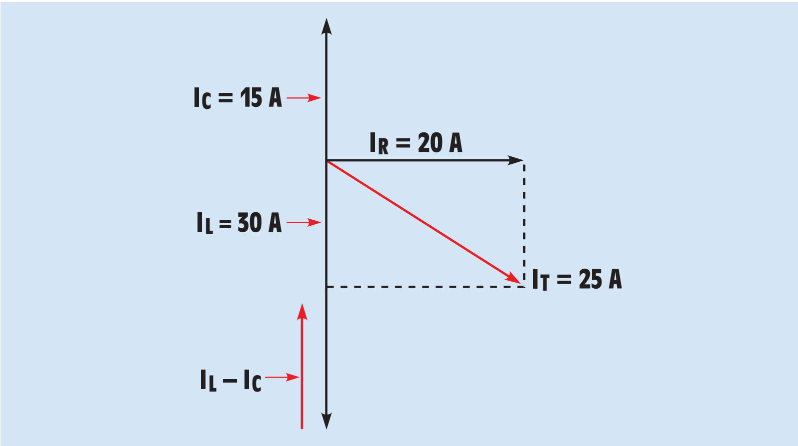

FIGURE 25–3 Vector diagram of resistive, inductive, and capacitive currents in example circuit.

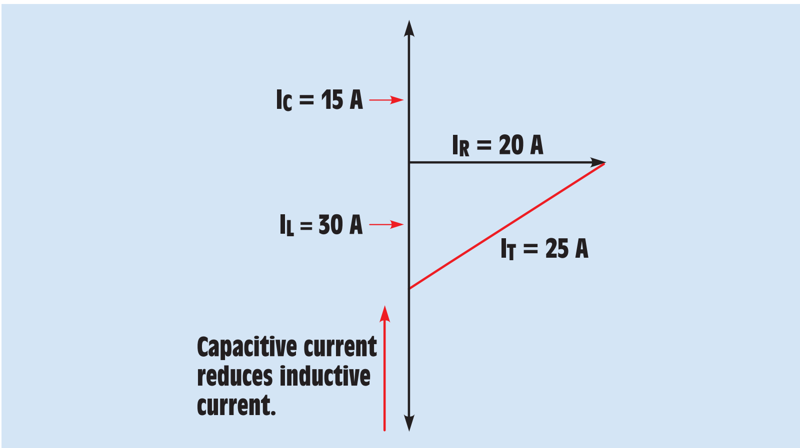

FIGURE 25–4 Inductive and capacitive currents cancel each other.

of the larger. The total circuit current is the hypotenuse of the resulting right triangle *(Figure 25–4)*. The following formula can be used to find total circuit current:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{(20\ A)^2 + (30\ A - 15\ A)^2}$$

$$I_T = \sqrt{(20\ A)^2 + (15\ A)^2}$$

$$I_T = \sqrt{400\ A + 225\ A}$$

$$I_T = \sqrt{625\ A}$$

$$I_T = 25\ A$$

The total current could also be calculated by using the value of impedance found earlier in the problem:

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{240\ V}{9.6\ \Omega}$$

$$I_T = 25\ A$$

Apparent Power

Now that the total circuit current has been calculated the apparent power, or VAs, can be found using the formula

$$VA = E \times I_T$$
$$VA = 240\ V \times 25\ A$$
$$VA = 6000$$

The apparent power can also be found by vector addition of the true power and reactive power:

$$VA = \sqrt{P^2 + (VARs_L - VARs_C)^2}$$

Power Factor

The power factor can now be calculated using the formula

$$PF = \frac{W}{VA} \times 100$$

$$PF = \frac{4800\ W}{6000\ VA} \times 100$$

$$PF = 0.80 \times 100$$

$$PF = 80\%$$

Angle Theta

The power factor is the cosine of angle theta. Angle theta is therefore

$$\cos \angle\theta = 0.80$$
$$\angle\theta = 36.87^\circ$$

The circuit with all calculated values is shown in *Figure 25–5*.

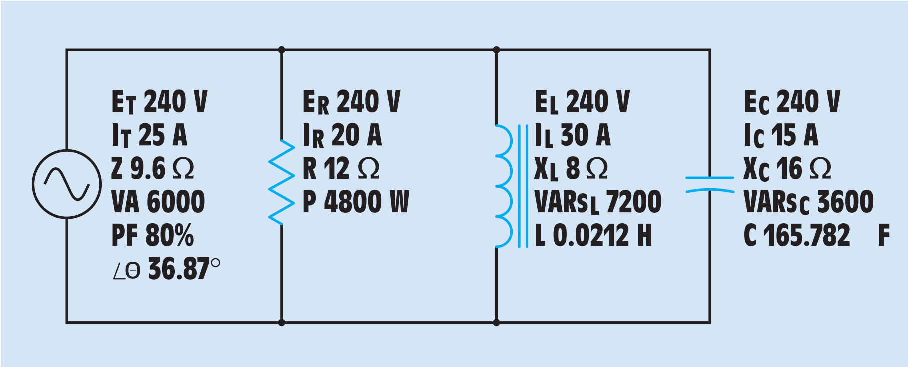

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FIGURE 25–5 Example circuit with all calculated values.

■ EXAMPLE 25-2

In the circuit shown in *Figure 25–6,* a resistor, an inductor, and a capacitor are connected to a 1200-Hz power source. The resistor has a resistance of 18 Ω, the inductor has an inductance of 9.76 mH (0.00976 H), and the capacitor has a capacitance of 5.5 μF. What is the impedance of this circuit?

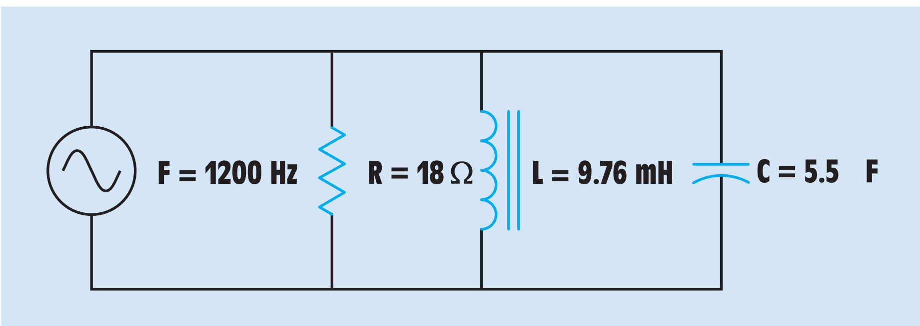

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FIGURE 25–6 Example circuit.

Solution

The first step in finding the impedance of this circuit is to find the values of inductive and capacitive reactance:

$$X_L = 2\pi fL$$

$$X_L = 2 \times 3.1416 \times 1200\ \text{Hz} \times 0.00976\ \text{H}$$

$$X_L = 73.589\ \Omega$$

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2 \times 3.1416 \times 1200\ \text{Hz} \times 0.0000055\ \text{F}}$$

$$X_C = 24.114\ \Omega$$

The impedance of the circuit can now be calculated using the formula

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{18\ \Omega}\right)^2 + \left(\frac{1}{74.589\ \Omega} - \frac{1}{24.114\ \Omega}\right)^2}}$$

$$Z = \frac{1}{\sqrt{(0.0555^2 + (0.0134 - 0.0415)^2)\frac{1}{\Omega^2}}}$$

$$Z = \frac{1}{\sqrt{(0.00387)\ \frac{1}{\Omega}}}$$

$$Z = 16.075\ \Omega$$

25–2 Parallel Resonant Circuits

When values of inductive reactance and capacitive reactance become equal, they are said to be resonant. In a parallel circuit, inductive current and capacitive current cancel each other because they are 180° out of phase with each other. This produces minimum line current at the point of resonance. An LC

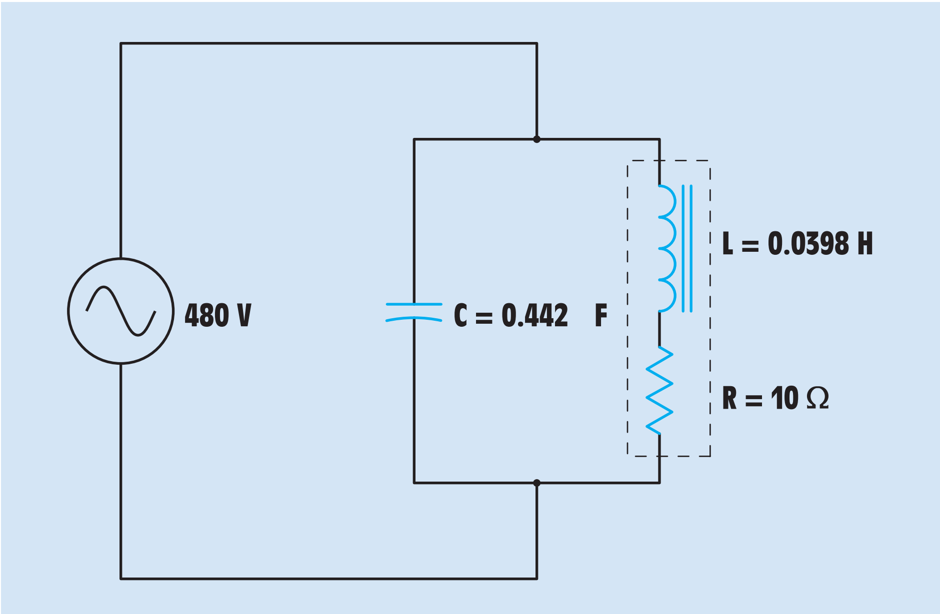

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FIGURE 25–7 Parallel resonant circuit.

parallel circuit is shown in *Figure 25–7*. LC parallel circuits are often referred to as **tank circuits.** In the example circuit, the inductor has an inductance of 0.0398 henrys and a wire resistance of 10 ohms. The capacitor has a capacitance of 0.442 microfarad. This circuit will reach resonance at 1200 hertz, when both the capacitor and inductor exhibit reactances of 300 ohms each.

Calculating the values for a parallel resonant circuit is a bit more involved than calculating the values for a series resonant circuit. In theory, when a parallel circuit reaches resonance, the total circuit current should reach zero and total circuit impedance should become infinite because the capacitive current and inductive currents cancel each other. In practice, the quality (Q) of the circuit components determines total circuit current and therefore total circuit impedance. Because capacitors generally have an extremely high Q by their very nature, the Q of the inductor is the determining factor *(Figure 25–8)*:

$$Q = \frac{I_{TANK}}{I_{LINE}}$$

or

$$Q = \frac{X_L}{R}$$

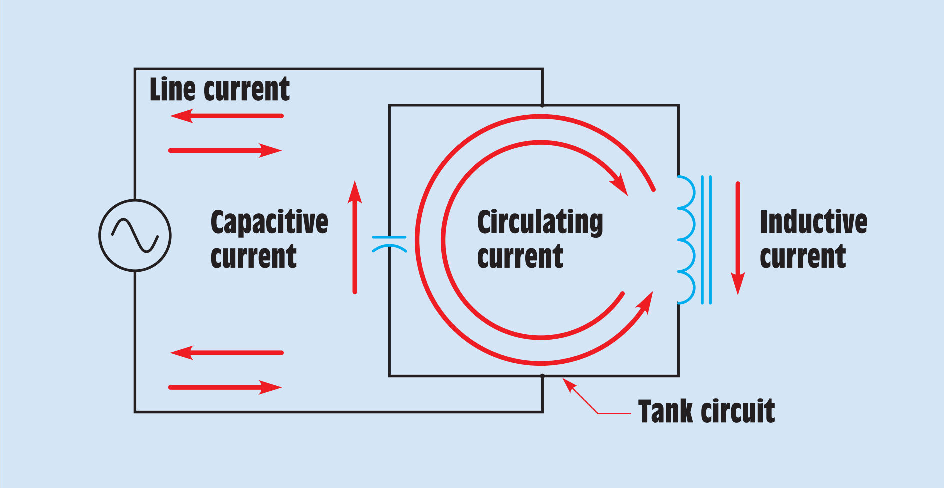

FIGURE 25–8 The amount of current circulating inside the tank is equal to the product of the line current and the Q of the circuit.

In the example shown in *Figure 25–7,* the inductor has an inductive reactance of 300 ohms at the resonant frequency and a wire resistance of 10 ohms. The Q of this inductor is 30 at the resonant frequency ($Q = X_L/R$). To determine the total circuit current at resonance, it is first necessary to determine the amount of current flow through each of the components at the resonant frequency. Because this is a parallel circuit, the inductor and capacitor will have the alternator voltage of 480 volts applied to them. At the resonant frequency of 1200 hertz, both the inductor and capacitor will have a current flow of 1.6 ampere (480 V/300 Ω = 1.6 A). The total current flow in the circuit will be the in-phase current caused by the wire resistance of the coil *(Figure 25–9)*. This value can be calculated by dividing the circulating current inside the LC parallel loop by the Q of the circuit. The total current in this circuit will be 0.0533 ampere (1.6 A/30 = 0.0533 A). Now that the total circuit current is known, the total impedance at resonance can be found using Ohm's law:

$$Z = \frac{E}{I_T}$$

$$Z = \frac{480\text{ V}}{0.0533\text{ A}}$$

$$Z = 9006.63\ \Omega$$

Another method of calculating total current for a tank circuit is to determine the true power in the circuit caused by the resistance of the coil. The resistive part of a coil is considered to be in series with the reactive part *(Figure 25–7)*.

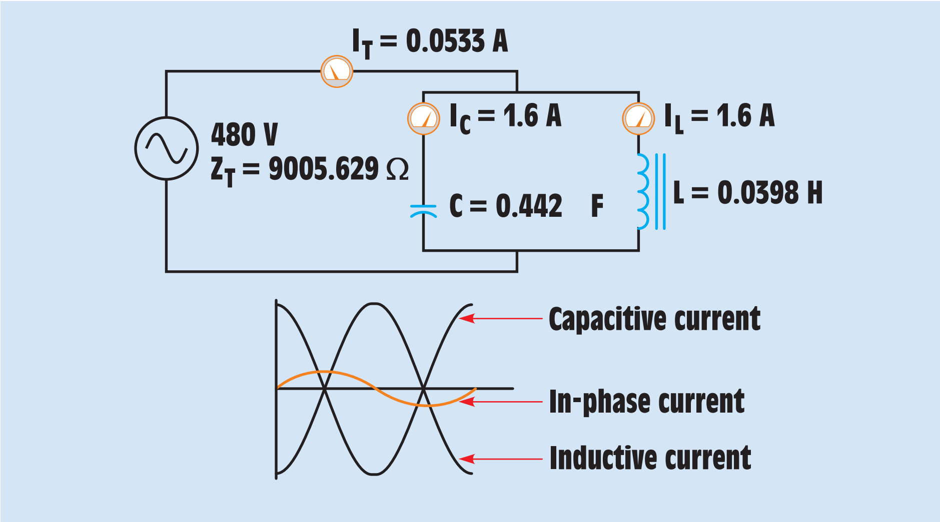

FIGURE 25–9 Total current is equal to the in-phase current.

Because this is a series connection, the current flow through the inductor is the same for both the reactive and resistive elements. The coil has a resistance of 10 ohms. The true power produced by the coil can be calculated by using the formula

$$P = I^2R$$
$$P = (1.6\ A)^2 \times (10\ \Omega)$$
$$P = 25.6\ W$$

Now that the true power is known, the total circuit current can be found using Ohm's law:

$$I_T = \frac{P}{E}$$
$$I_T = \frac{25.6\ W}{480\ V}$$
$$I_T = 0.0533\ A$$

Graphs illustrating the decrease of current and increase of impedance in a parallel resonant circuit are shown in *Figure 25–10*.

Bandwidth

The bandwidth for a parallel resonant circuit is determined in a manner similar to that used for a series resonant circuit. The bandwidth of a parallel circuit is

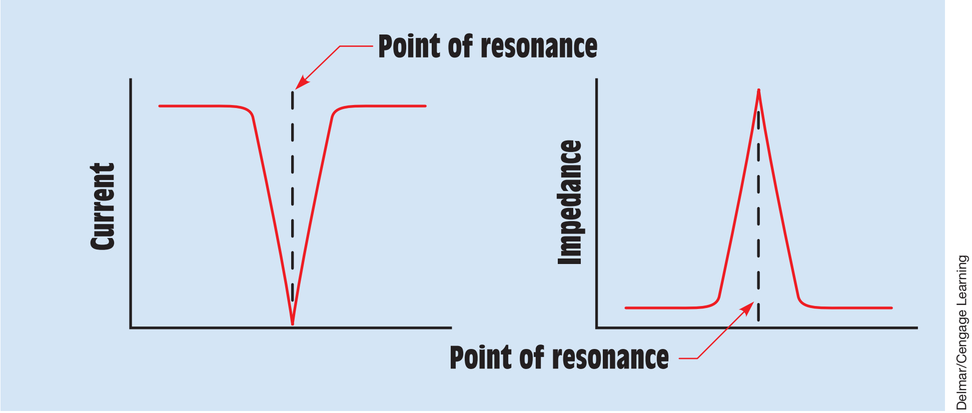

FIGURE 25–10 Characteristic curves of an LC parallel circuit at resonance.

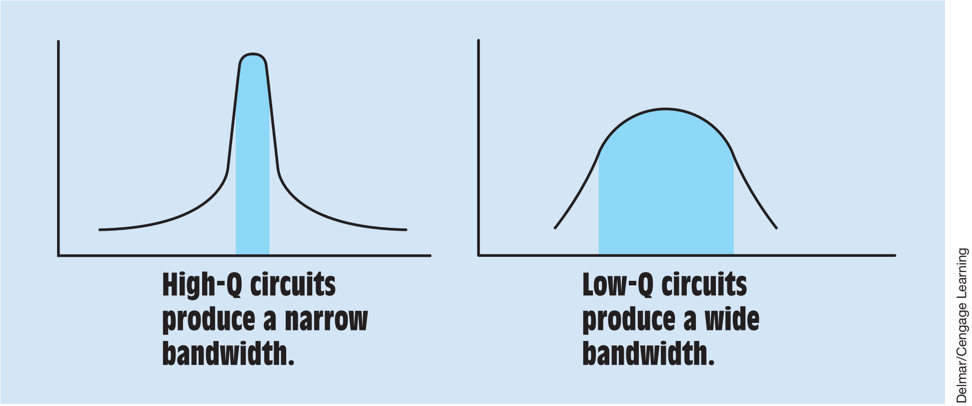

FIGURE 25–11 The Q of the circuit determines the bandwidth.

determined by calculating the frequency on either side of resonance at which the impedance is 0.707 of maximum. As in series resonant circuits, the Q of the parallel circuit determines the bandwidth. Circuits that have a high Q will have a narrow bandwidth, and circuits with a low Q will have a wide bandwidth *(Figure 25–11)*.

Induction Heating

The tank circuit is often used when a large amount of current flow is needed. Recall that the formula for Q of a parallel resonant circuit is

$$Q = \frac{I_{TANK}}{I_{LINE}}$$

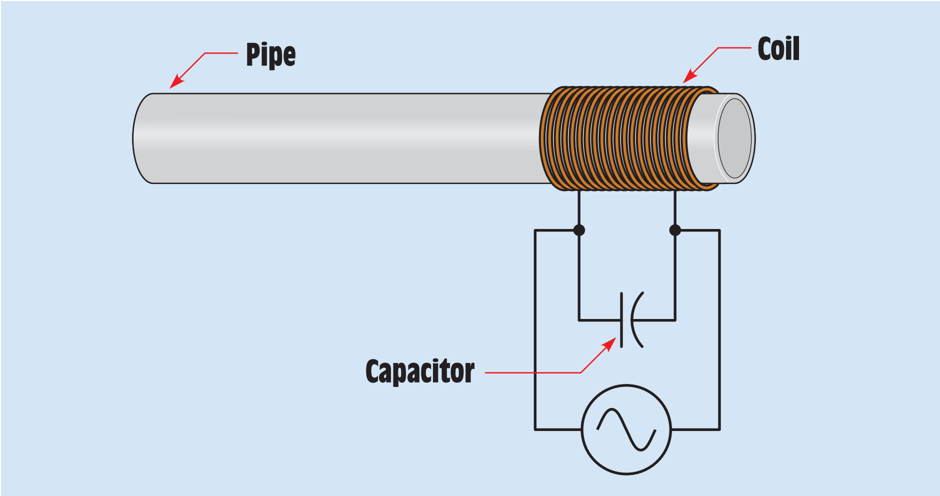

FIGURE 25–12 Induction heating system.

If this formula is changed, it can be seen that the current circulating inside the tank is equal to the line current times the Q of the circuit:

$$I_{TANK} = I_{LINE} \times Q$$

A high-Q circuit can produce an extremely high current inside the tank with very little line current. A good example of this is an induction heater used to heat pipe for tempering *(Figure 25–12)*. In this example the coil is the inductor and the pipe acts as the core of the inductor. The capacitor is connected in parallel with the coil to produce resonance at a desired frequency. The pipe is heated by eddy current induction. Assume that the coil has a Q of 10. If this circuit has a total current of 100 amperes, then 1000 amperes of current flow in the tank. This 1000 amperes is used to heat the pipe. Because the pipe acts as a core for the inductor, the inductance of the coil changes when the pipe is not in the coil. Therefore, the circuit is resonant only during the times that the pipe is in the coil.

Induction heaters of this type have another advantage over other methods that heat pipe with flames produced by oil- or gas-fired furnaces. When induction heating is used, the resonant frequency can be changed by adding or subtracting capacitance in the tank circuit. This ability to control the frequency greatly affects the tempering of metal. If the frequency is relatively low, 400 hertz or less, the metal is heated evenly. If the frequency is increased to 1000 hertz or greater, skin effect causes most of the heating effect to localize at the surface of the metal. This localization at the surface permits a hard coating to develop at the outer surface of the metal without greatly changing the temper of the inside of the metal *(Figure 25–13)*.

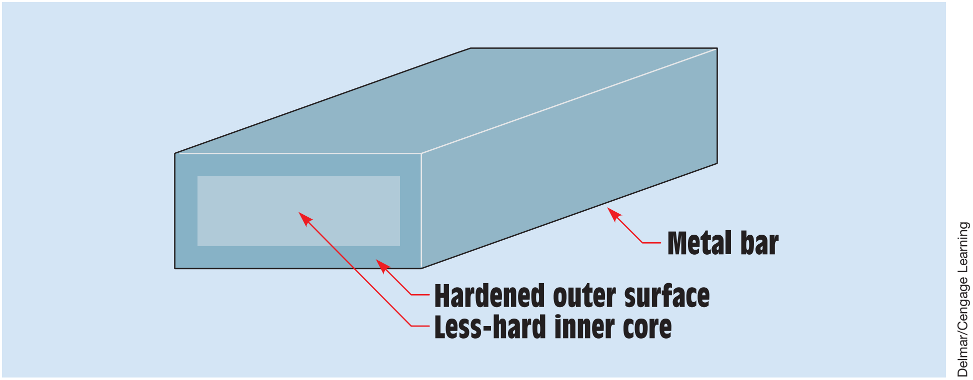

FIGURE 25–13 Frequency controls depth of heat penetration.

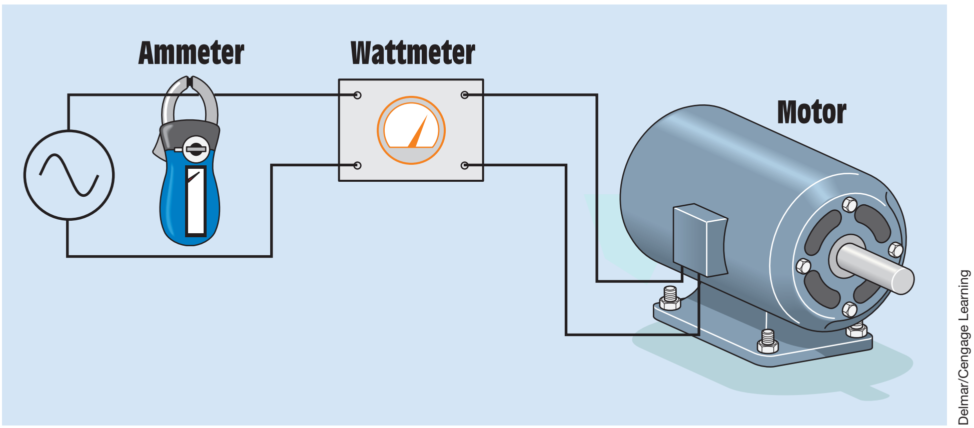

FIGURE 25–14 Determining motor power factor.

Power Factor Correction

Another very common application for LC parallel circuits is the **correction of power factor.** Assume that a motor is connected to a 240-volt single-phase line with a frequency of 60 Hz *(Figure 25–14)*. An ammeter indicates a current flow of 10 amperes and a wattmeter indicates a true power of 1630 watts when the motor is at full load. In this problem, the existing power factor will be determined and then the amount of capacitance needed to correct the power factor will be calculated.

Although an AC motor is an inductive device, when it is loaded it must produce true power to overcome the load connected to it. For this reason, the motor appears to be a resistance connected in series with an inductance *(Figure 25–15)*. Also, the inductance of the motor remains constant

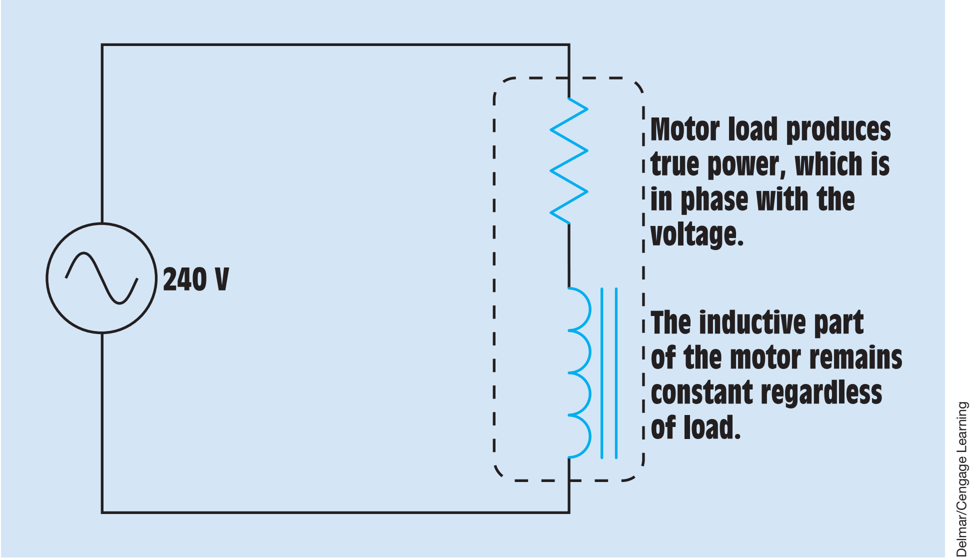

FIGURE 25–15 Equivalent motor circuit.

regardless of the load connected to it. Recall that true power, or watts, is produced only when electrical energy is converted into some other form. A resistor produces true power because it converts electrical energy into thermal (heat) energy. In the case of a motor, electrical energy is being converted into both thermal energy and kinetic (mechanical) energy. When a motor is operated at a no-load condition, the current is relatively small in comparison with the full-load current. At no load, most of the current is used to magnetize the iron core of the stator and rotor. This current is inductive and is 90° out of phase with the voltage. The only true power produced at no load is caused by motor losses, such as eddy currents being induced into the iron core, the heating effect caused by the resistance of the wire in the windings, hysteresis losses, and the small amount of mechanical energy required to overcome the losses of bearing friction and windage. At no load, the motor would appear to be a circuit containing a large amount of inductance and a small amount of resistance *(Figure 25–16)*.

As load is added to the motor, more electrical energy is converted into kinetic energy to drive the load. The increased current used to produce the mechanical energy is in-phase with the voltage. This causes the circuit to appear to be more resistive. By the time the motor reaches full load, the circuit appears to be more resistive than inductive *(Figure 25–17)*. Notice that as load is added or removed, only the resistive value of the motor changes, which means that once the power factor has been corrected, it will remain constant regardless of the motor load.

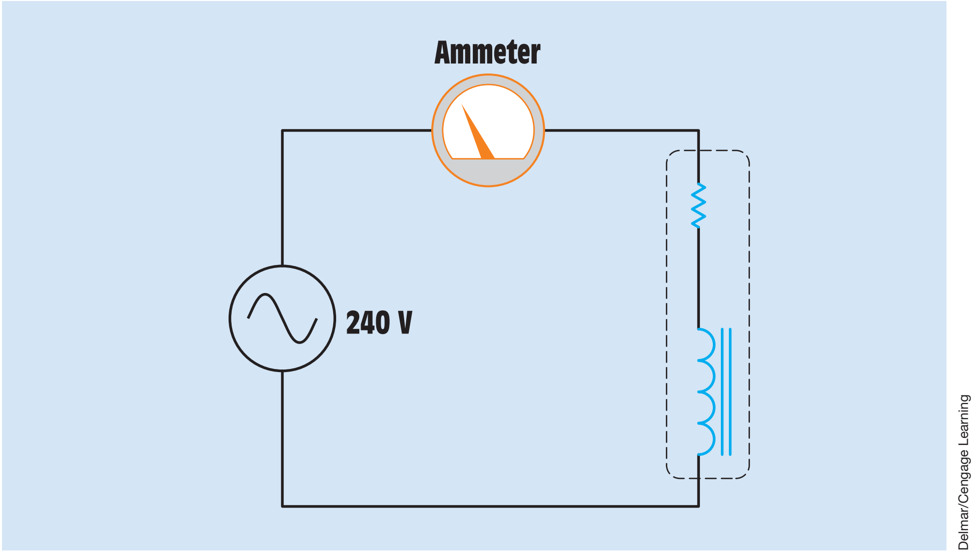

FIGURE 25–16 At no load, the motor appears to be an RL series circuit with a large amount of inductance and a small amount of resistance.

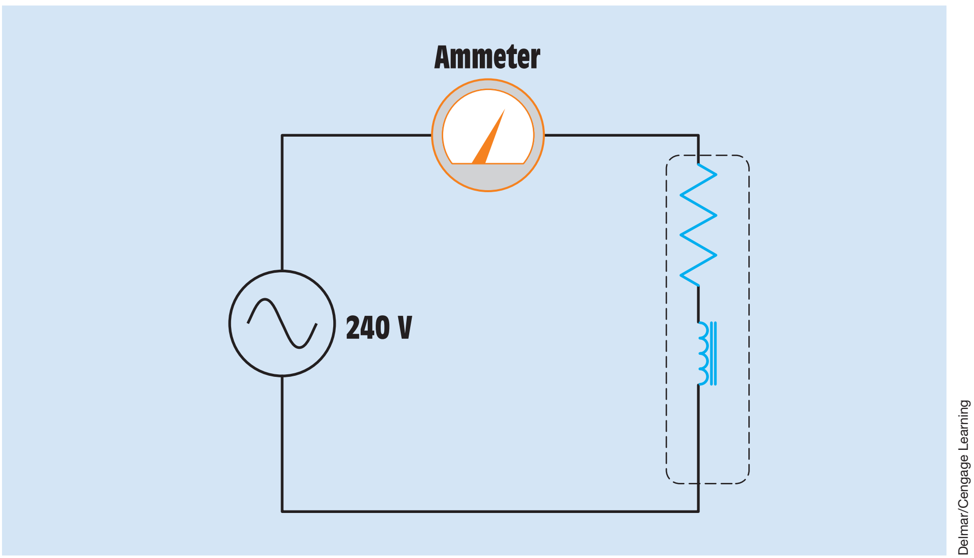

FIGURE 25–17 At full load, the motor appears to be an RL series circuit with a large amount of resistance and a smaller amount of inductance.

When determining the amount of capacitance needed to correct power factor, it is helpful to use a step-by-step procedure. The first step in this procedure is to determine the apparent power of the circuit:

$$VA = E \times I$$
$$VA = 240 \times 10$$
$$VA = 2400$$

Now that the apparent power is known, the power factor can be calculated using the formula

$$PF = \frac{P}{VA}$$
$$PF = \frac{1630}{2400}$$
$$PF = 0679 \text{ } \mathit{or} \text{ } 67.9\%$$

The second step is to determine the amount of reactive power in the circuit. The reactive part of the circuit can be determined by finding the reactive power produced by the inductance. Inductive VARs can be calculated using the formula

$$VARs_L = \sqrt{VA^2 - P^2}$$
$$VARs_L = \sqrt{2400^2 - 1630^2}$$
$$VARs_L = 1761.562$$

To correct the power factor to 100% or **unity,** an equal amount of capacitive VARs would be connected in parallel with the motor. In actual practice, however, it is generally not considered practical to correct the power factor to unity or 100%. It is common practice to correct motor power factor to a value of about 95%. Step three in this example is to determine the amount of apparent power necessary to produce a power factor of 95%:

$$VA = \frac{P}{PF}$$
$$VA = \frac{1630}{0.95}$$
$$VA = 1715.789$$

The fourth step in this example is to determine the amount of inductive VARs that would result in an apparent power of 1715.789 VA. The inductive VARs needed to produce this amount of apparent power can now be determined using the formula

$$VARs_L = \sqrt{VA^2 - P^2}$$

$$VARs_L = \sqrt{1715.789^2 - 1630^2}$$

$$VARs_L = 535.754$$

The fifth step in this example is to determine the amount of capacitive VARs needed to reduce the inductive VARs from 1715.789 to 535.754. To find the capacitive VARs needed to produce a total reactive power of 535.754 in the circuit, subtract the amount of reactive power needed from the present amount:

$$VARs_C = VARs_{L(present)} - VARs_{L(needed)}$$

$$VARs_C = 1761.562 - 535.754$$

$$VARs_C = 1225.808$$

Step six is to determine the amount of capacitive reactance that would produce 1225.808 capacitive VARs. To determine the capacitive reactance needed to produce the required reactive power at 240 volts, the following formula can be used:

$$X_C = \frac{E^2}{VARs_C}$$

$$X_C = \frac{240^2}{1225.808}$$

$$X_C = 46.989\ \Omega$$

The last step in this example is to determine the amount of capacitance needed to produce a capacitive reactance of 46.989 Ω. The amount of capacitance needed to produce the required capacitive reactance at 60 Hz can be calculated using the formula

$$C = \frac{1}{2\pi f X_C}$$

$$C = \frac{1}{377 \times 46.989}$$

$$C = 56.45\mu F$$

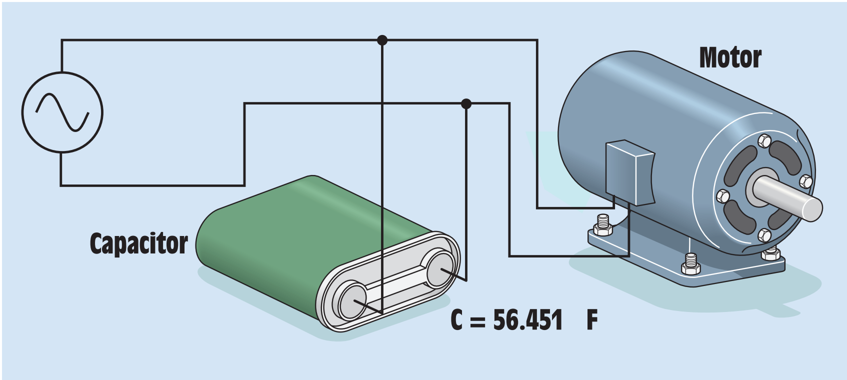

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FIGURE 25–18 The capacitor corrects the power factor to 95%.

The power factor will be corrected to 95% when a capacitor with a capacitance of 56.45 μF is connected in parallel with the motor *(Figure 25–18)*.

GREEN TIPS: Power factor correction results in less power loss on conductors by lowering the amount of current flow through the conductor. Reduced current flow results in less power loss due to heating the conductor. ■

Summary

- The voltage applied to all legs of an RLC parallel circuit is the same.
- The current flow in the resistive leg will be in phase with the voltage.
- The current flow in the inductive leg will lag the voltage by 90°.
- The current flow in the capacitive leg will lead the voltage by 90°.
- Angle theta for the circuit is determined by the amounts of inductance and capacitance.
- An LC resonant circuit is often referred to as a tank circuit.
- When an LC parallel circuit reaches resonance, the line current drops and the total impedance increases.

- When an LC parallel circuit becomes resonant, the total circuit current is determined by the amount of pure resistance in the circuit.
- Total circuit current and total impedance in a resonant tank circuit are proportional to the Q of the circuit.
- Motor power factor can be corrected by connecting capacitance in parallel with the motor. The same amount of capacitive VARs must be connected as inductive VARs.

Review Questions

1. An AC circuit contains a 24-Ω resistor, a 15.9-mH inductor, and a 13.3-μF capacitor connected in parallel. The circuit is connected to a 240-V, 400-Hz power supply. Find the following values.

   X_L = ________ Ω

   X_C = ________ Ω

   I_R = ________ A

   I_L = ________ A

   I_C = ________ A

   P = ________ W

   $VARs_L$ = ________

   $VARs_C$ = ________

   I_T = ________ A

   VA = ________

   PF = ________ %

   $\angle\theta$ = ________ °

2. An RLC parallel circuit contains a resistor with a resistance of 16 Ω, an inductor with an inductive reactance of 8 Ω, and a capacitor with a capacitive reactance of 20 Ω. What is the total impedance of this circuit?
3. The circuit shown in *Figure 25–2* has a current of 38 A flowing through the resistor, 22 A flowing through the inductor, and 7 A flowing through the capacitor. What is the total circuit current?
4. A tank circuit contains a capacitor and an inductor that produce 30 Ω of reactance at the resonant frequency. The inductor has a Q of 15. The voltage of 277 V is connected to the circuit. What is the total circuit current at the resonant frequency?

5. A 0.796-mH inductor produces an inductive reactance of 50 Ω at 10 kHz. What value of capacitance will be needed to produce a resonant circuit at this frequency?
6. An AC motor is connected to a 560-V, 60-Hz line. The motor has a current draw at full load of 53 A. A wattmeter indicates a true power of 18,700 W. Find the power factor of the motor and the amount of capacitance that should be connected in parallel with the motor to correct the power factor to 100%, or unity.

Practical Applications

A single-phase AC motor is connected to a 240-V, 60-Hz supply. A clamp-on ammeter indicates the motor has a current draw of 15 A at full load. A wattmeter connected to the motor indicates a true power of 2.2 kW. What is the power factor of the motor, and how much capacitance is needed to correct the power factor to 95%? ■

Practice Problems

Refer to the Resistive-Inductive-Capacitive Parallel Circuits Formula section of Appendix B and to *Figure 25–2*.

Find all the missing values in the following problems.

1. The circuit in *Figure 25–2* is connected to a 120-V, 60-Hz line. The resistor has a resistance of 36 Ω, the inductor has an inductive reactance of 40 Ω, and the capacitor has a capacitive reactance of 50 Ω.

E_T 120 V	E_R ______	E_L ______	E_C ______
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R 36 Ω	X_L 40 Ω	X_C 50 Ω
VA ______	P ______	$VARs_L$ ______	$VARs_C$ ______
PF ______	∠θ ______	L ______	C ______

2. The circuit in *Figure 25–2* is connected to a 400-Hz line with a total current flow of 22.267 A. There is a true power of 3840 W, and the inductor

has a reactive power of 1920 VARs. The capacitor has a reactive power of 5760 VARs.

E_T ______	E_R ______	E_L ______	E_C ______
I_T 22.267 A	I_R ______	I_L ______	I_C ______
Z ______	R ______	X_L ______	X_C ______
VA ______	P 3840 W	$VARs_L$ 1920	$VARs_C$ 5760
PF ______	$\angle\theta$ ______	L ______	C ______

3. The circuit in *Figure 25–2* is connected to a 60-Hz line. The apparent power in the circuit is 48.106 VA. The resistor has a resistance of 12 Ω. The inductor has an inductive reactance of 60 Ω, and the capacitor has a capacitive reactance of 45 Ω.

E_T ______	E_R ______	E_L ______	E_C ______
I_T ______	I_R ______	I_L ______	I_C ______
Z ______	R 12 Ω	X_L 60 Ω	X_C 45 Ω
VA 48.106	P ______	$VARs_L$ ______	$VARs_C$ ______
PF ______	$\angle\theta$ ______	L ______	C ______

4. The circuit in *Figure 25–2* is connected to a 1000-Hz line. The resistor has a current flow of 60 A, the inductor has a current flow of 150 A, and the capacitor has a current flow of 70 A. The circuit has a total impedance of 4.8 Ω.

E_T ______	E_R ______	E_L ______	E_C ______
I_T ______	I_R 60 A	I_L 150 A	I_C 70 A
Z 4.8 Ω	R ______	X_L ______	X_C ______
VA ______	P ______	$VARs_L$ ______	$VARs_C$ ______
PF ______	$\angle\theta$ ______	L ______	C ______

5. In an RLC parallel circuit, the resistor has resistance of 24 kΩ, the inductor has a reactance of 36 kΩ, and the capacitor has a reactance of 14 kΩ. Find Z.

6. In an RLC parallel circuit, the resistor has a resistance of 60 Ω, the inductor has a reactance of 180 Ω, and the capacitor has a reactance of 80 Ω. Find the circuit power factor.

7. In an RLC parallel circuit, the true power is 260 watts. The inductor has a reactive power of 360 VARs, and the capacitor has a reactive power

of 760 VARs. By how many degrees are the voltage and current out of phase with each other?

8. An RLC parallel circuit has an apparent power of 400 VA. The inductor has a reactive power of 450 VARs, and the capacitor has a reactive power of 200 VARs. Find the true power or watts.

9. In an RLC parallel circuit, the resistor has a value of 12 Ω and a current flow of 40 amperes. What is the voltage drop across the capacitor (E_C)?

10. An RLC parallel circuit is connected to 240 volts. The resistor has a power dissipation of 600 watts. If the circuit power factor is 75%, what is the total circuit current (I_T)?

Unit 26

Filters

Why You Need to Know

Filters are employed throughout the electrical field to separate different frequencies. They are the underlying principle behind radio and television. Without filters, it would be impossible to separate the different stations. Some filters are designed to pass particular frequencies, and others are designed to block particular frequencies. This unit introduces the different kinds of filters and the principles on which they work.

OUTLINE

KEY TERMS

Filter circuits
Notch filters
One-tenth
Pass
PI (π) filter
Q of the inductor
Reject
Trimmer capacitor
Trimmer inductor


Courtesy of Schneider Electric

Objectives

After studying this unit, you should be able to

- discuss the necessity of filter circuits.
- discuss the operation of low-pass filters.
- discuss the operation of high-pass filters.
- discuss the operation of bandpass filters.
- discuss the operation of band-reject filters.

Preview

Filter circuits are used to either **pass** (offer little opposition to) or **reject** (offer much opposition to) different frequencies. Many common electronic devices must use filters to operate. Radios and televisions are prime examples of these devices. Literally thousands of different radio and television stations are broadcasting at the same time. Filters are used to select one particular station from the thousands available.

In previous units, it was discussed that inductors and capacitors can be used to produce a circuit that is resonant at a particular frequency. Resonant circuits are one type of filter. In previous examples, fixed values of inductance and capacitance were used to produce circuit resonance at one particular frequency. In actual practice, most filter circuits are constructed with variable components so that they can be tuned for different frequencies or fine-tuned to adjust for the tolerance in inductor or capacitor values. Some filter circuits use a variable capacitor, some use a variable inductor, and some use both. Examples of tank circuits with a **trimmer inductor** and a **trimmer capacitor** are shown in *Figure 26–1*. ■

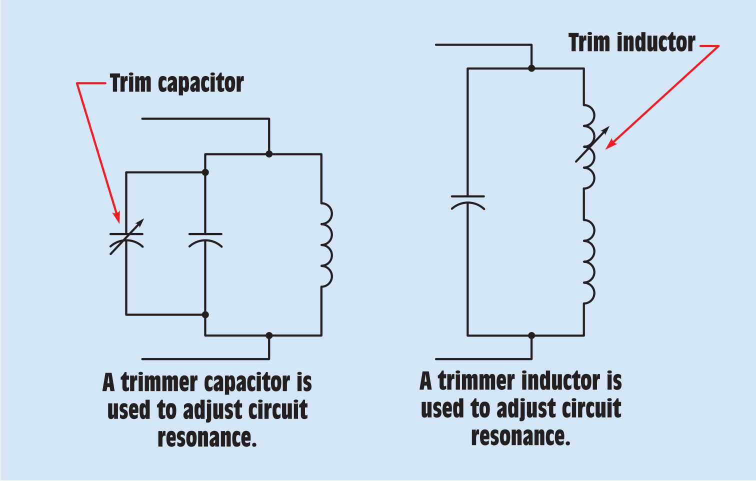

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FIGURE 26–1 Trimmer capacitors and trimmer inductors are used to overcome tolerance differences in capacitors and inductors.

26–1 Broadband Tuning

Some filter circuits must be capable of tuning over a broad band of frequencies. When this is the case, it is common practice to switch from one set of inductors or capacitors to another and then use a variable capacitor or inductor to adjust for a particular frequency. An example of a circuit that switches between different inductors and then uses a variable capacitor for tuning is shown in *Figure 26–2*. A circuit that functions by switching between different capacitors with an inductor for tuning is shown in *Figure 26–3*. Although either method can be used, tuning with a variable capacitor is the most common. Variable capacitors generally provide a wider range of tuning than variable inductors.

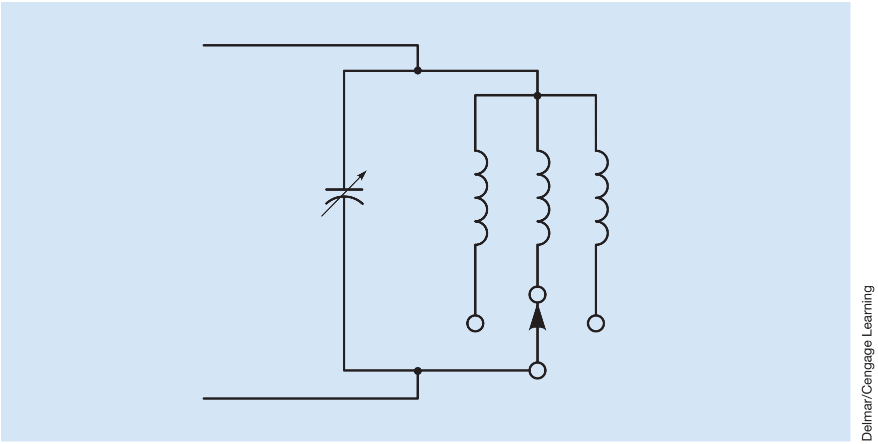

FIGURE 26–2 Broadband filter using multiple inductors and a tuning capacitor.

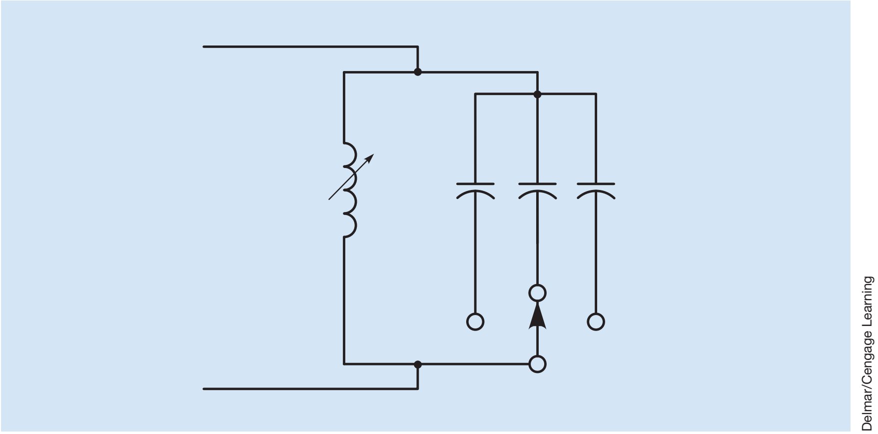

FIGURE 26–3 Broadband filter using multiple capacitors and a trimmer inductor.

26–2 Low-Pass Filters

Filter circuits can be divided into different types depending on the frequencies they either pass or reject. Low-pass filters offer little opposition to current flow when the frequency is low but increase their opposition dramatically after the frequency reaches a certain point *(Figure 26–4)*. Low-pass filters can be constructed in different ways. One of the most common types of low-pass filters is an inductor connected in series with a load resistor *(Figure 26–5)*. At low

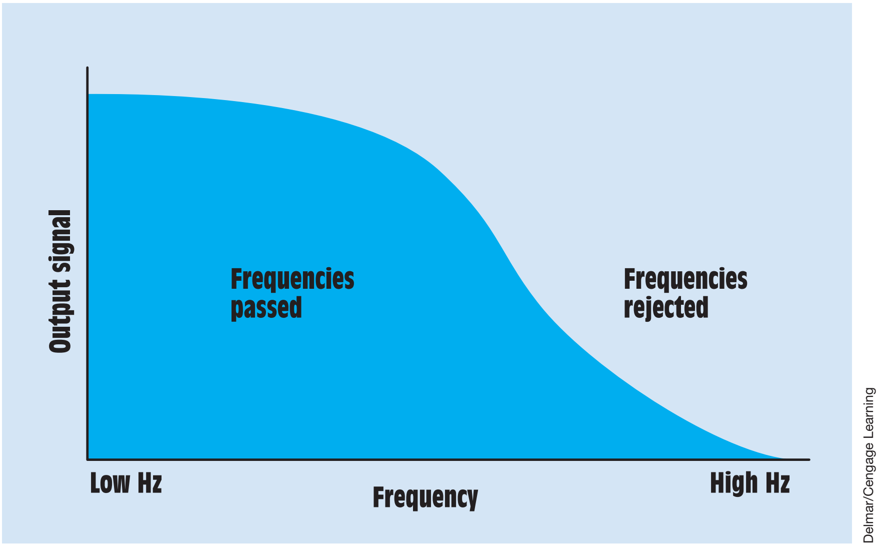

FIGURE 26–4 Low-pass filters pass low frequencies and reject high frequencies.

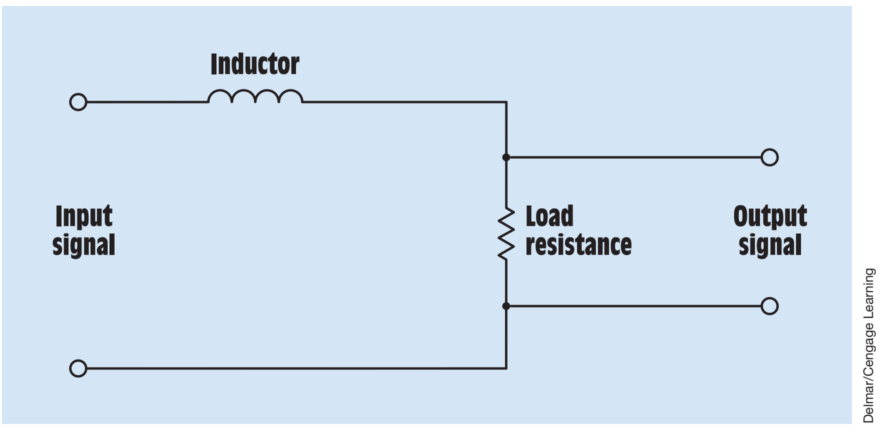

FIGURE 26–5 A low-pass filter can be constructed by connecting an inductor in series with the load resistance.

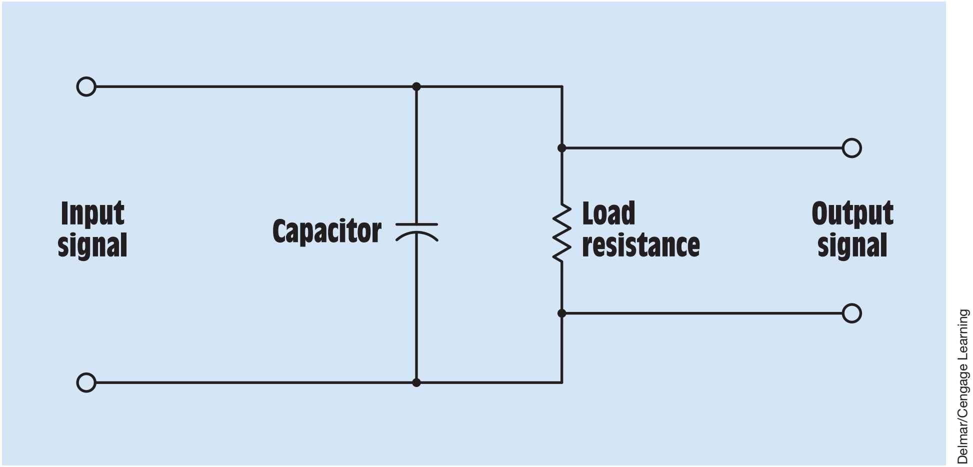

FIGURE 26–6 A low-pass filter using a capacitor connected in parallel with the load resistance.

frequencies, the inductive reactance of the inductor is very low, permitting current to flow with little opposition. This permits most of the circuit voltage drop to appear across the load resistor. As the frequency increases, the inductive reactance increases, permitting less current to flow through the circuit. When inductive reactance reaches the same ohmic value as the load resistor, half the circuit voltage is dropped across each component. As the frequency continues to increase, more voltage drops across the inductor and less voltage drops across the load resistor. When the frequency becomes high enough that the inductive reactance is 10 times greater than the load resistance, practically all the signal appears across the inductor and almost none across the load resistor.

Another method of constructing a low-pass filter is to connect a capacitor in parallel with the load resistor *(Figure 26–6)*. At low frequencies, the capacitive reactance of the capacitor is high, causing most of the circuit current to flow though the load resistor. This causes most of the circuit voltage to appear across the load resistor. As frequency increases, capacitive reactance decreases. The capacitor now begins to shunt part of the signal away from the load resistor. When the frequency reaches the point where the capacitive reactance is about **one-tenth** the ohmic value of the load resistor, practically all the current is shunted away from the load resistor, reducing the output signal to almost nothing.

Some low-pass filters are constructed by combining an inductor and capacitor *(Figure 26–7)*. When this is done, a sharper rejection curve is produced

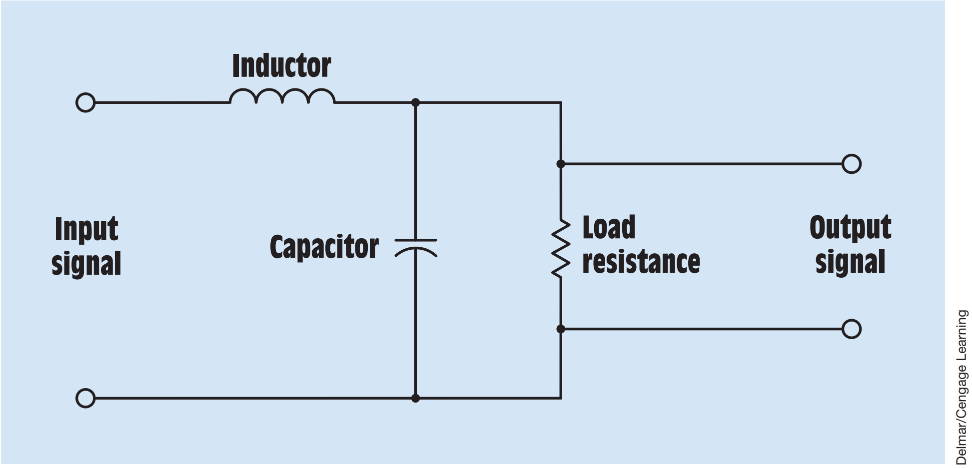

FIGURE 26–7 Low-pass filter combining the effects of an inductor and a capacitor.

(Figure 26–8). One characteristic of this type of filter is that the output signal will peak at the resonant frequency when the values of inductive reactance and capacitive reactance are equal. This will be followed by a sharp drop in the output signal.

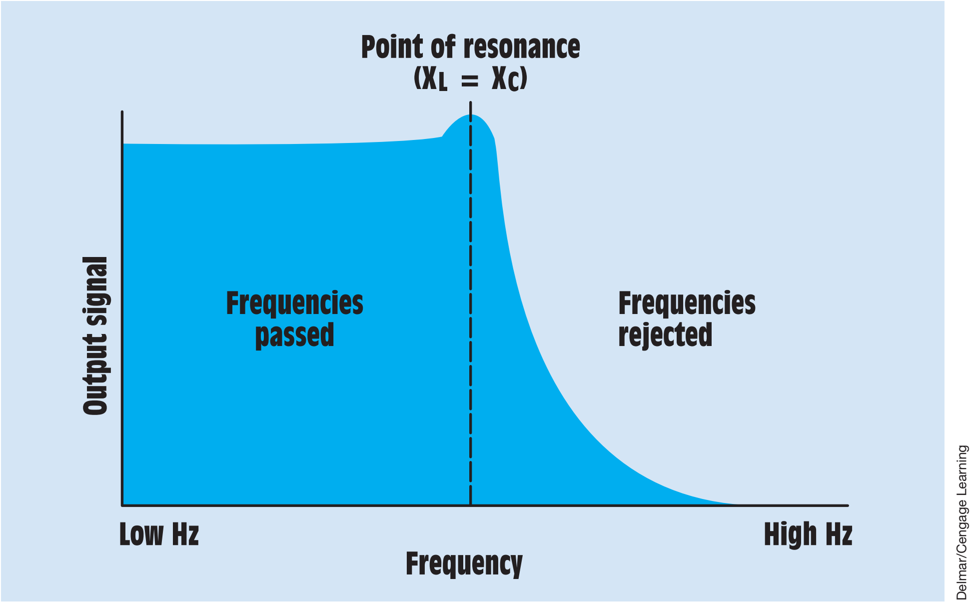

FIGURE 26–8 Combining inductance and capacitance produces a sharper rejection curve.

26–3 High-Pass Filters

High-pass filters are designed to reject low frequencies and pass high frequencies *(Figure 26–9)*. They can be constructed in a manner similar to low-pass filters, except that the capacitor is connected in series with the load resistor and the inductor is connected in parallel with the load resistor *(Figure 26–10)*. Because capacitive reactance decreases with an increase in frequency, the capacitor is connected in series with the load resistor. At low frequencies, capacitive reactance is high, causing most of the signal voltage to appear across the capacitor. As the frequency increases, the reduction in capacitive reactance permits more current to flow through the load resistor, producing more signal voltage across the resistor. When the ohmic value of the capacitive reactance becomes about one-tenth the ohmic value of the load resistor, almost all the signal is seen across the load resistor and practically none is across the capacitor.

The parallel inductor operates in the opposite way. At low frequencies, inductive reactance is low, shunting most of the current away from the load resistor. As frequency increases, inductive reactance becomes high, permitting more current to flow through the load resistor, producing an increase in output signal strength. When the ohmic value of the inductive reactance becomes about 10 times greater than the ohmic value of the load resistor, practically all the signal appears across the load resistor.

The effects of the capacitor and inductor can also be combined in high-pass filters *(Figure 26–11)*. The combination of inductance and capacitance in the

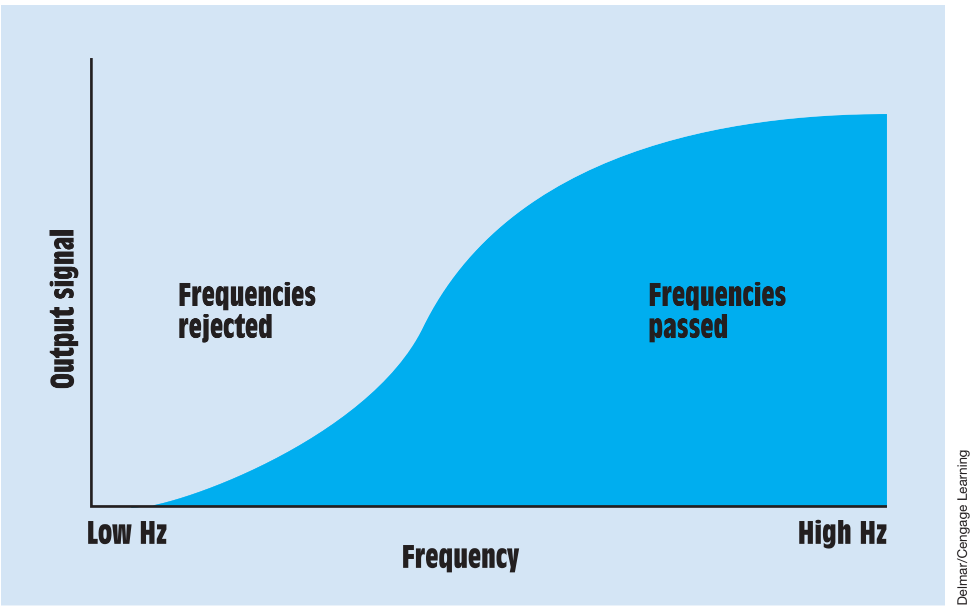

FIGURE 26–9 High-pass filters reject low frequencies and pass high frequencies.

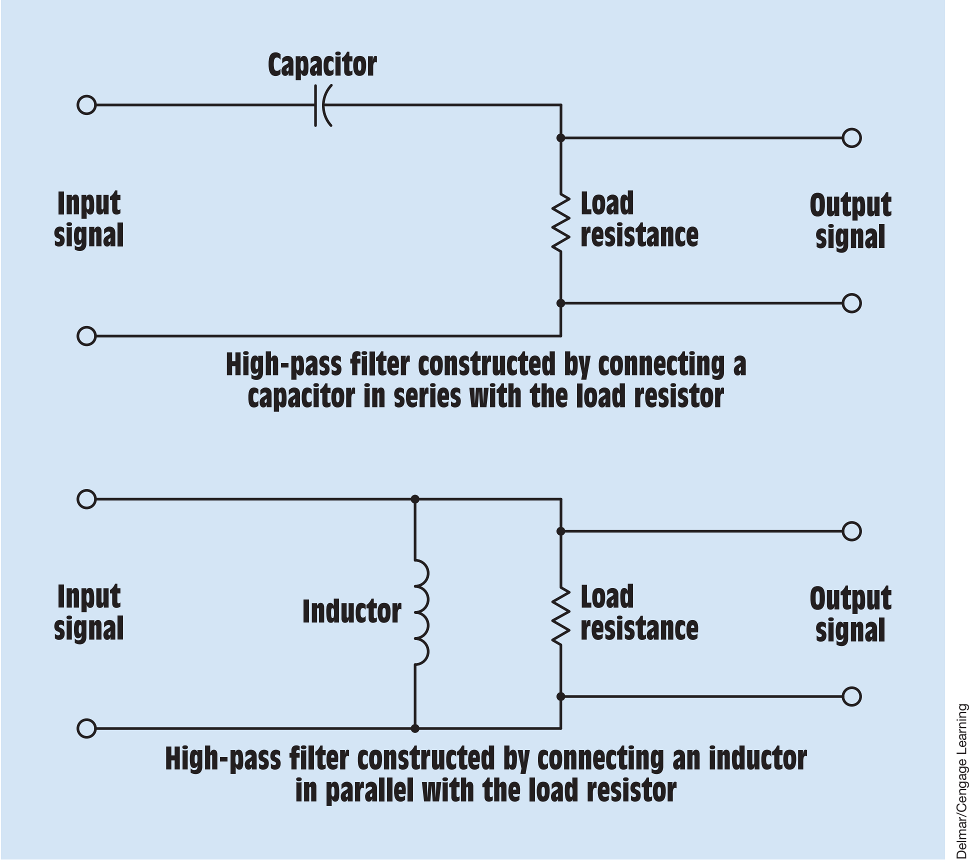

FIGURE 26–10 Construction of high-pass filters using capacitors and inductors.

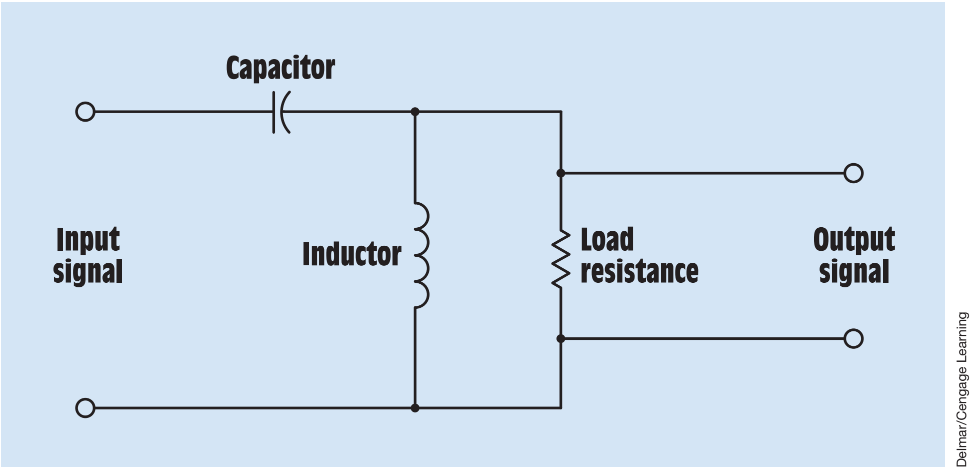

FIGURE 26–11 High-pass filters combining the effects of an inductor and a capacitor.

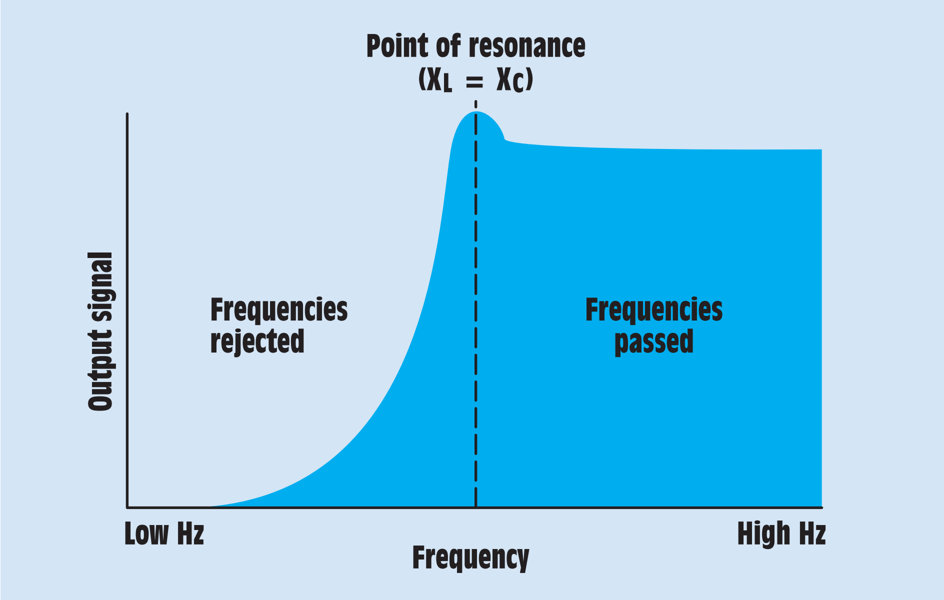

FIGURE 26–12 Combining inductance and capacitance produces a sharper curve.

high-pass filter has the same basic characteristics as the low-pass filter. It produces a sharper curve, and the output signal peaks at the point of resonance *(Figure 26–12)*.

26–4 Bandpass Filters

Bandpass filters permit a certain range of frequencies to pass while rejecting frequencies on either side. The desired frequency to pass is set at the resonant point of the inductor and capacitor. The bandwidth is determined by the Q of the components *(Figure 26–13)*. Because capacitors are generally high-Q components, the bandwidth is basically determined by the **Q of the inductor.** Inductors with a high Q produce a narrow bandwidth, and inductors with a low Q produce a wide bandwidth. Basic bandpass filters are shown in *Figure 26–14*. One filter uses the series resonance of the inductor and capacitor. At the resonant frequency, the impedance of the circuit is low, permitting most of the current to flow through the load resistance, producing a high output signal. The second filter operates by connecting a tank circuit in parallel with the load resistance. The impedance of the tank circuit is relatively low until the resonant frequency is reached. The low impedance of the tank circuit shunts most of the current away from the load resistor, producing a low output signal. The impedance of the tank circuit becomes high at the resonant frequency, permitting most of the circuit current to flow through the load resistor.

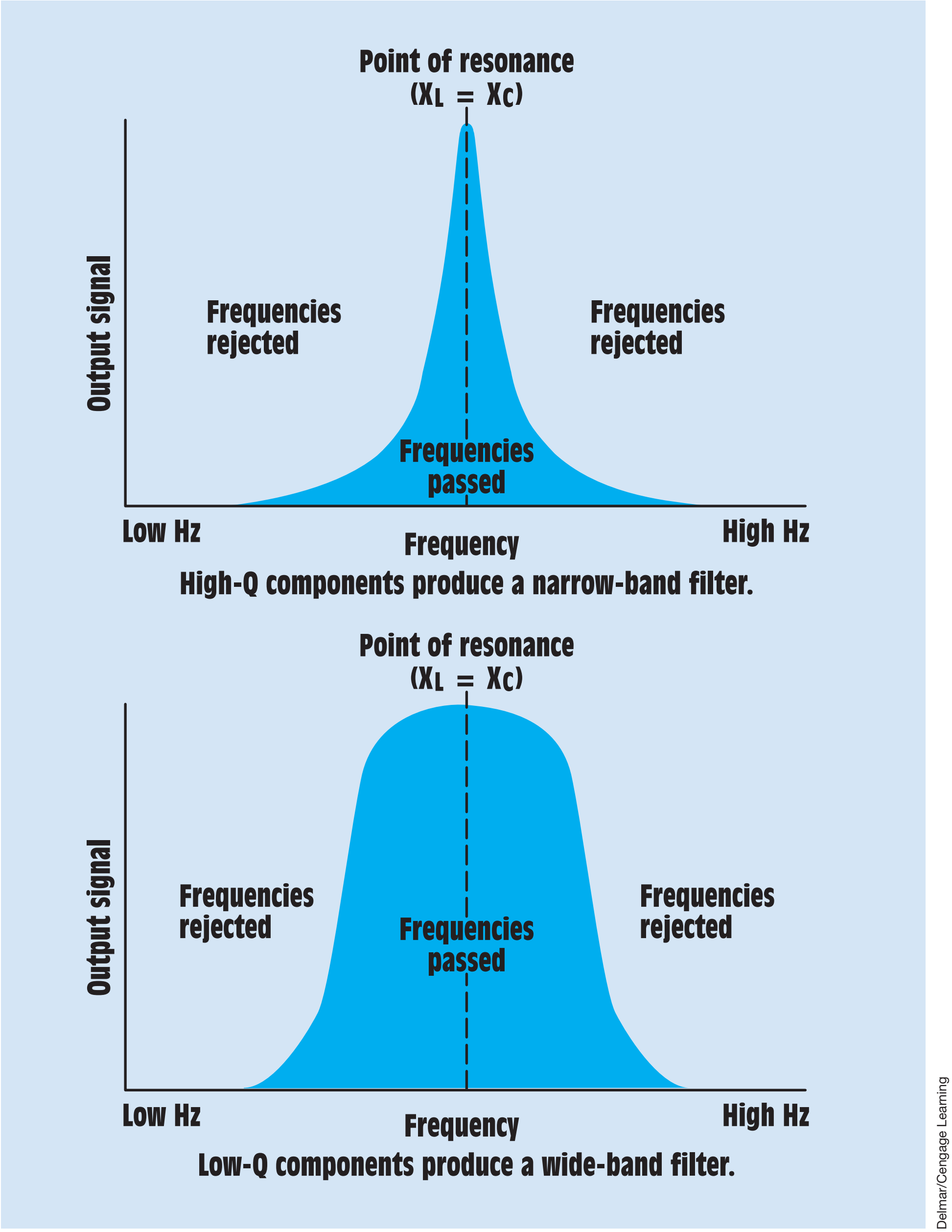

FIGURE 26–13 The bandwidth is controlled by the Q of the components.

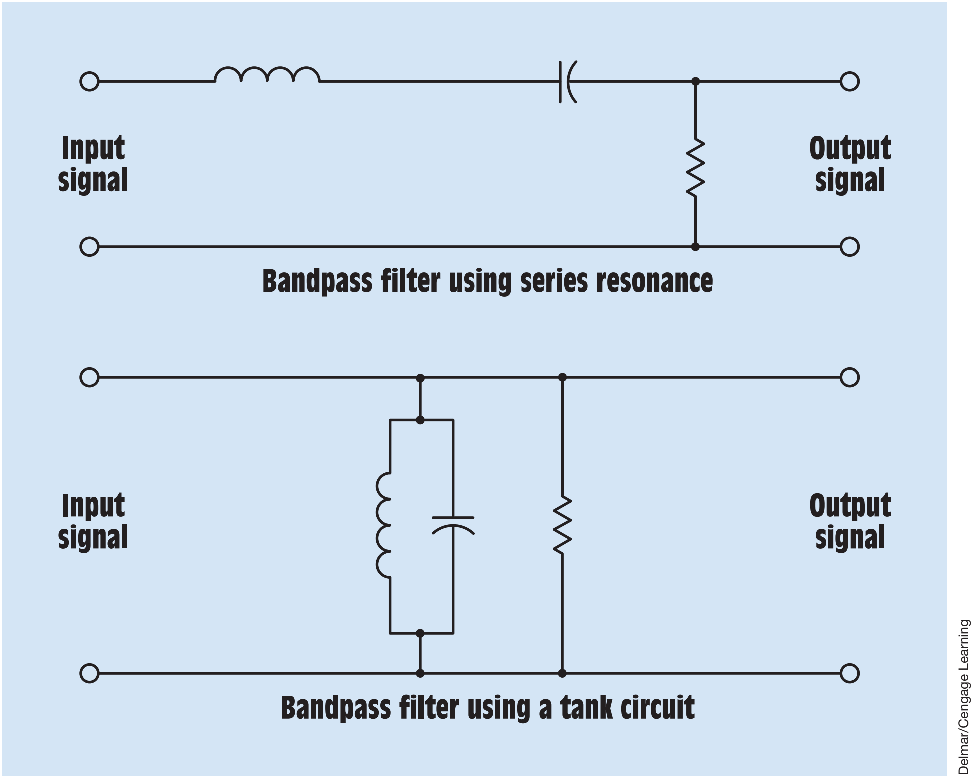

FIGURE 26–14 Basic bandpass filters.

26–5 Band-Rejection (Notch) Filters

Band-rejection or **notch filters** function in a manner opposite that of bandpass filters. Band-rejection filters are designed to exhibit low impedance to frequencies on either side of their resonant frequency. Band-rejection filters can be narrow band or wide band depending on the Q of the components *(Figure 26–15)*. Two common connections for band-rejection filters are shown in *Figure 26–16*. The parallel tank circuit connected in series with the load resistor exhibits a low impedance until the resonant frequency is reached. At that point the impedance increases and dramatically reduces the current flow to the load resistor.

The second band-rejection filter employs a series resonant circuit connected in parallel with the load resistance. The impedance of the series resonant circuit remains high at frequencies other than the resonant frequency, permitting most of the circuit current to flow through the load resistance. The circuit impedance dramatically drops when the frequency reaches resonance, shunting most of the circuit current away from the load resistance.

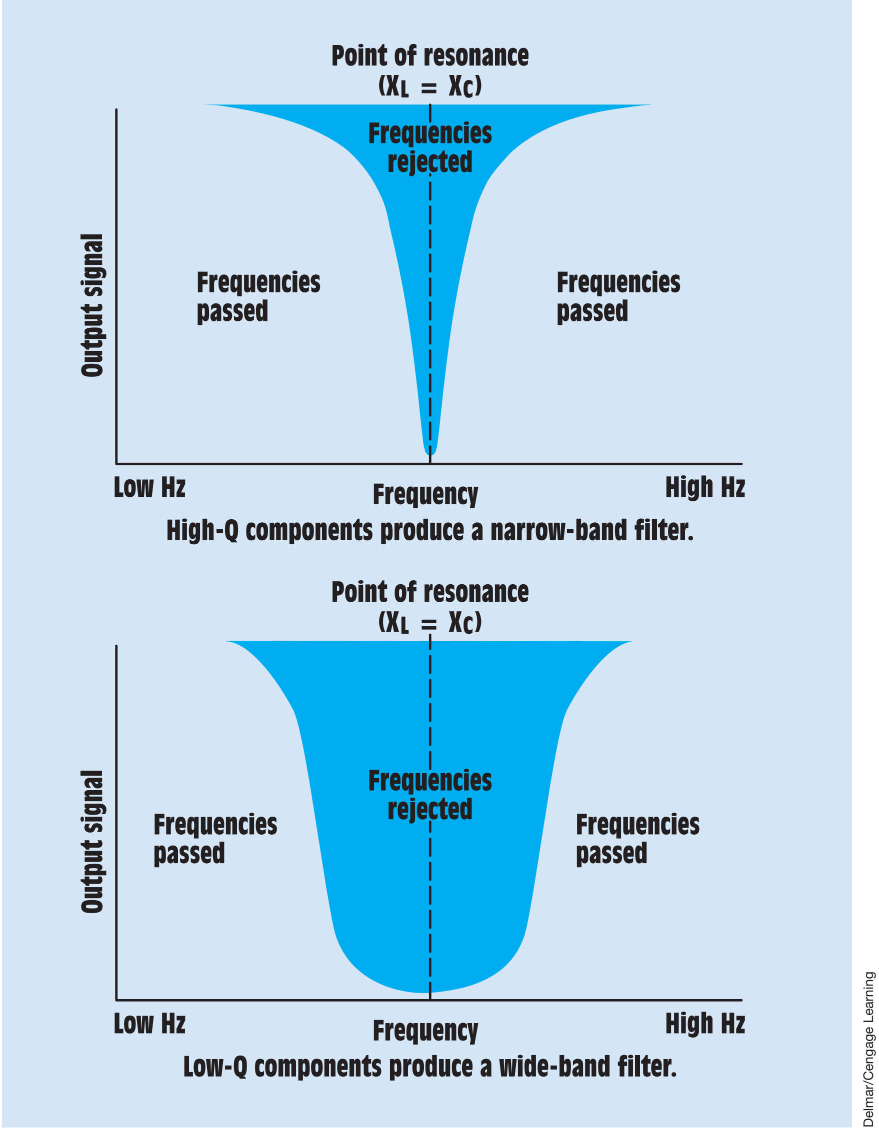

FIGURE 26–15 Band-rejection filters pass most frequencies and reject only a certain range.

26–6 T Filters

The filters discussed thus far have been simple connections involving inductors, capacitors, or a combination of the two. Filter circuits are often much more complex in nature. Filter circuits often fall into one of two classifications, T or

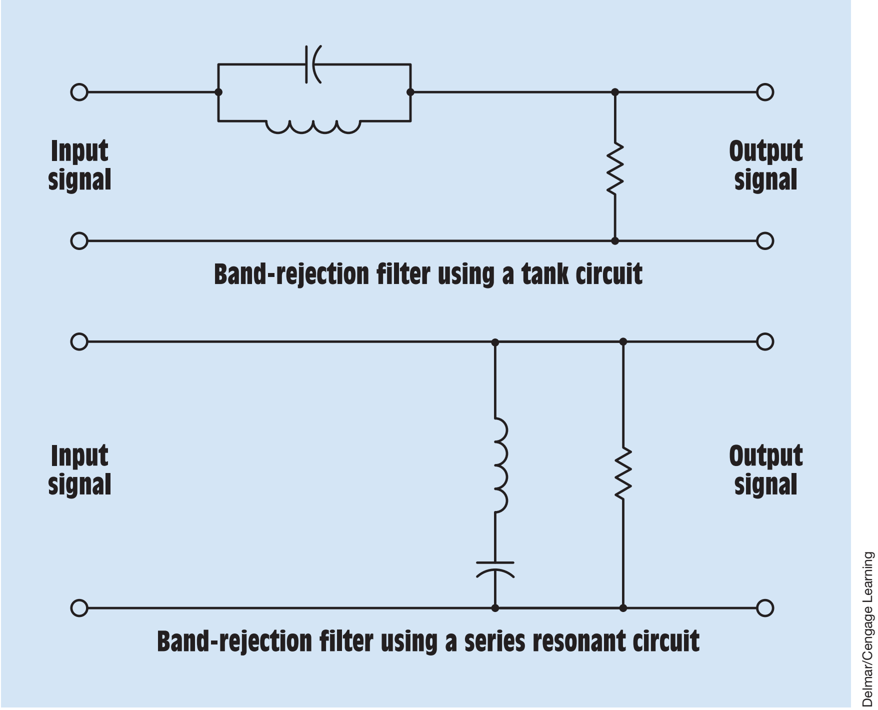

FIGURE 26–16 Basic band-rejection filters.

PI. *T filters* are so named because when schematically drawn they resemble the letter *T*. T filters are basically constructed by connecting two components in series with one component in parallel. Several different types of T filters are shown in *Figure 26–17*.

26–7 PI-Type Filters

PI-type filters are so named because they resemble the Greek letter PI (π) when connected. **PI (π) filters** are constructed with two parallel components and one series component. Several examples of PI-type filters are shown in *Figure 26–18*.

26–8 Crossover Networks

A good example of where and how filters are used can be seen in the typical crossover network for a set of speakers. Speakers are designed to produce sound from a particular range of frequencies. Tweeter speakers produce sounds

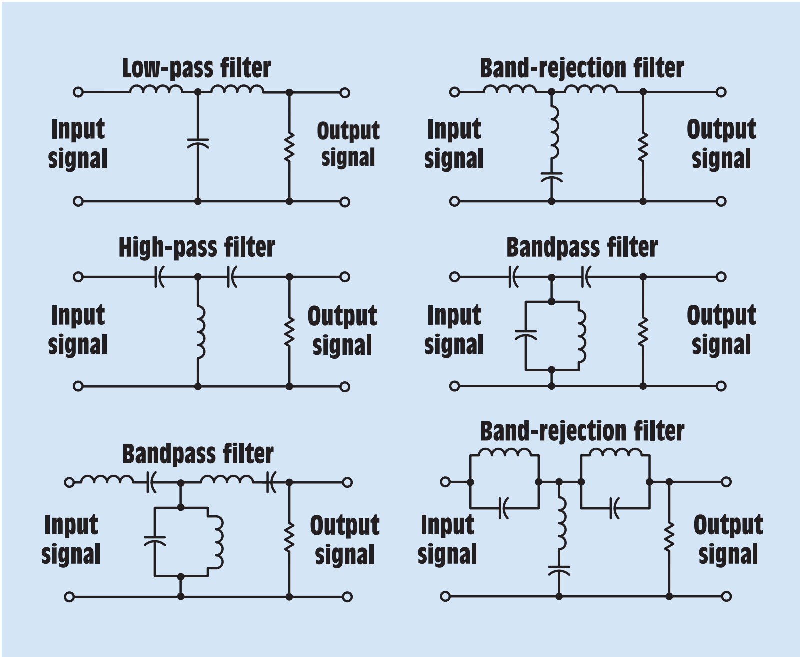

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FIGURE 26–17 Basic T-type filters.

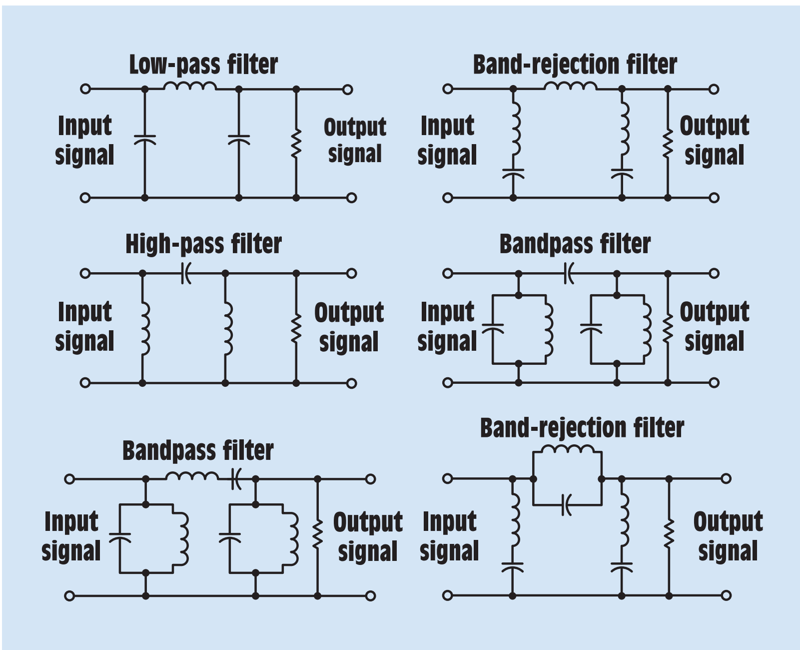

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FIGURE 26–18 Basic PI-type filters.