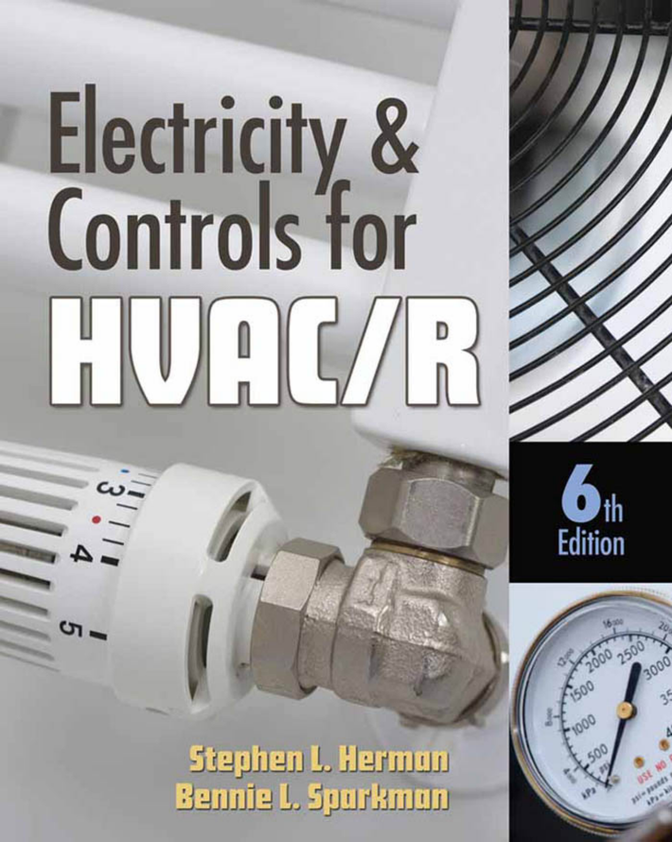
Electricity & Controls for HVAC/R

6th Edition



Stephen L. Herman
Bennie L. Sparkman

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Electricity and Controls for HVAC/R, 6th Edition
Stephen L. Herman, Bennie L. Sparkman

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PREFACE

Electricity and Controls for HVAC/R is written with the assumption that the student has no prior knowledge of electricity or control systems. Basic electrical theory is presented in a practical, straightforward manner. Mathematical explanations are used only when necessary to explain certain concepts of electricity. Each unit starts with the objectives of the unit and ends with a summary of important facts.

The text begins with the study of **basic electrical theory** and progresses to **series circuits, parallel circuits, alternating current, inductive circuits,** and **capacitive circuits**. The text also includes information on different types of three-phase services found in industrial and commercial locations as well as single-phase residential services. Individual devices and components common to the air conditioning, heating, and refrigeration field are presented in a practical manner. Devices are explained from a standpoint of how they operate and how they are used. The text contains testing procedures for many of the devices covered. The practical presentation of these devices makes this text a *must-have* reference book for the service technician working in the field.

Electricity and Controls for HVAC/R, sixth edition, includes information on isolation transformers, autotransformers, and current transformers. The three major types of three-phase motors—squirrel cage induction, wound rotor, and synchronous—are also covered. Coverage of single-phase motors includes: split-phase motors, resistance-start induction-run motors, capacitor-start induction-run motors, and permanent-split capacitor motors. Shaded-pole induction motors and multispeed motors are also covered. The sixth edition also provides information on variable-frequency drives.

Control circuits are developed using the components in the text. The text assumes that the student has no prior knowledge of control systems. **Operation of the manufacturer's control schematics is explained to aid the student in understanding how a control system operates and how to troubleshoot the system**.

Electricity and Controls for HVAC/R, sixth edition, includes information on **household and commercial icemaker controls**. These circuits are explained in a step-by-step procedure to ensure that students have a thorough working knowledge of these units.

Solid-state devices common to the HVAC/R field are covered in a straightforward manner. The devices covered are: **diode, transistor, SCR, diac, triac,** and **operational amplifier**. The last section of the text covers **programmable logic controllers**, which are becoming more and more common in the field.

NEW FOR THE SIXTH EDITION

The unit on atomic structure has been rewritten to reflect the most accepted theories concerning the structure of atoms. Many of the illustrations have been updated to help students gain a better understanding of the principles involved concerning the subject matter. The unit devoted to troubleshooting has been expanded to include an example of a step-by-step procedure for determining the problems with a central air conditioning system.

FEATURES OF THIS BOOK

Electricity and Controls for HVAC/R, sixth edition, contains many features to help enhance learning for the student:

- A special section covering **Safety** rules at the front of the book reminds students to follow correct procedures and take the necessary precautions when working around electricity.

- **Step-by-Step Procedures** are integrated throughout the text where applicable, and provide students with a thorough working knowledge of the HVAC systems.
- **Troubleshooting Questions** present situations in which students must develop critical-thinking and problem-solving skills to prepare them for the field.
- **Review Questions** and **Practice Problems** are included at the end of each unit to allow students to evaluate their comprehension of the material and apply what they have learned from the information presented in the unit.
- **An extensive art program** includes schematics, line drawings, and up-to-date photos that help to reinforce the information presented in the text.

SUPPLEMENT TO THIS BOOK

Also available to the instructor is the *Instructor Resource to Accompany Electricity & Controls for HVAC/R*, sixth edition. Thoroughly updated to reflect changes to the sixth-edition book, the *Instructor's Resource* contains:

- Instructors Guide with answers to the text's Review Questions
- PowerPoint presentations
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SECTION 1

Basic Electricity

A SPECIAL NOTE ON SAFETY

The purpose of this textbook is to provide the air conditioning and refrigeration technician with knowledge of electricity. Electricity is an extremely powerful force and should never be treated in a careless manner. The air conditioning and refrigeration technician commonly works with voltages ranging from 24 volts to 480 volts. One mistake can lead to serious injury or death.

Never work on an energized circuit if it is possible to disconnect the power. When possible, use a three-step check to make certain that the power is turned off. The three-step check is as follows:

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

Install a warning tag at the point of disconnection to warn people not to restore power to the circuit, as shown in Figure SF–1.

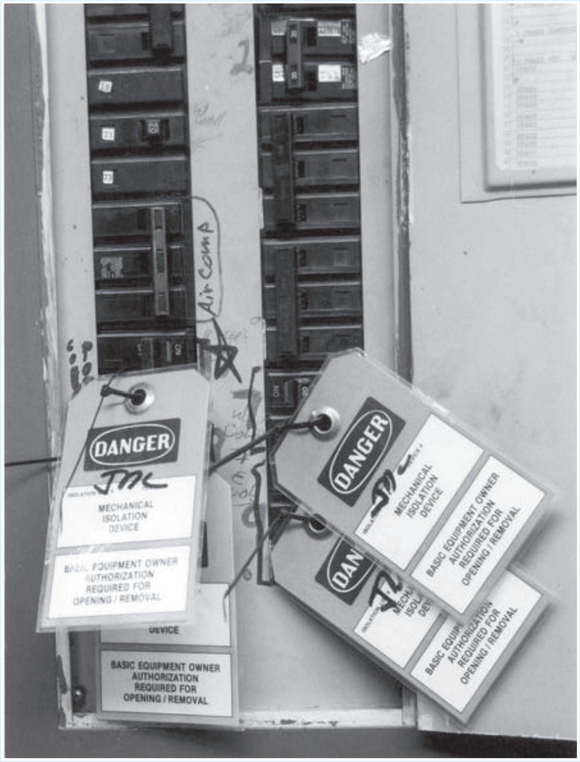


Figure SF–1
Warning tags warn people that the circuit should not be turned back on. (Source: Delmar/Cengage Learning)

GENERAL SAFETY RULES

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 the person's 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 designed to be used on the voltage being tested. Your life is your own, so *think* before you touch something that can take it away.

Certain pieces of equipment can be especially hazardous if you are not aware of them. Some central air conditioning units use a main contactor that has only one set of contacts to disconnect a 240-volt circuit, as shown in Figure SF–2. The contactor operates on the principle that a complete circuit must exist for current to flow. If one line is broken or open, no current can flow to the compressor. The hazard lies in the fact that one of the 240-volt lines is still supplying power to the unit. If a technician should touch the unbroken line and ground, a 120-volt circuit is completed through his body. Other contactors employ two load contacts to break the circuit to the compressor, as shown in Figure SF–3. This type of contactor is much safer and can prevent a serious injury.

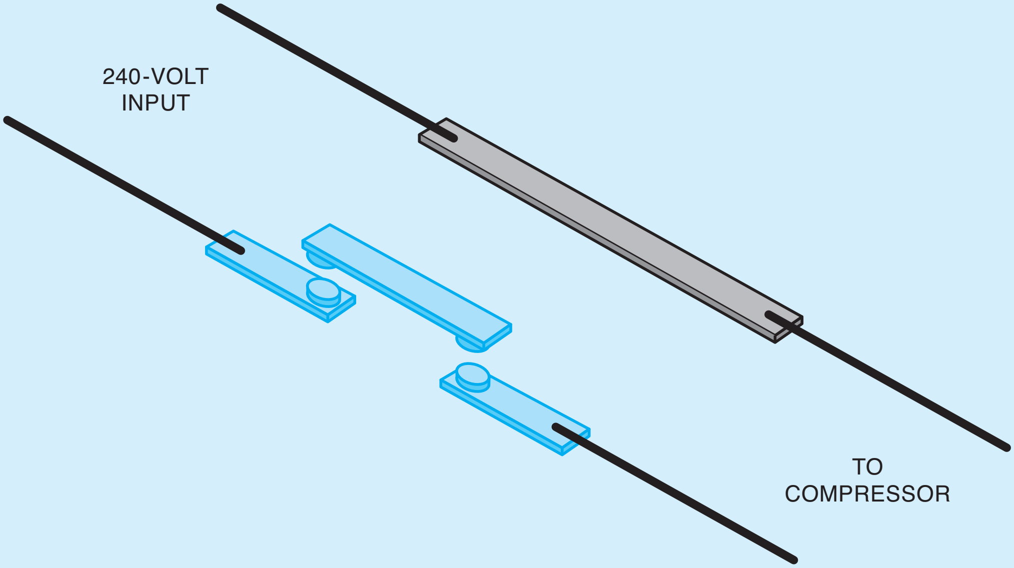


Figure SF–2
Some main contactors use one set of load contacts to break a 240-volt connection to the compressor.
(Source: Delmar/Cengage Learning)

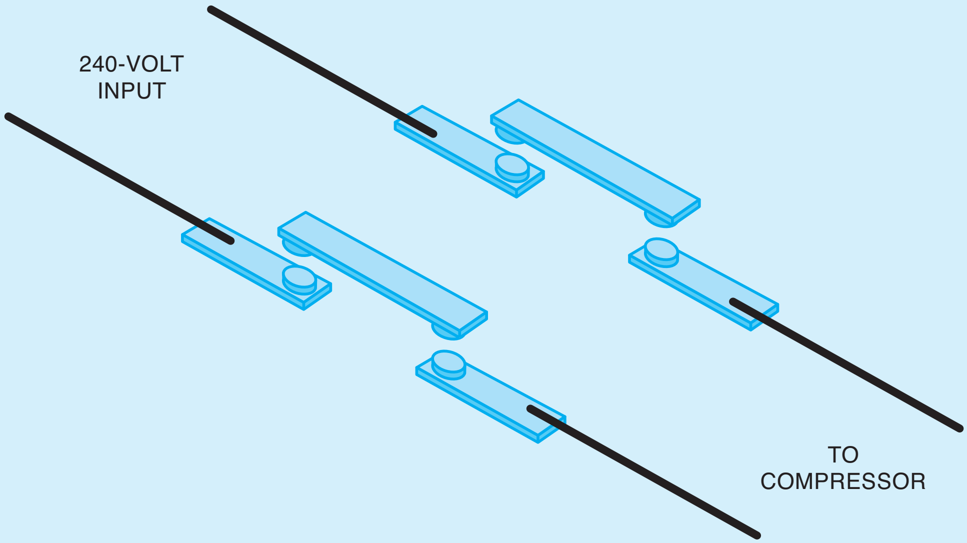


Figure SF–3
Contactors that employ two load contacts to break both sides of the 240-volt line are much safer and can prevent a serious injury. (Source: Delmar/Cengage Learning)

Avoid Horseplay

Jokes and horseplay have a time and place, but the time and place are 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 you being injured or killed.

Do Not Work Alone

Work with someone else, especially when working in a hazardous location or on a live circuit. Have someone with you to turn off the power or give artificial respiration or cardiopulmonary resuscitation (CPR). One of the effects of electrical shock is that it causes breathing difficulties and can cause the heart to go into fibrillation.

Work with One Hand When Possible

The worst case for electrical shock is when the current path is from one hand to the other. This path causes the current to pass directly through the heart. A person can survive a severe shock between the hand and one foot that would otherwise cause death if the current path were from one hand to the other.

Learn First Aid

Anyone working on electrical equipment should make an effort to learn first aid. Knowing first aid is especially important for anyone who must work with voltages above 50 volts. A knowledge of first aid and especially CPR may save your life or someone else's.

Effects of Electric Current on the Body

Most people have heard that it is not the voltage that kills but the current. Although this is a true statement, do not be misled into thinking voltage cannot harm you. Voltage is the force that pushes the current though the circuit. Voltage can be compared to the pressure that pushes water through a pipe. The more pressure available, the greater the volume of water flowing through a 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 will have less resistance on a hot day when sweating because salt water is a very good conductor. What you ate and drank for lunch can have an effect on your body resistance. The length of the current path can affect the resistance. Is the current path between two hands or from one hand to one foot? All of these factors affect body resistance.

The chart in Figure SF–4 illustrates the effects of different amounts of current on the body. This chart is general and shows the effects on most people. Some people may have less tolerance to electricity, and others may have greater tolerance.

A current of 2 to 3 milliamperes will generally cause a slight tingling sensation. The tingling sensation will increase as current increases and becomes very noticeable at about 10 milliamperes. The tingling sensation is very painful at about 20 milliamperes. Currents between 20 and 30 milliamperes generally cause a person to seize the line and become unable to let go of the circuit. Currents between 30 and 40 milliamperes cause muscular paralysis, and currents between 40 and 60 milliamperes cause breathing difficulty. By the time 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. Fibrillation is a condition in which the heart begins to "quiver" and the pumping action stops. Currents above 200 milliamperes generally cause the heart to squeeze shut. When the current is removed the heart will typically return to a normal pumping action. This is the principle of operation of a defibrillator. It is often said that 120 volts is the most dangerous voltage to work with. The reason is that 120 volts generally cause a current flow between 100 and 200 milliamperes through the bodies of most people. Large amounts of current can cause severe electrical burns. Electrical burns are usually very serious because the burn occurs on the inside of the body. The exterior of the body may not look seriously burned, but the inside may be severely burned.

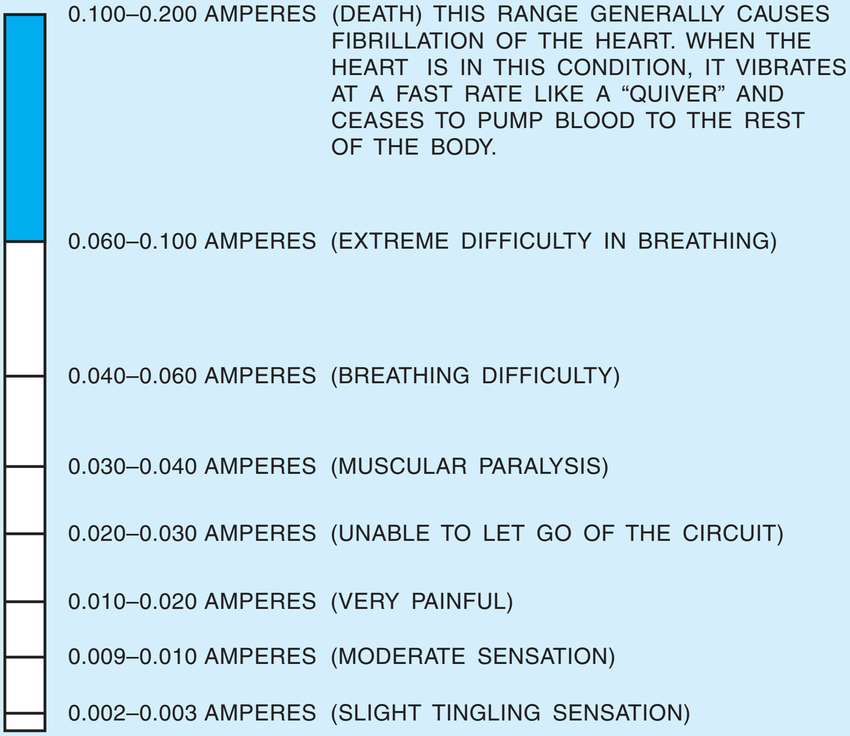


Figure SF–4
The effects of electric current on the body. (Source: Delmar/Cengage Learning)

UNIT 1

Atomic Structure

OBJECTIVES

After studying this unit the student should be able to:

- Discuss basic atomic theory
- Name the principal parts of an atom
- Discuss the law of charges
- Define electricity
- Discuss the differences between conductors and insulators

To understand electricity, one should start with the study of atoms. The **atom** is the basic building block of the universe. All matter is composed of atoms. An atom is the smallest part of any element. Atoms are composed of three principal parts, the electron, the proton, and the neutron. Electrons exhibit a negative charge, protons exhibit a positive charge, and neutrons have no charge. Some theories suggest that neutrons are composed of both a proton and an electron. The positive charge of the proton and the negative charge of the electron cancel each other.

Protons and neutrons are extremely massive particles as compared to the electron. It is believed that the electron is approximately three times larger than a proton, but the proton weighs approximately 1840 times more than an electron, as shown in Figure 1–1. It is like comparing a piece of lead shot to a soap bubble.

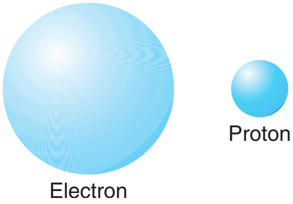


Figure 1–1
The electron is three times larger than the proton, but the proton weighs 1840 times more than the electron.
(Source: Delmar/Cengage Learning)

THE LAW OF CHARGES

One of the basic laws of physics concerning atoms is the **law of charges**. This law states that opposite charges attract each other and like charges repel each other. If charged particles were suspended from a string, a positively charged particle and negatively charged particle would attract each other, but two positively charged particles or two negatively charged particles would repel each other, as shown in Figure 1–2. Since **electrons** are negatively charged particles and **protons** are positively charged particles, they are attracted to each other.

STRUCTURE OF THE ATOM

The **nucleus** or center of the atom is composed of protons and **neutrons**. Electrons orbit the exterior of the atom in specific orbits or shells. The smallest of all atoms is hydrogen. Hydrogen does not contain a neutron in its nucleus. The hydrogen atom contains one proton and one electron, as shown in Figure 1–3. The smallest atom that contains both protons and neutrons in the nucleus is helium, shown in Figure 1–4. Helium contains two protons, two neutrons, and two electrons.

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. Thompson discovered the electron. Thompson 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,

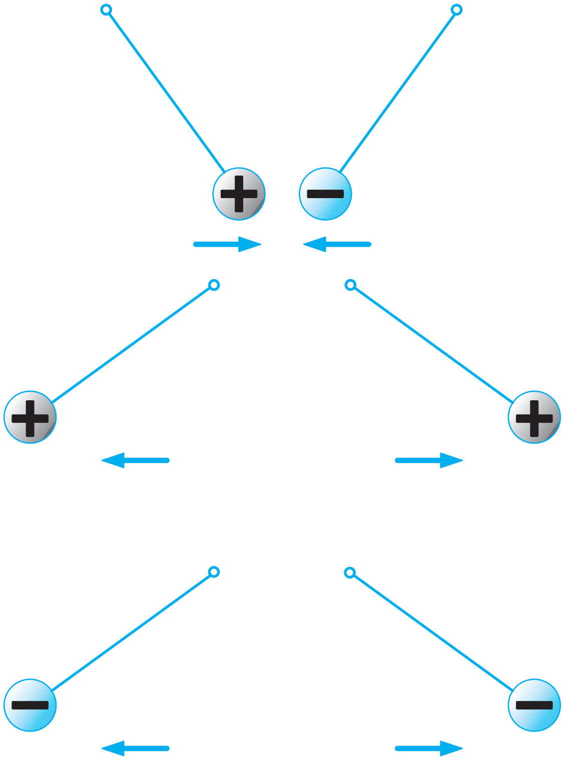


Figure 1–2
The law of charges states that opposite charges attract and like charges repel. (Source: Delmar/Cengage Learning)

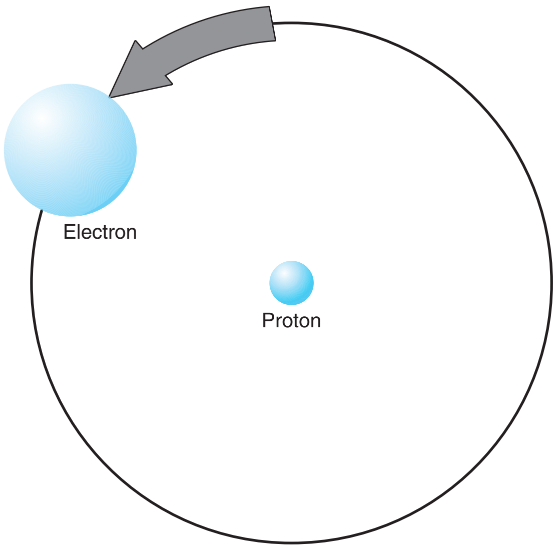


Figure 1–3
An atom of hydrogen contains one proton and one electron. (Source: Delmar/Cengage Learning)

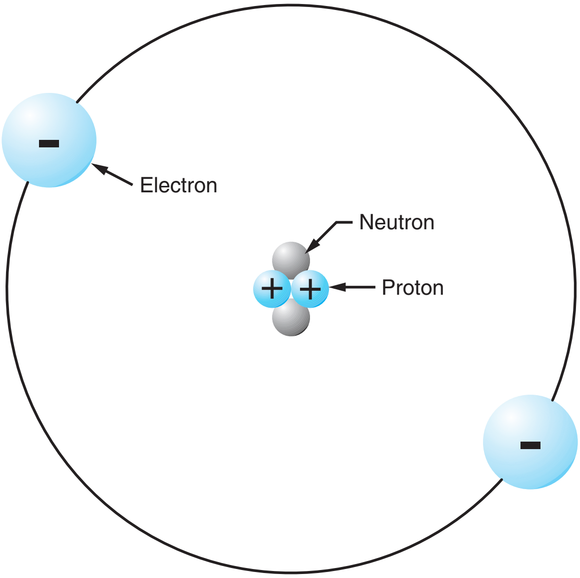


Figure 1–4
A helium atom contains both protons and neutrons in the nucleus. (Source: Delmar/Cengage Learning)

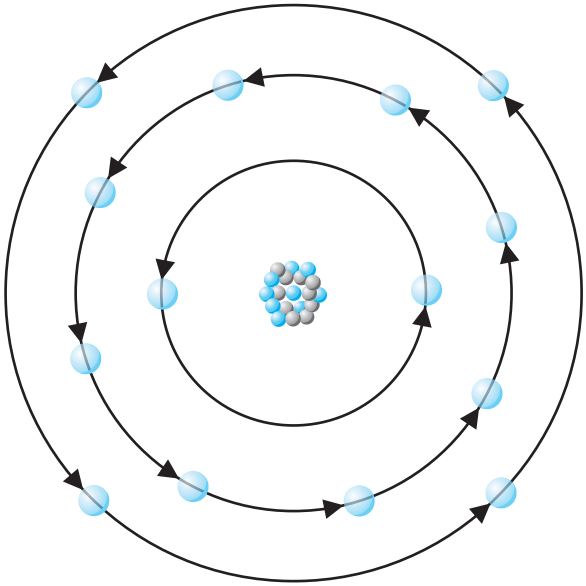


Figure 1–5
Electrons exist in allowed orbits or shells. (Source: Delmar/Cengage Learning)

positively charged, massive body with negatively charged electrons scattered throughout it. Thompson 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. Thompson'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 Niels 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, similar to the way that planets orbit the sun, as shown in Figure 1–5. The orbit in which the electron exists is 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.

Atoms have a set number of electrons that can be contained in one orbit or shell, as shown in Figure 1–6. The number of electrons that can be contained in any one shell is determined 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 two electrons.

$$2 \times (1)^2$$

$$2 \times 1 = 2$$

The second orbit can hold no more than eight electrons.

$$2 \times (2)^2$$

$$2 \times 4 = 8$$

The third orbit can contain no more than 18 electrons.

$$2 \times (3)^2$$

$$2 \times 9 = 18$$

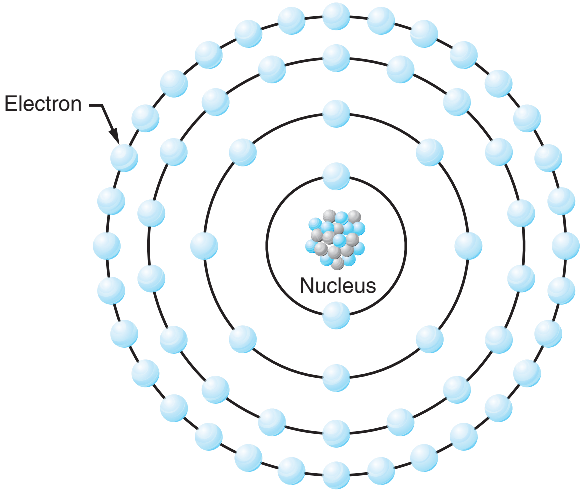


Figure 1–6
There is a maximum number of electrons that can be contained in one orbit or shell. (Source: Delmar/Cengage Learning)

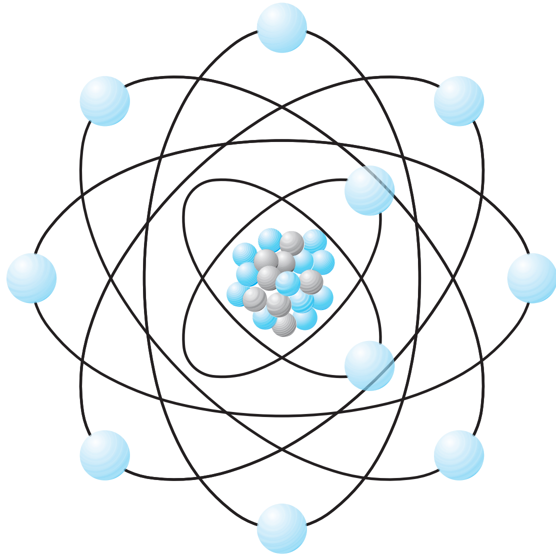


Figure 1–7
Electrons orbit the nucleus in a circular manner. (Source: Delmar/Cengage Learning)

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.

$$2 \times (4)^2$$

$$2 \times 16 = 32$$

Although atoms are often drawn flat, as illustrated in Figure 1–6, the electrons orbit around the nucleus in a circular fashion, as shown in Figure 1–7. The electrons travel at such a high rate of speed that they form a shell around the nucleus. It would be similar to a golf ball being surrounded by a tennis ball that is surrounded by a basketball. For this reason, electron orbits are often referred to as *shells*.

VALENCE ELECTRONS

The outermost 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**, as shown in Figure 1–8. The valence shell of an atom cannot hold more than eight electrons. It is the valence electrons that are of primary concern in the study of **electricity**, because it is these electrons that explain much of electrical theory. A **conductor**, for instance, is made from a material that contains one or two valence electrons. Atoms with one or two valence electrons are unstable and will give up these electrons easily. Conductors are materials that permit electrons to flow through them easily. 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 aluminum. An atom of copper is shown in Figure 1–9. 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 will conduct electricity more readily than any of the others. Aluminum, which contains three valence electrons, is a better conductor of electricity than platinum, which contains only one valence electron.

Electricity is composed of electrons. If it were possible to connect a spigot to a wall outlet and catch electricity in a glass, the glass would be full of electrons, as shown in Figure 1–10. Electric current is the flow of electrons, which means that

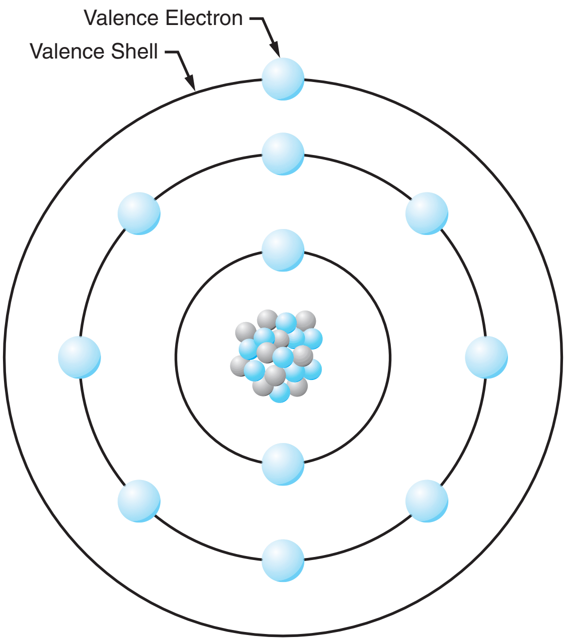


Figure 1–8
Valence electrons are located in the outermost orbit of an atom. (Source: Delmar/Cengage Learning)

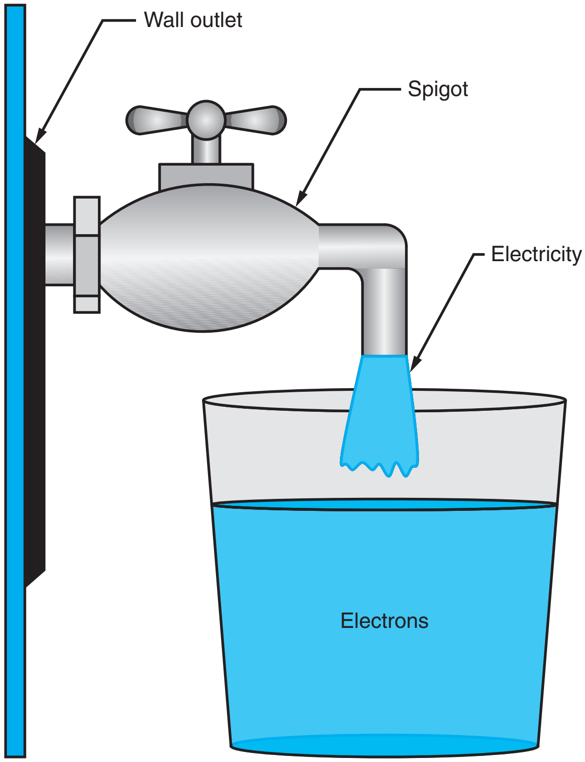


Figure 1–10
Electricity is composed of electrons. (Source: Delmar/Cengage Learning)

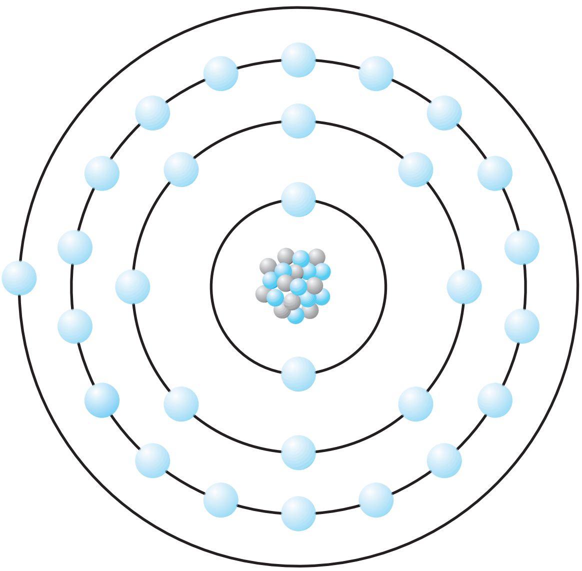


Figure 1–9
Copper atom. (Source: Delmar/Cengage Learning)

the electrons must be moving to produce current. It is the movement of the electrons that produces electrical energy. 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 electron from one atom knocks electrons of another atom out of orbit, as shown in Figure 1–11. The striking electron gives its energy to the electron being struck. The striking electron settles into orbit around the nucleus, and the electron that was struck moves off to strike another electron. This action can often be seen in the game of pool. The moving cue ball gives it energy to the ball being struck, as shown in Figure 1–12. The stationary ball then moves off with most of the energy of the cue ball, and the cue ball stops moving. Although most of the energy was transferred to the stationary ball, some energy was dissipated as heat caused by the impact of the cue ball striking the stationary ball.

Other theories deal with the fact that all electric power sources produce a positive and 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, as shown in Figure 1–13. 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 terminal, as shown in Figure 1–14. The greater the difference in the number of electrons between the negative and positive terminals, the greater the force of repulsion and attraction.

Most of the world's electric power is produced by rotating machines called alternators. Alternators work on the principle of cutting magnetic lines of flux with a conductor. One of the basic principles of electricity is that anytime a conductors cuts magnetic lines of flux, a voltage is inducted into the conductor. Another common source of electricity is batteries. Batteries produce electricity by chemical action. Other methods include solar cells, thermocouples, and piezoelectric devices. Solar cells produce electricity when they receive photons of light that cause electrons to move. Thermocouples produce electricity by heating the junction of two different types of metal, and the piezoelectric effect produces current flow from pressure.

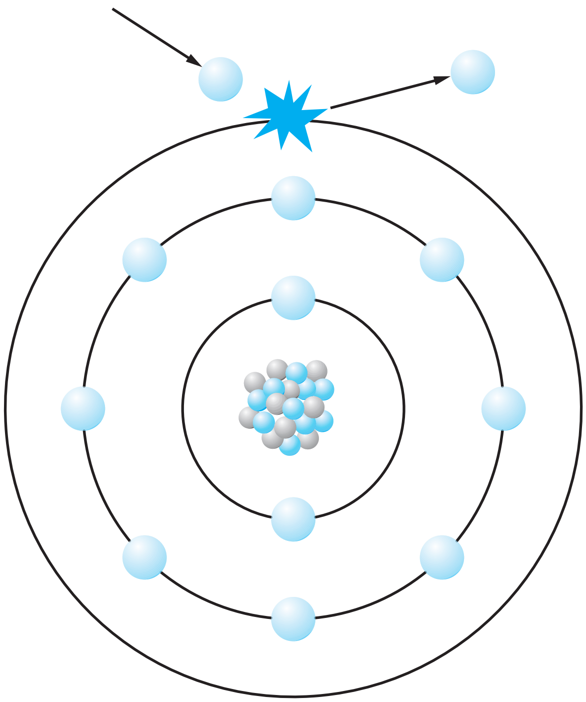


Figure 1–11
One electron knocks another electron out of orbit. (Source: Delmar/Cengage Learning)

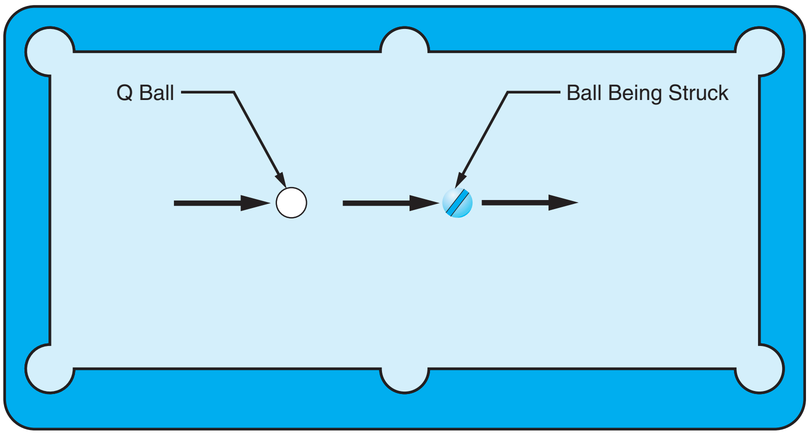


Figure 1–12
The cue ball gives its energy to the ball it strikes. (Source: Delmar/Cengage Learning)

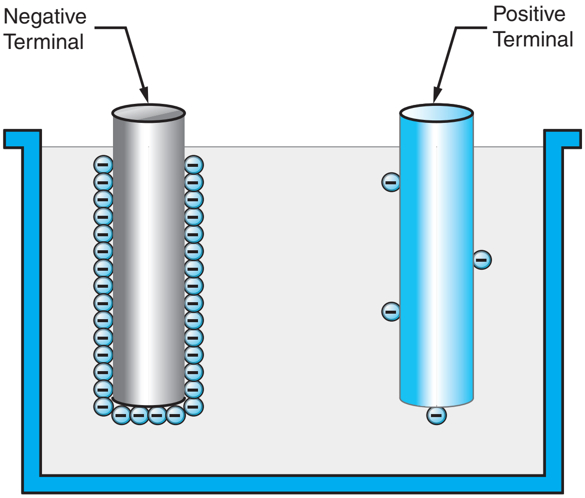


Figure 1–13
The negative terminal of a power source has an excess of electrons, and the positive terminal has a lack of electrons. (Source: Delmar/Cengage Learning)

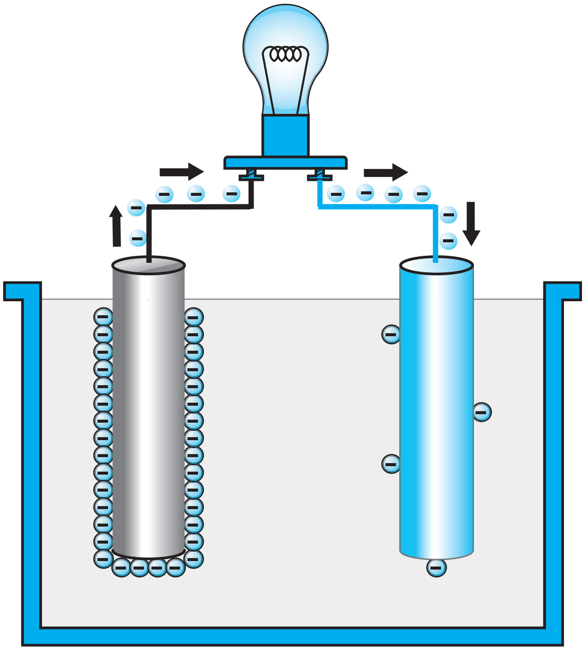


Figure 1–14
Electrons flow from the negative terminal, through the load, to the positive terminal of the power source. (Source: Delmar/Cengage Learning)

INSULATORS

Insulators are materials that do not permit electrons to flow through them easily. The atoms of an insulator generally contain seven or eight valence electrons. When an atom contains seven or eight valence electrons, they are tightly held by the atom and not easily given up. Insulator materials are generally made from compounds instead of a pure element. The molecules of the compounds are extremely stable and do not break their bond easily. Some examples of insulators are wood, ceramic, mica, rubber, and thermoplastic. Insulator materials are generally rated by voltage. The voltage rating indicates the amount of voltage they can withstand without breaking down. A very common electric cable used in residential wiring is the nonmetallic two-conductor cable with ground, shown in Figure 1–15. This cable is generally referred to as NM or Romex. The insulation around the conductors has a voltage rating of 600 volts.

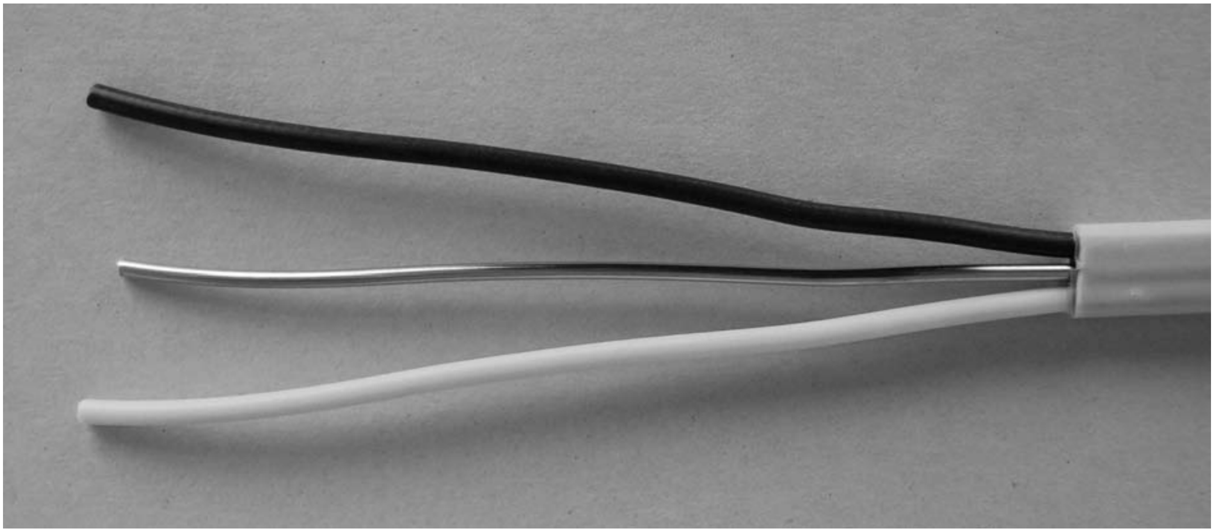


Figure 1–15
Two conductor cables with ground are commonly used in residential wiring. (Source: Delmar/Cengage Learning)

SUMMARY

- The three major parts of an atom are the electron, proton, and neutron.
- Electrons have a negative charge, protons have a positive charge, and neutrons have no charge.
- The nucleus of the atom contains protons and neutrons.
- An electron is about three times larger than a proton, but the proton weighs about 1840 times more than an electron.
- The law of charges states that opposite charges attract and like charges repel.
- Electrons exist in allowed orbits around the nucleus of the atom.
- Neutral atoms contain the same number of electrons and protons.
- Valence electrons are the electrons located in the outermost orbit of an atom.
- The best conductors of electricity generally contain one or two valence electrons.
- Insulators are materials that do not conduct electricity easily.
- Insulator materials are rated by voltage.

KEY TERMS

atom
conductor
electricity
electron
insulator
law of charges
neutron
nucleus
proton
valence electrons
valence shell

REVIEW QUESTIONS

1. What are the three subatomic parts of an atom, and what charge does each carry?
2. How many times larger is an electron than a proton?
3. The weight of a proton is how many times heavier than that of an electron?
4. State the law of charges.
5. What scientist presented the most accepted theory concerning the behavior of atoms?
6. Materials that make the best conductors generally contain how many valence electrons?
7. What are valence electrons?
8. What is the maximum number of electrons that can exist in the valence orbit?
9. How is most of the electric power in the world produced?
10. Insulator materials are generally rated by the amount of _____ they can withstand without breaking down.

UNIT 2

Electrical Quantities and Ohm's Law

OBJECTIVES

After studying this unit the student should be able to:

- Define a coulomb
- Define an ampere
- Define voltage
- Discuss resistance
- Define a watt
- Use Ohm's law to solve electrical problems

Electricity has a standard set of values. Before you can work with electricity, you must have a knowledge of 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 or foot. 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. A volt, ampere, or ohm is the same for everyone who uses them.

COULOMB

A **coulomb** is a quantity measurement of electrons. One coulomb contains 6.25×10^{18} electrons. The number shown in Figure 2–1 is the number of

6,250,000,000,000,000,000

Figure 2–1
The number of electrons in a coulomb. (Source: Delmar/Cengage Learning)

electrons in one coulomb. Because the coulomb is a unit of measurement, it is similar to a quart, gallon, or liter. It takes a certain amount of liquid to equal a quart, just as it takes a certain amount of electrons to equal a coulomb.

AMPERE

The **ampere**, or amp, is defined as one coulomb per second. Notice that the definition of an amp involves a quantity measurement (the coulomb) combined with a time measurement (the second). One amp of current flows through a conductor when one coulomb flows past a point on one second, Figure 2–2. Amperage is a measurement of the actual 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 2–3. If one coulomb were to flow past a point in a half second, there would be 2 amperes of current flow. If one coulomb were to flow past a point in two seconds there would be a half amp of flow. Current is normally measured in amperes, milliamperes, and microamperes. A milliamp is one-thousandth of an amp (0.001). A microamp is one-millionth of an amp (0.000,001).

VOLT

Voltage is actually defined as **electromotive force**, or EMF. It is the force that pushes the electrons through a wire and is often referred to as **electrical pressure**. One should remember that voltage cannot flow. To say that voltage flows 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. The voltage pushes current through a wire, but voltage cannot flow through a wire. In a water system, the voltage could be compared to the pressure of the system, Figure 2–4.

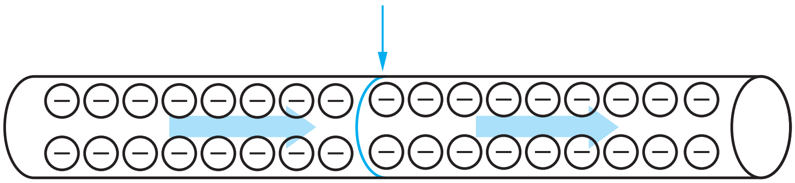


Figure 2–2
One coulomb flowing past a point in one second. (Source: Delmar/Cengage Learning)

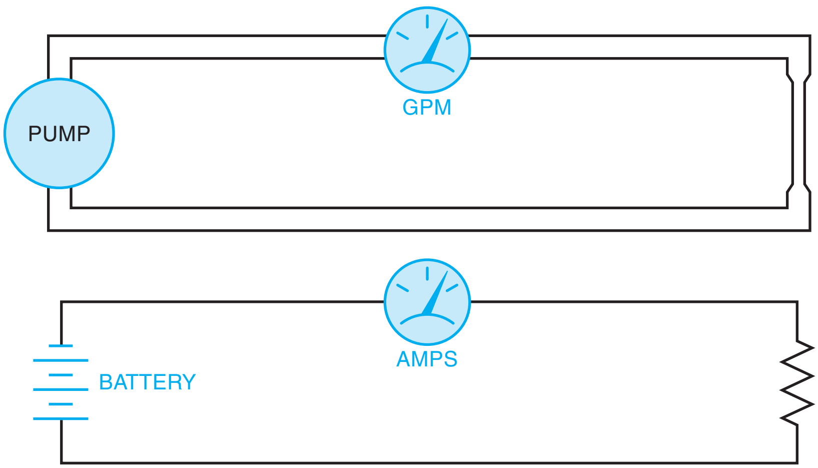


Figure 2–3
Water flow is similar to current flow. (Source: Delmar/Cengage Learning)

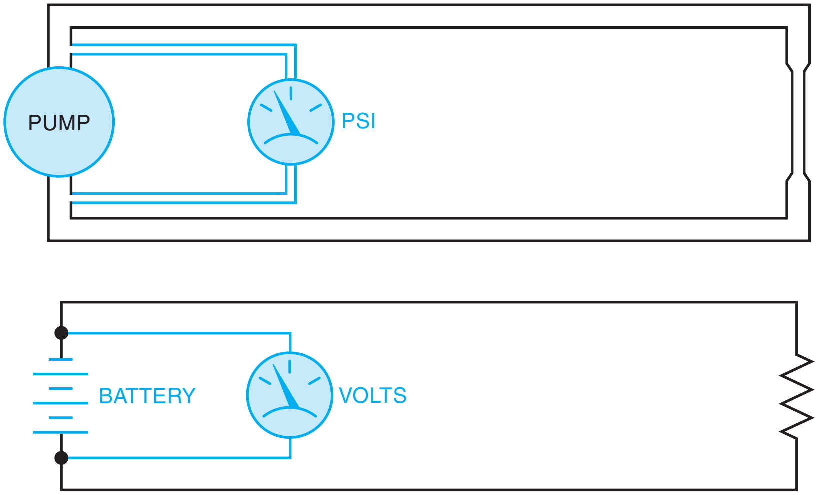


Figure 2–4
The pressure in a water system is comparable to the voltage in an electric circuit. (Source: Delmar/Cengage Learning)

OHM

The **ohm** is the measure of the **resistance** to the flow of current. The voltage of the circuit must overcome the resistance before it can cause electrons to flow through it. Without resistance, every electrical circuit would be a short circuit. All electrical loads, such as heating elements, lamps, motors, transformers, and so forth, are measured in ohms. In a water system, a reducer would be used to control the flow of water. In an electrical circuit, a resistor can be used to control the flow of electrons. Figure 2–5 illustrates this concept.

There are electrical quantities other than resistance that are also measured in ohms. Inductive reactance and capacitive reactance are current-limiting forces that exist in alternating current circuits and will be discussed later in the text. Another term used to describe a current-limiting force is impedance. **Impedance** is a combination of all current limiting forces in a circuit and can include resistance, inductive reactance, and capacitive reactance. Because resistance is only one of the current-limiting forces found in alternating current circuits, impedance is the quantity generally used to describe the current-limiting force in an alternating current circuit. Impedance will be discussed in more detail later in the text.

WATT

Wattage is a measure of the amount of power that is being used in the circuit. It is proportional to the amount of voltage and the amount of current flow.

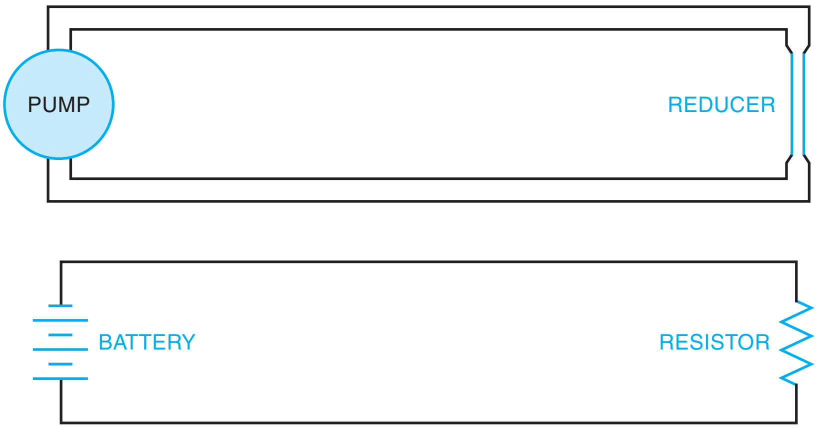


Figure 2–5
A reducer reduces the flow of water through a water system just as a resistor reduces the flow of electrons in an electric circuit.
(Source: Delmar/Cengage Learning)

To understand watts, return to the example of the water system. Assume that a water pump has a pressure of 120 psi (pounds per square inch) and causes a flow rate of one gallon per second. Now assume that this water is used to drive a waterwheel as shown in Figure 2–6. Notice that the waterwheel has a radius of 1 ft from the center shaft to the rim of the wheel. Since water weighs 8.34 pounds per gallon, and is being forced against the wheel at a pressure of 120 psi, the wheel could develop a torque of 1000.8 foot pounds ($120 \times 8.34 \times 1 = 1000.8$). If the pressure is increased to 240 psi, but the water flow remains constant, the force against the wheel will double ($240 \times 8.34 \times 1 = 2001.6$). If the pressure remains at 120 psi, but the water flow is increased to two gallons per second, the force against the wheel will again double ($120 \times 16.68 \times 1 = 2001.6$). Notice that the amount of power developed by the waterwheel is determined by both the amount of pressure driving the water and the amount of flow.

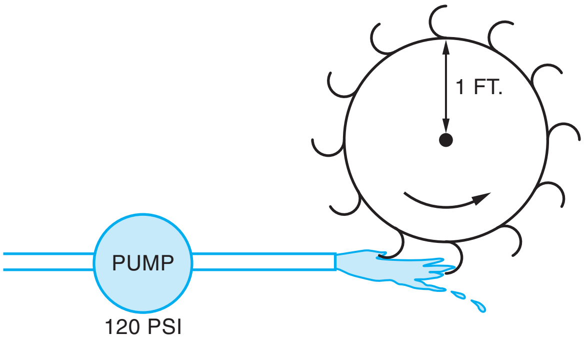


Figure 2–6
Pump used to drive a waterwheel. (Source: Delmar/Cengage Learning)

The power of an electrical circuit is very similar. Figure 2–7 shows a resistor connected to a circuit with a voltage of 120 volts and a current flow of 1 amp. The resistor shown represents an electric heating element. When 120 volts forces a current of 1 amp through it, the heating element will produce 120 watts of heat ($120 \times 1 = 120$ watts). If the voltage is increased to 240 volts, but the current remains constant, the element will produce 240 watts of heat ($240 \times 1 = 240$ watts). If the voltage remains at 120 volts, but the current is increased to 2 amps, the heating element will again produce 240 watts ($120 \times 2 = 240$). Notice that the amount of power used by the heating element is determined by the amount of current flow and the voltage driving it.

A good rule to remember concerning watts, or **true power,** is that before watts can exist in an electric circuit, electrical energy must be converted or changed into some other form. When current flows through a resistor, the resistor becomes hot and dissipates heat. Heat is a form of energy. The wattmeter connected in the circuit shown in Figure 2–7 measures the amount of electrical energy that is being converted into heat energy. If the resistor shown in Figure 2–7 were replaced with an electric motor the wattmeter would measure the amount of electrical energy that was converted into mechanical energy.

OHM'S LAW

Ohm's law is named for the German scientist George S. Ohm. Ohm discovered that all electrical quantities are proportional to each other and can therefore be expressed as mathematical formulas. In its simplest form, Ohm's law states that *it takes 1 volt to push 1 amp through 1 ohm.*

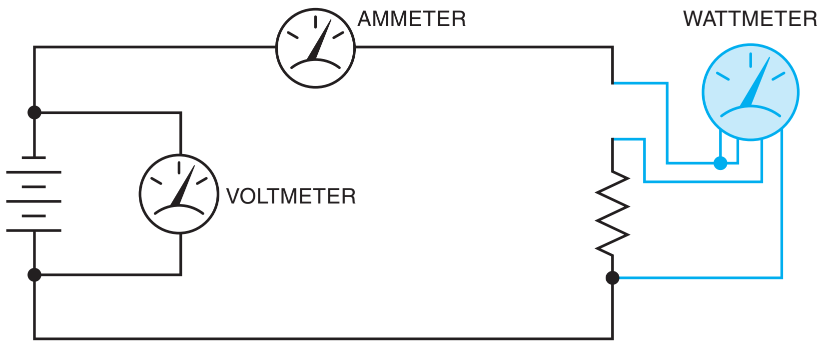


Figure 2–7
The amount of voltage and current determine the power.
(Source: Delmar/Cengage Learning)

Figure 2–8 shows three basic Ohm's law formulas. In these formulas, E stands for electromotive force and is used to represent the voltage. The I stands for the intensity of the current and is used to represent the amount of current flow or amps. The letter R stands for resistance and is used to represent the ohms.

The first formula states that the voltage can be found if the current and resistance are known. Voltage is equal to amps multiplied by ohms. For example, assume a circuit has a resistance of 50 ohms and a current flow through it of 2 amps. The voltage connected to this circuit is 100 volts (2 amps × 50 ohms = 100 volts). The second formula indicates that if the voltage and resistance of the circuit are known, the amount of current flow can be found. Assume a 120-volt circuit is connected to a resistance of 30 ohms. The amount of current that will flow in the circuit is 4 amps (120 volts/30 ohms = 4 amps). The third formula states that if the voltage and current flow in a circuit are known, the resistance can be found. Assume a circuit has a voltage of 240 volts and a current flow of 10 amps. The resistance in the circuit is 24 ohms (240 volts/10 amps = 24 ohms).

Figure 2–9 shows a simple chart that can be a great help when trying to remember the Ohm's law formula. To use the chart, cover the quantity 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. Therefore, $E = I \times R$. If the current is to be found, cover the I on the chart. The chart now shows E/R. Therefore, $I = E/R$. If the resistance of a circuit is to be found, cover the R on the chart. The chart now shows E/I. Therefore, $R = E/I$.

A larger chart that shows the formulas needed to find watts as well as the voltage, amperage, and resistance is shown in Figure 2–10. Because watt is the unit of electric power, the letter P is used to represent watts. The chart is divided into four quadrants. Each quadrant contains three formulas that can be used to find the electrical quantity represented in that quadrant.

EXAMPLE 1: An electric heating element is connected to 120 volts and has a resistance of 18 ohms. What is the power consumption of this element?

SOLUTION: The electrical quantity to be determined is power, or watts. The known electrical values are voltage and resistance. Using the formula chart in Figure 2–10, choose the formula for finding power that includes the two known electrical quantities. The formulas for determining power are located in the first quadrant of the chart. The formula that contains the known values of voltage and resistance is $P = E^2/R$, as shown in Figure 2–11.

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

$$P = \frac{120 \times 120}{18}$$

$$P = 800 \text{ watts}$$

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

Figure 2–8
Three Ohm's law formulas. (Source: Delmar/Cengage Learning)

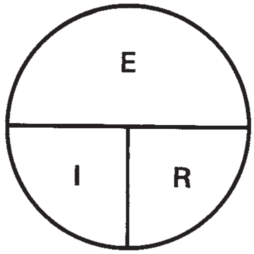


Figure 2–9
Ohm's law formula chart. (Source: Delmar/Cengage Learning)

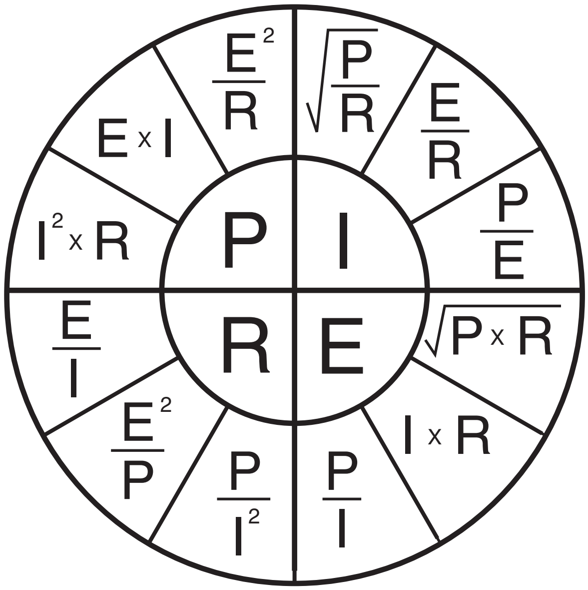


Figure 2–10
Ohm's law chart. (Source: Delmar/Cengage Learning)

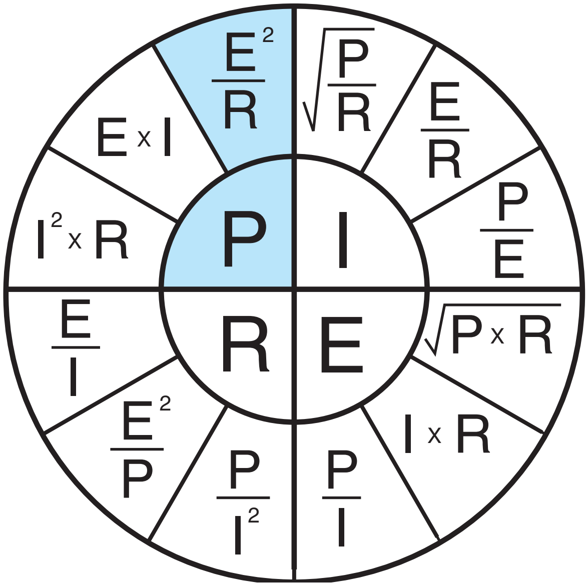


Figure 2–11
Power can be determined when the voltage and resistance are known. (Source: Delmar/Cengage Learning)

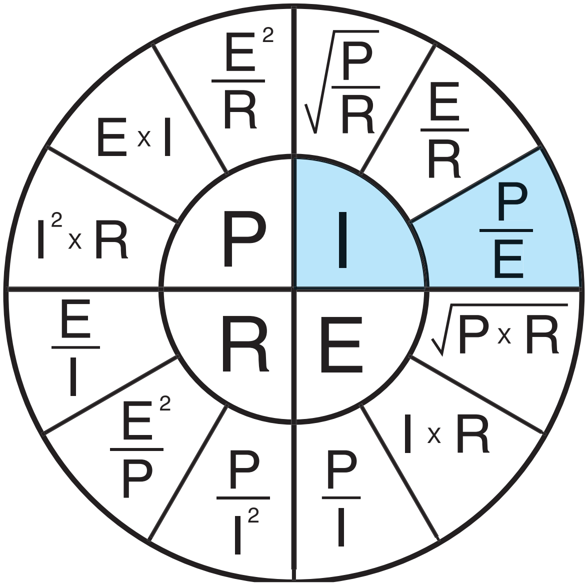


Figure 2–12
Current can be determined when the power and voltage are known. (Source: Delmar/Cengage Learning)

EXAMPLE 2: A 240-volt electric furnace has a power rating of 15,000 watts, or 15 kW. How much current will this furnace draw when in operation?

SOLUTION: The quantity you are looking for is current or amps, represented by the letter *I*.

Formulas for determining current are located in the second quadrant of the formula chart shown in Figure 2–10. The two known quantities are power (watts) and voltage. The correct formula is $I = P/E$, as shown in Figure 2–12.

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

$$I = \frac{15{,}000}{240}$$

$$I = 62.5 \text{ amperes}$$

METRIC PREFIXES

Metric prefixes are used in the electrical field just as they are in most other scientific fields. In the English system of measure, different divisions are used for different measurements. A yard, for example, can be divided into 3 feet. A foot is generally divided into 12 inches, and an inch is often divided into sixteenths. In the metric system, ten or a multiple of ten is always the dividing factor. A kilometer can be divided into 10 hectometers. A hectometer can be divided into 10 dekameters, and a dekameter can be divided into 10 meters. A chart listing standard metric prefixes is shown in Figure 2–13.

kilo	1000
hecto	100
deka	10
Base unit	1
deci	$\frac{1}{10}$ or 0.1
centi	$\frac{1}{100}$ or 0.01
milli	$\frac{1}{1000}$ or 0.001

Figure 2–13
Standard metric prefixes. (Source: Delmar/Cengage Learning)

In the electrical field, a different type of metric notation called *engineering notation* is used instead of the standard metric prefixes. Engineering notation is in steps of one thousand instead of ten. A chart listing common engineering notation prefixes and their symbols is shown in Figure 2–14. Starting with the base unit or one, the first engineering unit greater than one is kilo, or one thousand. The next engineering unit greater than kilo is Mega, or one million. A million is one thousand times larger than a thousand. The first engineering unit less than the base unit is milli, or one one thousandth. The next engineering unit less than milli is micro, or one one-millionth. A millionth is one thousand times smaller than a thousandth.

These prefixes are used to simplify standard electrical measurements. Five billion watts can be written as 5,000,000,000 W or as 5 GW. Twenty-five microamperes can be written as 0.000,025 A or as 25 μA.

ENGINEERING UNIT	SYMBOL	MULTIPLY BY:	
Tera	T	1,000,000,000,000	$X10^{12}$
Giga	G	1,000,000,000	$X10^{9}$
Meg	M	1,000,000	$X10^{6}$
kilo	k	1,000	$X10^{3}$
Base unit		1	
Milli	m	.001	$X10^{-3}$
Micro	μ	.000,001	$X10^{-6}$
Nano	n	.000,000,001	$X10^{-9}$
Pico	p	.000,000,000,001	$X10^{-12}$

Figure 2–14
Standard prefixes used in engineering notation. (Source: Delmar/Cengage Learning)

SUMMARY

- A coulomb is a quantity measurement of electrons that is equal to 6.25×10^{18} electrons.
- An ampere is the amount of current that flows through a circuit.
- An ampere is defined as one coulomb per second.
- Voltage is the force that pushes the electrons through a circuit.
- Voltage is defined as electromotive force (EMF).
- Voltage is sometimes referred to as electrical pressure.
- Resistance to the flow of electricity is measured in ohms.
- Wattage is a measurement of electric power.
- Before an electric circuit can have true power, or watts, electrical energy must be converted into some other form of energy.
- Ohm's law can be used to mathematically find electrical values when at least two of these values are known.

KEY TERMS

ampere
coulomb
electrical pressure
electromotive force
impedance
ohm
Ohm's law
resistance
true power
voltage
wattage

REVIEW QUESTIONS

1. What is a coulomb?
2. What is the definition of an amp?
3. Define the term *voltage*.
4. Define the term *ohm*.
5. Define the term *watt*.
6. An electric heating element has a resistance of 16 ohms and is connected to a voltage of 120 volts. How much current (amps) will flow in the circuit?
7. How many watts of heat are being produced by the heating element in question 6?
8. A 240-volt circuit has a current flow of 20 amps. How much resistance (ohms) is connected in the circuit?
9. An electric motor has an apparent resistance of 15 ohms. If a current of 8 amps is flowing through the motor, what is the connected voltage?
10. A 240-volt air conditioning compressor has an apparent resistance of 8 ohms. How much current (amps) will flow in the circuit?
11. How much power (watts) is being used by the compressor in question 10?

12. A 5,000-watt electric heating unit is connected to a 240-volt line. What is the current flow (amps) in the circuit?
13. If the voltage in question 12 is reduced to 120 volts, how much current (amps) 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 volts or on 120 volts? Explain your answer.

UNIT 3

Measuring Instruments

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation and connection of a voltmeter
- Measure voltage using a multirange voltmeter
- Discuss the operation of an ammeter
- Describe different types of ammeters
- Measure current with an ammeter

Anyone who wants to work in the air conditioning and refrigeration field must become proficient with the common instruments used to measure electrical quantities. These instruments are the **voltmeter, ammeter**, and **ohmmeter**. In the air-conditioning and refrigeration field, the technician works almost exclusively with alternating current. For this reason, the meters covered in this unit are intended to be used in an alternating current system.

VOLTMETER

The voltmeter is designed to be connected directly across the source of power. Figure 3–1 shows a voltmeter being used to test the voltage of a panel box. Notice that the leads of the meter are connected directly across the source of voltage. The reason a voltmeter can be connected directly across the power

Figure 3–1
Voltmeter being used to test the voltage of a panel.
(Source: Delmar/Cengage Learning)

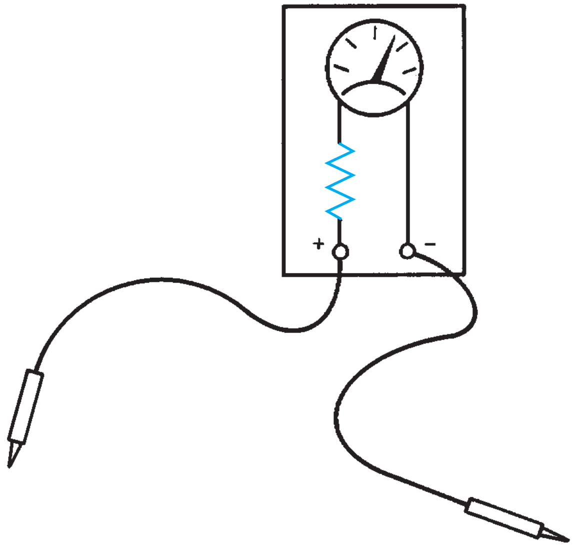


Figure 3–2
A voltmeter has high resistance connected in series with the meter movement. (Source: Delmar/Cengage Learning)

line is because it has a very high resistance connected in series with the meter movement, Figure 3–2. A common resistance for a voltmeter is about 20,000 ohms per volt for DC and 5,000 ohms per volt AC. Assume the voltmeter shown in Figure 3–2 is an AC meter and has a full-scale range of 300 volts. The resistor connected in series with the meter would, therefore, have a resistance of 1,500,000 ohms (300 volts × 5,000 ohms per volt = 1,500,000 ohms).

Most voltmeters are **multiranged**, 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. The reason for making a meter with this number of scales is to make the meter 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. If it becomes necessary to check a control voltage of 24 volts, however, it would be very difficult to do on the 600-volt range. If the meter is set on the 30-volt range, however, it becomes a simple matter to test for a voltage of 24 volts. The meter shown in Figure 3–3 has multirange selection for voltage.

When the selector switch of this meter is turned, steps of resistance are inserted in the circuit to increase the range, or removed from the circuit to decrease the range, Figure 3–4. Notice that when the higher voltage settings are selected, more resistance is inserted in the circuit.

Another type of voltmeter that is gaining popularity is the **digital meter**. A digital meter displays the voltage in digits instead of using a meter movement, Figure 3–5. Digital meters have several advantages over voltmeters that use a meter movement (commonly called **analog meters**). The greatest advantage is that the **input impedance**, or resistance, is higher. Analog meters commonly have a resistance of about 5,000 ohms per volt. This means that on a 3-volt full-scale range, the meter movement has a resistance of 15,000 ohms connected in series with it (3 × 5,000 = 15,000). On the 600-volt full-scale range, the meter movement has a resistance of 3,000,000 ohms connected in series with it (600 × 5,000 = 3,000,000). Digital meters commonly have an input impedance of 10,000,000 ohms (10 megohms), regardless of the range they are set on. The advantage of this high input impedance is that it does not interfere with a low-power circuit. The advantage of this may not be too clear at first, because most technicians are used to working with circuits that have more than enough power to operate the meter. However, many of the newer controls are electronic; these circuits may be greatly altered if tested with a low impedance meter.

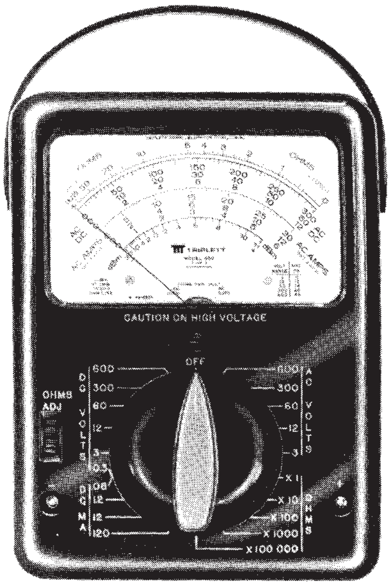


Figure 3–3
Multimeter with an analog scale. (Courtesy of Triplett Corp.).

For example, assume an electronic control is operated on 5 volts, and has a total current capacity of 100 microamps (.000100 amps). Now assume that a 5,000-ohm-per-volt meter is set on the 12-volt scale and is to be used to check the control circuit. The voltmeter has a resistance of 5,000 × 12 = 60,000 ohms. If this meter is used to test the circuit, the meter will have a current draw of 83.3 microamps (5 volts/60,000 ohms = .0000833 amps). Because the control circuit only has a total current capacity of 100 microamps, the meter is using most of the current to operate. The circuit has been changed to such a degree that it can no longer operate.

If the digital meter is used to test this same circuit, it will have a current draw of 0.5 microamp (5 volts/10,000,000 = .00000005 amp). The circuit will be able to furnish the 0.5 microamp needed to operate the meter without a problem or altering the circuit.

Another advantage of the digital meter is that it is generally easier for an inexperienced person to learn to read. Analog meters can be used for about

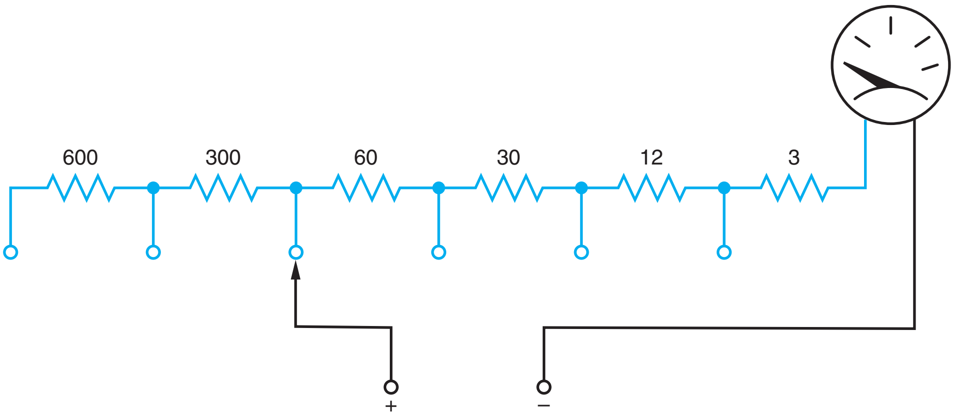


Figure 3–4
A multirange voltmeter.
(Source: Delmar/Cengage Learning)

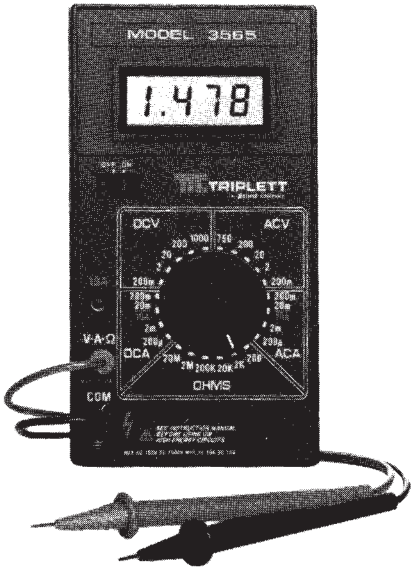


Figure 3–5
Digital multimeter. (Courtesy of Triplett Corp.).

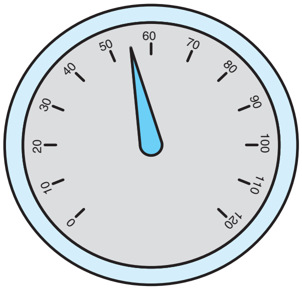


Figure 3–6
Speedometer. (Source: Delmar/Cengage Learning)

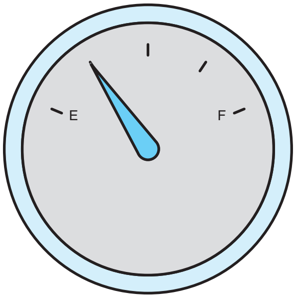


Figure 3–7
Fuel gauge. (Source: Delmar/Cengage Learning)

99% of the measurements that must be taken, but it generally takes some time and practice to read them properly.

Learning to read the scale of a multimeter takes time and practice. Most people use meters everyday without thinking about it. A very common type of meter used daily by most people is shown in Figure 3–6. The meter illustrated is a speedometer similar to those seen in an automobile. 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 mph. If the pointer is positioned as shown in Figure 3–6, most people would know instantly that the speed of the automobile is 55 mph.

Figure 3–7 illustrates another common meter used by most people. This meter is used to measure the amount of fuel in the tank of an 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 now indicating that there are a total of 5 gallons of fuel remaining in the tank.

Learning to read the scale of a multimeter is similar to learning to read a speedometer or fuel

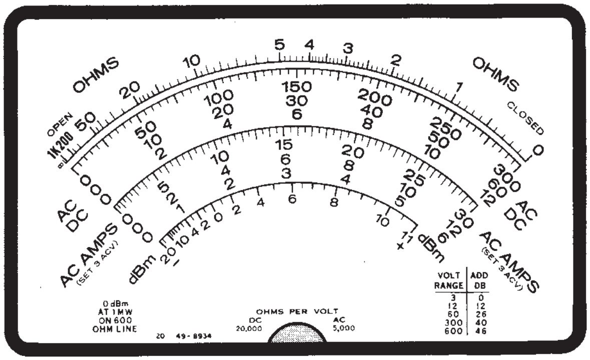


Figure 3–8
Multimeter face. (Source: Delmar/Cengage Learning)

gauge. The meter scale shown in Figure 3–8 has several scales used to measure different values and quantities. The very top of the scale is used to measure resistance or ohms. Notice that the scale begins at the left-hand side with infinity, and zero can be found at the far right-hand side. Ohmmeters will be covered later in this unit. The second scale is labeled AC–DC and is used to measure voltage. Notice this scale has three different full-scale values. The top scale is 0 to 300, the second scale is 0 to 60, and the third scale is 0 to 12. The scale used is determined by the setting of the range control switch. The third set of scales is labeled AC AMPS. This scale is used with a clamp-on ammeter attachment that can be used with some meters. The last scale is labeled dbm and is seldom if ever used by the technician in the field.

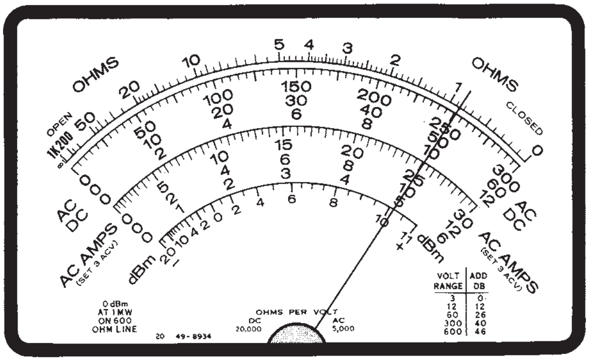


Figure 3–9
Reading an analog multimeter. (Source: Delmar/Cengage Learning)

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 these numbers are in multiples of 10, it is an easy matter 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 is set to permit the meter to indicate a voltage of 3 volts full-scale, the 300-volt scale would be used, and the reading divided by 100. The reading can be divided by 100 by moving the decimal point 2 places to the left. In Figure 3–9, the meter is indicating a voltage of 2.5 volts if the selector switch is set for 3 volts full-scale. The pointer is indicating a value of 250. Moving the decimal point 2 places to the left will give a reading of 2.5 volts. If the selector switch is set for a full-scale value of 30 volts, the meter shown in Figure 3–9 would be indicating a value of 25 volts. This 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 meter shown in Figure 3–10 is indicating a voltage of 440 volts. Since 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. This can be done by moving the decimal point one place to the right. The pointer in Figure 3–10 is indicating a value of 44. If this value is multiplied by 10, the correct voltage reading becomes 440 volts.

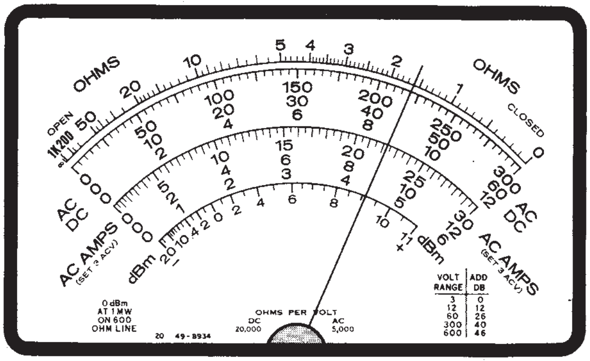


Figure 3–10
Reading an analog multimeter. (Source: Delmar/Cengage Learning)

There are three distinct steps that should be followed when reading a meter. Following the steps is especially important for someone who has not had a great deal of experience reading a multimeter. These steps are:

1. **Determine what the meter indicates.** Is the meter set to read a value of DC voltage, DC current, AC voltage, AC current, ohms? It is impossible to read a meter if you do not know what the meter is measuring.
2. **Determine the full-scale value of the meter.** The advantage of a multimeter is that it has the ability to 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 readings when the meter is set to indicate a value of 600 volts full-scale and when it is set for 30 volts full-scale.

If you are not sure of the voltage value being tested, always set the meter on its highest range and then reduce the range until the indicator moves up scale to a value that can be easily read. A meter can never be damaged by placing it on a high range setting and then reducing it, but it can be damaged by placing it on a low range setting and then connecting it to a high voltage.

Another consideration is the position of the indicator. Analog meters are more accurate at the upper end of the scale than at the lower end. If possible, adjust the range setting so that the indicator is more than halfway up the scale.

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 hatch marks on the meter face for the range the selector switch is set for. If the meter in Figure 3–8 is set for a value of 300 volts full-scale, each hatch mark has a value of 5 volts. If the full-scale value of the meter is 60 volts, however, each hatch mark has a value of 1 volt.

When reading a meter, always look straight at the indicator. Viewing the indicator from the side causes a parallax view and the reading will not be accurate. It is the same effect as produced when trying to determine the speed of an automobile by looking at the speedometer from the passenger seat. The only way to accurately determine the speed is to view the speedometer straight on, not from the side. Some meters have a mirror section on the meter face. This permits the person using the meter to line up the indication with the reflection behind it to ensure an accurate reading.

AMMETER

There are several different types of ammeters used to measure electric current. Clamp-on types are generally used in the field for troubleshooting, and inline ammeters are panel mounted. The inline ammeter, unlike the voltmeter, is a very-low-impedance device. Inline ammeters must be connected in series with the load to permit the load to limit the current flow, Figure 3-11.

An ammeter has a typical impedance of less than .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 an impedance of .1 ohm is connected across a 240-volt AC line. The current flow in this circuit would be 2,400 amps (240/.1 = 2,400).The blinding flash of light would be followed by the destruction of the ammeter. Ammeters that are connected directly into the circuit as shown in Figure 3–11 are referred to as **inline** ammeters. Figure 3–12 shows an inline ammeter.

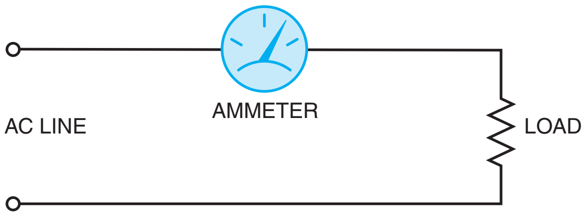


Figure 3–11
An ammeter must be connected in series with the load. (Source: Delmar/Cengage Learning)

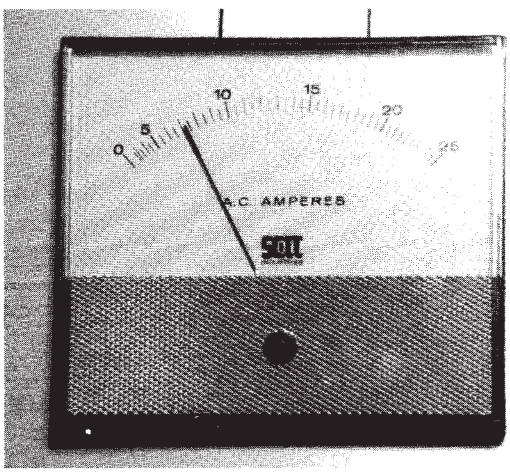


Figure 3–12
AC inline ammeter. (Source: Delmar/Cengage Learning)

Notice that the meter in Figure 3–12 has several ranges. AC ammeters use a **current transformer** to provide multiscale capability. The primary of the transformer is connected in series with the load, and the ammeter is connected to the secondary of the transformer. Figure 3–13 illustrates this type of connection. 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.

When a large amount of AC current must be measured, a current transformer is connected in to the power line. The ammeter is then connected to the secondary of the transformer. The AC ammeters are designed to indicate a current of 5 amps, and the current transformer determines the value of line current that must flow to produce a current of 5 amps on the secondary of the transformer. The incoming line may be looped around the opening in the transformer several times to produce the proper turns ratio between the primary and the secondary windings. Figure 3–14 shows a transformer of this type. This type of connection is often used for panel meters mounted on large commercial units.

The type of ammeter used in the field by most air conditioning service technicians is the **clamp-on** type of ammeter similar to the one shown in Figure 3–15. To use this meter, the jaw of the meter is clamped around one of the conductors supplying power to the load. Figure 3–16 shows this connection. Notice that the meter is clamped around only one of the power 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.

This type of meter also uses a current transformer to operate the meter. 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 current induces a voltage into the current transformer. The strength of the magnetic field and its frequency determine the amount of voltage induced in the current transformer. Since 60 Hz 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 of ammeter can have different range settings by changing the **turns ratio** of the secondary of the transformer just as the inline ammeter does in Figure 3–13. The primary of the current transformer is the conductor the ammeter is connected around. If the ammeter is connected around one wire as shown in Figure 3–16, the

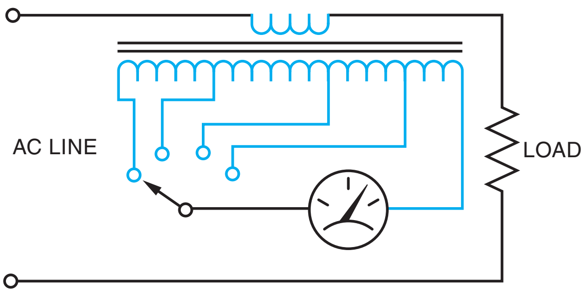


Figure 3–13
A current transformer provides different scales.
(Source: Delmar/Cengage Learning)

Figure 3–14
Current transformer used to meter large AC currents.
(Source: Delmar/Cengage Learning)

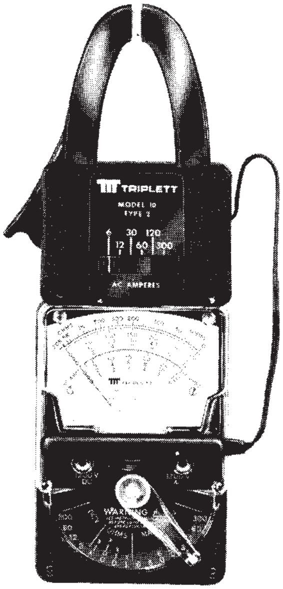


Figure 3–15
Multirange and clamp-on ammeter combination.
(Courtesy of Triplett Corp.).

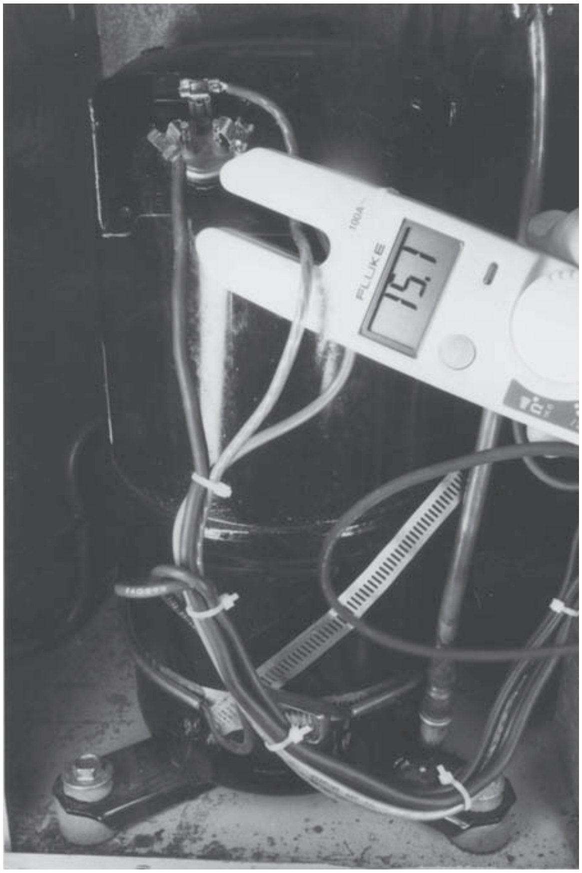


Figure 3–16
Clamp-on ammeter used to measure the running current of a compressor. (Source: Delmar/Cengage Learning)

primary has one turn of wire as compared to the number of turns of wire in the secondary. If two turns of wire are wrapped around the jaw of the ammeter, the primary winding now contains two turns instead of one, and the turns ratio of the transformer is changed, Figure 3–17. 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 two to get the correct reading. For example, assume two turns of wire have been wrapped around the ammeter jaw, and the meter indicates a current of 3 amps. The actual current in this circuit is 1.5 amps ($3 \div 2 = 1.5$). The ability to change the turns ratio of a clamp-on ammeter can be very useful for measuring low currents such as those found in a control circuit. Changing the turns ratio of the transformer is not limited to wrapping two turns of wire around the jaw of the ammeter. Any number of turns of wire can be wrapped around the jaw of the ammeter and the reading will be divided by that number. If three turns of wire are wrapped around the jaw of the meter, the reading will be divided by three.

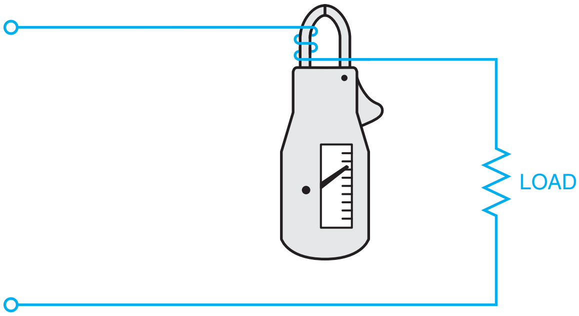


Figure 3–17
Two turns of wire change the turns ratio of the transformer. (Source: Delmar/Cengage Learning)

Figure 3–18
Scale divider used with clamp-on ammeter. The ammeter indicates a value of 3.25 amperes. If the scale divider has a ratio of 10:1, the actual current is 0.325 amps. (Source: Delmar/Cengage Learning)

Figure 3–19
Digital clamp-on ammeter. (Courtesy of Simpson Electric Co.).

A very handy device can be made by wrapping 10 turns of wire around some core of nonmagnetic material, such as a thin piece of plastic pipe. Because the device is intended to be used for low current readings, the wire size does not have to be large. A #20 or #18 American Wire Gauge (AWG) wire is large enough. Plastic tape is used to secure the turns of wire to the core material, and two alligator clips are connected to the ends of the wire. This device is shown in Figure 3–18. To use this device, break connection in the circuit to be tested, and insert the 10 turns of wire using the alligator clips. The jaw of the ammeter is placed around the plastic core. The primary of the transformer now contains 10 turns of wire, and the scale factor can now be divided by a factor of 10. The correct ammeter reading is found by moving the decimal point one place to the left. If the ammeter has a low scale of 6 amps full-scale, it can now be used to measure .6 amps full-scale. This can be a real advantage when it is necessary to measure control currents that may not be greater than .2 amps under normal operating conditions.

Some clamp-on ammeters use a digital read-out instead of a meter movement. A digital type meter is shown in Figure 3–19. The digital ammeters are generally better for measuring low current values, but the 10 turn scale divider can be used with these ammeters also. Just remember to divide the reading shown by a factor of 10. The clamp-on ammeters discussed in this unit are intended to be used for measuring AC currents only, and will not operate if connected to a DC line. There are clamp-on type ammeters, however, that can be used to measure DC current.

Many clamp-on ammeters are designed to measure AC volts and ohms as well as AC current. This makes the meter a more versatile instrument. When voltage or resistance is to be measured, a set of leads is attached to the meter.

OHMMETER

The ohmmeter is used to measure resistance. The common **volt-ohm-milliammeter (VOM)** contains an ohmmeter. The ohmmeter must provide its own power supply to measure resistance. This is done with batteries located inside the instrument. When resistance is to be measured, the meter must

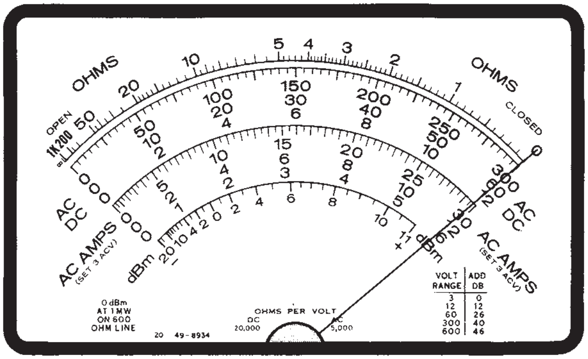


Figure 3–20
The ohmmeter must be set at zero. (Source: Delmar/Cengage Learning)

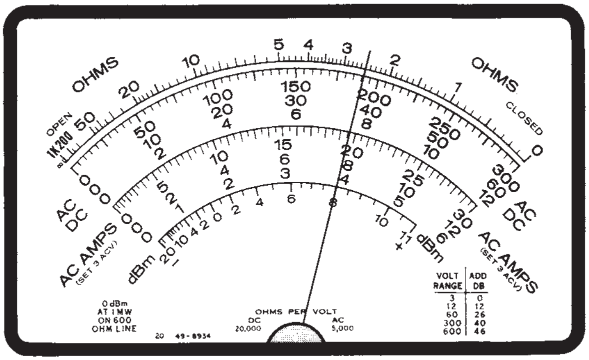


Figure 3–21
Read the ohmmeter from right to left. (Source: Delmar/Cengage Learning)

first be zeroed. Zeroing is done with the ohms adjust control located on the front of the meter. To zero the meter, connect the leads together and adjust the ohms adjust knob until the meter indicates 0 at the far right end of the scale, Figure 3–20. When the leads are separated, the meter will again indicate infinity resistance at the far left side of the meter scale. When the leads are connected across a resistance, the meter will again indicate up scale. Figure 3–21 shows a meter indicating a resistance of 25 ohms, assuming the range setting is R × 10.

Ohmmeters can have different range settings such as R × 1, R × 100, R × 1,000, or R × 10,000. 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 × 1,000, however, the reading must be multiplied by 1,000. The ohmmeter reading shown in Figure 3–21 would be indicating a resistance of 2,500 ohms if the range had been set for R × 1,000. 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.

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 1,000, and *mega* means 1,000,000.) If the meter is showing a resistance of (.200 K), it means .2 × 1,000, or 200 ohms. If the meter indicates (1.65 M), it means 1.65 × 1,000,000, or 1,650,000 ohms.

The ohmmeter must never be connected to a circuit with power on. Because the ohmmeter uses its own internal power supply, it has a very low operating voltage. If a meter is connected to power when it is set in the ohms position, it will probably damage or destroy the meter.

SUMMARY

- A voltmeter is a high resistance device and is designed to be connected directly to the power line.
- The resistance of an analog voltmeter, a voltmeter with a scale and moving pointer, changes with the setting of the meter.
- An analog voltmeter typically has a resistance of 5,000 ohms per volt on the AC setting and 20,000 ohms per volt on the DC setting.
- Digital voltmeters generally have a resistance of 10 million ohms on all range settings.

- The three basic steps to reading an analog meter are:
  A. Determine what the meter indicates.
  B. Determine the full-scale value of the meter.
  C. Read the meter.
- Ammeters are low resistance devices and must be connected in series with the load.
- AC ammeters generally use a current transformer to change scale values.
- Current transformers designed to measure large amounts of current have a standard output current of 5 amps.
- Most clamp-on ammeters can measure values of AC current only because they depend on magnetic induction to operate.
- The range setting of clamp-on ammeters can be changed by wrapping more turns of wire around the meter jaw.
- Ohmmeters are used to measure the resistance of a circuit.
- Ohmmeters should never be connected to a circuit that has power applied to it.
- Ohmmeters must have their own source of power to operate.

KEY TERMS

ammeter
analog meter
clamp-on
current transformer
digital meter
inline
input impedance
multiranged
ohmmeter
turns ratio
voltmeter
volt-ohm-milliammeter (VOM)

REVIEW QUESTIONS

1. What type of meter has a high resistance connected in series with the meter movement?
2. How is a voltmeter connected into the circuit?
3. If a voltmeter has a resistance of 5,000 ohms per volt, what is the resistance of the meter when it is set on the 300-volt range?
4. What is the advantage of using a voltmeter that has a high impedance as opposed to a low-impedance meter?
5. What is an analog meter?
6. Why must an ammeter be connected in series with the load?
7. What device is used to change the scale values of an AC ammeter?
8. What is meant by the term *inline* ammeter?
9. A clamp-on ammeter has three turns of wire wrapped around the movable jaw. If the meter is indicating a current of 15 amps, how much current is actually flowing in the circuit?
10. List the three steps for reading a meter.
11. What type of meter contains its own internal power supply?
12. What precaution must be taken when using an ohmmeter?

UNIT 4

Electrical Circuits

OBJECTIVES

After studying this unit the student should be able to:

- Define a series circuit
- Find Ohm's law values for series circuits
- Define a parallel circuit
- Find Ohm's law values for parallel circuits
- Discuss combination circuits
- Find Ohm's law values for combination circuits

Electrical circuits can be divided into three basic types. These are **series**, **parallel**, and **combination**. The simplest of these circuits is the series circuit shown in Figure 4–1. A series circuit is characterized by the fact that it has only one path for current flow. If it is assumed that current must flow from point A to point B in the circuit shown in Figure 4–1, it will flow through each of the resistors. Therefore, *the current flow in a series circuit must be the same at any point in the circuit*. Another rule of series circuits states that *the sum of the voltage drops around the circuit must equal the applied voltage*. A third rule of series circuits states that *the total resistance is equal to the sum of the individual resistors*.

The circuit shown in Figure 4–2 shows the values of **current flow, voltage drop**, and resistance for each of the resistors. Notice that the total resistance of the circuit can be found by adding the

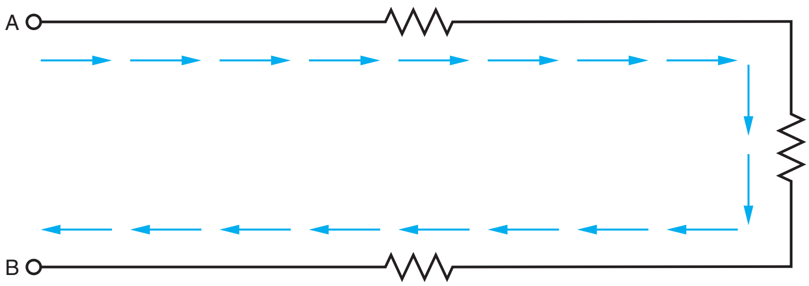


Figure 4–1
Series circuit. (Source: Delmar/Cengage Learning)

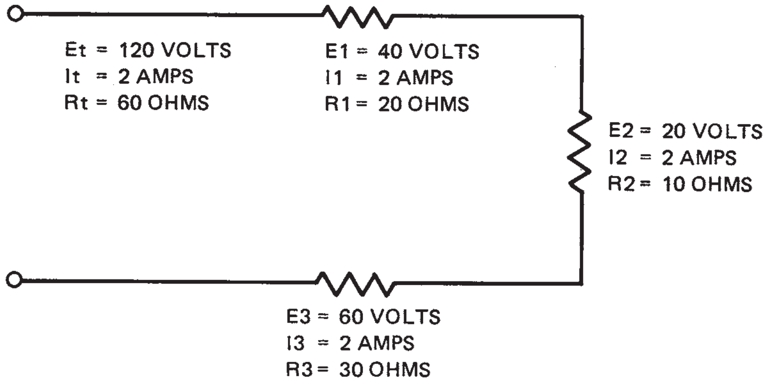


Figure 4–2
Series circuit. (Source: Delmar/Cengage Learning)

values of each of the individual resistors (20 + 10 + 30 = 60 ohms). The amount of current flow in the circuit can be found by using Ohm's law.

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

$$I = \frac{120}{60}$$

$$I = 2 \text{ amps}$$

There is a current flow in the circuit of 2 amps. Notice that the same current flows through each of the resistors. The voltage drop across each resistor can be found using Ohm's law ($E = I \times R$). The voltage dropped across resistor R1 is $2 \times 20 = 40$ volts. This means that it takes a voltage of 40 volts to push 2 amps of current through 20 ohms of resistance. If a voltmeter is connected across resistor R1, it would indicate a voltage drop of 40 volts. The voltage drop of resistor R2 can be found the same way ($E = I \times R$), ($2 \times 10 = 20$). The voltage dropped across resistor R2 is 20 volts. The third resistor has a voltage drop of $2 \times 30 = 60$ volts. Notice that if the voltage drops are added together, they will equal the voltage applied to the circuit ($40 + 20 + 60 = 120$).

Because a series circuit has only one path for current flow, if any point in the circuit should become open, current flow throughout the entire circuit will stop. Some strings of Christmas tree lights are wired in series. If any bulb in the string burns out, all of the lights will go out. When the defective bulb is replaced, all of the lights will operate. Because of this characteristic of series circuits, fuses and circuit breakers are connected in series with what they are intended to protect. Figure 4–3 shows a fuse used to protect an air conditioning unit. If the fuse should open, current flow to the entire circuit will stop.

PARALLEL CIRCUITS

Parallel circuits are characterized by the fact that they have more than one path for current flow. The circuit shown in Figure 4–4 illustrates multiple paths of a parallel circuit. If the current in this

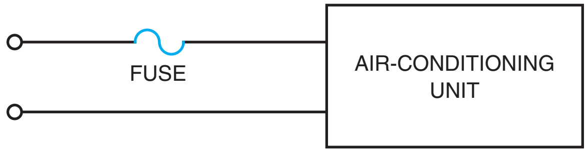


Figure 4–3
Fuses are connected in series. (Source: Delmar/Cengage Learning)

circuit is assumed to flow from point A to point B, there are three separate paths through which it can flow. Current can flow from point A, through resistor R1 to point B, or it can flow from point A through resistor R2 to point B, or from point A through resistor R3 to point B. Because current can flow through each of these resistors, the total current flow in the circuit is the sum of these individual currents. A rule for parallel circuits states that *the total current in a parallel circuit is the sum of the currents through the individual paths* ($It = I1 + I2 + I3$). Notice in Figure 4–4 that each of the resistors is connected directly across the incoming power line. Therefore, *all the components in a parallel circuit have the same voltage drop.*

Each time a new component is added to a parallel circuit, a new path for current flow is created. Because there is less opposition to current flow each time a component is added, the total resistance of the circuit is decreased. The total resistance of a parallel circuit can be found using either of three formulas. The first of these formulas is:

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

The second formula is:

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \frac{1}{RN}$$

or

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \frac{1}{RN}$$

The third formula is:

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

The third formula can be used only when all resistors connected in parallel are the same value. Assume that four resistors with a value of 100 ohms each are connected in parallel. The total resistance would be 25 ohms. To use this formula, divide the resistance of one resistor by the total number of resistors.

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

$$Rt = \frac{100}{4}$$

$$Rt = 25\ \Omega$$

Figure 4–5 shows a parallel circuit containing three resistors with the values of 15, 10, and 30 ohms. The total resistance of the circuit can be found by using either of the two formulas.

$$Rt = \frac{15 \times 10}{15 + 10} = \frac{150}{25} = 6$$

Notice that in this formula only two of the resistors can be found at a time. It is now necessary to use the total resistance of the first two resistors and use that value for R1 in the formula. Resistor R3 is used in the R2 position in the formula.

$$Rt = \frac{6 \times 30}{6 + 30}$$

$$Rt = \frac{180}{36}$$

$$Rt = 5 \text{ ohms}$$

The total resistance of this parallel circuit is 5 ohms. The second formula can be used to find the total

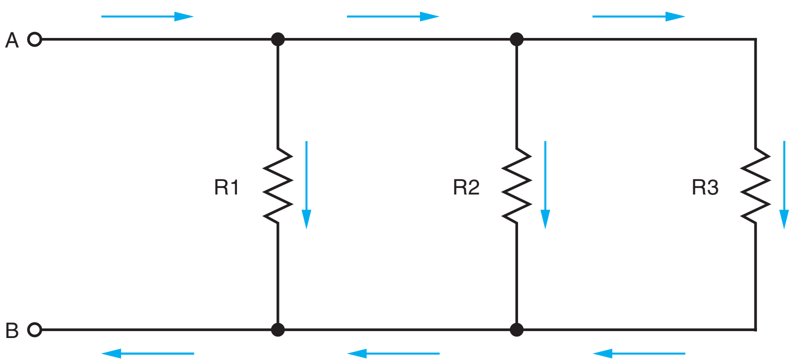


Figure 4–4
Parallel circuits have more than one path for current flow.
(Source: Delmar/Cengage Learning)

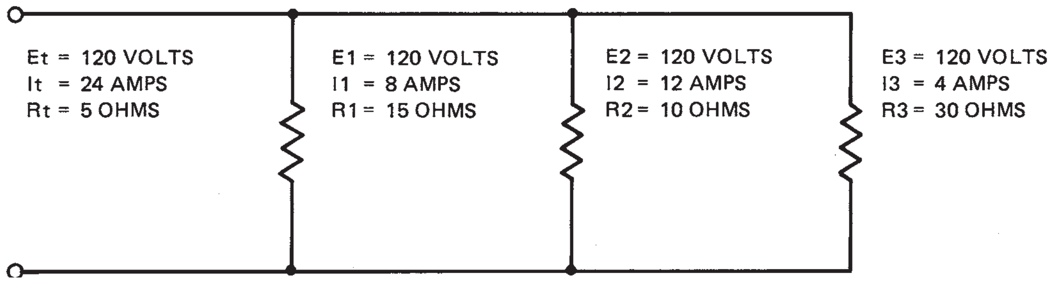


Figure 4–5
Three parallel resistors. (Source: Delmar/Cengage Learning)

resistance by plugging the values of resistance into the formula. With these values, it becomes a matter of adding fractions. When fractions are to be added, the first thing that must be done is to find some number all the denominators will divide into. This is called finding a **common denominator**. For this problem, 30 will be the common denominator.

$$\frac{1}{Rt} = \frac{1}{15} + \frac{1}{10} + \frac{1}{30}$$
$$\frac{1}{Rt} = \frac{2}{30} + \frac{3}{30} + \frac{1}{30}$$
$$\frac{1}{Rt} = \frac{6}{30}$$
$$\frac{Rt}{1} = \frac{30}{6}$$
$$Rt = 5 \text{ ohms}$$

Notice that the two formulas give the same answer.

Another method of finding the total resistance in a parallel circuit is to find the **reciprocal** of each individual resistor. A third rule for parallel circuits states that *total resistance is the reciprocal of the sum of the reciprocals of the individual resistors*. The problem can, therefore, be solved by finding the reciprocal of each individual resistor, adding them together, and finding the reciprocal of the sum. (The reciprocal of any number can be found by dividing that number into 1.) The problem can be solved as follows:

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$$
$$\frac{1}{Rt} = \frac{1}{15} + \frac{1}{10} + \frac{1}{30}$$
$$\frac{1}{Rt} = .0667 + .1 + .0333$$
$$\frac{1}{Rt} = .02$$
$$Rt = 5 \text{ ohms}$$

If 120 volts is applied to the circuit, the values of voltage and current for the entire circuit can be found. Because each of the resistors is connected directly across the power line, each resistor will have the same voltage drop of 120 volts. The current flow through resistor R1 can be found using Ohm's law.

$$I = \frac{E}{R}$$
$$I = \frac{120}{15}$$
$$I = 8 \text{ amps}$$

The current flow through resistor R2 is (120/10 = 12 amps). The current flow through resistor R3 is (120/30 = 4 amps). The total current flow in the circuit can be found by using the formula

$$It = \frac{Et}{Rt}$$
$$It = 120/5$$
$$It = 24 \text{ amps}$$

Notice that the total current can also be found by adding the currents flowing through the individual resistors (8 + 12 + 4 = 24 amps).

Most circuits are connected in parallel. The lights and outlets in a house are connected in parallel. Because all of the lights and outlets are connected in parallel, each light has an applied voltage of 120 volts, and each outlet can supply 120 volts to whatever is connected to it. If the lights in a house were wired in series, all of the lights would have to be turned on before any of them would burn.

COMBINATION CIRCUITS

A combination circuit contains both series and parallel connections within the same circuit. In

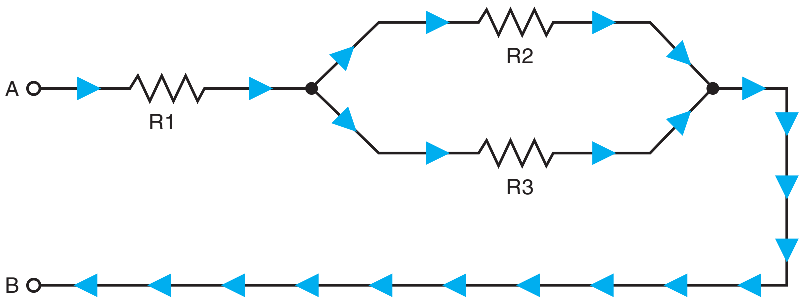


Figure 4–6
Combination circuit. (Source: Delmar/Cengage Learning)

Figure 4–6, resistor R1 is connected in series with resistors R2 and R3. Resistors R2 and R3 are connected in parallel with each other. If it is assumed that current flows from point A to point B, all of the current will have to flow through resistor R1. At the junction of resistors R2 and R3, however, the current divides and flows through separate paths. The amount of current that flows through each resistor is determined by its resistance. Notice that all of the circuit current must flow through R1. Because there is only one current path through R1, it is connected in series with the rest of the circuit. When the current reaches the junction of resistors R2 and R3, there is more than one path for current flow. These resistors are, therefore, connected in parallel.

Values will now be added to the example circuit shown in Figure 4–6. It will be assumed that resistor R1 has a value of 75 ohms; resistor R2 has a value of 100 ohms; and resistor R3 has a value of 125 ohms. It will also be assumed that a voltage of 24 volts is connected to the circuit, Figure 4–7. To find the missing values in this circuit, it is first necessary to determine the total resistance. The first step in determining the total resistance is to calculate the resistance of the parallel block formed by resistors R2 and R3. This value will become RC (resistance of the combination).

$$Rc = \frac{1}{\frac{1}{R2} + \frac{1}{R3}}$$

$$Rc = \frac{1}{\frac{1}{100} + \frac{1}{125}}$$

$$Rc = \frac{1}{0.01} \times 0.008$$

$$Rc = \frac{1}{0.018}$$

$$Rc = 55.556\ \Omega$$

Now that the combined resistance of resistors R2 and R3 is known, this value can be treated as one single resistor. The circuit will now be redrawn as shown in Figure 4–8. The circuit is now a simple series circuit containing resistors R1 and RC.

The total circuit resistance of the circuit can be determined by adding the values of resistors R1 and RC.

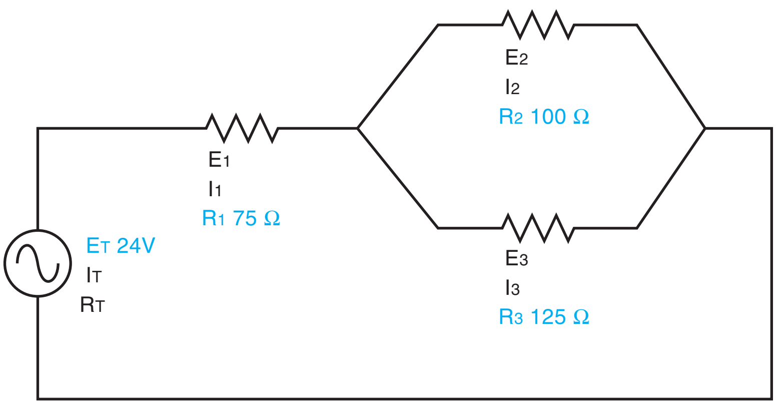


Figure 4–7
Adding circuit values. (Source: Delmar/Cengage Learning)

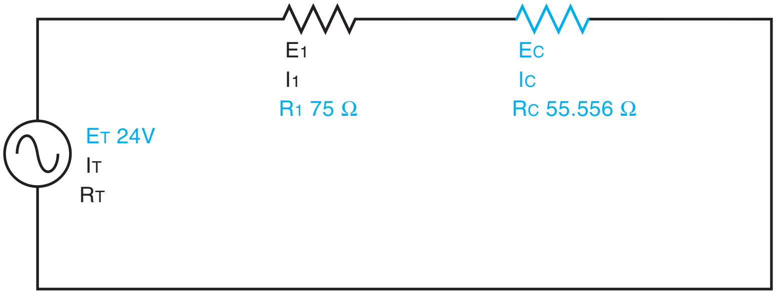


Figure 4–8
Resistors R2 and R3 become RC.
(Source: Delmar/Cengage Learning)

$$Rt = R1 + RC$$
$$Rt = 75 + 55.556$$
$$Rt = 130.556\ \Omega$$

Because the applied or total circuit voltage is known and the total resistance is known, the total circuit current can be determined using Ohm's law.

$$It = \frac{Et}{Rt}$$
$$It = \frac{24}{130.556}$$
$$It = 0.184 \text{ amps}$$

In a series circuit the current is the same at any point in the circuit. The voltage drop across resistors R1 and RC can now be determined.

$$E1 = I1 \times R1$$
$$E1 = 0.184 \times 75$$
$$E1 = 13.8 \text{ volts}$$
$$EC = IC \times RC$$
$$EC = 0.184 \times 55.556$$
$$EC = 10.2 \text{ volts}$$

The computed circuit values are shown in Figure 4–9.

Resistor RC in reality is the combined values of resistors R2 and R3. The values that apply to resistor RC, therefore, apply to the parallel block formed by resistors R2 and R3. In a parallel circuit, the voltage is the same across each branch. Therefore, the voltage dropped across resistor RC is dropped across both R2 and R3. Now that the voltage drop across each is known, the current flow through each can be determined using Ohm's law.

$$I2 = \frac{E2}{R2}$$
$$I2 = \frac{10.2}{100}$$
$$I2 = 0.102 \text{ amps}$$
$$I2 = \frac{E3}{R3}$$
$$I2 = \frac{10.2}{125}$$
$$I2 = 0.0816 \text{ amps}$$

The circuit with all calculated values is shown in Figure 4–10.

Another example of a combination circuit is shown in Figure 4–11. In this circuit, resistors R1 and R2 are connected in series with each other and resistors R3 and R4 are connected in series with each other. Resistors R1 and R2 are connected in

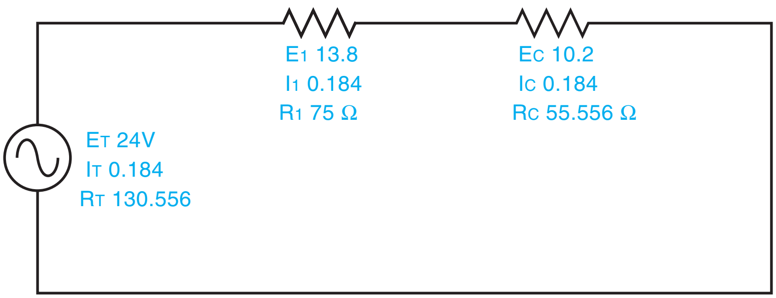


Figure 4–9
Circuit values for the series circuit are determined. (Source: Delmar/Cengage Learning)

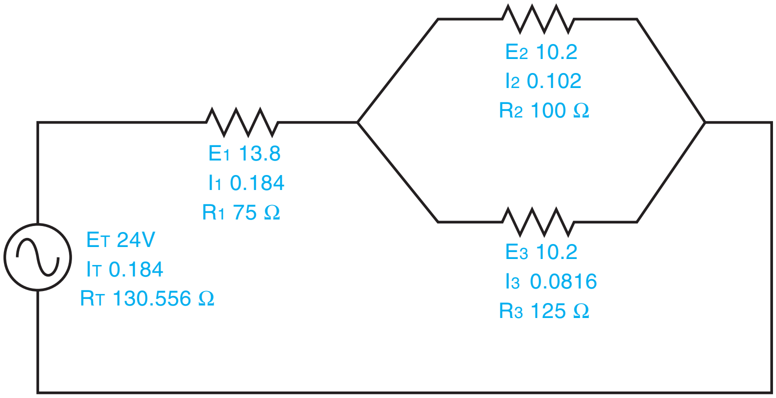


Figure 4–10
Circuit with all computed values.
(Source: Delmar/Cengage Learning)

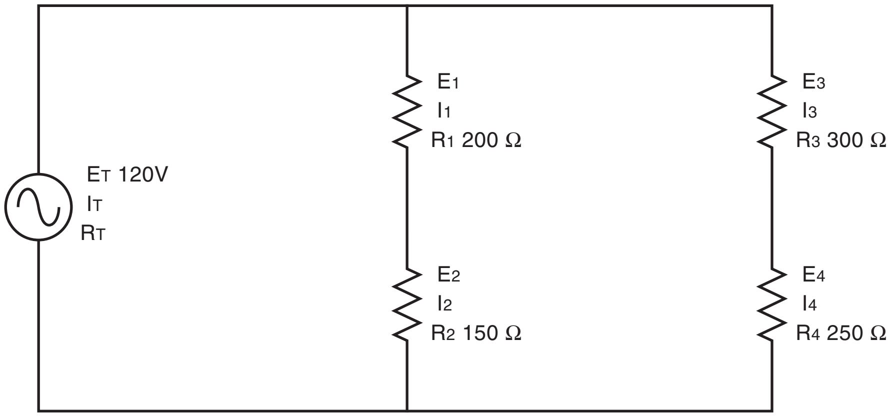


Figure 4–11
Example combination circuit 2. (Source: Delmar/Cengage Learning)

parallel with resistors R3 and R4. It is assumed that resistor R1 has a value of 200 ohms, resistor R2 has a value of 150 ohms, resistor R3 has a value of 300 ohms, and resistor R4 has a value of 250 ohms. It is also assumed that 120 volts is applied to the circuit.

The first step in solving this circuit is to compute the total circuit resistance. This can be done by computing the total resistance of the branch containing resistors R1 and R2 and the branch containing resistors R3 and R4. Resistors R1 and R2 are connected in series. The total resistance of this branch can be computed by adding the values of resistors R1 and R2. This value will be RC1 (resistance of combination 1).

$$RC1 = R1 + R2$$
$$RC1 = 200 + 150$$
$$RC1 = 350\ \Omega$$

The resistance of the second branch can be computed by adding the values of R3 and R4. This resistance value will be RC2 (resistance of combination 2).

$$RC2 = R3 + R4$$
$$RC2 = 300 + 250$$
$$RC2 = 550\ \Omega$$

The circuit can now be reduced to a simple parallel circuit containing a 300-ohm and a 550-ohm resistor, Figure 4–12. The total resistance can now be computed using one of the parallel resistance formulas.

$$Rt = \frac{Rc1 \times Rc2}{Rc1 + Rc2}$$
$$Rt = \frac{350 \times 550}{350 + 550}$$
$$Rt = \frac{192.500}{900}$$
$$Rt = 213.889\ \Omega$$

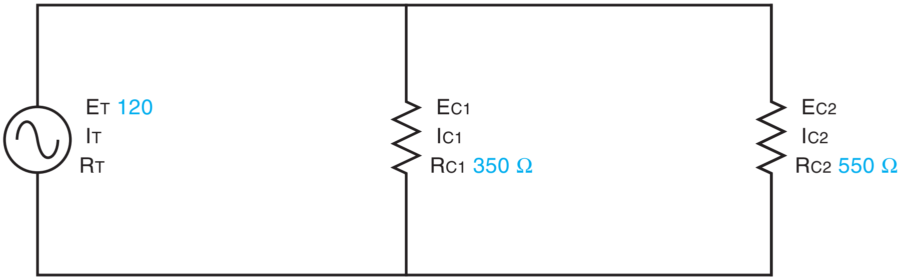


Figure 4–12 Reducing the circuit to a simple parallel circuit. (Source: Delmar/Cengage Learning)

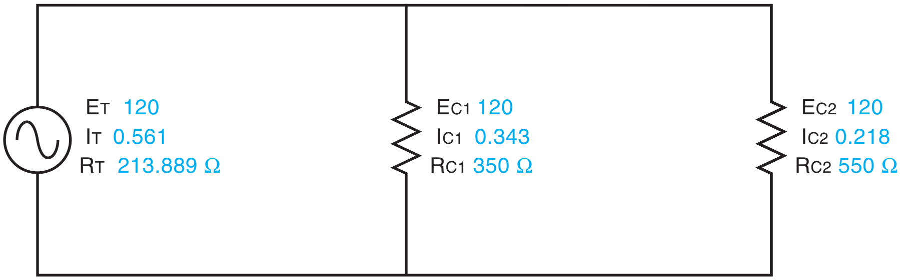


Figure 4–13 The values for the parallel circuit have been determined. (Source: Delmar/Cengage Learning)

The total current can now be computed using Ohm's law.

$$It = \frac{Et}{Rt}$$

$$It = \frac{120}{213.889}$$

$$It = 0.561 \text{ amps}$$

Because resistors RC1 and RC2 are connected in parallel, the voltage across each is the same as the applied voltage of the circuit. The current through each branch can now be determined.

$$IC1 = \frac{120}{350}$$

$$IC1 = 0.343 \text{ amps}$$

$$IC2 = \frac{120}{350}$$

$$IC2 = 0.218 \text{ amps}$$

The complete values for the parallel circuit are shown in Figure 4–13.

The values of RC1 and RC2 can now be substituted in the original circuit. Resistor RC1 is a combination of resistors R1 and R2. The values of RC1 apply to the branch composed of R1 and R2. Resistors R1 and R2 are connected in series. In a series circuit, the current flow is the same through any part of the circuit. Therefore, the current flowing through RC1 is the same current flowing through R1 and R2. Likewise, the current flowing through RC2 is the same current that flows through resistors R3 and R4, Figure 4–14. Now that the value of resistance and current are known for each of the resistors, the voltage drop across each can be computed.

$$E1 = I1 \times R1$$

$$E1 = 0.343 \times 200$$

$$E1 = 68.6 \text{ V}$$

$$E2 = I2 \times R2$$

$$E2 = 0.343 \times 150$$

$$E2 = 51.45 \text{ V}$$

$$E3 = I3 \times R3$$

$$E3 = 0.218 \times 300$$

$$E3 = 65.4 \text{ V}$$

$$E4 = I4 \times R4$$

$$E4 = 0.218 \times 250$$

$$E4 = 54.5 \text{ V}$$

All values for the circuit are shown in Figure 4–15.

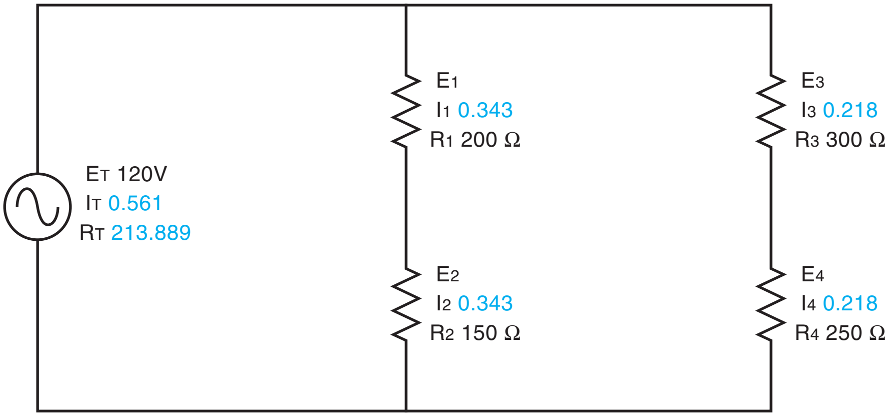


Figure 4–14 Determining the current flow through each branch. (Source: Delmar/Cengage Learning)

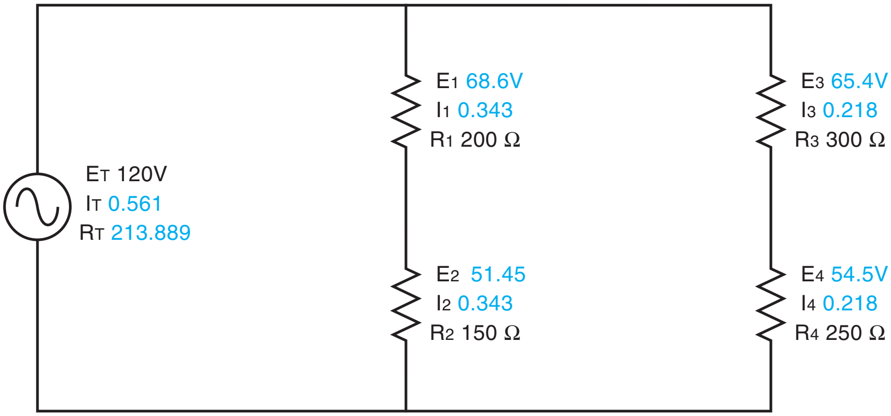


Figure 4–15 All missing values have been determined. (Source: Delmar/Cengage Learning)

SUMMARY

- Three basic types of electric circuits are the series, parallel, and combination.
- Series circuits contain only one path for current flow.
- Three rules concerning the electrical values in a series circuit are:
  A. The current flow is the same in all parts of a series circuit.
  B. The sum of the voltage drops across each element is equal to the applied voltage.
  C. The total resistance can be determined by adding the resistance of each element in the circuit.
- Parallel circuits contain more than one path for current flow.
- Three rules concerning the electrical values in a parallel circuit are:
  A. The voltage is the same across all branches in a parallel circuit.
  B. The total current can be found by adding the current flow through each branch of the circuit.

C. The total resistance can be found by adding the reciprocal of the resistance of each branch and then taking the reciprocal of that sum.

- Combination circuits contain both series and parallel branches.

KEY TERMS

combination
common denominator
current flow
parallel
reciprocal
series
voltage drop

REVIEW QUESTIONS

1. List the three basic types of electrical circuits.
2. What is the major characteristic of a series circuit?
3. List the three basic rules for series circuits.
4. What is the major characteristic of a parallel circuit?
5. List the three basic rules for the parallel circuit.
6. What type of circuit is used most often in industry and the home?
7. What type of circuit is used the least in industry and the home?
8. Three resistors valued at 300 ohms, 200 ohms, and 600 ohms are connected in series. What is their total resistance?
9. If the three resistors in question 8 are connected in parallel, what is their total resistance?
10. How are fuses and circuit breakers connected in a circuit and why are they connected this way?

PRACTICE PROBLEMS SET 1

1. Refer to the circuit shown in Figure 4–2. Find the missing values.

ET = 240	E1	E2	E3
IT	I1	I2	I3
RT	R1 = 1,200 Ω	R2 = 2,000 Ω	R3 = 1,800 Ω

2.

ET = 48	E1	E2	E3 = 22.795
IT	I1	I2	I3
RT = 990 Ω	R1 = 220 Ω	R2 = 300 Ω	R3

3.

ET = 120	E1 = 24.75	E2	E3 = 59.4
IT	I1	I2	I3
RT	R1	R2 = 2.2 kΩ	R3

4. Refer to the circuit shown in Figure 4–5. Find the missing values.

ET	E1	E2	E3
IT = 26	I1	I2	I3
RT	R1 = 24 Ω	R2 = 18 Ω	R3 = 36 Ω

5.

ET	E1	E2	E3
IT	I1	I2	I3 = 1.5
RT = 8 Ω	R1 = 24 Ω	R2 = 48 Ω	R3

6.

ET	E1	E2	E3
IT = 0.289	I1 = 0.139	I2 = 0.1	I3
RT	R1 = 860 Ω	R2 = 1,200 Ω	R3 = 2,400 Ω

7. Refer to the circuit shown in Figure 4–7. Find all missing values.

ET = 120	E1	E2	E3
IT	I1	I2	I3
RT	R1 = 360 Ω	R2 = 1,200 Ω	R3 = 1,600 Ω

8.

ET	E1	E2	E3
IT	I1 = 0.080	I2	I3
RT = 2,600 Ω	R1	R2 = 2,400 Ω	R3 = 4,800 Ω

9.

ET	E1	E2	E3 = 114.18
IT = 0.466	I1	I2	I3
RT	R1 = 270 Ω	R2 = 510 Ω	R3 = 470 Ω

10. Refer to the circuit shown in Figure 4–11. Find all missing values.

ET = 277	E1	E2	E3	E4
IT	I1	I2	I3	I4
RT	R1 = 3,300 Ω	R2 = 4,300 Ω	R3 = 2,700 Ω	R4 = 5,100 Ω

11.

ET	E1	E2	E3	E4
IT	I1 = 0.06	I2	I3	I4
RT = 960 Ω	R1	R2 = 1,000 Ω	R3 = 650 Ω	R4 = 950 Ω

12.

ET	E1	E2	E3	E4
IT	I1 = 0.0444	12	I3 = 0.0369	I4
RT	R1 = 3,000Ω	R2 = 2,400 Ω	R3 = 1,800 Ω	R4 = 4,700 Ω

PRACTICE PROBLEMS SET 2

Ohm's Law

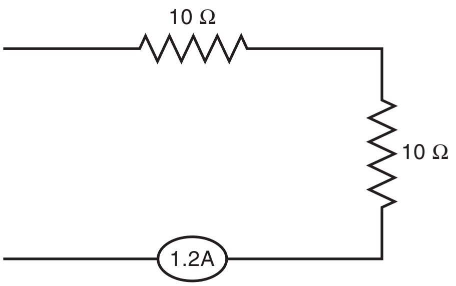
1. E =
I = 10 A
R = 12 Ω

2. I =
E = 220 V
R = 10 Ω

3. R =
E = 120 V
I = 3 A

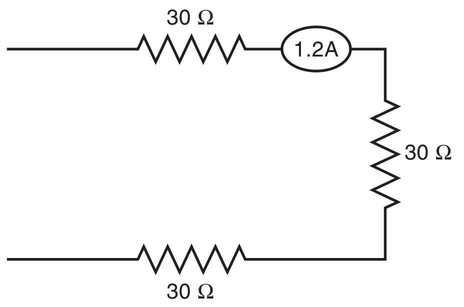
4. E =
I = 1 A
R = 240 Ω

5.



V = ____________

6.

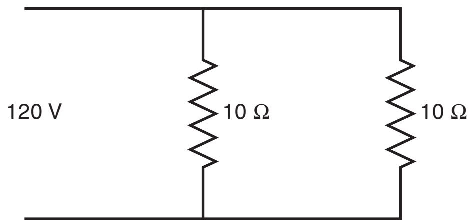


V = ______________

PRACTICE PROBLEMS SET 3

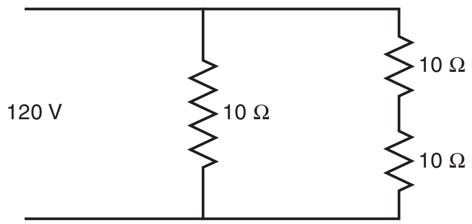
Ohm's Law

1.



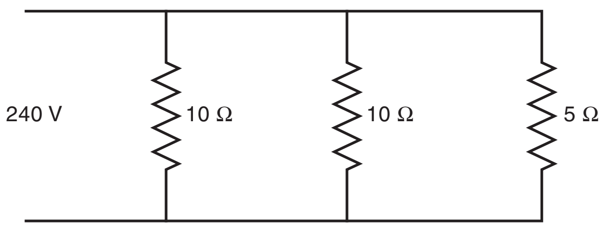
I_T = ______________

2.



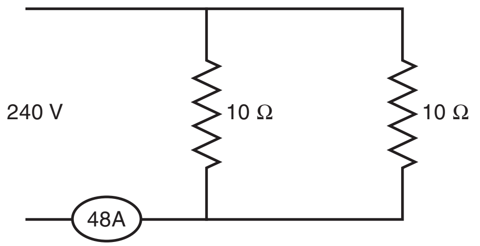
I_T = ______________

3.



I_T = ______________

4.



I_T = ______________

PRACTICE PROBLEMS SET 4

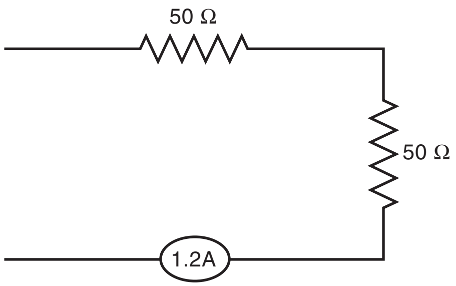
Ohm's Law

1. E =
I = 1 A
R = 12 Ω

2. I =
E = 220V
R = 5 Ω

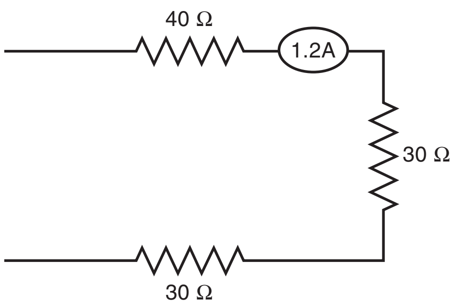
3. R =
E = 120V
I = 5 A

4. E =
I = .5 A
R = 240 Ω



5. V_T = ______________

6. R_T = ______________

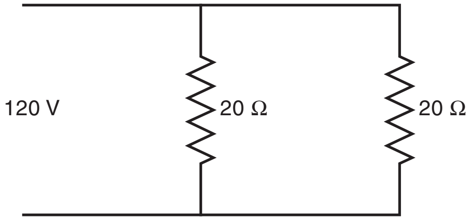


7. V_T = ______________

8. R_T = ______________

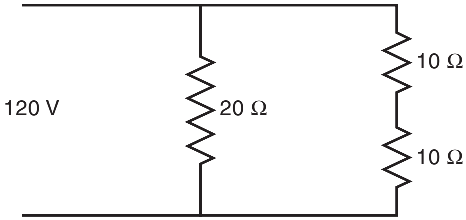
PRACTICE PROBLEMS SET 5

1.



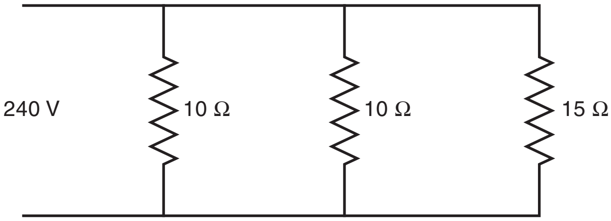
I_T = ______________

2.

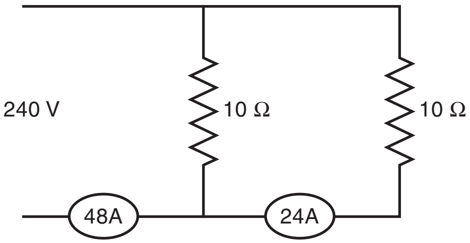


I_T = ______________

3.



I_T = ______________



4. I_T = ______________

5. R_T = ______________

UNIT 5

Electrical Services

OBJECTIVES

After studying this unit the student should be able to:

- Discuss alternating current
- Discuss three-phase power
- Find voltage and current values for a wye-connected three-phase service
- Find voltage and current values for a delta-connected three-phase service
- Discuss a high-leg three-phase connection
- Discuss an open-delta three-phase service
- Discuss a 120/240 volt single-phase service
- Describe different kinds of circuit-breakers
- Discuss fuses
- Be able to find standard fuse rating in accord with the *National Electrical Code®*
- Install a single-phase panel box

Air conditioning equipment must be connected to an electrical service. The type of air conditioning equipment used is generally determined by the type of electrical service available to operate it. The air conditioning technician must have knowledge of different types of electrical services.

POWER GENERATION

In the United States and Canada, power is generated as a three-phase 60-hertz voltage. The term **hertz** means 60 cycles per second. This means that the voltage increases from zero to its maximum positive value, returns to zero, increases to its maximum negative value and returns to zero 60 times each second. Figure 5–1 shows one complete cycle of AC voltage.

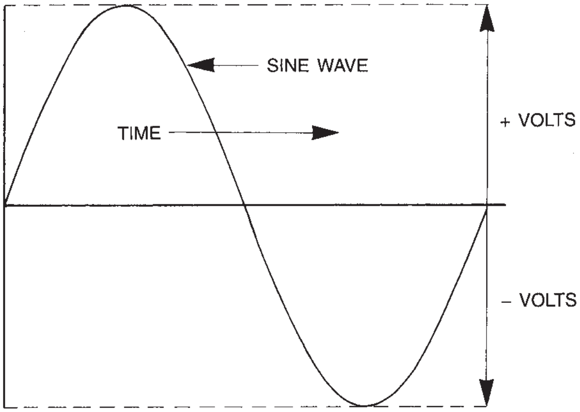


Figure 5–1
AC sine wave. (Source: Delmar/Cengage Learning)

The term **three phase** means that there are three separate voltage waveforms produced by the **alternator**. An alternator is a generator that produces AC voltage. For the alternator to produce the three phases, the internal windings of the alternator—called the **stator**—are wound 120° apart. Figure 5–2 illustrates the windings of an alternator. The moving part of the alternator, called the **rotor**, is actually a large electromagnet. When the magnet is turned, the magnetic field cuts through the windings of the stator and induces a voltage into them. The amount of voltage induced is controlled by the strength of the magnetic field, and the frequency or hertz is controlled by the speed of the rotation of the magnet. Because the windings of the stator are physically wound 120° apart, the three voltages are 120° out of phase with each other. The windings of the stator are connected to form one of the two basic three-phase connections. These connections are the **delta** and **wye**.

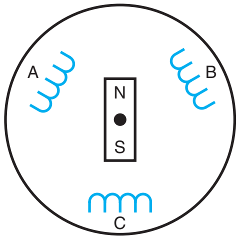


Figure 5–2
The windings of an alternator are 120° apart.
(Source: Delmar/Cengage Learning)

WYE CONNECTION

The wye connection is also referred to as the **star** connection. This connection is made by joining one end of each of the windings together as shown in Figure 5–3. The connection shown in Figure 5–4 is a wye connection that has been drawn schematically to make it easier to see and understand. Notice how one end of each of the windings is joined at the centerpoint. The wye connection can be used to provide an increase in the output or line voltage. The phase voltage is the voltage produced across one of the windings. The line voltage is the voltage produced across the output points of the connection. Figure 5–5 shows a wye connection connected to a three-phase load bank. Ammeters and voltmeters are used to illustrate the differences between phase values and line values. Notice that the phase value of voltage is measured from the output of the winding, at point C, to the centerpoint of the wye

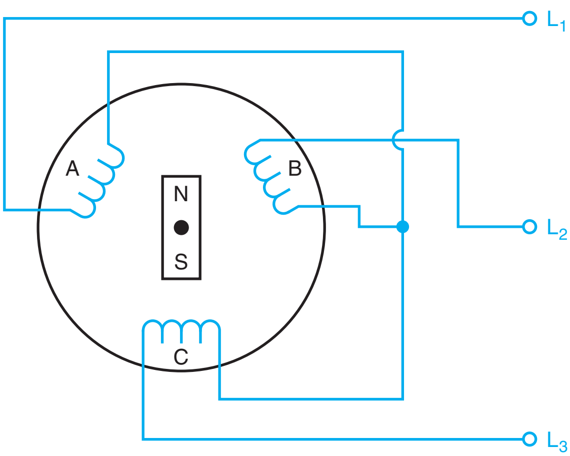


Figure 5–3
Wye or star connection. (Source: Delmar/Cengage Learning)

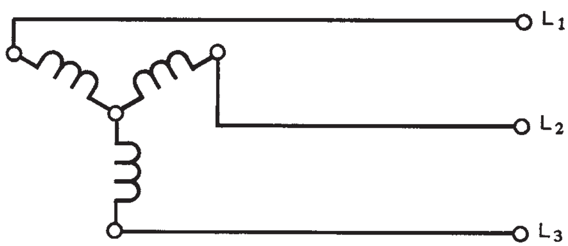


Figure 5–4
Schematic of a wye connection. (Source: Delmar/Cengage Learning)

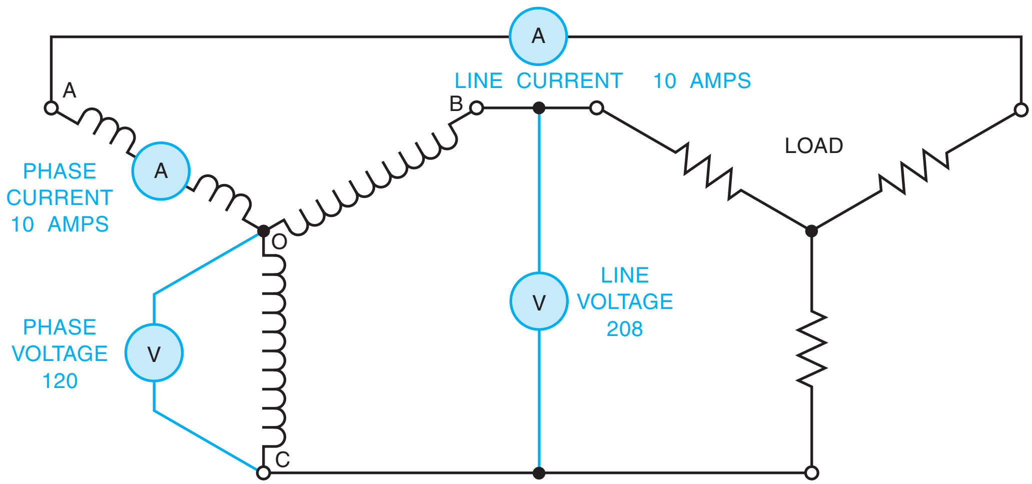


Figure 5–5
Phase and line values of a wye connection. (Source: Delmar/Cengage Learning)

connection at the point labeled O. The line value is measured across two of the output points of the connection (B&C). The phase current meter is inserted in the winding of the alternator, and the line current meter is inserted in the output line. Notice also that the two ammeters are indicating the same value of current. *In a wye connection, phase current and line current are equal.* The voltages, however, are not. *The line voltage in a wye connection is 1.732 times greater than the phase voltage* (1.732 is the square root of 3). The reason for this voltage increase is that the voltages are 120° out of phase with each other. Figure 5–6 shows a diagram to illustrate this. Because the three voltages are out of phase with each other, they will be added. Vector addition must be used, however, because of the 120° phase shift. If three voltages are shown in a length that corresponds to 120 volts, and a resultant is drawn to the point of intersection, it will be found that the length of the resultant corresponds to 208 volts. The 120° phase shift between voltages is the reason the two 120-volt phases add to produce 208 volts instead of 240 volts.

Wye-connected systems often use a fourth conductor connected to the center of the connection. This conductor becomes the neutral, Figure 5–7. Notice in this connection that the voltage between any line and neutral is the phase voltage or 120 volts,

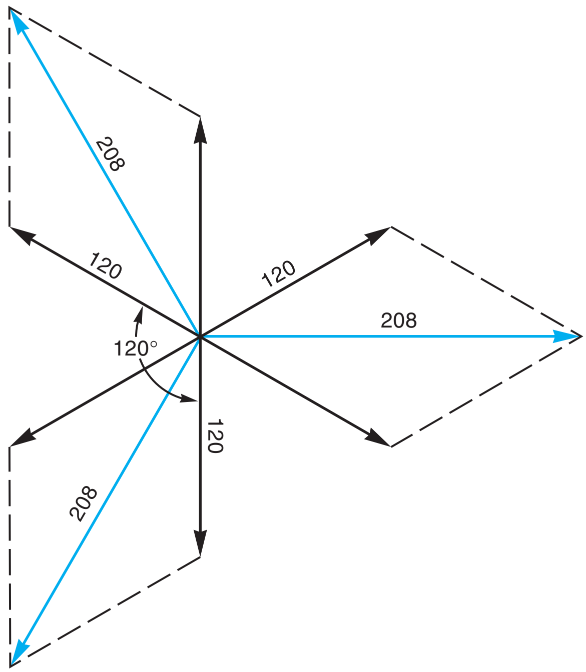


Figure 5–6
Vector diagram of the phase and line values in a three-phase system. (Source: Delmar/Cengage Learning)

and the voltage between any two of the lines is 208 volts. The 208/120-volt three-phase connection is very common in industry and commercial buildings. Another very common three-phase

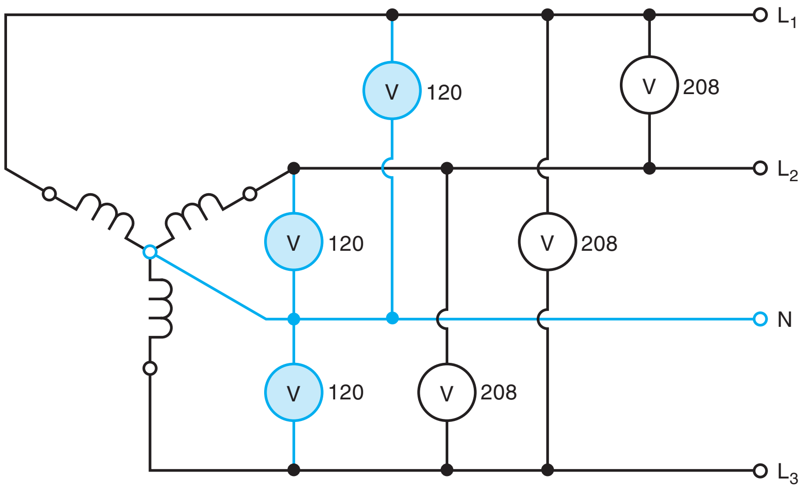


Figure 5–7
Fourth wire connected for a neutral. (Source: Delmar/Cengage Learning)

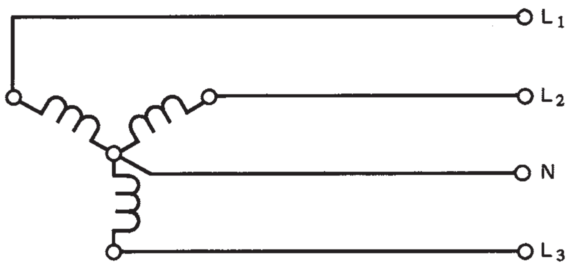


Figure 5–8
A 480/277-volt connection. (Source: Delmar/Cengage Learning)

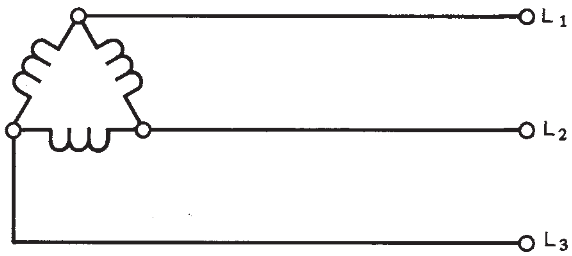


Figure 5–9
The delta connection. (Source: Delmar/Cengage Learning)

four-wire connection is shown in Figure 5–8. This is a 480/277-volt connection. Two hundred seventy-seven volts is often used in large stores and office buildings to operate the fluorescent lights while the 480-volt is used to operate large air conditioning systems. The 120-volt connections are provided by transformers that step down the 480 volts to 120 volts.

DELTA CONNECTION

The next connection to be covered is the delta. A schematic diagram of a delta connection is shown in Figure 5–9. This connection gets its name from the fact that it looks like the Greek letter delta (Δ).

Figure 5–10 shows a delta system connected to a three-phase load bank. Ammeters and voltmeters are used to illustrate the differences in phase and line values of voltage and current. Notice that the values of phase voltage and line voltage are equal for the delta connection. One of the rules for three-phase systems states that *line voltage and phase voltage are equal in a delta connection*. The ammeters, however, are not equal. *In a delta connection, the line current is 1.732 times greater than the phase current*. This is the reason that the delta connection is so popular in industry. The current flow through the windings of a transformer are less than the line amps if the transformer bank is connected in delta.

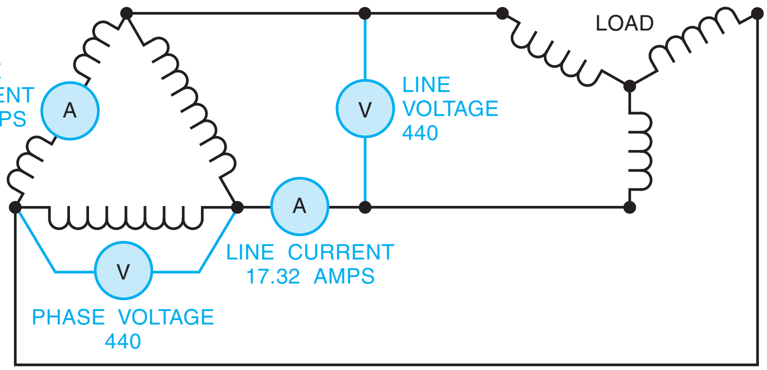


Figure 5–10
Voltage and current relationships in a delta connection.
(Source: Delmar/Cengage Learning)

HIGH-LEG SYSTEM

Figure 5–11 illustrates another common type of transformer connection. This is a 240/120-volt system with a **high-leg**. Three transformers are connected to form a delta connection. One of the transformers is larger than the other two, however, and is center tapped. The large transformer must be able to supply power for both three-phase and single-phase loads. The other two transformers supply power for the three-phase loads only. If the phase voltage of the transformers is 240 volts, the voltage between any of the three lines is 240 volts. If the center-tap connection is used as a neutral conductor, however, the voltages between L2 and neutral, and L3 and neutral will be 120 volts. Therefore, L2, L3, and neutral are used to supply 240/120 volts for single-phase loads. Care must be taken not to connect a 120-volt device across L1 and neutral. Line L1 is known as a high leg and a voltage of about 208 volts exists between these two points.

OPEN-DELTA SYSTEM

Another type of three-phase service is known as the open delta. The **open-delta system** has the advantage of needing only two transformers to provide three-phase voltage. This connection is often used when the amount of three-phase power needed is low, or if the power needs are expected to increase in the future. The open-delta connection, however, does have some disadvantages. The total

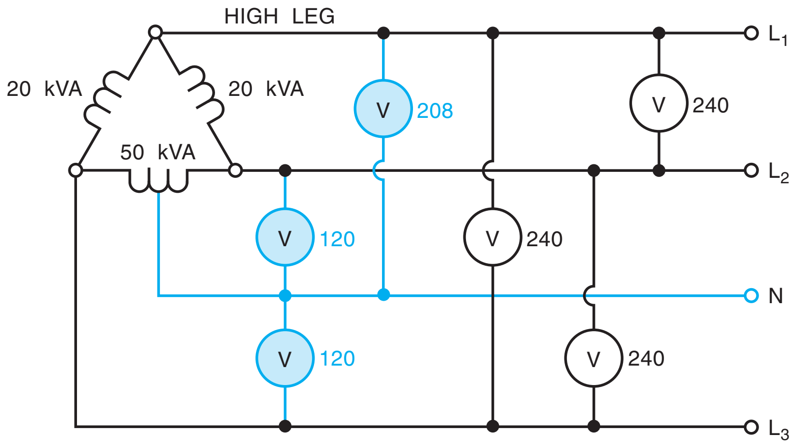


Figure 5–11
High-leg system. (Source: Delmar/Cengage Learning)

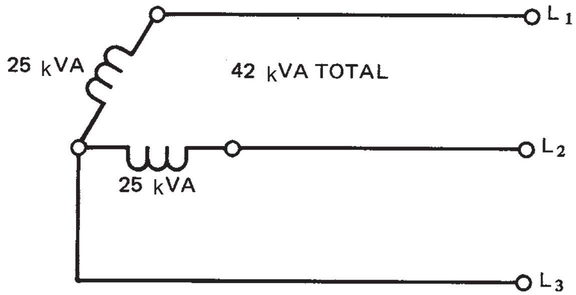


Figure 5–12
Open-delta system. (Source: Delmar/Cengage Learning)

output power is only 84% of the combined rating of the transformers. If the two transformers shown in Figure 5–12 each have a power rating of 25 kVA (kilovolt amps), the total delivered power of this connection is only 42 kVA (25 + 25 = 50) (50 × 84% = 42). If at a later date the power requirements increase, a third transformer can be added to close the delta. The total output power of this connection is the combined rating of all three transformers. In this case it will be 75 kVA (25 + 25 + 25 = 75).

SINGLE-PHASE SERVICE

A **single-phase** 240/120-volt system can be obtained by connecting a single transformer to two lines of a three-phase system. The primary of the transformer shown in Figure 5–13 is connected to two of the three-phase lines of the power company.

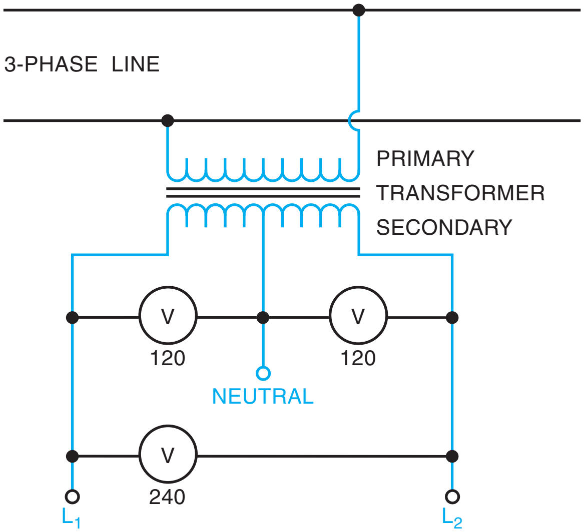


Figure 5–13
Single-phase transformer. (Source: Delmar/Cengage Learning)

The secondary voltage of the transformer is 240 volts. The secondary winding of the transformer is center tapped. The center tap is grounded and becomes the **neutral** conductor. If the voltage across the entire secondary is measured, it will be 240 volts. If the voltage between either of the secondary leads is measured to the center tap, it will be 120 volts. The reason this is true for single-phase and not three-phase is that the voltages of the single-phase system are in phase with each other, Figure 5–14. Because the transformer center tap

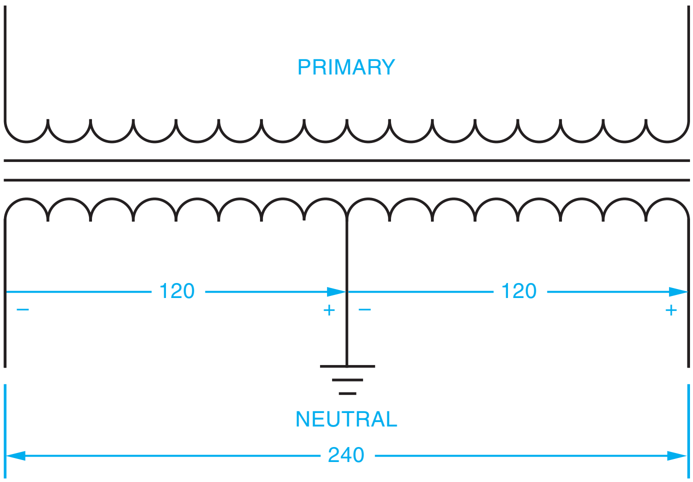


Figure 5–14
The voltages across the winding of the secondary of the single-phase transformer are in phase with each other. (Source: Delmar/Cengage Learning)

is the neutral conductor, it will be 120 volts more positive than one side of the secondary winding and 120 volts more negative than the other side of the secondary winding at a particular point in time. Because these two vectors are in phase or are in the same direction, they will produce a total voltage of 240 volts.

PANEL BOX

Regardless of the type of service used, connection will be made at a **fuse** or **circuit-breaker** box. Figure 5–15 shows a 150-amp single-phase circuit-breaker panel. Circuit breakers are made in different sizes and types. Figure 5–16 shows three different types of circuit breakers. The **single-pole breaker** is used for connecting a 120-volt circuit, the **two-pole breaker** is used for connecting a 240-volt single-phase circuit, and the **three-pole breaker** is used for connecting a three-phase circuit. The three-pole breaker must be used with a three-phase circuit-breaker panel and cannot be used in a single-phase panel.

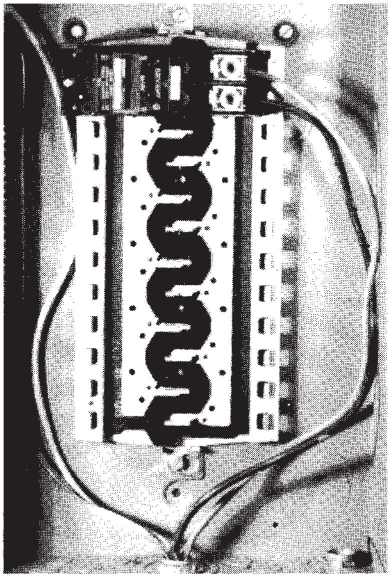


Figure 5–15
150-amp single-phase panel. (Source: Delmar/Cengage Learning)

Figure 5–16
Single-pole, double-pole, and three-pole circuit breakers. (Source: Delmar/Cengage Learning)

When a 120-volt connection is to be made, cable is brought into the panel. A **two-conductor romex** cable contains three wires—a black, white, and bare copper. The bare copper wire is the grounding wire or safety wire and is not considered a circuit conductor. Only the black and white wires are considered to be circuit conductors. The black wire is used as the "hot" conductor and the white wire is used as the neutral. Figure 5–17 shows a 120-volt single-phase circuit connected into the panel box. Notice that the black wire is connected to the circuit breaker, and the white wire is connected to the neutral bus. Notice also that the bare copper wire is connected to the neutral bus with the white wire.

When a 240-volt connection must be made, a two-pole circuit breaker is used. If the connection is to use only two-circuit conductors as shown in Figure 5–18, the black wire connects to one pole of the two-pole breaker. The *National Electrical Code*® does not permit a white wire to be used as a hot circuit conductor. For this reason the wire must be identified by wrapping a piece of colored tape around it. The tape can be any color except white, gray, or green. Black or red tape is generally used. The identified conductor is then connected to the other pole of the two-pole breaker. The bare copper wire is connected to the neutral bus.

If a 240-volt three-wire circuit is to be connected to the panel, a three-conductor cable is used. The three-conductor cable contains four wires—a black, red, white, and green. The green is the grounding or safety wire and is not considered a circuit conductor.

Figure 5–17
120-volt single-phase connection. (Source: Delmar/Cengage Learning)

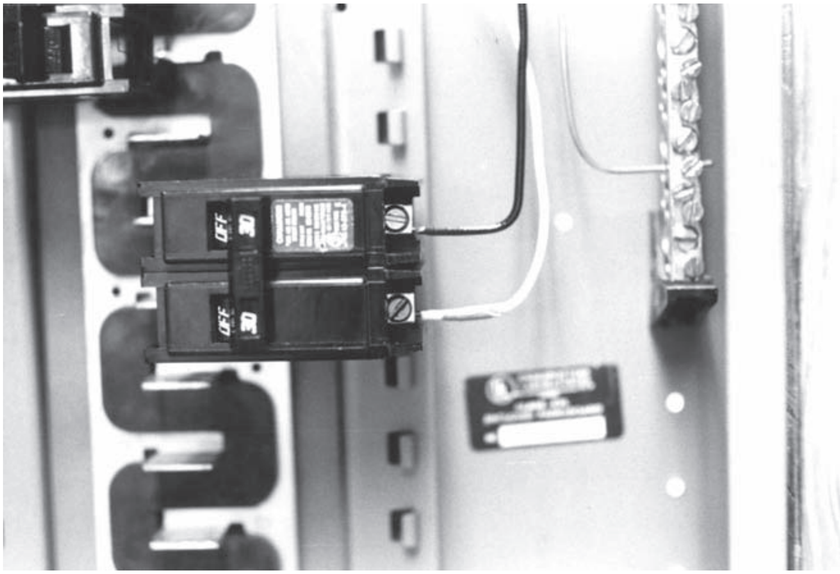


Figure 5–18
240-volt single-phase two-wire connection. (Source: Delmar/Cengage Learning)

Figure 5–19 shows a 240-volt three-wire connection. The black and red wires are connected to the two poles of the circuit breaker. The white and green wires are connected to the neutral bus.

When a three-phase panel connection is made, a three-pole circuit breaker is used. There may or may not be a neutral depending on the type of circuit. For example, a 208/120-volt connection would use a fourth wire connected to the neutral bus. A 440-volt straight, three-phase connection would use only three conductors connected to a three-pole breaker.

Figure 5–19
240-volt single-phase three-wire connection. (Source: Delmar/Cengage Learning)

FUSES

Circuit breakers are not the only means used to provide circuit protection. Fuses are still used to a great extent. Fuses are rated in two ways—by voltage and current. The voltage rating of a fuse indicates the amount of voltage the fuse is designed to interrupt without arcing across. Although fuses can be obtained that have ratings of several thousand volts, the most common fuses used in the air conditioning field are 250 volt and 600 volt. The 600-volt fuse is longer to provide a greater distance between the two contact ends if the fuse link should blow. The extra length is needed at higher voltages to prevent **arc-over**.

Figure 5–20 shows a type of fuse that uses a replaceable link. When this fuse blows, the fuse cartridge can be taken apart and the fuse link replaced. This type of fuse is more expensive to purchase, but it could be a savings if the fuse has to be replaced frequently.

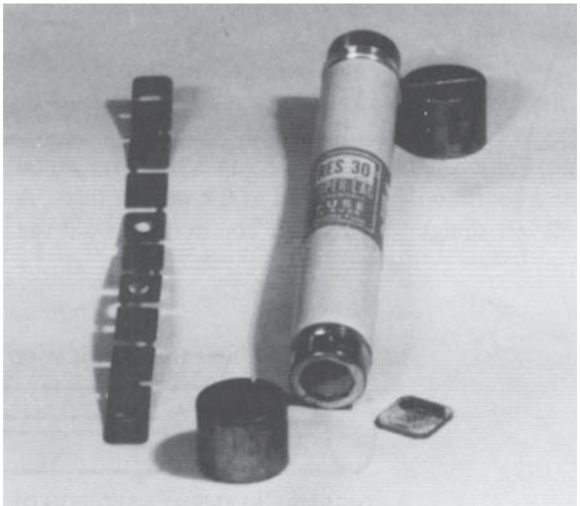


Figure 5–20
Replaceable-link type of fuse. (Source: Delmar/Cengage Learning)

Fuses used for circuit protection are made in standard ampere ratings. Figure 5–21 shows these ratings as taken from the *National Electrical Code*®. Fuses for air conditioning and refrigeration equipment are normally sized at 175% of the rated full-load current of the motor. If this does not permit the motor to start, however, compressors can be fused as much as 225% of their full-load running current. If the fuse size needed does not correspond with one of the standard fuse sizes, the next smaller size fuse will have to be used. For example, assume it has been determined that a fuse rating of 130 amps is needed. The standard ratings chart for fuses shown in Figure 5–21 does not list a 130 amp fuse. Therefore, the closest standard rating less than 130 amps

240.6 Standard Ampere Ratings.
(A) Fuses and Fixed-Trip Circuit Breakers. The standard ampere ratings for fuses and inverse time circuit breakers shall be considered 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 700, 800, 1000, 1200, 1600, 2000, 2500, 3000, 4000, 5000, and 6000 amperes. Additional standard ampere ratings for fuses shall be 1, 3, 6, 10, and 601. The use of fuses and inverse time circuit breakers with nonstandard ampere ratings shall be permitted.

Figure 5–21
Standard fuse ratings. (Reprinted with permission from NFPA 70™, *National Electrical Code®*. Copyright 2008, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety. *National Electrical Code®* and *NEC®* are registered trademarks of the National Fire Protection Association, Inc., Quincy MA 02269).

is 125 amps. A 125-amp fuse will be used. Notice that fuses can be sized as much as 225% of the full-load current of the compressor. Fuses are sized this much above the running current of the motor to permit the fuse the ability to withstand the starting current of the motor. Fuses are designed to protect the circuit against short circuits; they are not used to protect the motor from overloads.

Overload protection for the motor is provided by the overload relay, which will be covered later, or by dual-element time delay fuses. Dual-element time delay fuses are designed to provide both types of protection. Figure 5–22 illustrates a dual-element time delay fuse. The fuse link is designed to open quickly in the event of a short circuit. Short circuit currents are generally several hundred times the rating of the fuse. The fuse link is also designed to allow some amount of overload for a short period of time. This time delay permits the motor to start without opening the fuse link. The overload protection is provided by a solder link. The solder is intended to melt at a specific temperature and a spring is used to pull the link apart. Although the motor starting current is greater than the overload protection would permit, it takes time for the solder to melt, permitting the motor to start.

FUSED DISCONNECTS

Fused disconnects provide both a disconnect switch and fuse holders. Figure 5–23 shows a fused disconnect used for three-phase circuits. Fused disconnects,

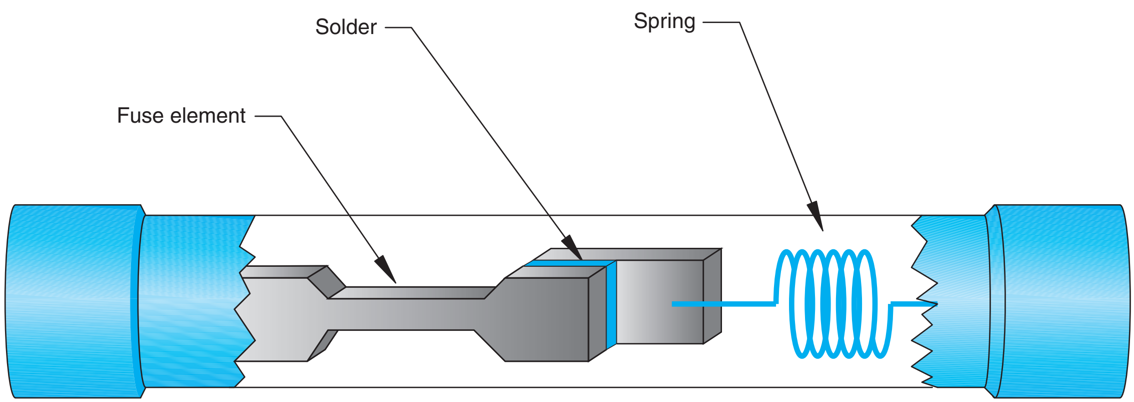


Figure 5–22
Dual-element time-delay fuse. (Source: Delmar/Cengage Learning)

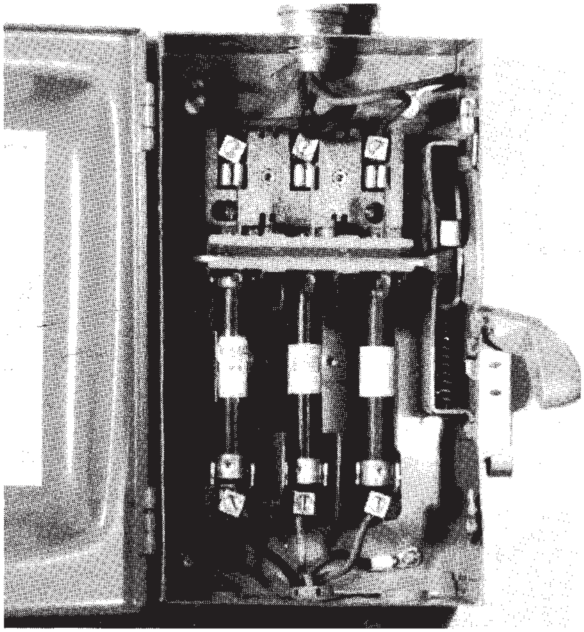


Figure 5–23
Three-phase fused disconnect. (Source: Delmar/Cengage Learning)

STANDARD DISCONNECT SIZES
30 amp
60 amp
100 amp
200 amp
400 amp
600 amp
1,000 amp
1,200 amp
1,600 amp
2,000 amp
3,000 amp
4,000 amp
5,000 amp
6,000 amp

Figure 5–24
Standard disconnect sizes. (Source: Delmar/Cengage Learning)

like fuses, have standard ratings. The standard sizes for fused disconnects are shown in Figure 5–24. The rating of the disconnect indicates the maximum size of fuse that can be used in that enclosure. For example, assume the 125-fuse discussed earlier in this unit is to be mounted in a disconnect. Because the fuse size is greater than 100 amps, it cannot be mounted in a 100-amp enclosure. The next standard size enclosure is 200 amps. The 125-amp fuses will have to be mounted in a 200-amp disconnect.

When servicing equipment, it is often necessary to turn off the power to the equipment. When this is necessary, certain precautions should be taken by the service technician. Remember that your life is your own and do not trust someone else not to turn the circuit back on while it is being serviced. Most industries provide a tag that is hung on the disconnect while it is being serviced. A paper tag, however, cannot stop someone from turning the power back on. For this reason, a small padlock should be used to lock the disconnect in the off position. If a lock is not available, the fuses should be removed with fuse pullers. There is no such thing as being too safe when working with high-voltage electricity.

SUMMARY

- The electric power in the United States and Canada is generated as three phase with a frequency of 60 Hz.
- The voltages of a three-phase system are 120° out of phase with each other.
- The two basic types of three-phase connections are the wye and delta.
- In a wye-connected system, the line voltage is greater than the phase voltage by a factor of the $\sqrt{3}$ (1.732).

- In a wye-connected system, the line current and phase current are equal.
- In a delta-connected system, the line voltage and phase voltage are equal.
- In a delta-connected system, the line current is greater than the phase current by a factor of $\sqrt{3}$.
- Some delta-connected systems can produce a high-leg that has one phase with a voltage that is 1.732 times greater than the other two-phase voltages.
- Open-delta systems use only two transformers.
- In an open-delta system, the total kVA capacity is only about 84% of the combined kVA capacity of the two transformers.
- Single-phase services produce voltages that are 180° out of phase with each other.
- Single-phase services generally provide a 120/240-volt connection by grounding the center tap of a transformer secondary and using it as a neutral conductor.
- A single-pole circuit breaker is used to provide power to a 230-volt circuit.
- A two-pole circuit breaker is used to provide power to a 240-volt circuit.
- A three-pole circuit breaker is used to provide power to a three-phase circuit.
- Fuses are sometimes used instead of circuit breakers.
- Section 240.6 of the *National Electrical Code*® lists standard sizes of fuses and circuit breakers.

KEY TERMS

alternator
arc-over
circuit breaker
delta
fuse
hertz
high-leg
neutral
open-delta system
rotor
single-phase
single-pole breaker
star
stator
three phase
three-pole breaker
two-conductor romex
two-pole breaker
wye

REVIEW QUESTIONS

1. What is an alternator?
2. What controls the output voltage of an alternator?
3. What controls the frequency of the alternator?
4. How many degrees out of phase with each other are the voltages of a three-phase system?
5. What are the two major types of three-phase connections?
6. List the rules concerning line and phase values of current and voltage in a wye connection.

7. List the rules concerning line and phase values of current and voltage in a delta connection.
8. In a high-leg delta-connected system, what is the voltage between the high leg and neutral?
9. What type of three-phase transformer connection uses only two transformers?
10. How many degrees out of phase are the voltages of a single-phase system?
11. A two-conductor romex cable contains three wires. Which wire is not counted and why.
12. What type of circuit breaker is used to make a 240-volt connection?
13. Where does the grounding conductor connect in a panel?
14. In what two electrical units are fuses rated?
15. It has been calculated that a 290-amp fuse is needed to protect the circuit supplying an air conditioning compressor. What standard rating of fuse should be used?
16. What size fuse disconnect will be used for the fuse in question 15?
17. What is a dual-element fuse?

UNIT 6

Wire Size and Voltage Drop

OBJECTIVES

After studying this unit the student should be able to:

- List factors that determine wire resistance
- Determine the resistance of a piece of wire
- Use the *National Electrical Code*® to determine wire size
- Test an installation of excessive voltage drop on the conductors

When installing air conditioning equipment it is important to use the proper size wire. If wire is used that is larger than needed, it is an unnecessary expense. If wire is used that is too small, it will cause excessive voltage drop and damage the equipment.

WIRE RESISTANCE

Most people think of wire as having zero resistance. In fact, many electrical calculations are made that assume the resistance of the wire is so little that it is negligible. In actual practice, however, all wire has resistance. There are four factors that determine the resistance of a piece of wire. The factors are:

1. The diameter of the wire.
2. The material the wire is made of.
3. The length of the wire.
4. The temperature of the wire.

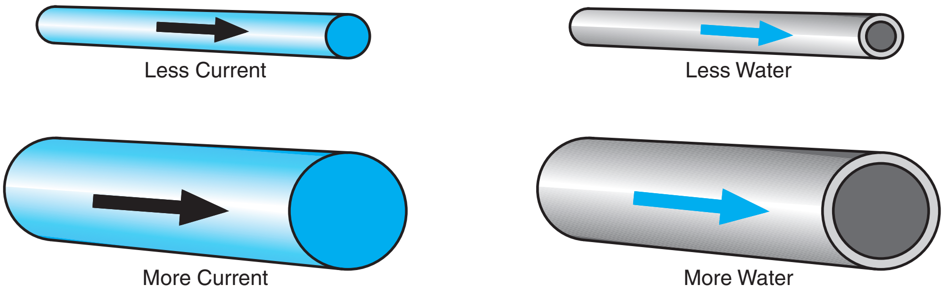


Figure 6–1 Larger wire can carry more current. (Source: Delmar/Cengage Learning)

AREA

The cross-sectional area of wire is measured in **circular mils**. The circular mil area of a wire can be found by finding the diameter of the wire in thousandths of an inch (1 mil $= \frac{1}{1{,}000}$ inch) and squaring that number. (Squaring a number means to multiply that number by itself.) For example, assume a piece of wire is measured with a micrometer and is found to have a diameter of 8 thousandths of an inch (.008). The circular mil area of the wire is 64 ($8 \times 8 = 64$). Notice that 64 is written as a whole number, not a decimal number. A wire that has a diameter of .064 inch has a circular mil area of 4096 ($64 \times 64 = 4{,}096$).

The circular mil area of stranded wire is determined by finding the area of one of the strands and then multiplying by the number of strands. For example, assume that a wire has 24 strands of wire that are .012 inches in diameter. The area of one wire is 144 CM (circular mils). The entire conductor has a circular mil area of 3,456 CM ($144 \times 24 = 3{,}456$). Large wire is generally stranded to make it easier to bend.

The larger the diameter of a wire, the less resistance it will have and the more current it can carry, Figure 6–1. Current flowing through a wire is very similar to water flowing through a pipe. A large wire can carry more current at a specific voltage than a small wire. A large pipe can carry more water at a specific pressure than a small pipe.

MATERIAL

A standard measurement used for finding the resistance of wire is the **mil-foot**. A mil-foot of wire is a piece of wire one circular mil in diameter and one foot long. If the resistance of a mil-foot of different types of wire is found, a mathematical formula can be used to determine the resistance of different types, sizes, and lengths of wire. This formula is:

$$R = K \times L/CM$$

Where: K = the ohms per mil-foot of the wire.
L = the length of the wire in feet.
CM = the circular mil area of the wire.

The table in Figure 6–2 gives the resistance of different types of wire in ohms per mil-foot. Using the table shown in Figure 6–3, the diameter and circular mil area for different sizes of wire can be found.

K = OHMS RESISTANCE PER MIL-FOOT (AT 70°F)	
Aluminum	17
Brass	42
Cadmium Bronze	12
Copper	10.4
Copperclad Aluminum (20% Cu)	15.2
Copperweld	26–34
Iron	60
Nichrome	600
Silver	9.6
Steel	75
Tungsten	33

Figure 6–2 Larger wire can carry more current. (Source: Delmar/Cengage Learning)

American Wire Gauge Table												
			Ohms per 1000 Ft. (ohms per 100 meters)						Pounds per 1000 Ft. (kg per 100 meters)			
B & S Gauge No.	Diam. in Mils	Area in Circular Mils	Copper * 68°F	Copper * (20°C)	Copper * 167°F	Copper * (75°C)	Aluminum 68°F	Aluminum (20°C)	Copper		Aluminum	
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%

Figure 6–3
American Wire Gauge table. (Source: Delmar/Cengage Learning)

PROBLEM 1: What is the resistance of a piece of #18 **AWG (American Wire Gauge)** copper wire 400 feet long?

SOLUTION: First, state the formula to be used.

$$R = \frac{K \times L}{CM}$$

Second, substitute known numeric values in the formula. The value of K can be found in the table shown in Figure 6–2. The K value for copper is 10.4. The CM area of #18 AWG wire can be found from the chart in Figure 6–3. The circular mil area of #18 AWG wire is 1624 CM. If these values are substituted in the formula for letters, the formula will be:

$$R = \frac{10.4 \times 400}{1624}$$

$$R = \frac{4160}{1624}$$

$$R = 2.56 \text{ ohms}$$

PROBLEM 2: What is the resistance of a piece of #12 AWG aluminum wire 250 feet long?

SOLUTION:

$$R = \frac{K \times L}{CM}$$

$$R = \frac{17 \times 250}{6530}$$

$$R = \frac{4250}{6530}$$

$$R = .6508 \text{ ohms}$$

TEMPERATURE

The resistance of a piece of wire is also affected by **temperature**. As the temperature increases, the resistance of wire increases also. Notice that the charts in Figures 6–2 and Figure 6–3 state the resistance of wire at a specific temperature. Most wire tables will provide some means for determining the resistance of wire as temperature increases. Figure 6–4 shows *Table 310.16* of the *National Electrical Code®*. Notice that at the bottom of the table ampacity correction factors are given.

INSULATION

The type of **insulation** around the wire also partly determines the amount of current the wire is permitted to carry. Some types of insulation can withstand more heat than others, and are, therefore, permitted to carry more current. For example, in *Table 310.16*, the type of wire insulation is listed at the top of each column. Notice the different temperature ratings for the types of insulation listed. Also notice the amount of current a wire is permitted to carry for different types of insulation. Find a #2 AWG conductor on the far left-hand side of the wire table. Notice the different amounts of current this conductor is permitted to carry with different types of insulation.

VOLTAGE RATING

Wire also has a **voltage rating**. The voltage rating of wire has nothing to do with the type of material the wire is made of or its diameter. The voltage rating is determined by the type of insulation. Most wire used in industry has a voltage rating of 600 volts. The amount of voltage the insulation can effectively hold off is determined by the material the insulation is made of and its thickness.

SIZING CONDUCTORS FOR HERMETICALLY SEALED COMPRESSORS

Requirements for the installation of hermetically sealed compressors are covered in *Article 440* of the *National Electrical Code®*. Note that this section covers hermetically sealed units only and does not apply to separate motor and compressor units. *NEC® Section 440.6(A)* states that the rated-load current marked on the nameplate of the equipment is to be used in determining the rating or ampacity of the disconnecting means, branch circuit conductors, controller, fuses or circuit breakers, ground fault protection equipment, and overload protection. If the rated-load current is not shown on the equipment nameplate, the rated load current shown on the compressor is to be used. Note the difference

Table 310.16 Allowable Ampacities of Insulated Conductors Rated 0 Through 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

	Temperature Rating of Conductor (See Table 310.13.)						
	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, 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	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
Size AWG or kcmil	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			Size AWG or kcmil
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14*	20	20	25	—	—	—	—
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	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	255	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	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	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	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000
	CORRECTION FACTORS						
Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

* See 240.4(D).

Figure 6–4

between the equipment nameplate and compressor nameplate. The equipment nameplate is generally shown on the unit itself, Figure 6–5. The compressor nameplate is located on the compressor.

NEC® *Section 440.6(A) Ex. 1* states that where so marked, the branch circuit selection current shall be used instead of the rated load current to determine the rating or ampacity of the disconnecting

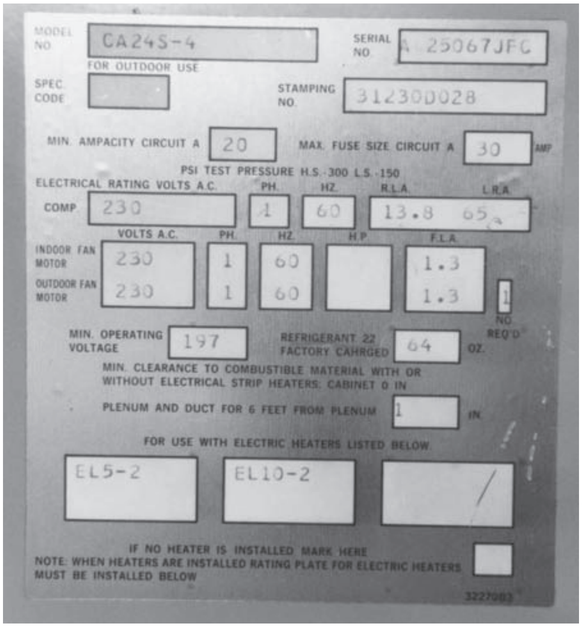


Figure 6–5
Equipment nameplate. (Source: Delmar/Cengage Learning)

means, branch circuit conductors, controller, short circuit protective device, and ground fault protective device. *NEC® Section 440.32* states that for a single motor compressor, the branch circuit conductors shall have an ampacity not less than 125% of either the motor compressor rated load current or the branch circuit selection current, whichever is greater. As a general rule the branch circuit selection current will be greater than the compressor rated load amps because the selection current includes any indoor and/or outdoor fans.

Termination Temperature

Another factor that must be taken into consideration is the temperature rating of different terminations. The termination is the point of attachment for conductors such as circuit breakers, disconnects, switches, and so forth. *NEC® Section 110.14(C)* basically states that the temperature rating of the termination cannot be exceeded. Although a wire with a higher temperature rating may be used, the ampacity of the wire must be selected on the basis of the lowest temperature rating in the circuit. Type THHN insulation has a temperature rating of 90°C, but assume that it is connected to a device with a temperature rating of 75°C. The ampacity of the wire would have to be selected on the basis of 75°C, not 90°C.

Occasionally the temperature rating of a device will be listed on the device or in the manufacturer's literature, but as a general rule it is not known. For this reason, the *National Electrical Code®* states that conductors for circuits rated at 100 amperes or less will be selected from the 60°C column, and conductors rated over 100 amperes are to be selected from the 75°C column. An exception to this is if the insulation type is rated less than 75°C as is the case with type TW and UF. If either of these two types of insulation are employed, the ampere rating of the conductor must be determined from the 60°C column regardless of the circuit current.

EXAMPLE

Assume that an equipment nameplate lists the rated load amps (RLA) of the compressor at 14.8 amps and the circuit selection current at 22 amps. To determine the correct conductor size for this unit, multiply the larger of the two rating by 125%.

$$22 \times 1.25 = 27.5 \text{ amps}$$

The next step is to determine the conductor size from *NEC® Table 310.16*. It will be assumed that copper conductors with type THWN insulation will be used for this installation. Although THWN insulation is located in the 75°C column, the conductor size will be selected from the 60°C column because the total circuit current is less than 100 amperes. *Table 310.16* indicates a #10 AWG conductor is the closest size without going under 27.5 amperes. A #10 AWG conductor will be used for this installation.

The *National Electrical Code®* also requires that a disconnecting means be located within sight from and readily accessible to the air conditioning or refrigeration equipment, Figure 6–6. The *NEC®* does permit the disconnect to be installed on or within the equipment provided it is not installed on a panel that is designed to allow access to the equipment. The disconnect may be located away from the air conditioning or refrigeration equipment provided there is a working clearance of at least 30 inches to allow service accessibility. This is to enable the service technician to disconnect power from the unit without having to enter the building to find the main

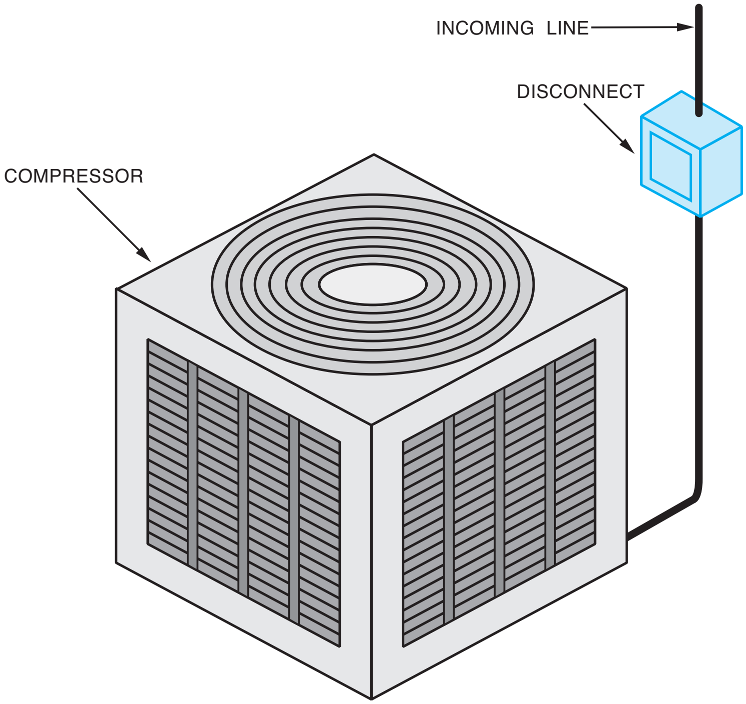


Figure 6–6
A disconnecting means must be located in sight of the compressor. (Source: Delmar/Cengage Learning)

power panel. A typical disconnect used for air conditioning service is shown in Figure 6–7.

Figure 6–7
Disconnect switch used for air conditioning equipment. (Source: Delmar/Cengage Learning)

TESTING FOR EXCESSIVE VOLTAGE DROP

Testing a unit for excessive voltage can be done with a voltmeter. First, test the voltage at the panel with the unit turned off. Assume this voltage to be 240 volts. Next, start the air conditioning unit and again check the voltage at the panel. If the voltage remains unchanged, it is an indication that there is no voltage drop at the panel and that all connections for the part of the circuit are good. If there is excessive voltage drop at the panel, it is an indication of bad connections, or the service entrance is too small for the load. For this example, assume the voltage remains at 240 volts when the unit is turned on. Next, check the voltage at the unit, Figure 6–8. If there is a significant voltage drop at the unit, it indicates that the wire size is too small and that too much voltage is being used to push current through the wire. This problem can be corrected by connecting larger wires from the panel to the unit.

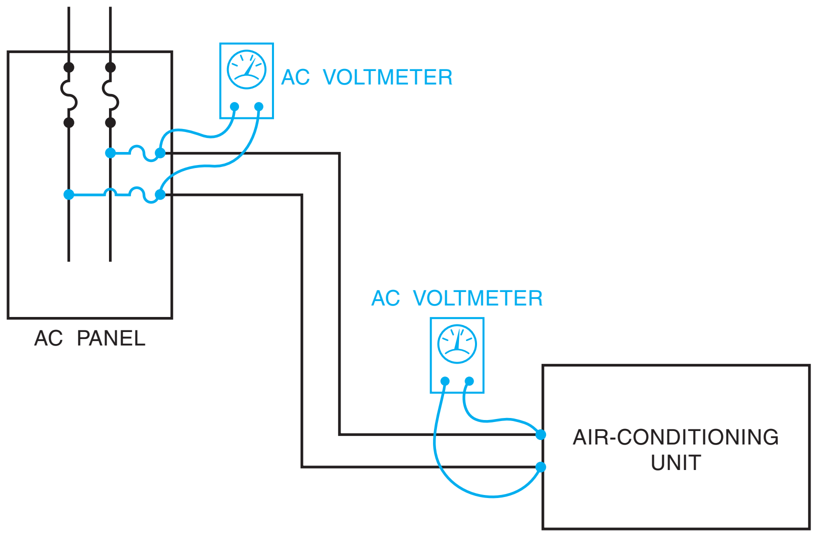


Figure 6–8
Testing for voltage drop.
(Source: Delmar/Cengage Learning)

SUMMARY

- The resistance of wire is determined by four factors:
  A. The diameter of the wire.
  B. The material the wire is made of.
  C. The length of the wire.
  D. The temperature of the wire.
- The cross-sectional area of wire is measured in circular mils.
- Circular mil area is found by squaring the diameter of the wire.
- The standard measurement for wire resistance in the English system is the mil-foot.
- Different types of materials have different resistances per mil-foot.
- The wire tables in the *National Electrical Code*® are often used to determine the size wire needed for a particular installation.
- The voltage rating of wire is determined by the type of insulation.
- Excessive voltage drop can be determined by measuring the voltage at the source and at the load when the unit is in operation.

KEY TERMS

AWG (American Wire Gauge)
circular mils
insulation
mil-foot
temperature
termination temperature
voltage rating

REVIEW QUESTIONS

1. Name four factors that determine the resistance of wire.
2. A wire has a diameter of .057 inches. What is its circular mil area?
3. What is a mil-foot of wire?
4. When the temperature of wire increases, does its resistance increase or decrease?
5. What determines the voltage rating of wire?
6. What two factors determine the amount of voltage rating a certain type of insulation will have?
7. How much resistance does 75 feet of #24 AWG wire have?
8. If a current of 4 amps flows through the wire in question 7, how much voltage will be dropped by the wire?

UNIT 7

Inductance

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the voltage and current relationship in an AC circuit containing pure resistance and pure inductance
- Discuss the properties of an inductive circuit
- Calculate values of inductive reactance
- Calculate values of impedance in circuit containing resistance and inductance
- Discuss true power, apparent power, and reactive power
- Discuss the power factor of an alternating-current circuit

Alternating-current circuits contain three basic types of loads. These are (1) resistive, (2) inductive, and (3) capacitive.

RESISTIVE CIRCUITS

The simplest of the AC loads is a circuit that contains only pure resistance, Figure 7–1. In a **pure-resistive circuit**, the voltage and current are **in phase** with each other, Figure 7–2. Voltage and current are in phase when they cross the zero line at the same point, and have their peak positive and negative values at the same time. A pure-resistive circuit is very similar to a direct-current circuit in the respect that true power or watts is equal to the voltage times the current. Examples of pure-resistive circuits are the heating elements of an electric range, an electric hot-water heater, and the resistive elements of an electric furnace.

Figure 7–1
Pure-resistive circuit. (Source: Delmar/Cengage Learning)

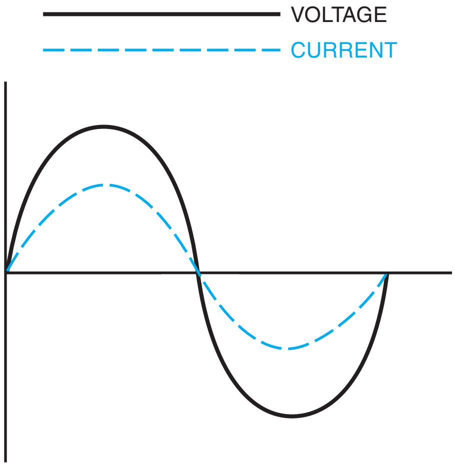


Figure 7–2
Current and voltage are in phase. (Source: Delmar/Cengage Learning)

INDUCTIVE CIRCUITS

An inductive circuit contains an inductor or coil as the load instead of a resistor, Figure 7–3. The two most common types of inductive circuits are motors and transformers. Inductors are measured in units called the **henry**. The unit of inductance is named in honor of Joseph Henry, a physicist who studied electricity. The electrical symbol for inductance is *L*.

Inductors differ from resistors in several ways. One way is that the current of an inductor is not limited by the resistance of the coil. When an inductor is connected into an AC circuit and the voltage begins to rise from zero toward its peak value, a **magnetic field** is created around the coil, Figure 7–4. As the expanding magnetic field cuts through the wires of the coil, a voltage is induced in the coil. *The voltage induced in a coil is always opposed to the voltage that creates it*. As the applied voltage begins to drop from its peak value back toward zero, the magnetic field around the inductor begins to collapse, Figure 7–5. Notice that the induced voltage is opposite in polarity to the applied voltage. An induced voltage is 180° out of phase with the applied voltage, Figure 7–6.

Figure 7–3
A pure inductive circuit. (Source: Delmar/Cengage Learning)

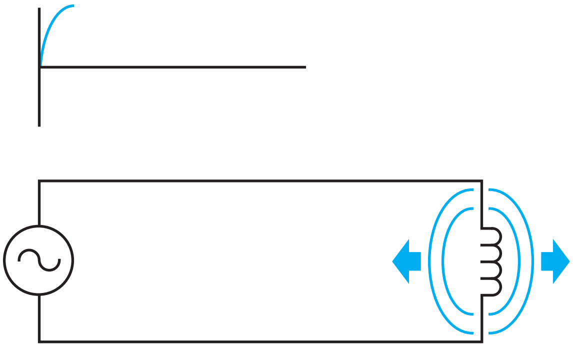


Figure 7–4
Magnetic field expands. (Source: Delmar/Cengage Learning)

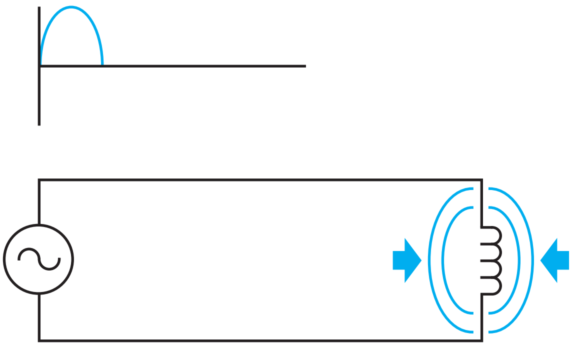


Figure 7–5
Magnetic field collapses. (Source: Delmar/Cengage Learning)

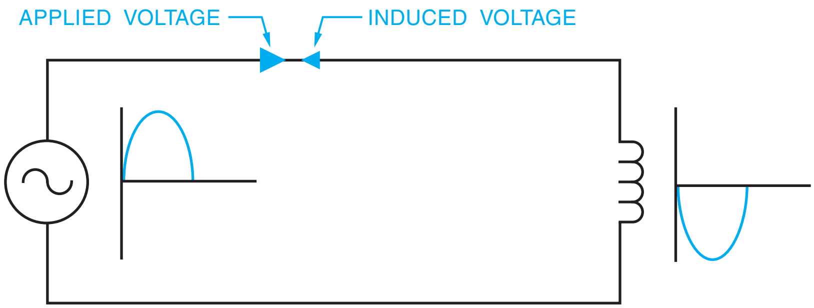


Figure 7–6
The induced voltage is opposed to the applied voltage. (Source: Delmar/Cengage Learning)

Because the induced voltage is opposed to the applied voltage, it will limit current flow through the circuit just as resistance will. Although the induced voltage of a coil will limit the current flow "like" resistance, it is not resistance and cannot be treated as resistance. The unit of measure used to describe the current-limiting effect of an induced voltage is **reactance** and is given the electrical symbol *X*. Because this reactance is caused by an inductance, it is called **inductive reactance** and is given the electrical symbol X_L (pronounced *X* sub *L*). Inductive reactance is measured in ohms just as resistance is.

The inductive reactance of a coil is determined by two factors. These are:

1. The inductance of the coil.
2. The frequency of the applied voltage.

If these factors are known, a formula can be used to find the inductive reactance of the coil. This formula is:

$X_L = 2 \times \pi \times F \times L$

X_L = inductive reactance

π = the Greek letter Pi, which has a value of 3.1416

F = the frequency of the AC voltage

L = the inductance of the coil in henrys

EXAMPLE

In the circuit shown in Figure 7–7, a coil has an inductance of .7 henrys, and is connected to a 120-volt, 60-Hz line. Find the current flow in the circuit.

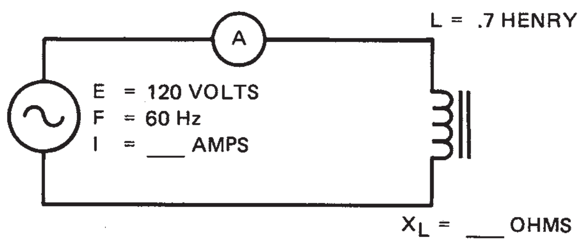


Figure 7–7
Current flow is limited by inductive reactance. (Source: Delmar/Cengage Learning)

To solve the problem, the first step is to find the amount of inductive reactance in the circuit.

$X_L = 2 \times \pi \times F \times L$

$X = 2 \times 3.1416 \times 60 \times .7$

$X_L = 263.9$ ohms

Now that the inductive reactance of the coil is known, the current flow in the circuit can be calculated. If the value of inductive reactance is used like resistance, the formula to find current in a pure-inductive circuit is $I = E/X_L$.

$$I = \frac{120}{263.9}$$

$I = .455$ amps

VOLTAGE AND CURRENT RELATIONS

As stated previously, the voltage and current in a pure-resistive circuit are in phase with each other. In a **pure-inductive circuit**, however, the current lags behind the voltage by 90°, Figure 7–8.

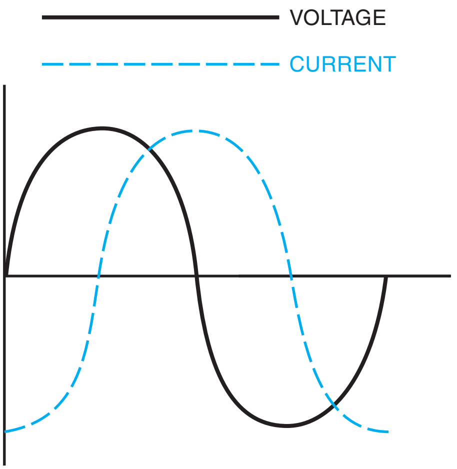


Figure 7–8
Current lags voltage by 90° in a pure inductive circuit.
(Source: Delmar/Cengage Learning)

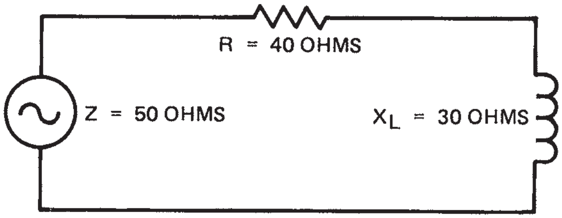


Figure 7–9
A series circuit containing resistance and inductance.
(Source: Delmar/Cengage Learning)

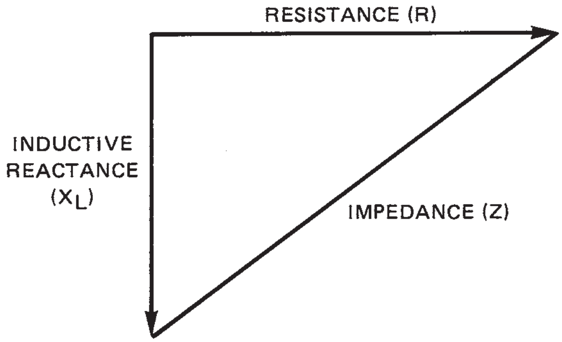


Figure 7–10
Impedance is the sum of resistance and inductive reactance. (Source: Delmar/Cengage Learning)

In this type of circuit there is no true power or watts. In a resistive circuit, the resistor limits the current flow by converting the energy of the moving electrons into heat. This conversion of one form of energy into another represents a true power loss. In an inductive circuit, the energy of the moving electrons is stored in the magnetic field created around the inductor. When the magnetic field collapses, this energy is given back into the circuit. Notice that the resistor used the electrical energy by converting it into heat, but the inductor stored the energy and then returned it to the circuit.

IMPEDANCE

In an alternating-current circuit that contains only resistance, the current is limited by the value of the resistor only. In this type of circuit the current flow can be calculated using the Ohm's law formula $I = E/R$.

In an AC circuit that contains only inductance, the current is limited only by the value of inductive reactance. In this type of circuit, the current flow can be calculated using the formula $I = E/X_L$.

In a circuit like the one shown in Figure 7–9, there are elements of both resistance and inductive reactance contained in the same circuit. In this type of circuit, it cannot be said that the current is limited by resistance, because there is also inductive reactance. It can also not be said that the current is limited by inductive reactance because of the resistance. Alternating-current circuits use a different value to represent the total amount of opposition to current flow in the circuit regardless of what type of components are found in the circuit. This value is known as **impedance** and is given the symbol Z.

The resistor and inductor in Figure 7–9 are connected in series. Because these two components are connected in series, they will be added. They cannot be added in the normal way, however, because the inductance is not in phase with the resistance. Because inductive reactance is 90° out of phase with resistance, the total amount of opposition to current flow will be the value of the hypotenuse of the right triangle formed by the resistance and inductive reactance, Figure 7–10. To find the total value of impedance in this circuit, the formula $Z = \sqrt{R^2 + X_L^2}$ can be used. If the resistor has a value of 40 ohms and the inductor has an inductive reactance of 30 ohms, the impedance will be:

$$Z = \sqrt{R^2 + X_L^2}$$
$$Z = \sqrt{40^2 + 30}$$
$$Z = \sqrt{1600 + 90}$$
$$Z = \sqrt{2500}$$
$$Z = 50 \text{ ohms}$$

APPARENT POWER

In a direct-current circuit, the true power or watts is always equal to the voltage multiplied by the current because the current and voltage are never out of phase with each other. This also is true for an AC circuit that contains only pure resistance because the voltage and current are in phase.

In a circuit that contains pure inductance, however, there is no true power or watts. In this type of circuit, the voltage multiplied by the current equals a value known as **VARs**, which stands for **Volt-Amps Reactive**. VARs is often referred to as wattless power.

The **apparent power** or **volt-amps** of an AC circuit is the applied voltage multiplied by the current flow in the circuit. The amount of apparent power as compared to the true power or VARs is determined by the elements of the circuit itself. In the circuit shown in Figure 7–11, the amount of true power is 400 watts. The amount of reactive power is 300 VARs. The apparent power is 500 volt-amps. Notice that the apparent power is found by adding the watts and VARs together in the same manner that the resistance and inductive reactance were added to find the total value of impedance. Volt-amps can be calculated by the formula:

$$\text{Volt-amps} = \sqrt{W^2 + \text{VARs}^2}$$

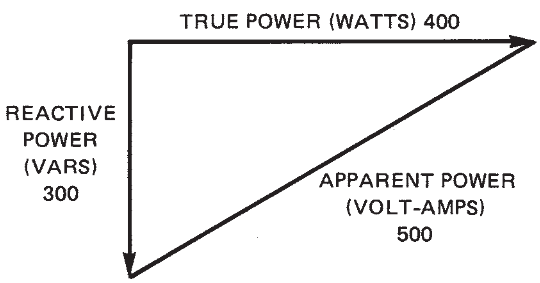


Figure 7–11
Volt-amps is the vector sum of watts and VARs.
(Source: Delmar/Cengage Learning)

POWER FACTOR

The **power factor** of an alternating-current circuit is a ratio of the apparent power compared to the true power. Power factor is important because utility companies charge industries large penalties for a poor power factor. The power factor of the circuit shown in Figure 7–11 can be found by:

$$PF = \frac{W}{VA}$$
$$PF = \frac{400}{500}$$
$$PF = .8$$
$$PF = 80\%$$

Notice in this circuit, the power factor is 80%. This means 80% of the load is resistive and 20% is reactive. If the load is pure resistive, the power factor will be 100% or **unity**.

Utility companies become very concerned about power factor because they must furnish the amount of current needed to produce the volt-amp value. The company, however, is charged by the amount of true power or watts used. In this instance, if the applied voltage is 120 volts, the utility company must supply 4.16 amps to operate the load (500 volt-amps/120 volts = 4.16 amps). The actual amount of current being used to operate the load, however, is 3.33 amps (400 watts/120 volts = 3.33 amps). Because the air conditioning load is often the major part of the electrical power consumed by an industry or office building, power factor can become an important consideration to the service technician.

SUMMARY

- In 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°.
- Inductive reactance (X_L) is the current-limiting property of inductance.
- Inductive reactance is actually a counter voltage, which opposes the applied or line voltage.
- Inductive reactance is proportional to two factors:
  A. The inductance of the coil.
  B. The frequency of the applied voltage.
- Inductive reactance is measured in ohms like resistance.
- Impedance (Z) is a measurement of the total current limiting effect in an alternating-current circuit.
- Impedance is a combination of all current limiting properties of an AC circuit and is measured in ohms.
- True power is measured in watts.
- Watts is a measurement of the amount of electrical energy converted to some other form such as heat or mechanical.
- VARs is a measure of the amount of power in a pure inductive circuit sometimes referred to as wattless power.
- Apparent power or volt amperes (VA) is a combination of true power or watts and VARs.
- In an AC circuit, apparent power is determined by multiplying the applied voltage by the circuit current.
- Power factor (PF) is a comparison of the amount of true power with the apparent power in an alternating-current circuit.
- Power factor is measured in a percent.

KEY TERMS

apparent power
henry
impedance
inductive reactance
in phase
magnetic field
power factor
pure-inductive circuit
pure-resistive circuit
reactance
unity
VARs (Volt-Amps Reactive)
volt-amps

REVIEW QUESTIONS

1. Name the three basic types of alternating-current loads.
2. What type of load always has its voltage and current in phase with each other?

3. In a pure-inductive circuit, how many degrees out of phase is the current with the voltage?
4. Does the current lead or lag the voltage in question 3?
5. What electrical value is used to measure inductance?
6. What is inductive reactance?
7. What electrical value is used to measure the total opposition to current flow in an AC circuit?
8. What is power factor?

UNIT 8

Capacitance

OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operating theory of a capacitor
- List the factors that determine the amount of capacitance a capacitor will have
- Discuss the voltage and current relationship in an AC circuit containing pure capacitance
- Discuss the voltage and current relationship in an AC circuit containing resistance and capacitance
- Compute values of capacitive reactance
- Compute values of impedance for circuits that contain both resistance and capacitive reactance
- Discuss power factor correction
- Compute the amount of capacitance needed to correct the power factor of a motor
- Discuss different types of capacitors and methods for testing

The third type of alternating-current load to be discussed is **capacitance**. A capacitor can be made by separating two metal plates with an insulating material, Figure 8–1. The insulating material used to isolate the plates from each other is called the **dielectric**. There are three factors that determine how much capacitance a capacitor will have. These are:

1. The surface area of the plates.
2. The distance between the plates.
3. The type of dielectric material used between the plates.

CHARGING A CAPACITOR

In Figure 8–2, the terminals of a capacitor have been connected to a battery. Electrons are negative particles. Therefore, the positive terminal of

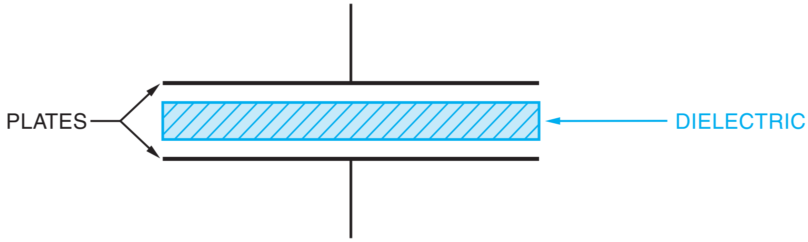


Figure 8–1
A capacitor is made with two metal plates separated by a dielectric.
(Source: Delmar/Cengage Learning)

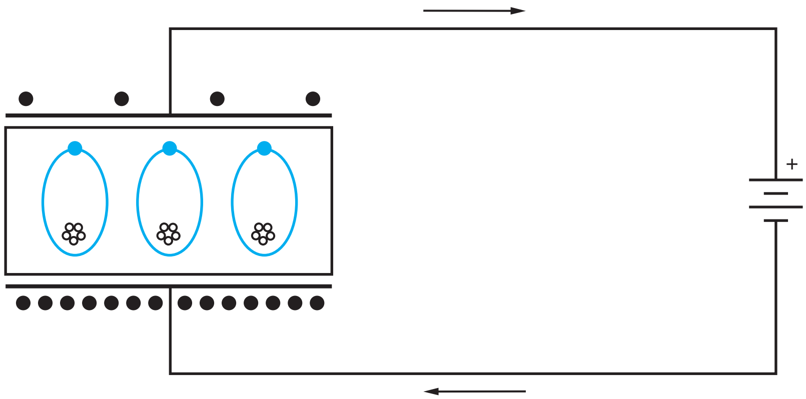


Figure 8–2
An electrostatic charge is stored in the atoms of the dielectric. (Source: Delmar/Cengage Learning)

the battery attracts electrons from one plate of the capacitor. The negative terminal of the battery will cause electrons to flow to the other capacitor plate. This flow of current will continue until the voltage across the capacitor plates is equal to the battery voltage. If the battery is disconnected, the capacitor will be left in a charged state. ***CAUTION:*** *It is the habit of some people to charge a capacitor to a high voltage and then hand the capacitor to another person. While 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 certain conditions, a capacitor can have enough power to cause a person's heart to go into fibrillation.*

ELECTROSTATIC CHARGE

Notice the illustration of the atoms in the dielectric material in Figure 8–2. When a capacitor has been charged, the negative electrons of the dielectric material are repelled from the negative plate of the capacitor and attracted to the positive plate. This causes the electron orbit of the atoms in the dielectric to extend. This places the atoms of the dielectric material in tension. This is known as **dielectric stress**. Placing the atoms of the dielectric under stress has the same effect as drawing back a bow and arrow and holding it, Figure 8–3.

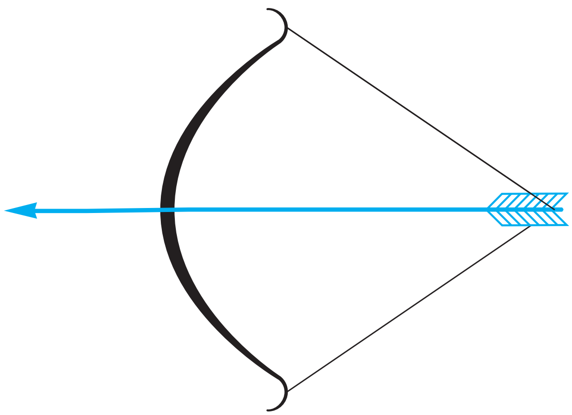


Figure 8–3
Dielectric stress is similar to drawing back a bow and arrow, and holding it. (Source: Delmar/Cengage Learning)

The amount of dielectric stress is determined by the voltage between the plates. The greater the voltage, the greater the dielectric stress. If the voltage becomes too great, the dielectric will break down and destroy the capacitor. This is the reason capacitors have a voltage rating that must be followed.

The energy of a capacitor is stored in the dielectric and is known as 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 charged capacitor are shorted together, it has the same effect as releasing the drawn bow in Figure 8–3. The arrow will be propelled forward at great speed. The same is true for the electrons of the capacitor. When the electron orbits of the dielectric snap back, the electrons stored on the negative capacitor plate are propelled toward the positive plate at great speed.

CAPACITOR RATINGS

Capacitors are rated in units called the **farad**. The farad is actually such a large amount of capacitance it is not practical to use. For this reason a unit called the **micro-farad** is generally used. A micro-farad is one millionth of a farad. The Greek lowercase letter mu is used to symbolize micro, μ. The term micro-farad is indicated by combining mu and lowercase f, μf. Because the letter mu is not included on a standard typewriter, the term micro-farad is sometimes shown as uf or mf. All of these terms mean the same thing.

Another term used is the **pico-farad**. This termis used for extremely small capacitors found in electronics applications. A pico-farad is one millionth of a micro-farad and is generally shown as μμf or pf.

When AC voltage is applied to a capacitor, Figure 8–4, the plates of the capacitor are alternately charged and discharged each time the current changes direction of flow. When a capacitor is charged, the voltage across its plates becomes the same as this applied voltage. As the voltage across the plates of a capacitor increases, it offers resistance to the flow of current. The applied voltage must continually overcome the voltage of the capacitor to produce current flow. The current in a **pure-capacitive circuit** is limited by the voltage of the charged capacitor. Because current is limited by a counter voltage and not resistance, the counter voltage of the capacitor is referred to as reactance. Recall that the symbol for reactance is X. Because this reactance is caused by capacitance, it is called **capacitive reactance** and is symbolized by X_C (pronounced X sub c).

Figure 8–4
A pure capacitive circuit. (Source: Delmar/Cengage Learning)

The amount of capacitive reactance in a circuit is determined by two factors. These are:

1. Frequency of the AC voltage.
2. The size of the capacitor.

If the frequency of the line and the capacitance rating of the capacitor are known, the capacitive reactance can be found using the following formula:

$$X_C = \frac{1}{2 \times \pi \times F \times C}$$

The value of capacitive reactance is measured in ohms. In the formula to find capacitive reactance:

X_C = Capacitive Reactance

π = The Greek letter Pi, which has a value of 3.1416

F = Frequency in Hz

C = The value of capacitance in farads. Because most capacitors are rated in micro-farads, be sure to write the capacitance value in farads. This can be done by dividing the micro-farad rating by 1,000,000, or moving the decimal point six places to the left. Example: to change a 50-μf capacitor to a value expressed in farads, move the decimal point after the 50 six places to the left. This capacitor has a value of .000050 farads.

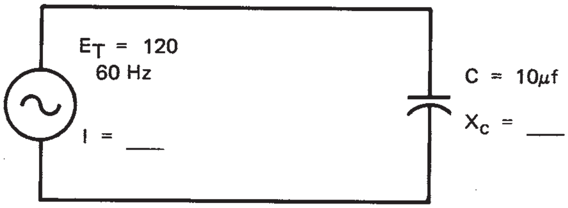


Figure 8–5
Capacitive reactance limits current flow. (Source: Delmar/Cengage Learning)

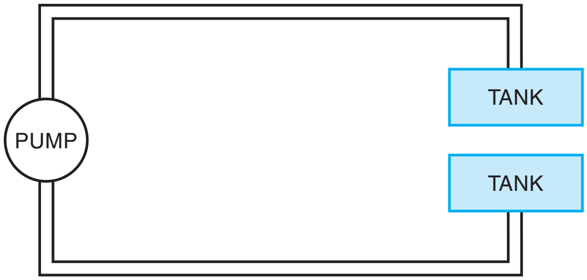


Figure 8–6
Water flows in this system in a manner similar to the way current flows in a capacitive circuit. (Source: Delmar/Cengage Learning)

EXAMPLE

Find the current flow in the circuit shown in Figure 8–5.

Solution: To find the current flowing in this circuit, the amount of capacitive reactance of the capacitor must first be found.

$$X_C = \frac{1}{2 \times \pi \times F \times C}$$

$$X_C = \frac{1}{2 \times 3.1416 \times 60 \times .000010}$$

$$X_C = \frac{1}{.0037699}$$

$$X_C = 265.2 \text{ ohms}$$

Now that the capacitive reactance of the circuit is known, the value of current can be found using the formula: $I = E/X_C$.

$$I = \frac{120}{265.2}$$

$$I = .452 \text{ amps}$$

CURRENT FLOW IN A CAPACITIVE CIRCUIT

Notice that a capacitor is constructed of two metal plates separated by an insulator. One of the metal plates is connected to one side of the circuit, and the other metal plate is connected to the other side of the circuit. Because there is an insulator separating the two plates, current cannot flow through a capacitor. When a capacitor is connected into a direct-current circuit, current will flow until the capacitor has been charged to the value of the applied voltage, and then stop. When a capacitor is connected into an alternating-current circuit, current will "appear" to flow through the capacitor. This is because the plates of the capacitor are alternately charged and discharged each time the current reverses direction. To understand this concept better, refer to the water circuit shown in Figure 8–6. In this illustration, a water pump is connected to two tanks. The pump is used to pump water back and forth between the two tanks. When one tank becomes full, the direction of the pump is reversed and water is pumped from the full tank back into the empty tank. Notice that there is no complete loop in this hydraulic circuit for water to flow from one side of the pump to the other, but water does flow because it is continuously pumped from one tank to the other.

CURRENT AND VOLTAGE RELATIONSHIPS

In a pure-capacitive circuit, the voltage and current are out of phase with each other. Figure 8–7 shows that the current in a pure-capacitive circuit leads the voltage by 90°. Because the voltage and current are 90° out of phase with each other, there is no true power or watts consumed in a pure-capacitive circuit. The capacitor stores the energy in an electro-static field, and then returns it to the circuit at the end of each half cycle.

In the circuit shown in Figure 8–8, a resistor and capacitor are connected in series with each other. Since this circuit contains elements of both resistance and capacitive reactance, the current is limited by impedance. The impedance for a circuit

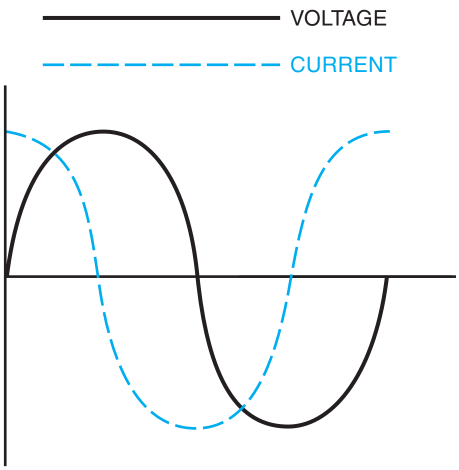


Figure 8–7
Current leads voltage by 90° in a pure capacitive circuit. (Source: Delmar/Cengage Learning)

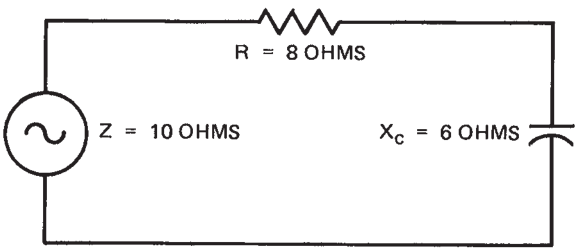


Figure 8–8
Impedance must be used to determine the current flow in a circuit that contains resistance and capacitive reactance. (Source: Delmar/Cengage Learning)

of this type can be found by using the formula $Z = \sqrt{R^2 + X_C^2}$. Notice this is the same basic formula as the one used to find the impedance of a circuit that contains both resistance and inductive reactance. The impedance of the circuit shown in Figure 8–8 can be found by the following:

$$Z = \sqrt{R^2 + X_C^2}$$
$$Z = \sqrt{8^2 + 6^2}$$
$$Z = \sqrt{64 + 36}$$
$$Z = \sqrt{100}$$
$$Z = 10 \text{ ohms}$$

Figure 8–9 shows a vector diagram of the circuit in Figure 8–8.

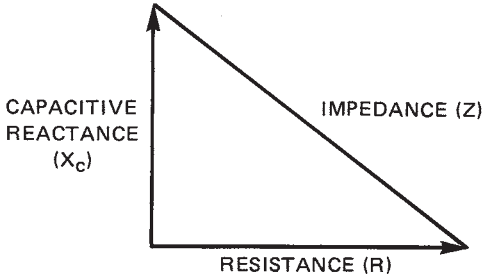


Figure 8–9
Impedance is the vector sum of R and X_C. (Source: Delmar/Cengage Learning)

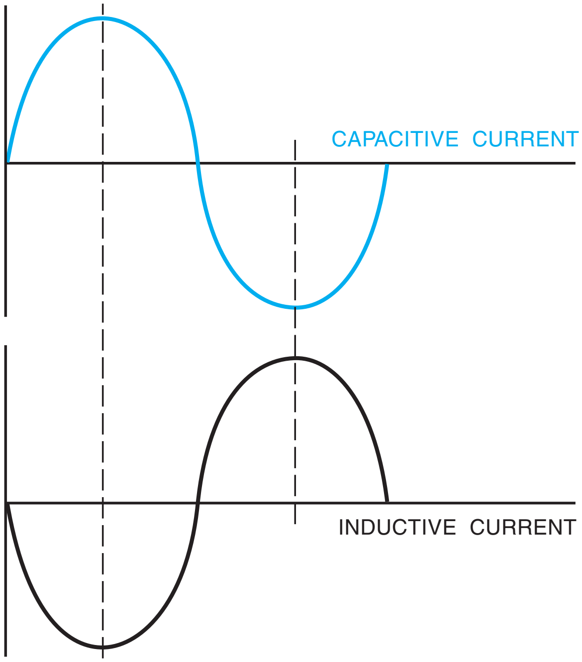


Figure 8–10
Capacitive and inductive current are 180° out of phase with each other. (Source: Delmar/Cengage Learning)

POWER FACTOR CORRECTION

Because the current flow in a capacitive circuit leads the voltage by 90° and the current in an inductive circuit lags the voltage by 90°, the current of a capacitive circuit is in direct opposition to the current of an inductive circuit. Figure 8–10 illustrates the currents of capacitive and inductive circuits

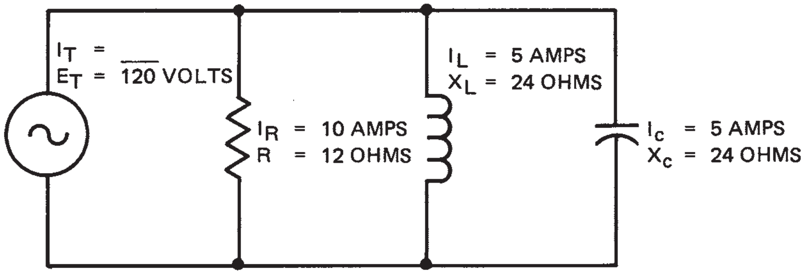


Figure 8–11
A parallel circuit has resistance, inductance, and capacitance.
(Source: Delmar/Cengage Learning)

as compared with each other. These two currents are 180° out of phase with each other. When the capacitive current is at its peak positive value, the inductive current is at its peak negative value. When the capacitive current is at its peak negative value, the inductive current is at its peak positive value. Because these two currents are in direct opposition, one can be used to cancel the other.

The circuit shown in Figure 8–11 shows a parallel circuit that contains a resistor, an inductor, and a capacitor. The applied voltage of the circuit is 120 volts at 60 Hz. Because this is a parallel circuit, the voltage applied to each component will be the same—120 volts. The resistor has a resistance of 12 ohms. This permits a current flow of 10 amps through the resistor (120/12 = 10). The inductor has an inductive reactance of 24 ohms. This permits a current flow through the inductor of 5 amps (120/24 = 5). The capacitor has a capacitive reactance of 24 ohms. This permits a current flow through the capacitor of 5 amps.

QUESTION

What is the total current flow in the circuit? In a parallel circuit, current is added. Therefore, it would appear that the current flow would be 20 amps (10 + 5 + 5 = 20). The currents of this circuit, however, are out of phase with each other. Figure 8–12 shows a vector diagram of this circuit. Notice that the 5 amps of capacitive current is 180° out of phase with the 5 amps of inductive current. These two currents will cancel each other. The AC alternator sees only the resistance in this circuit. The current is, therefore, the same as the current flow through the resistor, or 10 amps.

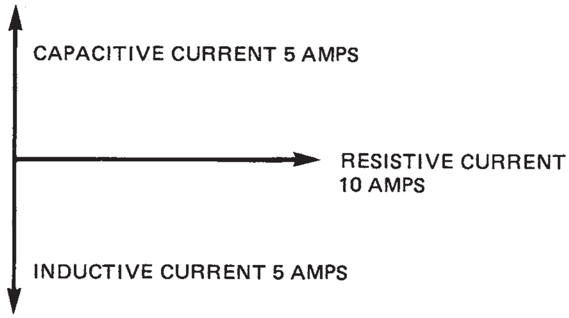


Figure 8–12
Capacitive current and inductive current are 180° out of phase with each other. (Source: Delmar/Cengage Learning)

POWER FACTOR CORRECTION OF A MOTOR

In the circuit shown in Figure 8–13, an AC induction motor is connected to a 120-volt line. A wattmeter is used to measure the amount of true power in the circuit. For this example it will be assumed that the wattmeter has a reading of 720 watts. An ammeter has also been inserted in the circuit. Assume the ammeter has a reading of 10 amps. The apparent power or volt-amp value for this circuit is 1,200 VA (120 volts × 10 amps = 1,200 VA). The power factor of this circuit can now be computed using the formula ($PF = W/VA$).

$$PF = \frac{W}{VA}$$

$$PF = \frac{720}{1200}$$

$$PF = .6 \text{ or } 60\%.$$

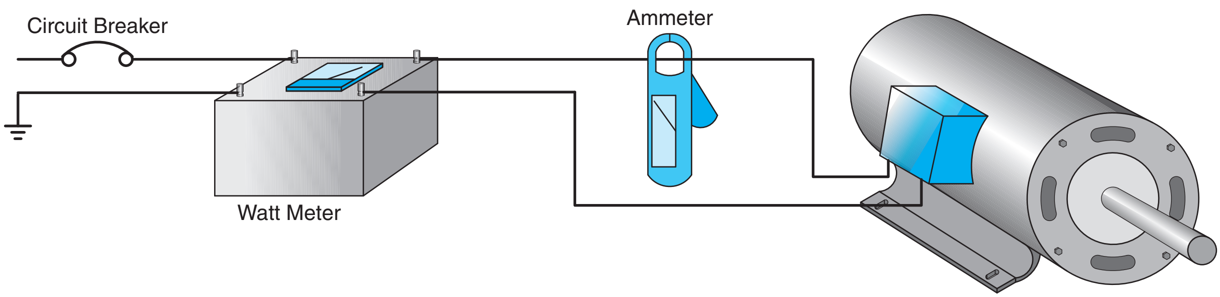


Figure 8–13
Finding the power factor of a motor. (Source: Delmar/Cengage Learning)

If the power factor of this motor is to be corrected, it must be determined how much of this circuit is comprised of true power and how much is composed of reactive power. Because the true power (watts) and the apparent power (volt-amps) is known, the reactive power (VARs) can be found using the following formula:

$$\text{VARs} = \sqrt{VA^2 - W^2}$$

$$\text{VARs} = \sqrt{1200^2 - 720^2}$$

$$\text{VARs} = \sqrt{1{,}440{,}000 - 518{,}400^2}$$

$$\text{VARs} = \sqrt{921{,}600}$$

$$\text{VARs} = 960$$

Because a motor is an inductive device, the reactive power in this circuit can be canceled by an equal amount of capacitive VARs. If a capacitor of the correct value is connected in parallel with the motor, the power factor will be corrected. To find the correct value of capacitance, determine the amount of capacitance needed to produce a VAR reading of 960. The amount of capacitive reactance can be found using the formula:

$$X_C = \frac{E^2}{\text{VARs}}$$

$$X_C = \frac{120^2}{960}$$

$$X_C = 15 \text{ ohms}$$

The amount of capacitance needed to produce 15 ohms of capacitive reactance at 60 Hz can be calculated using the following formula:

$$C = \frac{1}{2 \times \pi \times F \times X_C}$$

$$C = \frac{1}{2 \times 3.1416 \times 60 \times 15}$$

$$C = \frac{1}{5654.88}$$

$$C = .0001768 \text{ farads}$$

The answer for the value of C is in farads. To convert farads to micro-farads, multiply the answer by 1,000,000, or move the decimal point 6 places to the right .0001768 farads becomes 176.8 µf. If a capacitor of this value is connected in parallel with the motor as shown in Figure 8–14, the power factor will be corrected.

CAPACITOR TYPES

The most common types of capacitors used in the air conditioning field fall into two categories. One kind is known as an oil-filled type. Figure 8–15 shows a photograph of this type of capacitor. The **oil-filled capacitor** is made with two metal foil plates separated by paper. The paper is soaked in a special dielectric oil. These capacitors are true AC capacitors and are generally used as the run capacitors on many single-phase air conditioning compressors. They are also used as the starting capacitors on some units. The important ratings on these capacitors are the micro-farad rating and the voltage rating. The voltage rating of a capacitor should never be exceeded. It is permissible to use a capacitor of higher voltage

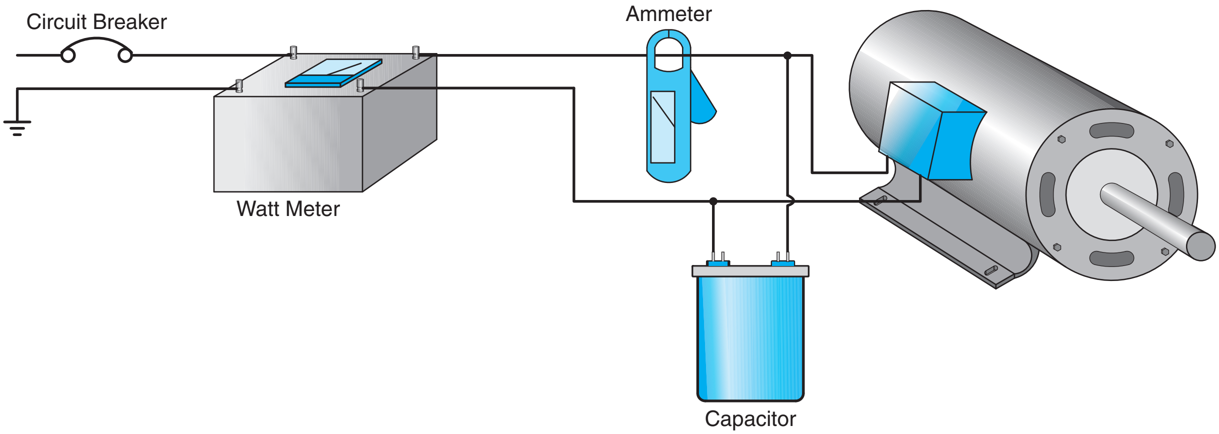


Figure 8–14
A capacitor corrects the motor power factor. (Source: Delmar/Cengage Learning)

Figure 8–15
Oil-filled capacitor. (Courtesy Westinghouse Electric Corp.)

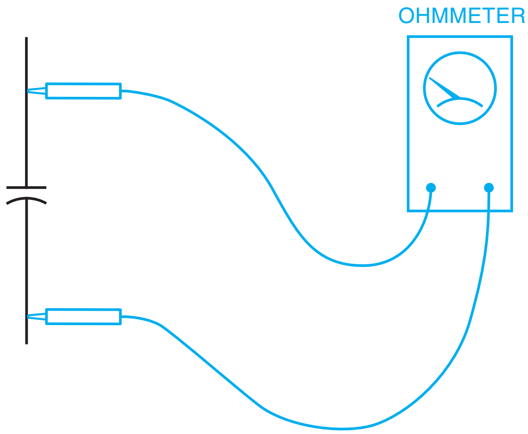


Figure 8–16
Testing a capacitor with an ohmmeter. (Source: Delmar/Cengage Learning)

rating, but never use a capacitor with less voltage rating.

The second type of capacitor frequently used in air conditioning systems is the **AC electrolytic capacitor**. The AC electrolytic capacitor is used as the starting capacitor on many small single-phase motors. This type of capacitor is designed to be used for a short period of time only. If an AC electrolytic capacitor were to be used in a continuous circuit such as the running capacitor of a compressor, it would fail in a short period of time. The advantage of the AC electrolytic capacitor is that a large amount of capacitance can be housed in a small case size. This makes the AC electrolytic capacitor a good choice for starting circuits, because the capacitor is in the circuit for only a few seconds when the motor is started.

TESTING A CAPACITOR

Capacitors can be tested for a short with an ohmmeter. If an ohmmeter is connected across the terminals of a capacitor as shown in Figure 8–16, the meter should show a deflection up scale and then return to infinity ohms. The deflection up scale indicates current flow to the capacitor when it is being charged by the ohmmeter battery. If the leads of the ohmmeter are reversed, the meter should deflect twice as far up scale and then return to infinity ohms.

The ohmmeter test basically indicates if the capacitor is shorted or not. A short indicates the dielectric has been punctured. This test will not indicate a broken plate, which would result in a lower capacitance value. Many digital meters contain a capacitance testing function, as shown in Figure 8–17. These meters actually measure the capacitance value, which can be compared to the rating marked on the capacitor.

Neither of these tests, however, can measure the dielectric strength. A capacitor may test OK with an ohmmeter or digital meter but break down when connected to line voltage. Ohmmeters and common digital meters do not supply enough voltage to test the dielectric at rated voltage. To test the dielectric strength, a dielectric test set should be used, as shown in Figure 8–18. The dielectric test set is sometimes referred to as a *hipot* because it provides a high potential or high voltage. The dielectric tester can provide rated voltage to the capacitor, and a microamperes meter measures any leakage current.

Figure 8–17
Digital meter capable of measuring capacitance.
(Source: Delmar/Cengage Learning)

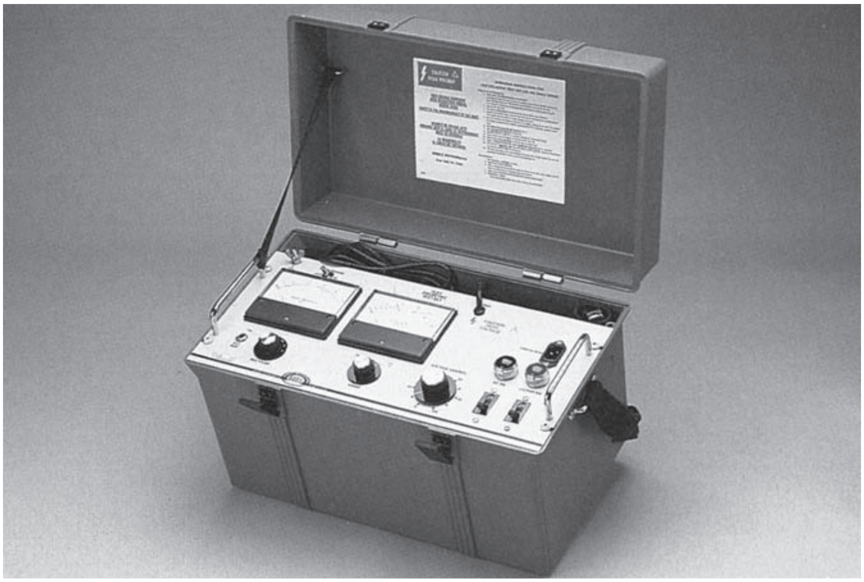


Figure 8–18
A dielectric test set. (Courtesy of Megger®)

SUMMARY

- A capacitor can be constructed by separating two metal plates with an insulating material.
- The insulating material is called the dielectric.
- Three factors that determine the amount of capacitance a capacitor will have are
  A. The surface area of the plates.
  B. The distance between the plates.
  C. The type of dielectric material used.
- Most of the energy of a capacitor is stored in an electrostatic charge.
- Capacitors can produce extremely high current for a short period of time.
- The basic unit of capacitance is the farad.
- Capacitance values are generally rated in micro-farads (μf), which are one-millionth of a farad.
- In an AC circuit containing pure capacitance, the current is limited by capacitive reactance.
- In a pure-capacitive circuit the current leads the voltage by 90 electrical degrees.
- Capacitors are often used to correct the power factor of a motor.

KEY TERMS

AC electrolytic capacitor
capacitance
capacitive reactance
dielectric
dielectric stress
electrostatic charge
farad
micro-farad
oil-filled capacitor
pico-farad
pure-capacitive circuit

REVIEW QUESTIONS

1. What three factors determine the capacitance of a capacitor?
2. What is the dielectric of a capacitor?
3. In what type of field is the energy of a capacitor stored?
4. In a pure-capacitive circuit, how many degrees are the current and voltage out of phase with each other?
5. Does a capacitive current lead the voltage or lag the voltage?
6. What limits the current in a pure capacitive circuit?
7. Name two common types of capacitors used in the air conditioning field.
8. What type of capacitor is generally used as the running capacitor on many air conditioning compressors?
9. What is the advantage of an AC electrolytic capacitor?
10. What is the disadvantage of an AC electrolytic capacitor?

SECTION 2

Control Circuits