Principles of Basic Electricity

There is an urgent need to stop subsidizing the fossil fuel industry, dramatically reduce wasted energy, and significantly shift our power supplies from oil, coal, and natural gas to wind, solar, geothermal, and other renewable energy sources.

—Bill McKibben, author and environmentalist

INTRODUCTION*

1. Do I need to be an electrical engineer?
2. Do I need to be an electrician?
3. Do I need electrical work experience?

When I was teaching renewable energy and other environmental courses, these three questions were among those most frequently asked by my renewable energy students, potential students, and curious wannabes. The sample curriculum sheet for a renewable energy associate of applied science degree (see Table 3.1) that I provided upon enrollment or by request always gave rise to many questions. So, now let’s answer those three questions:

1. No, not exactly.
2. No, not exactly.
3. No, not exactly.

The “no” part of the answer is clear; no usually means no. But how about the “not exactly” part of the answer? I say “not exactly” because if you are an electrical engineer, an electrician, or a person with electrical work experience then you are a huge step ahead of those who desire to work in the renewable energy field. Consider, for example, Table 3.1 and its slate of electrical subject areas and then consider the energy producers or converters such as wind turbines, solar technology, fuel cells, and hydropower plants—these renewable energy sources produce electricity in one form or another. In most cases, they transform mechanical energy into electrical energy, such as the turning of wind turbines that turn generators, solar production of steam to turn turbines that turn generators, or chemical reactions that produce electricity to power an electrical motor.

Because the renewable energy practitioner must have a sound grounding or foundation in basic electrical principles, this chapter is included in this book. Again, you do not need to be an electrical engineer or an electrician or have worked in the electrical field to become a competent renewable energy practitioner but you need to have a fundamental knowledge of the principles of basic electricity.

BASIC ELECTRICAL PRINCIPLES

People living and working in modern societies generally have little difficulty in recognizing electrical equipment; electrical equipment is everywhere and (if one pays attention to his or her surroundings) is easy to spot. Despite its great importance in our daily lives, however, few of us probably stop

The word “electricity” is derived from the Greek word electron, meaning “amber.” Amber is a translucent (semitransparent), yellowish, fossilized mineral resin. The ancient Greeks used the term “electric force” to describe the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the nature of this force, and they could
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not answer the question, “What is electricity?” This question still remains unanswered. Today, we often attempt to answer this question by describing the effect and not the force. That is, the standard answer given in physics is that electricity is the “force that moves electrons,” which is about the same as defining a sail as “the force that moves a sailboat.”

At the present time, we know little more about the fundamental nature of electricity than the ancient Greeks did, but we have made tremendous strides in harnessing and using it. As with many other unknown (or unexplainable) phenomena, elaborate theories concerning the nature and behavior of electricity have been advanced and have gained wide acceptance because of their apparent truth—and because they work.

Scientists have determined that electricity seems to behave in a constant and predictable manner in given situations or when subjected to given conditions. Faraday, Ohm, Lenz, and Kirchoff described the predictable characteristics of electricity and electric current in the form of certain rules. These rules are often referred to as laws. Thus, although electricity itself has never been clearly defined, its predictable nature and easily used nature have made it one of the most widely used power sources in modern times.

The bottom line: We can learn about electricity by becoming familiar with the rules, or laws, that apply to the behavior of electricity and by understanding the methods of producing, controlling, and using it. Learning about electricity, then, can be accomplished without ever having determined its fundamental identity.

You are probably scratching your head, puzzled. We understand the main question running through your brain at this exact moment: “This is a section in the text about the physics of electricity and the author can’t even explain what electricity is?” That is correct; I cannot. The point is, no one can definitively define electricity. Electricity is one of those subject areas where the old saying that “we don’t know what we don’t know about it” fits perfectly.

Only a few theories about electricity have so far stood the test of extensive analysis and much time (relatively speaking, of course). One of the oldest and the most generally accepted theories concerning electric current flow (or electricity) is known as the electron theory. The electron theory basically states that electricity or current flow is the result of the flow of free electrons in a conductor. Thus, electricity is the flow of free electrons or simply electron flow. This is how this text defines electricity: Electricity is the flow of free electrons. Electrons are extremely tiny particles of matter. To gain an understanding of electrons and exactly what is meant by electron flow, it is necessary to briefly review our earlier discussion about the structure of matter.

Structure of Matter

Matter is anything that has mass and occupies space. To study the fundamental structure or composition of any type of matter, it must be reduced to its fundamental components. All matter is made of molecules, or combinations of atoms (from the Greek word for “not able to be divided”), that are bound together to produce a given substance, such as salt, glass, or water. For example, if you keep dividing water into smaller and smaller drops, you would eventually arrive at the smallest particle that was still water. That particle is the molecule, which is defined as the smallest bit of a substance that retains the characteristics of that substance.

A molecule of water (H₂O) is composed of one atom of oxygen and two atoms of hydrogen. If the molecule of water was further subdivided, only unrelated atoms of oxygen and hydrogen would remain, and the water would no longer exist as such. Thus, the molecule is the smallest particle to which a substance can be reduced and still be called by the same name. This applies to all substances—solids, liquids, and gases.

Note: Molecules are made up of atoms, which are bound together to produce a given substance.
Atoms are composed, in various combinations, of subatomic particles of electrons, protons, and neutrons. These particles differ in weight (a proton is much heavier than the electron) and charge. We are not concerned with the weights of particles in this text, but the charge is extremely important in electricity. The electron is the fundamental negative (–) charge of electricity. Electrons revolve about the nucleus or center of the atom in paths of concentric orbits, or shells. The proton is the fundamental positive (+) charge of electricity. Protons are found in the nucleus. The number of protons within the nucleus of any particular atom determines the atomic number of that atom; for example, the helium atom has two protons in its nucleus so the atomic number is 2. The neutron, which is the fundamental neutral charge of electricity, is also found in the nucleus.

Most of the weight of the atom is in the protons and neutrons of the nucleus. Whirling around the nucleus are one or more negatively charged electrons. Normally, there is one proton for each electron in the entire atom so the net positive charge of the nucleus is balanced by the net negative charge of the electrons rotating around the nucleus (see Figure 3.1).

Note: Most batteries are marked with the symbols + and – or even with the abbreviations POS (positive) and NEG (negative). The concept of a positive or negative polarity and its importance in electricity will become clear later; however, for the moment, you need to remember that an electron has a negative charge and that a proton has a positive charge.

We stated earlier that in an atom the number of protons is usually the same as the number of electrons. This is an important point because this relationship determines the kind of element in question (the atom is the smallest particle that makes up an element; an element retains its characteristics when subdivided into atoms). Figure 3.2 provides simplified drawings of atoms of various
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materials based on the concept of electrons orbiting about the nucleus. Hydrogen, for example, has a
nucleus consisting of one proton, around which rotates one electron. The helium atom has a nucleus
containing two protons and two neutrons with two electrons encircling the nucleus. Both of these
elements are electrically neutral (or balanced) because each has an equal number of electrons and
protons. Because the negative (−) charge of each electron is equal in magnitude to the positive (+)
charge of each proton, the two opposite charges cancel.

A balanced (neutral or stable) atom has a certain amount of energy that is equal to the sum of the
energies of its electrons. Electrons, in turn, have different energies called energy levels. The energy
level of an electron is proportional to its distance from the nucleus; therefore, the energy levels of
electrons in shells farther from the nucleus are higher than the energy levels of electrons in shells
closer to the nucleus.

When an electric force is applied to a conducting medium, such as copper wire, electrons in the
outer orbits of the copper atoms are forced out of orbit (they are liberated or freed) and travel along
the wire. This electrical force, which forces electrons out of orbit, can be produced in a number of
ways, such as by moving a conductor through a magnetic field; by friction, as when a glass rod is
rubbed with cloth (silk); or by chemical action, as in a battery.

When the electrons are forced from their orbits they are referred to as free electrons. Some of the
electrons of certain metallic atoms are so loosely bound to the nucleus that they are relatively free to
move from atom to atom. These free electrons constitute the flow of an electric current in electrical
conductors. If the internal energy of an atom is raised above its normal state, the atom is said to be
excited. Excitation may be produced by causing the atoms to collide with particles that are impelled
by an electric force, as shown in Figure 3.3. In effect, energy is transferred from the electric source
to the atom. The excess energy absorbed by the atom may be sufficient to cause loosely bound outer
electrons (as shown in Figure 3.3) to leave the atom, resisting the force that acts to hold them within.

Note: An atom that has lost or gained one or more electrons is said to be ionized. If the atom loses
electrons it becomes positively charged and is referred to as a positive ion. Conversely, if the atom
gains electrons, it becomes negatively charged and is referred to as a negative ion.

Note: When an electric force is applied to a copper wire, free electrons are displaced from the
copper atoms and move along the wire, producing an electric current, as shown in Figure 3.3.

CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

Electric current moves easily through some materials but with greater difficulty through others.
Substances that permit the free movement of a large number of electrons are conductors. The most
widely used electrical conductor is copper because of its high conductivity and cost effectiveness.
Electrical energy is transferred through a copper or other metal conductor by the movement of free
electrons that migrate from atom to atom inside the conductor (see Figure 3.3). Each electron moves
a very short distance to the neighboring atom, where it replaces one or more electrons by forcing
them out of their orbits. The replaced electrons repeat the process in other nearby atoms until their
movement is transmitted throughout the entire length of the conductor. A good conductor is said
to have a low opposition, or resistance, to the electron (current) flow. Below are listed many of the
metals commonly used as electric conductors; the best conductors appear at the top of the list, the
poorer ones lower:
Silver
Copper
Gold
Aluminum
Zinc
Brass
Iron
Tin
Mercury

Note: If lots of electrons flow through a material with only a small force (voltage) applied, we refer to that material as a conductor. A convenient way in which to understand the purpose and function of an electrical conductor is to visualize a pipe or other conveyor of water or other liquid or gaseous substance. Just as a liquid or gas is conveyed or conducted through a pipe, so too are electrons (electricity) through a conductor. Force to push water or other liquid through a pipe is applied by a pump; in the case of electricity, voltage pushes the electrons. It is important to remember that in an electrical circuit voltage does not move; rather, voltage is the force that makes electrons move.

Note: The movement of each electron in copper wire, for example, takes a very small amount of time; it is almost instantaneous. This is an important point to keep in mind later in the book, when it might seem that events in an electrical circuit occur simultaneously.

Although electron motion is known to exist to some extent in all matter, some substances, such as rubber, glass, and dry wood, have very few free electrons. In these materials, large amounts of energy must be expended to break the electrons loose from the influence of the nucleus. Substances containing very few free electrons are called insulators. Insulators are important in electrical work because they prevent the current from being diverted from the wires, which in turn helps to prevent electrocutions and fires. Below are some materials that we often use as insulators in electrical circuits; these materials are listed in decreasing order of their ability to withstand high voltages without conducting:

- Rubber
- Mica
- Wax or paraffin
- Porcelain
- Bakelite
- Plastics
- Glass
- Fiberglass
- Dry wood
- Air

A material that is neither a good conductor nor a good insulator is called a semiconductor. Silicon and germanium are substances that fall into this category. Because of their peculiar crystalline structure, these materials may, under certain conditions, act as conductors and, under other conditions, as insulators. As the temperature is raised, however, a limited number of electrons become available for conduction.

Note: If the voltage is large enough, even the best insulators (rubber, plastic, wood) will break down and allow the electrons to flow.
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Static Electricity

Electricity at rest is often referred to as static electricity. More specifically, when two bodies of matter with unequal charges are near one another, an electric force is exerted between them because of their unequal charges; however, because they are not in contact, their charges cannot equalize. Static electricity (or electricity at rest) will flow when given the opportunity, because static electricity is an imbalance of negative and positive charges. An example of this phenomenon is when we walk across a dry carpet and then touch a doorknob—we usually feel a slight shock and might notice a spark at our fingertips. Another familiar example is static cling; for example, when we rub an air-filled balloon against the hair on our heads and then place the balloon against a wall, the balloon will stick to the wall, defying gravity, due to static cling. In the workplace, static electricity is prevented from building up by properly bonding or grounding equipment to ground or earth.

Charged Bodies

The fundamental law of charged bodies states: “Like charges repel each other and unlike charges attract each other.” A positive charge and a negative charge, being opposite or unlike, tend to move toward each other; that is, they are attracted to each other. In contrast, like bodies tend to repel each other. Electrons repel each other because of their like negative charges, and protons repel each other because of their like positive charges. Figure 3.4 demonstrates the law of charged bodies.

It is important to point out another significant aspect of the fundamental law of charged bodies: The force of attraction or repulsion existing between two magnetic poles decreases rapidly as the poles are separated from each other. More specifically, the force of attraction or repulsion varies directly as the product of the separate pole strengths and inversely as the square of the distance separating the magnetic poles, provided the poles are small enough to be considered as points. Let’s look at an example. If you increase the distance between two magnet north poles from 2 feet to 4 feet, the force of repulsion between them is decreased to one fourth of its original value. If either pole strength is doubled and the distance remains the same, the force between the poles will be doubled.

Coulomb’s Law

Coulomb’s law states that the amount of attracting or repelling force that acts between two electrically charged bodies in free space depends on two things:

1. Their charges
2. The distance between them

![Diagram of Coulomb’s Law](https://via.placeholder.com/150)

**FIGURE 3.4** Reaction between two charged bodies. The opposite charges in (A) attract. The like charges in (B) and (C) repel each other.
Specifically, Coulomb’s law states that charged bodies attract or repel each other with a force that is directly proportional to the product of their charges and is inversely proportional to the square of the distance between them.

**Note:** The magnitude of electric charge a body possesses is determined by the number of electrons compared with the number of protons within the body. The symbol for the magnitude of electric charge is \( Q \), expressed in units of coulombs \((C)\). A charge of one positive coulomb means a body contains a charge of \( 6.25 \times 10^{18} \). A charge of one negative coulomb means a body contains a charge of \( 6.25 \times 10^{18} \) more electrons than protons.

**Electrostatic Fields**

The fundamental characteristic of an electric charge is its ability to exert force. The space between and around charged bodies in which their influence is felt is the electric field of force. The electric field is always terminated on material objects and extends between positive and negative charges. This region of force can consist of air, glass, paper, or a vacuum and is referred to as an electrostatic field. When two objects of opposite polarity are brought near each other, the electrostatic field is concentrated in the area between them. The field is generally represented by lines referred to as electrostatic lines of force. These lines are imaginary and are used merely to represent the direction and strength of the field. To avoid confusion, the positive lines of force are always shown leaving, and the negative lines of force are shown entering. Figure 3.5 illustrates the use of lines to represent the field about charged bodies.

**Note:** A charged object will retain its charge temporarily if there is no immediate transfer of electrons to or from it. In this condition, the charge is said to be at rest. Remember, electricity at rest is called static electricity.

**Magnetism**

Most electrical equipment depends directly or indirectly on magnetism, a phenomenon associated with magnetic fields that has the power to attract such substances as iron, steel, nickel, or cobalt (metals known as magnetic materials). A substance is said to be a magnet if it has the property of magnetism; for example, when a piece of iron is magnetized it becomes a magnet. When magnetized, that piece of iron will have two points, opposite each other, that most readily attract other pieces of iron. (For this discussion, we will assume the piece of iron is a flat bar 6 inches long \( \times \) 1 inch wide \( \times \) 0.5 inch thick—in other words, a bar magnet; see Figure 3.6.) The points of maximum
attraction (one on each end) are the magnetic poles of the magnet: the north (N) pole and the south (S) pole. Just as like electric charges repel each other and opposite charges attract each other, like magnetic poles repel each other and unlike poles attract each other. Although invisible to the naked eye, magnetic force can be shown to exist by sprinkling small iron filings on a glass covering a bar magnet, as shown in Figure 3.6. Figure 3.7 shows how the field looks without the iron filings; it is shown as lines of force. The group of magnetic field lines, which flow from the north pole of a magnet toward the south pole, is referred to as the magnetic flux; the symbol for magnetic flux is the Greek lowercase letter \( \phi \) (phi).

**Note:** A magnetic circuit is a complete path through which magnetic lines of force may be established under the influence of a magnetizing force. Most magnetic circuits are composed largely of magnetic materials to contain the magnetic flux. These circuits are similar to the electric circuit (an important point), which is a complete path through which current is caused to flow under the influence of an electromotive force.

The three types or groups of magnets are as follows:

1. **Natural magnets** are found in the natural state in the form of the mineral magnetite (an iron compound).
2. **Permanent magnets** (artificial magnets) are hardened steel or some alloy such as Alinco bars that have been permanently magnetized. The permanent magnet most people are familiar with is the horseshoe magnet; this red U-shaped magnet is the universal symbol of magnets, recognized throughout the world (see Figure 3.8).
3. **Electromagnets** (artificial magnets) are composed of soft iron cores around which are wound coils of insulated wire. When an electric current flows through the coil, the core becomes magnetized. When the current ceases to flow, the core loses most of the magnetism.
MAGNETIC MATERIALS

Natural magnets are no longer used in electrical circuitry because more powerful and more conveniently shaped permanent magnets can be produced artificially. Commercial magnets are made from such magnetic materials as special steels and alloys. Magnetic materials are those materials that are attracted or repelled by a magnet and that can be magnetized themselves. Iron, steel, and alloy bars are the most common magnetic materials. These materials can be magnetized by inserting the material (in bar form) into a coil of insulated wire and passing a heavy direct current through the coil. The same material may also be magnetized if it is stroked with a bar magnet. It will then have the same magnetic property that the magnet used to induce the magnetism has—namely, there will be two poles of attraction, one at either end. This process produces a permanent magnet by induction; that is, the magnetism is induced in the bar by the influence of the stroking magnet. Even though they are classified as permanent magnets, it is important to point out that hardened steel and certain alloys are relatively difficult to magnetize and are said to have a low permeability because the magnetic lines of force do not easily permeate or distribute themselves readily through the steel.

Note: Permanent magnets are made of hard magnetic materials (hard steel or alloys) that retain their magnetism when the magnetizing field is removed. A temporary magnet is one that has no ability to retain a magnetized state when the magnetizing field is removed.

Note: Permeability refers to the ability of a magnetic material to concentrate magnetic flux. Any material that is easily magnetized has high permeability. A measure of permeability for different materials in comparison with air or a vacuum is the relative permeability, symbolized by μ (mu).

When hard steel and other alloys have been magnetized, they retain a large part of their magnetic strength and are considered to be permanent magnets. Conversely, materials that are relatively easy to magnetize—such as soft iron and annealed silicon steel—are said to have a high permeability. Such materials retain only a small part of their magnetism after the magnetizing force is removed and are called temporary magnets. The magnetism that remains in a temporary magnet after the magnetizing force is removed is called residual magnetism.

Early magnetic studies classified magnetic materials as being magnetic or nonmagnetic, based on the strong magnetic properties of iron; however, because even weak magnetic materials can be important in some applications, current studies classify materials into one of three groups:

- **Paramagnetic materials** include aluminum, platinum, manganese, and chromium, materials that become only slightly magnetized even under the influence of a strong magnetic field. This slight magnetization is in the same direction as the magnetizing field. Relative permeability is slightly more than 1 (i.e., they are considered to be nonmagnetic materials).
- **Diamagnetic materials** include bismuth, antimony, copper, zinc, mercury, gold, and silver, materials that can also be slightly magnetized when under the influence of a very strong field. Relative permeability is less than 1 (i.e., they are considered to be nonmagnetic materials).
- **Ferromagnetic materials** include iron, steel, nickel, cobalt, and commercial alloys, materials that comprise the most important group in applications of electricity and electronics. Ferromagnetic materials are easy to magnetize and have high permeabilities, ranging from 50 to 3000.

MAGNETIC EARTH

Earth is a huge magnet, and surrounding Earth is a magnetic field produced by Earth’s magnetism. Most people would have no problem understanding or at least accepting this statement; however, they might question being told that Earth’s north geographic pole is actually its south magnetic pole.
and that the south geographic pole is actually Earth’s north magnetic pole. But, in terms of a magnet, this is true. Figure 3.9 indicates the magnetic polarities of Earth. The geographic poles are also shown at each end of the axis of rotation of Earth. Clearly, the magnetic axis does not coincide with the geographic axis; therefore, the magnetic and geographic poles are not at the same place on the surface of Earth. Recall that magnetic lines of force are assumed to emanate from the north pole of a magnet and enter the south pole as closed loops. Because Earth is a magnet, lines of force emanate from its north magnetic pole and enter the south magnetic pole. A compass needle aligns itself in such a way that Earth’s lines of force enter at its south pole and leave at its north pole. Because the north pole on a compass is defined as the point where the needle points in a northerly direction, it follows that the magnetic pole in the vicinity of the north geographic pole is in reality a south magnetic pole, and vice versa.

**DIFFERENCE IN POTENTIAL**

Because of the force of its electrostatic field, an electric charge has the ability to do the work of moving another charge by attraction or repulsion. The force that causes free electrons to move in a conductor as an electric current may be referred to as

- Electromotive force (emf)
- Voltage
- Difference in potential

When a difference in potential exists between two charged bodies that are connected by a wire (conductor), electrons (current) will flow along the conductor. This flow is from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

**Note:** The basic unit of potential difference is the volt (V). The symbol for potential difference is \( V \), indicating the ability to do the work of forcing electrons (current flow) to move. Because the volt unit is used, potential difference is called voltage.
When training individuals in the concepts of basic electricity, especially with regard to potential difference (voltage), current, and resistance relationships in a simple electrical circuit, it has been common practice to use what is referred to as the water analogy. We use the water analogy later to explain (in simple, straightforward fashion) voltage, current, and resistance and their relationships in more detail, but for now we will use the analogy to explain the basic concept of electricity: the potential difference, or voltage. Because a difference in potential causes current flow (against resistance), it is important that this concept be understood first before exploring the concept of current flow and resistance. Consider the two water tanks connected by a pipe and valve in Figure 3.10. At first, the valve is closed and all the water is in Tank A; the water pressure across the valve is at maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe, because there is no longer a difference in water pressure (difference in potential) between the two tanks. Just as the flow of water through the pipe in Figure 3.10 is directly proportional to the difference in water level in the two tanks, current flow through an electric circuit is directly proportional to the difference in potential across the circuit.

**Note:** A fundamental law of current electricity is that the current is directly proportional to the applied voltage: if the voltage is increased, the current is increased. If the voltage is decreased, the current is decreased.

**Principal Methods of Producing a Voltage**

There are many ways to produce electromotive force, or voltage. Some of these methods are much more widely used than others. The following is a list of the seven most common methods of producing electromotive force (USDOE, 1992):

1. **Friction** is the voltage produced by rubbing two materials together (static electricity or electrostatic force). Remember our discussion of static electricity? Let’s refresh our memories. Have you ever walked across a carpet and received a shock when you touched a metal door knob? The soles of your shoes built up a charge when they rubbed on the carpet, and this charge was transferred to your body. Your body became positively charged, and when you touched the zero-charged door knob electrons were transferred to your body until both you and the door knob had equal charges.

2. **Pressure (piezoelectricity)** is the voltage produced by squeezing or applying pressure to crystals of certain substances (e.g., quartz, Rochelle salts, certain ceramics such as barium titanate). When pressure is applied to such substances, electrons can be driven out of orbit in the direction of the force. Electrons leave one side of the material and accumulate on the other side, building up positive and negative charges on opposite sides. When the pressure
is released, the electrons return to their orbits. Some materials will react to bending pressure, while others will respond to twisting pressure. This generation of voltage is known as the piezoelectric effect. If external wires are connected while pressure and voltage are present, electrons will flow and current will be produced. If the pressure is held constant, the current will flow until the potential difference is equalized. When the force is removed, the material is decompressed and immediately causes an electric force in the opposite direction. The power capacity of these materials is extremely small; however, these materials are very useful because of their extreme sensitivity to changes of mechanical force. One example is the crystal phonograph cartridge that contains a Rochelle salt crystal. A phonograph needle is attached to the crystal. As the needle moves in the grooves of a record, it swings from side to side, compressing and decompressing the crystal. The mechanical motion applied to the crystal generates a voltage signal that is used to reproduce sound.

3. Heat (thermoelectricity) is the voltage produced by heating the joint (junction) where two unlike metals are joined. Some materials readily give up their electrons and others readily accept electrons; for example, when two dissimilar metals such as copper and zinc are joined together, a transfer of electrons can take place. Electrons will leave the copper atoms and enter the zinc atoms. The zinc gets a surplus of electrons and becomes negatively charged. The copper loses electrons and takes on a positive charge. This creates a voltage potential across the junction of the two metals. The heat energy of normal room temperature is enough to make them release and gain electrons, causing a measurable voltage potential. As more heat energy is applied to the junction, more electrons are released, and the voltage potential becomes greater. When heat is removed and the junction cools, the charges will dissipate and the voltage potential will decrease. This process is known as thermoelectricity. A device like this is generally referred to as a thermocouple. Thermocouple voltage is dependent on the heat energy applied to the junction of the two dissimilar metals. Thermocouples are widely used to measure temperature and as heat-sensing devices in automatic temperature-controlled equipment. Thermocouple power capacities are very small compared to some other sources, but they are somewhat greater than those of crystals. Generally speaking, a thermocouple can be subjected to higher temperatures than ordinary mercury or alcohol thermometers.

4. Light (photoelectricity) is the voltage produced by light (photons) striking photosensitive (light-sensitive) substances. When the photons in a light beam strike the surface of a material, they release their energy and transfer it to the atomic electrons of the material. This energy transfer may dislodge electrons from their orbits around the surface of the substance. Upon losing electrons, the photosensitive (light-sensitive) material becomes positively charged and an electric force is created. This phenomenon is called the photoelectric effect and has wide applications in electronics (e.g., photoelectric cells, photovoltaic cells, optical couplers, television camera tubes). Three uses of the photoelectric effect are described below.

- Photovoltaic—The light energy in one of two plates that are joined together causes one plate to release electrons to the other; the plates build up opposite charges, as in a battery.
- Photoemission—The photon energy from a beam of light can cause a surface to release electrons in a vacuum tube, and a plate then collects the electrons.
- Photoconduction—The light energy applied to some materials that are normally poor conductors causes free electrons to be produced in the materials so they become better conductors.

5. Chemical action is the voltage produced by chemical reaction in a battery cell; an example is a voltaic chemical cell, in which a chemical reaction produces and maintains opposite charges on two dissimilar metals that serve as positive and negative terminals. The metals are in contact with an electrolyte solution. Connecting more than one of these cells will produce a battery.
6. **Magnetism** is the voltage produced in a conductor when the conductor moves through a magnetic field or a magnetic field moves through the conductor in such a manner as to cut the magnetic lines of force of the field. A generator is a machine that converts mechanical energy into electrical energy by using the principle of **magnetic induction**. Magnetism is used to produce vast quantities of electric power.

7. **Thermionic emission** is produced by a thermionic energy converter, which consists of two electrodes placed near one another in a vacuum. One electrode is normally the cathode, or emitter, and the other is the anode, or plate. Ordinarily, electrons in the cathode are prevented from escaping from the surface by a potential-energy barrier. When an electron starts to move way from the surface, it induces a corresponding positive charge in the material, which tends to pull it back into the surface. To escape, the electron must somehow acquire enough energy to overcome this energy barrier. At ordinary temperatures, almost none of the electrons can acquire enough energy to escape; however, when the cathode is very hot, the electron energies are greatly increased by thermal motion. At sufficiently high temperatures, a considerable number of electrons are able to escape. The liberation of electrons from a hot surface is thermionic emission. The electrons that have escaped from the hot cathode form a cloud of negative charges near it called a **space charge**. If the plate is maintained positive with respect to the cathode by a battery, the electrons in the cloud are attracted to it. As long as the potential difference between the electrodes is maintained, there will be a steady current flow from the cathode to the plate. The simplest example of a thermionic device is a vacuum tube diode, in which the only electrodes are the cathode and plate, or anode. The diode can be used to convert alternating current (AC) flow to a pulsating direct current (DC) flow.

In the study of the basic electricity related to renewable energy production, we are most concerned with magnetism (e.g., generators powered by hydropower), light (photoelectricity produced by solar cells), and chemistry (chemical energy converted to electricity in batteries) as the means to produce voltage. Friction has little practical application, although we discussed it earlier with regard to static electricity. Pressure and heat do have useful applications, but we do not need to consider them in this text. Magnetism used in generators, electricity produced by solar light, and the chemistry involved in storing electricity in batteries, on the other hand, are the principal sources of voltage and are discussed at length in this text.

**Electric Current**

The movement or the flow of electrons is called **current**. To produce current, the electrons must be moved by a potential difference or pressure (voltage).

**Note:** The terms **current**, **current flow**, **electron flow**, and **electron current** all describe the same phenomenon.

For our purposes in this text, electron flow, or current, in an electric circuit is from a region of less negative potential to a region of more positive potential—from negative to positive.

**Note:** Current is represented by the letter **I**. The basic unit in which current is measured is the **ampere**, or **amp** (A). One ampere of current is defined as the movement of one coulomb past any point of a conductor during one second of time.

Recall that we used the water analogy to help us understand potential difference. We can also use the water analogy to help us understand current flow through a simple electric circuit. Consider Figure 3.11, which shows a water tank connected via a pipe to a pump with a discharge pipe. If the water tank contains an amount of water above the level of the pipe opening to the pump, the water
exerts pressure (a difference in potential) against the pump. When sufficient water is available for pumping with the pump, water flows through the pipe against the resistance of the pump and pipe. The analogy should be clear—in an electric circuit, if a difference in potential exists, current will flow in the circuit. Another simple way of looking at this analogy is to consider Figure 3.12, where the water tank has been replaced with a generator, the pipe with a conductor (wire), and water flow with the flow of electric current. Again, the key point illustrated by Figures 3.11 and 3.12 is that, to produce current, the electrons must be moved by a potential difference.

Electric current is generally classified into two general types:

- Direct current (DC)
- Alternating current (AC)

Direct current is current that moves through a conductor or circuit in one direction only. Alternating current periodically reverses direction.

Resistance

Earlier we pointed out that free electrons, or electric current, could move easily through a good conductor, such as copper, but that an insulator, such as glass, was an obstacle to current flow. In the water analogy shown in Figure 3.11 and the simple electric circuit shown in Figure 3.12, resistance is indicated by either the pipe or the conductor. Every material offers some resistance, or opposition, to the flow of electric current through it. Good conductors such as copper, silver, and aluminum offer very little resistance. Poor conductors, or insulators, such as glass, wood, and paper, offer a high resistance to current flow.

Note: The amount of current that flows in a given circuit depends on two factors: voltage and resistance.

Note: Resistance is represented by the letter \( R \). The basic unit in which resistance is measured is the ohm (\( \Omega \)). One ohm is the resistance of a circuit element, or circuit, that permits a steady current of 1 ampere (1 coulomb per second) to flow when a steady electromotive force (emf) of 1 volt is applied to the circuit. Manufactured circuit parts containing definite amounts of resistance are called resistors.
The size and type of material of the wires in an electric circuit are chosen so as to keep the electrical resistance as low as possible. In this way, current can flow easily through the conductors, just as water flows through the pipe between the tanks in Figure 3.10. If the water pressure remains constant, the flow of water in the pipe will depend on how far the valve is opened. The smaller the opening, the greater the opposition (resistance) to the flow and the smaller will be the rate of flow in gallons per second. In the electric circuit shown in Figure 3.12, the larger the diameter of the wire, the lower will be its electrical resistance (opposition) to the flow of current through it. In the water analogy, pipe friction opposes the flow of water between the tanks. This friction is similar to electrical resistance. The resistance of a pipe to the flow of water through it depends on (1) the length of the pipe, (2) the diameter of the pipe, and (3) the nature of the inside walls (rough or smooth). Similarly, the electrical resistance of the conductors depends on (1) the length of the wires, (2) the diameter of the wires, and (3) the material of the wires (e.g., copper, silver). It is important to note that temperature also affects the resistance of electrical conductors to some extent. In most conductors (e.g., copper, aluminum) the resistance increases with temperature. Carbon is an exception. In carbon, the resistance decreases as temperature increases.

**Note:** Electricity is a study that is frequently explained in terms of opposites. The term that is exactly the opposite of resistance is conductance. Conductance \( G \) is the ability of a material to pass electrons. The SI unit of conductance is the siemens. The commonly used unit of conductance is the mho, which is ohm spelled backward. The relationship that exists between resistance and conductance is the reciprocal. A reciprocal of a number is obtained by dividing the number into one. If the resistance of a material is known, dividing its value into one will give its conductance. Similarly, if the conductance is known, dividing its value into one will give its resistance.

**BATTERY-SUPPLIED ELECTRICITY**

Battery-supplied direct current electricity has many applications and is widely used in household, commercial, and industrial operations. Applications include providing electrical energy for industrial vehicles, emergency diesel generators, material handling equipment (forklifts), portable electric/electronic equipment, backup emergency power for light packs, hazard warning signal lights, flashlights, and standby power supplies or uninterruptible power supplies (UPS) for computer systems. In some instances, they are used as the only source of power, whereas in others they are used as a secondary or standby power supply. In renewable energy applications, batteries are used to store electrical energy; for example, a battery pack can store electricity produced by a solar electric system. Today, they are commonly used in specialized applications such as plug-in hybrid electric vehicle energy storage systems. Batteries are often used in hybrid wind systems to store excess wind energy and then provide supplementary energy when the wind cannot generate sufficient power to meet the electric load. Batteries are also used in roadside solar-charging systems; that is, solar energy is used to charge a battery pack that supplies electrical power to some type of electrical signaling device, navigation buoys, or other remote application (e.g., emergency telephone) where it would be impractical and costly to run miles of electrical supply cable.

**Battery Terminology**

- A voltaic cell is a combination of materials used to convert chemical energy into electrical energy.
- A battery is a group of two or more connected voltaic cells.
- An electrode is a metallic compound, or metal, that has an abundance of electrons (negative electrode) or an abundance of positive charges (positive electrode).
- An electrolyte is a solution capable of conducting an electric current.
Specific gravity is defined as the ratio comparing the weight of any liquid to the weight of an equal volume of water.

An ampere-hour is defined as a current of 1 ampere flowing for 1 hour.

**Voltaic Cell**

The simplest cell (a device that transforms chemical energy into electrical energy) is the voltaic (or galvanic) cell (see Figure 3.13). It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a solution of water (H₂O) and sulfuric acid (H₂SO₄).

*Note:* A simple cell consists of two strips, or electrodes, placed in a container that holds the electrolyte. A battery is formed when two or more cells are connected.

The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell described above, they are carbon and zinc strips placed in the electrolyte. Zinc contains an abundance of negatively charged atoms, and carbon has an abundance of positively charged atoms. When the plates of these materials are immersed in an electrolyte, chemical action between the two begins. In the dry cell (Figure 3.14), the electrodes are the carbon rod in the center and the zinc container in which the cell is assembled. The electrolyte is the solution that acts upon the electrodes that are placed in it. The electrolyte may be a salt, an acid, or an alkaline solution. In the simple voltaic cell and in the automobile storage battery, the electrolyte is in a liquid form; in the dry cell, the electrolyte is a moist paste.
Primary and Secondary Cells

Primary cells are normally those that cannot be recharged or returned to good condition after their voltage drops too low. Dry cells in flashlights and transistor radios are examples of primary cells. Some primary cells have been developed to the state where they can be recharged. A secondary cell is one in which the electrodes and the electrolyte are altered by the chemical action that takes place when the cell delivers current. These cells are rechargeable. During recharging, the chemicals that provide electric energy are restored to their original condition. Recharging is accomplished by forcing an electric current through them in the opposite direction of the discharge. Figure 3.15 shows how a secondary cell is recharged. Some battery chargers have a voltmeter and an ammeter that indicate the charging voltage and current. The automobile storage battery is the most common example of the secondary cell.

Battery

As stated previously, a cell is an electrochemical device capable of supplying the energy that results from an internal chemical reaction to an external electrical circuit. A battery consists of two or more cells placed in a common container. The cells are connected in series, in parallel, or in some combination of series and parallel, depending on the amount of voltage and current required of the battery. The connection of cells in a battery is discussed in more detail later.

Battery Operation

The chemical reaction within a battery provides the voltage. This occurs when a conductor is connected externally to the electrodes of a cell which causes electrons to flow under the influence of a difference in potential across the electrodes from the zinc (negative) through the external conductor to the carbon (positive), returning within the solution to the zinc. After a short period of time, the zinc will begin to waste away because of the acid. The voltage across the electrodes depends on the materials from which the electrodes are made and the composition of the solution. The difference of potential between the carbon and zinc electrodes in a dilute solution of sulfuric acid and water is about 1.5 volts. The current that a primary cell may deliver depends on the resistance of the entire circuit, including that of the cell itself. The internal resistance of the primary cell depends on the size of the electrodes, the distance between them in the solution, and the resistance of the solution. The larger the electrodes and the closer together they are in solution (without touching), the lower the internal resistance of the primary cell and the more current it is capable of supplying to the load.

Note: When current flows through a cell, the zinc gradually dissolves in the solution and the acid is neutralized.

Combining Cells

In many operations, battery-powered devices may require more electrical energy than one cell can provide. Various devices may require either a higher voltage or more current, and in some cases both. Under such conditions it is necessary to combine, or interconnect, a sufficient number of cells...
to meet the higher requirements. Cells connected in series provide a higher voltage, and cells connected in parallel provide a higher current capacity. To provide adequate power when both voltage and current requirements are greater than the capacity of one cell, a series–parallel network of cells must be interconnected.

When cells are connected in \textit{series} (Figure 3.16), the total voltage across the battery of cells is equal to the sum of the voltage of each of the individual cells. In Figure 3.16, the four 1.5-V cells in series provide a total battery voltage of 6 V. When cells are placed in series, the positive terminal of one cell is connected to the negative terminal of the other cell. The positive electrode of the first cell and negative electrode of the last cell then serve as the power takeoff terminals of the battery. The current flowing through such a battery of series cells is the same as from one cell because the same current flows through all of the series cells.

To obtain a greater current, cells can be connected in \textit{parallel}, as shown in Figure 3.17. In this parallel connection, all of the positive electrodes are connected to one line, and all negative electrodes are connected to the other. Any point on the positive side can serve as the positive terminal of the battery and any point on the negative side can be the negative terminal. The total voltage output

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{series.png}
\caption{Cells in series (schematic representation).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{parallel.png}
\caption{Cells in parallel (schematic representation).}
\end{figure}
of a battery of three parallel cells is the same as that for a single cell (Figure 3.17), but the available current is three times that of one cell; that is, the current capacity has been increased. Identical cells in parallel all supply equal parts of the current to the load; for example, of three different parallel cells producing a load current of 210 milliamperes (mA), each cell contributes 70 mA. Figure 3.18 is a schematic of a series–parallel battery network supplying power to a load requiring both a voltage and current greater than one cell can provide. To provide the required increased voltage, groups of three 1.5-V cells are connected in series. To provide the required increased amperage, four series groups are connected in parallel.

Types of Batteries
In the past 30 years, several different types of batteries have been developed. In this text, we briefly discuss the dry cell battery and those batteries that are currently used to store electrical energy in a reversible chemical reaction as applied to renewable energy production. The renewable energy source (solar, wind, or hydro) produces the energy, and the battery stores it for times of low or no renewable energy production. The types of batteries used in this application and discussed here include the lead–acid, alkaline, nickel–cadmium, mercury, nickel–metal hydride, lithium-ion, and lithium-ion polymer batteries. Keep in mind that a battery does not create energy; rather, it stores energy. For most renewable energy applications, the preferred battery type is the deep-cycle battery. A deep-cycle battery is designed to deliver a constant voltage as the battery discharges. A car-starting battery, in contrast, is designed to deliver sporadic current spikes. Battery-driven vehicles, such as forklifts, golf carts, and floor sweepers, commonly use deep-cycle batteries. Deep-cycle batteries can be charged with a lower current than regular batteries. Following are descriptions of the various types of batteries (National Renewable Energy Laboratory, 2009):

- **Dry cell**—In the dry cell, or carbon–zinc cell, the electrolyte is not in a liquid state but is a moist paste. A carbon rod placed in the center of the cell is the positive terminal. The case of the cell is made of zinc and is the negative terminal (see Figure 3.14). Between the carbon electrode and the zinc case is the electrolyte, a moist, chemical, paste-like mixture. The cell is sealed to prevent the liquid in the paste from evaporating. The voltage of a cell of this type is about 1.5 V.

- **Lead–acid battery**—The lead–acid battery is a secondary cell (e.g., storage battery or rechargeable battery) that stores chemical energy until it is released as electrical energy. The lead–acid battery differs from a primary cell battery mainly in that it may be recharged, whereas most primary cells cannot be recharged. As the name implies, the lead–acid battery consists of a number of lead–acid cells immersed in a dilute solution of sulfuric acid. Each cell has two groups of lead plates; one set is the positive terminal and the other is the negative terminal. Active materials within the battery (lead plates and sulfuric acid electrolyte) react chemically to produce a flow of direct current whenever current-consuming devices are connected to the battery terminal posts. This current is produced by a chemical reaction between the active material of the plates (electrodes) and the electrolyte (sulfuric acid). This type of cell produces slightly more than 2 V. Most automobile batteries contain
six cells connected in series so the output voltage from the battery is slightly more than 12 V. In addition to being rechargeable, the main advantage of the lead–acid battery over the dry cell battery is that it can supply current for a much longer time than the average dry cell. Lead–acid batteries can be designed to be high power and are inexpensive, safe, and reliable; also, a recycling infrastructure is in place for them. But, low specific energy, poor cold-temperature performance, and short calendar and cycle life are still impediments to their use. Advanced high-power, deep-cycle lead–acid batteries are being developed for hybrid electric vehicle (HEV) applications; however, lead–acid batteries are used for residential solar electric systems because of their low maintenance requirements and cost.

**Safety Note:** Whenever a lead–acid storage battery is charging, the chemical action produces dangerous hydrogen gas; thus, the charging operation should take place only in a well-ventilated area.

- **Alkaline cell**—The alkaline cell is a secondary cell that gets its name from its alkaline electrolyte, potassium hydroxide. The alkaline battery has a negative electrode of zinc and a positive electrode of manganese dioxide. It generates 1.5 V.
- **Nickel–cadmium cell**—The nickel–cadmium cell, or NiCad cell, is the only dry cell that is a true storage battery with a reversible chemical reaction, allowing recharging many times. In the secondary nickel–cadmium dry cell, the electrolyte is potassium hydroxide, the negative electrode is nickel hydroxide, and the positive electrode is cadmium oxide. The operating voltage is 1.25 V. Because of its rugged characteristics (stands up well to shock, vibration, and temperature changes) and availability in a variety of shapes and sizes, it is ideally suited for powering portable communication equipment. NiCad batteries are very expensive. Moreover, although nickel–cadmium batteries are used in many electronic consumer products and have a higher specific energy and better life cycle than lead–acid batteries, they are low efficiency (65 to 80%). They do not deliver sufficient power and are not being considered for HEV applications. Cadmium is a heavy metal that is toxic and is very expensive to dispose of which reduces its desirability for use in hybrid applications.
- **Mercury cell**—The mercury cell was developed for space exploration activities, for which small transceivers and miniaturized equipment required a small power source. In addition to reduced size, the mercury cells have a good shelf life and are very rugged; they also produce a constant output voltage under different load conditions. Two types of mercury cells are available. One is a flat cell shaped like a button; the other is a cylindrical cell that looks like a standard flashlight cell. The advantage of the button-type cell is that several of them can be stacked inside one container to form a battery. A mercury cell produces 1.35 V.
- **Nickel–metal hydride battery**—Nickel–metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Their components are recyclable, but a recycling structure is not yet in place. Nickel–metal hydride batteries have a much longer life cycle than lead–acid batteries; they are safe and tolerate abuse. These batteries have been used successfully in production electric vehicles and recently in low-volume production of HEVs. The main challenges with nickel–metal hydride batteries are their high cost, high rate of self-discharge, very high gassing/waste consumption, heat generation at high temperatures, the need to control hydrogen loss, and their low cell efficiency (may be as low as 50%, typically 60 to 65%).
- **Lithium-ion battery**—Lithium-ion batteries are rapidly penetrating the laptop and cell phone markets because of their high specific energy. They also have high specific power, high energy efficiency, good high-temperature performance, and low self-discharge rates. Components of lithium-ion batteries can be recycled. These characteristics make lithium-ion batteries suitable for HEV applications; however, to make them commercially viable for HEVs, further development is necessary, including improvements in their calendar and cycle life, a greater degree of cell and battery safety, improved abuse tolerance, and acceptable costs.
• Lithium-ion polymer battery—Lithium-ion polymer batteries with high specific energy (i.e., high energy per unit mass), initially developed for cell phone applications, also have the potential to provide high specific power for HEV applications. Other key characteristics of the lithium-ion polymer battery are safety and a good cycle life. The battery could be commercially viable if the costs are lowered and even higher specific power batteries are developed.

Battery Characteristics

Batteries are generally classified by their various characteristics. Parameters such as internal resistance, specific gravity, capacity, shelf life, C rate, mid-point voltage (MPV), gravimetric energy density, volumetric energy density, constant-voltage charge, constant-current charge, and specific power are used to describe and classify batteries by operation and type.

When discussing internal resistance, it is important to keep in mind that a battery is a DC voltage generator. As such, the battery has internal resistance or equivalent series resistance (ESR). In a chemical cell, the resistance of the electrolyte between the electrodes is responsible for most of the internal resistance of the cell. Because any current in the battery must flow through the internal resistance, this resistance is in series with the generated voltage. With no current, the voltage drop across the resistance is zero, so fully generated voltage develops across the output terminals. This is the open-circuit voltage, or no-load voltage. If a load resistance is connected across the battery, the load resistance is in series with internal resistance. When current flows in this circuit, the internal voltage drop reduces the terminal voltage of the battery.

The ratio of the weight of a certain volume of liquid to the weight of the same volume of water is the specific gravity of the liquid. Pure sulfuric acid has a specific gravity of 1.835 because it weighs 1.835 times as much as water per unit volume. The specific gravity of a mixture of sulfuric acid and water varies with the strength of the solution from 1.000 to 1.830.

The specific gravity of the electrolyte solution in a lead–acid cell ranges from 1.210 to 1.300 for new, fully charged batteries. The higher the specific gravity, the less internal resistance of the cell and the higher the possible load current. As the cell discharges, the water formed dilutes the acid and the specific gravity gradually decreases to about 1.150, at which time the cell is considered to be fully discharged.

The specific gravity of the electrolyte is measured with a hydrometer, which has a compressible rubber bulb at the top, a glass barrel, and a rubber hose at the bottom of the barrel. When taking readings with a hydrometer, the decimal point is usually omitted; for example, a specific gravity of 1.260 is read simply as “twelve-sixty.” A hydrometer reading of 1210 to 1300 indicates a full charge; about 1250, half-charge; and 1150 to 1200, complete discharge.

The capacity of a battery is measured in ampere-hours (Ah). The ampere-hour capacity is equal to the product of the current in amperes and the time in hours during which the battery is supplying this current; it is defined as the amount of current that a battery can deliver for 1 hour before the battery voltage reaches the end-of-life point. In other words, 1 ampere-hour is the equivalent of drawing 1 amp steadily for 1 hour or 2 amps steadily for 1/2 an hour. A typical 12-volt system may have 800 ampere-hours of battery capacity; that is, the battery can draw 100 amps for 8 hours if fully discharged and starting from a fully charged state. This is equivalent to 1200 watts for 8 hours (power in watts = amps × volts). The ampere-hour capacity varies inversely with the discharge current. The size of a cell is determined generally by its ampere-hour capacity. The capacity of a storage battery determines how long it will operate at a given discharge rate and depends on many factors; the most important of these are as follows:

- The area of the plates in contact with the electrolyte
- The quantity and specific gravity of the electrolyte
- The type of separators
• The general condition of the battery (e.g., degree of sulfating, buckled plates, warped separators, sediment in bottom of cells)
• The final limiting voltage

The shelf life of a cell is that period of time during which the cell can be stored without losing more than approximately 10% of its original capacity. The loss of capacity of a stored cell is due primarily to the electrolyte in a wet cell drying out and to chemical actions that alter the materials within the cell. The shelf life of a cell can be extended by keeping it in a cool, dry place.

The C rate of a current is numerically equal to the ampere-hour rating of the cell. Charge and discharge currents are typically expressed in fractions of multiples of the C rate. The mid-point voltage (MPV) is the nominal voltage of the cell, the voltage that is measured when the battery has discharged 50% of its total energy. The gravimetric energy density of a battery is a measure of how much energy a battery contains in comparison to its weight. The volumetric energy density of a battery is a measure of how much energy a battery contains in comparison to its volume.

A constant-voltage charger is a circuit that recharges a battery by sourcing only enough current to force the battery voltage to a fixed value. A constant-current charger is a circuit that charges a battery by sourcing a fixed current into the battery, regardless of battery voltage. In batteries, specific power usually refers to the power-to-weight ratio, measured in kilowatts per kilogram (kW/kg).

DC CIRCUITS

An electric circuit includes an energy source (the source of the electromotive force or voltage, such as a battery or generator), a conductor (wire), a load, and a means of control (see Figure 3.19). The energy source could be a battery, as shown in Figure 3.19, or some other means of producing a voltage. The load that dissipates the energy could be a lamp, a resistor, or some other device that does useful work, such as an electric toaster, a power drill, a radio, a soldering iron, a laptop computer, or a battery pack that stores energy and serves as a backup to a renewable energy source such as solar or wind. Again, conductors are wires that offer low resistance to current; they connect all the loads in the circuit to the voltage source. No electrical device dissipates energy unless current flows through it. Because conductors, or wires, are not perfect conductors, they heat up (dissipate energy), so they are actually part of the load. For simplicity, however, we usually think of the connecting wiring as having no resistance, as it would be tedious to assign a very low resistance value to the wires every time we wanted to solve a problem. Control devices might be switches, variable resistors, circuit breakers, fuses, or relays.

A complete pathway for current flow, or closed circuit (Figure 3.19), is an unbroken path for current from the electromotive force, through a load, and back to the source. An open circuit (see Figure 3.20) has a break in the circuit (e.g., open switch) that does not provide a complete path for current.
Note: Current flows from the negative (–) terminal of the battery (Figures 3.19 and 3.20), through the load to the positive (+) battery terminal, and continues through the battery from the positive (+) terminal back to the negative (–) terminal. As long as this pathway is unbroken, it is a closed circuit and current will flow; however, if the path is broken at any point, it is an open circuit and no current flows.

To protect a circuit, a fuse is placed directly into the circuit (Figure 3.21). A fuse will open the circuit whenever a dangerous large current begins to flow; a short-circuit condition occurs when an accidental connection between two points in a circuit offers very little resistance. A fuse will permit currents smaller than the fuse value to flow but will melt and therefore break or open the circuit if a larger current flows.

Schematic Representation

The simple circuits shown in Figures 3.19, 3.20, and 3.21 are displayed in schematic form. A schematic is a simplified drawing that represents the electrical, not the physical, situation in a circuit. The symbols used in schematic diagrams are the electrician’s shorthand; they make the diagrams easier to draw and easier to understand. Consider the symbol shown in Figure 3.22 that is used to represent a battery power supply. The symbol is rather simple and straightforward, but it is very important. By convention, the shorter line in the symbol for a battery represents the negative terminal. It is important to remember this, because sometimes when you examine the schematic it is necessary to note the direction of current flow, which is from negative to positive. The battery symbol shown in Figure 3.22 represents a single cell, so only one short and one long line are used. The number of lines used to represent a battery vary (and they are not necessarily equivalent to the number of cells), but they are always in pairs, with long and short lines alternating. In the circuit shown in Figure 3.21, the current would flow in a counterclockwise direction. If the long and short lines of the battery symbol (see Figure 3.22) were reversed, the current in the circuit shown in Figure 3.21 would flow clockwise.

Note: When studying electricity and electronics, many circuits are analyzed that consist mainly of specially designed resistive components. These components are resistors. Throughout the remaining analysis of the basic circuit, the resistive component will be a physical resistor; however, resistive components could be any of several electrical devices.

Keep in mind that, in the simple circuits shown in the figures to this point, we have only illustrated and discussed a few of the many symbols used in schematics to represent circuit components. (Other symbols will be introduced as we need them.) It is also important to keep in mind that a closed loop of wire (conductor) is not necessarily a circuit. A source of voltage must be included to make it an electric circuit. In any electric circuit where electrons move around a closed loop, current, voltage, and resistance are present. The
physical pathway for current flow is actually the circuit. By knowing any two of the three quantities, such as voltage and current, the third (resistance) may be determined. This is done using Ohm’s law, which is the foundation on which electrical theory is based.

**OHM’S LAW**

Simply put, *Ohm’s law* defines the relationship among current, voltage, and resistance in electric circuits. Ohm’s law can be expressed mathematically in three ways:

1. The current (*I*) in a circuit is equal to the voltage applied to the circuit divided by the resistance of the circuit. Stated another way, the current in a circuit is directly proportional to the applied voltage and inversely proportional to the circuit resistance. Ohm’s law may be expressed by the equation:

   \[ I = \frac{E}{R} \]  

   where *I* = current in amps, *E* = voltage in volts, and *R* = resistance in ohms.

2. The resistance (*R*) of a circuit is equal to the voltage applied to the circuit divided by the current in the circuit:

   \[ R = \frac{E}{I} \]  

3. The applied voltage (*E*) to a circuit is equal to the product of the current and the resistance of the circuit:

   \[ E = I \times R = IR \]  

If any two of the quantities in Equations 3.1, 3.2, or 3.3 are known, the third may be easily found. Let’s look at an example.

**EXAMPLE 3.1**

*Problem:* Figure 3.23 shows a circuit containing a resistance of 6 ohms and a source voltage of 3 volts. How much current flows in the circuit?

*Solution:*

Given:

- \( R = 6 \) ohms
- \( E = 3 \) volts
- \( I = ? \)

\[
I = \frac{E}{R} = \frac{3}{6} = 0.5 \text{ amp}
\]

**FIGURE 3.23** Determining current in a simple circuit.
To observe the effect of source voltage on circuit current, we can use the circuit shown in Figure 3.23 but double the voltage to 6 volts.

■ EXAMPLE 3.2

*Problem:* How much current is flowing when $E = 6$ volts and $R = 6$ ohms?

*Solution:*

$$I = \frac{E}{R} = \frac{6}{6} = 1 \text{ amp}$$

Notice that as the source of voltage doubles, the circuit current also doubles. To verify that current is inversely proportional to resistance, assume that the resistor in Figure 3.23 has a value of 12 ohms.

*Note:* Circuit current is directly proportional to the applied voltage and will change by the same factor that the voltage changes.

■ EXAMPLE 3.3

*Problem:* Given $E = 3$ volts and $R = 12$ ohms, what is $I$?

*Solution:*

$$I = \frac{E}{R} = \frac{3}{12} = 0.25 \text{ amp}$$

Comparing this current of 0.25 amp for the 12-ohm resistor to the 0.5-amp of current obtained with the 6-ohm resistor shows that doubling the resistance will reduce the current to one half the original value.

*Note:* Circuit current is inversely proportional to the circuit resistance.

Recall that if you know any two quantities of $E$, $I$, and $R$, you can calculate the third. In many circuit applications, current is known and either the voltage or the resistance will be the unknown quantity. To solve a problem in which current and resistance are known, the basic formula for Ohm’s law must be transposed to solve for $E$, for $I$, or for $R$; however, the Ohm’s law equations can be memorized and practiced effectively by using an Ohm’s law circle (see Figure 3.24).

To find the equation for $E$, $I$, or $R$ when two quantities are known, cover the unknown third quantity with your finger, as shown in Figure 3.25:

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

![FIGURE 3.24 Ohm’s law circle.](image1)

![FIGURE 3.25 Putting the Ohm’s law circle to work.](image2)
EXAMPLE 3.4

Problem: Find \( I \) when \( E = 120 \text{ V} \) and \( R = 40 \text{ ohms} \).
Solution: Place your finger on \( I \), as shown in the figure. Use Equation 3.1 to find the unknown \( I \):

\[ I = \frac{E}{R} = \frac{120}{40} = 3 \text{ A} \]

EXAMPLE 3.5

Problem: Find \( R \) when \( E = 220 \text{ V} \) and \( I = 10 \text{ A} \).
Solution: Place your finger on \( R \), as shown in the figure:

\[ R = \frac{E}{I} = \frac{220}{10} = 22 \text{ ohms} \]

EXAMPLE 3.6

Problem: Find \( E \) when \( I = 2.5 \text{ A} \) and \( R = 25 \text{ ohms} \).
Solution: Place your finger on \( E \), as shown in the figure.

\[ E = I \times R = 2.5 \times 25 = 62.5 \text{ V} \]

Note: In the previous examples, we have demonstrated how we can use the Ohm’s law circle to help us solve simple voltage, current, and amperage problems. Beginning students, however, are cautioned not to rely entirely on the use of this circle when transposing simple formulas but rather to use it to supplement their knowledge of the algebraic method. Algebra is a basic tool in the solution of electrical problems, and the importance of knowing how to use it should not be underemphasized or bypassed after the operator has learned a shortcut method such as the one shown in this circle.

EXAMPLE 3.7

Problem: An electric light bulb draws 0.5 A when operating on a 120-V DC circuit. What is the resistance of the bulb?
Solution: The first step in solving a circuit problem is to sketch a schematic diagram of the circuit itself, labeling each of the parts and showing the known values (see Figure 3.26). Because \( I \) and \( E \) are known, we use Equation 3.2 to solve for \( R \):

\[ R = \frac{E}{I} = \frac{120}{0.5} = 240 \text{ ohms} \]

FIGURE 3.26 Circuit for Example 3.7.
ELECTRIC POWER

Power, whether electrical or mechanical, pertains to the rate at which work is being done, so the power consumption in your plant is related to current flow. A large electric motor or air dryer consumes more power (and draws more current) in a given length of time than, for example, an indicating light on a motor controller. Work is done whenever a force causes motion. If a mechanical force is used to lift or move a weight, work is done; however, force exerted without causing motion, such as the force of a compressed spring acting between two fixed objects, does not constitute work.

Note: Power is the rate at which work is done.

ELECTRICAL POWER CALCULATIONS

The electric power \( P \) used in any part of a circuit is equal to the current \( I \) in that part multiplied by the voltage \( E \) across that part of the circuit. In equation form:

\[
P = E \times I
\]

(3.4)

where

\[
\begin{align*}
P & = \text{Power (watts, W).} \\
E & = \text{Voltage (volts, V).} \\
I & = \text{Current (amps, A).}
\end{align*}
\]

If we know the current \( I \) and the resistance \( R \) but not the voltage, we can find the power \( P \) by using Ohm’s law for voltage, so by substituting Equation 3.3,

\[
E = I \times R
\]

into Equation 3.4, we obtain

\[
P = (I \times R) \times I = I^2 \times R
\]

(3.5)

In the same manner, if we know the voltage \( V \) and the resistance \( R \) but not the current \( I \), we can find \( P \) by using Ohm’s law for current, so by substituting Equation 3.1:

\[
I = E/R
\]

into Equation 3.4, we obtain

\[
P = E \times (E/R) = E^2/R
\]

(3.6)

Note: If we know any two quantities, we can calculate the third.

■ EXAMPLE 3.8

Problem: The current through a 200-ohm resistor to be used in a circuit is 0.25 A. Find the power rating of the resistor.

Solution: Because \( I \) and \( R \) are known, use Equation 3.5 to find \( P \):

\[
P = I^2 \times R = (0.25)^2 \times 200 = 0.0625 \times 200 = 12.5 \text{ W}
\]
**Note:** The power rating of any resistor used in a circuit should be twice the wattage calculated by the power equation to prevent the resistor from burning out. Thus, the resistor used in Example 3.8 should have a power rating of 25 watts.

**EXAMPLE 3.9**

*Problem:* How many kilowatts of power are delivered to a circuit by a 220-V generator that supplies 30 A to the circuit?

*Solution:*

\[ P = E \times I = 220 \times 30 = 6600 \text{ W} = 6.6 \text{ kW} \]

**EXAMPLE 3.10**

*Problem:* If the voltage across a 30,000-ohm resistor is 450 V, what is the power dissipated in the resistor?

*Solution:*

\[ P = \frac{E^2}{R} = \frac{(450)^2}{30,000} = 202,500/30,000 = 6.75 \text{ W} \]

In this section, \( P \) was expressed in terms of various pairs of the other three basic quantities \( E, I, \) and \( R \). In practice, you should be able to express any one of the three basic quantities, as well as \( P \), in terms of any two of the others. Figure 3.27 is a summary of 12 basic formulas you should know. The four quantities \( E, I, R, \) and \( P \), are at the center of the figure. Adjacent to each quantity are three segments. Note that in each segment the basic quantity is expressed in terms of two other basic quantities, and no two segments are alike.

**ELECTRIC ENERGY**

*Energy* (the mechanical definition) is defined as the ability to do work (energy and time are essentially the same and are expressed in identical units). Energy is expended when work is done, because it takes energy to maintain a force when that force acts through a distance. The total energy expended to do a certain amount of work is equal to the working force multiplied by the distance through which the force moved to do the work. In electricity, total energy expended is equal to the rate at which work is done multiplied by the length of time the rate is measured. Essentially, energy
(watts) is equal to the power \((P)\) times time \((t)\). The kilowatt-hour \((\text{kWh})\) is a unit commonly used for large amounts of electric energy or work. The amount of kilowatt-hours is calculated as the product of the power in kilowatts \((\text{kW})\) and the time in hours \((\text{h})\) during which the power is used:

\[
\text{kWh} = \text{kW} \times \text{h}
\]

\[(3.7)\]

**EXAMPLE 3.11**

**Problem:** How much energy is delivered in 4 hours by a generator supplying 12 kW?

**Solution:**

\[
\text{kWh} = \text{kW} \times \text{h} = 12 \times 4 = 48
\]

The energy delivered is 48 kWh.

**SERIES DC CIRCUIT CHARACTERISTICS**

As previously mentioned, an electric circuit is made up of a voltage source, the necessary connecting conductors, and the effective load. If the circuit is arranged so the electrons have only one possible path, the circuit is a *series circuit*. A series circuit, then, is defined as a circuit that contains only one path for current flow. Figure 3.28 shows a series circuit having several loads (resistors).

*Note:* A series circuit is a circuit having only one path for current to flow along.

**Resistance**

To follow its electrical path, the current in a series circuit must flow through resistors inserted in the circuit (Figure 3.28). Thus, each additional resistor offers added resistance. In a series circuit, the total circuit resistance \((R_T)\) is equal to the sum of the individual resistances:

\[
R_T = R_1 + R_2 + R_3 \ldots R_n
\]

\[(3.8)\]

where

- \(R_T\) = Total resistance (ohms).
- \(R_1, R_2, R_3\) = Resistance in series (ohms).
- \(R_n\) = Any number of additional resistors in the equation.

**EXAMPLE 3.12**

**Problem:** Three resistors of 10 ohms, 12 ohms, and 25 ohms are connected in series across a battery whose emf is 110 volts (Figure 3.29). What is the total resistance?

![Figure 3.28 Series circuit.](image1)

![Figure 3.29 Solving for total resistance in a series circuit.](image2)
Solution:

Given:

- \( R_1 = 10 \text{ ohms} \)
- \( R_2 = 12 \text{ ohms} \)
- \( R_3 = 25 \text{ ohms} \)
- \( R_T = ? \)

\[
R_T = R_1 + R_2 + R_3 = 10 + 12 + 25 = 47 \text{ ohms}
\]

Transposition can be used in some circuit applications where the total resistance is known but the value of a circuit resistor has to be determined.

**EXAMPLE 3.13**

**Problem:** The total resistance of a circuit containing three resistors is 50 ohms (see Figure 3.30). Two of the circuit resistors are 12 ohms each. Calculate the value of the third resistor.

**Solution:**

Given:

- \( R_T = 50 \text{ ohms} \)
- \( R_1 = 12 \text{ ohms} \)
- \( R_2 = 12 \text{ ohms} \)
- \( R_3 = ? \)

\[
R_T = R_1 + R_2 + R_3
\]

Subtracting \((R_1 + R_2)\) from both sides of the equation, we obtain:

\[
R_3 = R_T - R_1 - R_2
\]

\[
R_3 = 50 - 12 - 12
\]

\[
R_3 = 50 - 24 = 26 \text{ ohms}
\]

**Note:** When resistances are connected in series, the total resistance in the circuit is equal to the sum of the resistances of all parts of the circuit.

![Figure 3.30](image-url) Calculating the value of one resistance in a series circuit.
Because there is but one path for current in a series circuit, the same current ($I$) must flow through each part of the circuit. To determine the current throughout a series circuit, only the current through one of the parts must be known. The fact that the same current flows through each part of a series circuit can be verified by inserting ammeters into the circuit at various points as shown in Figure 3.31. As indicated in Figure 3.31, each meter indicates the same value of current.

**Note:** In a series circuit, the same current flows in every part of the circuit. *Do not* add the currents in each part of the circuit to obtain $I$.

**Voltage**

The voltage drop across the resistor in the basic DC circuit is the total voltage across the circuit and is equal to the applied voltage. The total voltage across a series circuit is also equal to the applied voltage but consists of the sum of two or more individual voltage drops. This statement can be proven by an examination of the circuit shown in Figure 3.32. In this circuit, a source potential ($E_T$) of 30 volts is impressed across a series circuit consisting of two 6-ohm resistors. The total resistance of the circuit is equal to the sum of the two individual resistances, or 12 ohms. Using Ohm’s law, the circuit current may be calculated as follows:

$$I = \frac{E_T}{R_T} = \frac{30}{12} = 2.5 \text{ amps}$$

**FIGURE 3.31** DC current in a series circuit.

**FIGURE 3.32** Calculating total resistance in a series circuit.
Because we know that the value of the resistors is 6 ohms each, and the DC current through the resistors is 2.5 amps, the voltage drops across the resistors can be calculated. The voltage \( E_1 \) across \( R_1 \) is, therefore:

\[
E_1 = I \times R_1
\]

\[
E_1 = 2.5 \text{ amps} \times 6 \text{ ohms} = 15 \text{ volts}
\]

Because \( R_2 \) is the same ohmic value as \( R_1 \) and carries the same current, the voltage drop across \( R_2 \) is also equal to 15 volts. Adding these two 15-volt drops together gives a total drop of 30 volts, exactly equal to the applied voltage. For a series circuit, then:

\[
E_T = E_1 + E_2 + E_3 + \ldots + E_n
\]

where

- \( E_T \) = Total voltage (V).
- \( E_1 \) = Voltage across resistance \( R_1 \) (V).
- \( E_2 \) = Voltage across resistance \( R_2 \) (V).
- \( E_3 \) = Voltage across resistance \( R_3 \) (V).

**EXAMPLE 3.14**

*Problem:* A series DC circuit consists of three resistors having values of 10, 20, and 40 ohms. Find the applied voltage if the current through the 20-ohm resistor is 2.5 amps.

*Solution:* To solve this problem, first draw a circuit diagram and label it as shown in Figure 3.33.

\[
E_T = E_1 + E_2 + E_3 + \ldots + E_n
\]

Given:

- \( R_1 = 10 \text{ ohms} \)
- \( R_2 = 20 \text{ ohms} \)
- \( R_3 = 40 \text{ ohms} \)
- \( I = 2.5 \text{ amps} \)

Because the circuit involved is a DC series circuit, the same 2.5 amps of current flows through each resistor. Using Ohm’s law, the voltage drops across each of the three resistors can be calculated:

\[
E_1 = 25 \text{ V}
\]

\[
E_2 = 50 \text{ V}
\]

\[
E_3 = 100 \text{ V}
\]

**FIGURE 3.33** Solving for applied voltage in a series circuit.
When the individual drops are known they can be added to find the total or applied voltage:

\[ E_T = E_1 + E_2 + E_3 \]
\[ E_T = 25 \text{ V} + 50 \text{ V} + 100 \text{ V} = 175 \text{ V} \]

**Note:** The total voltage \( E_T \) across a DC series circuit is equal to the sum of the voltages across each resistance of the circuit.

**Note:** The voltage drops that occur in a series circuit are in direct proportions to the resistance across which they appear. This is the result of having the same current flow through each resistor. Thus, the larger the resistor, the larger will be the voltage drop across it.

### Power

Each resistor in a DC series circuit consumes power. This power is dissipated in the form of heat. Because this power must come from the source, the total power must be equal in amount to the power consumed by the circuit resistances. In a series circuit, the total power is equal to the sum of the powers dissipated by the individual resistors. Total power \( P_T \), then, is equal to

\[ P_T = P_1 + P_2 + P_3 + \ldots + P_n \]  
\[ (3.10) \]

where

- \( P_T \) = Total power (W).
- \( P_1 \) = Power used in the first part (W).
- \( P_2 \) = Power used in the second part (W).
- \( P_3 \) = Power used in the third part (W).
- \( P_n \) = Power used in the \( n \)th part (W).

■ **EXAMPLE 3.15**

**Problem:** A DC series circuit consists of three resistors having values of 5, 15, and 20 ohms. Find the total power dissipation when 120 volts is applied to the circuit (see Figure 3.34).

**Solution:**

Given:

- \( R_1 = 5 \) ohms
- \( R_2 = 15 \) ohms
- \( R_3 = 20 \) ohms
- \( E = 120 \) volts

\[ \text{FIGURE 3.34 Solving for total power in a series circuit.} \]
First find the total resistance:

\[ R_T = R_1 + R_2 + R_3 = 5 + 15 + 20 = 40 \, \text{ohms} \]

Using total resistance and the applied voltage, calculate the circuit current:

\[ I = \frac{E_T}{R_T} = \frac{120}{40} = 3 \, \text{amps} \]

Using the power formula, calculate the individual power dissipations:

For resistor \( R_1 \):

\[ P_1 = I^2 \times R_1 = (3)^2 \times 5 = 45 \, \text{watts} \]

For resistor \( R_2 \):

\[ P_2 = I^2 \times R_2 = (3)^2 \times 15 = 135 \, \text{watts} \]

For resistor \( R_3 \):

\[ P_3 = I^2 \times R_3 = (3)^2 \times 20 = 180 \, \text{watts} \]

To obtain total power:

\[ P_T = P_1 + P_2 + P_3 = 45 + 135 + 180 = 360 \, \text{watts} \]

To check the answer, calculate the total power delivered by the source:

\[ P = E \times I = 120 \, \text{volts} \times 3 \, \text{amps} = 360 \, \text{watts} \]

Thus, the total power is equal to the sum of the individual power dissipations.

We found that Ohm’s law can be used for total values in a DC series circuit as well as for individual parts of the circuit. Similarly, the formula for power may be used for total values:

\[ P_T = E_T \times I \] (3.11)

**Summary of the Rules for Series DC Circuits**

To this point, we have covered many of the important factors governing the operation of basic DC series circuits. In essence, what we have really done is to lay a strong foundation to build upon in preparation for more advanced circuit theory that follows. Following is a summary of the important factors governing the operation of a DC series circuit:

- The same current flows through each part of a series circuit.
- Total resistance of a series circuit is equal to the sum of the individual resistances.
- Total voltage across a series circuit is equal to the sum of the individual voltage drops.
- Voltage drop across a resistor in a series circuit is proportional to the size of the resistor.
- Total power dissipated in a series circuit is equal to the sum of the individual dissipations.

**General DC Series Circuit Analysis**

Now that we have discussed the pieces required to put together the puzzle of DC series circuit analysis, we now move on to the next step in the process: series circuit analysis in total.
**EXAMPLE 3.16**

*Problem:* Three resistors of 20, 20, and 30 ohms are connected across a battery supply rated at 100 volts terminal voltage. Completely solve the circuit shown in Figure 3.35.

*Note:* When current is known, the voltage drops and power dissipations can be calculated.

*Solution:* The total resistance is

\[ R_T = R_1 + R_2 + R_3 = 20 \text{ ohms} + 20 \text{ ohms} + 30 \text{ ohms} = 70 \text{ ohms} \]

By Ohm’s law, the current is

\[ I = E/R_T = 100/70 = 1.43 \text{ amps} \text{ (rounded)} \]

The voltage \( (E_1) \) across \( R_1 \) is

\[ E_1 = I \times R_1 = 1.43 \text{ amp} \times 20 \text{ ohms} = 28.6 \text{ volts} \]

The voltage \( (E_2) \) across \( R_2 \) is

\[ E_2 = I \times R_2 = 1.43 \text{ amp} \times 20 \text{ ohms} = 28.6 \text{ volts} \]

The voltage \( (E_3) \) across \( R_3 \) is

\[ E_3 = I \times R_3 = 1.43 \text{ amp} \times 30 \text{ ohms} = 42.9 \text{ volts} \]

The power dissipated by \( R_1 \) is

\[ P_1 = E_1 \times I = 28.6 \text{ volts} \times 1.43 \text{ amp} = 40.9 \text{ watts} \]

The power dissipated by \( R_2 \) is

\[ P_2 = E_2 \times I = 28.6 \text{ volts} \times 1.43 \text{ amp} = 40.9 \text{ watts} \]

The power dissipated by \( R_3 \) is

\[ P_3 = E_3 \times I = 42.9 \text{ volts} \times 1.43 \text{ amp} = 61.3 \text{ watts} \]

*FIGURE 3.35* Solving for various values in a series circuit.
The total power dissipated is

\[ P_T = E_T \times I = 100 \text{ volts} \times 1.43 \text{ amps} = 143 \text{ watts} \]

**Note:** When applying Ohm’s law to a DC series circuit, consider whether the values used are component values or total values. When the information available enables the use of Ohm’s law to find total resistance, total voltage, and total current, total values must be inserted into the formula.

To find total resistance:

\[ R_T = \frac{E_T}{I_T} \]

To find total voltage:

\[ E_T = I_T \times R_T \]

To find total current:

\[ I_T = \frac{E_T}{R_T} \]

**Kirchoff’s Voltage Law**

Kirchoff’s voltage law states that the voltage applied to a closed circuit equals the sum of the voltage drops in that circuit. It should be obvious that this fact was used in the study of series circuits to this point. It was expressed as follows:

\[ \text{Voltage applied} = \text{Sum of voltage drops} \]

\[ E_A = E_1 + E_2 + E_3 \]  \hspace{1cm} (3.12)

where \( E_A \) is the applied voltage and \( E_1, E_2, \) and \( E_3 \) are voltage drops.

Another way of stating Kirchoff’s law is that the algebraic sum of the instantaneous emf values and voltage drops around any closed circuit is zero. Kirchoff’s law can be used to solve circuit problems that would be difficult and often impossible to solve with only knowledge of Ohm’s law. When Kirchoff’s law is properly applied, an equation can be set up for a closed loop and the unknown circuit values may be calculated.

**Polarity of Voltage Drops**

When there is a voltage drop across a resistance, one end must be more positive or more negative than the other end. The polarity of the voltage drop is determined by the direction of current flow. In the circuit shown in Figure 3.36 the current is seen to be flowing in a counterclockwise direction due to the arrangement of the battery source (\( E \)). Notice that the end of resistor \( R_1 \) into which the current flows is marked negative (–). The end of \( R_1 \) at which the current leaves is marked positive (+). These polarity markings are used to show that the end of \( R_1 \) into which the current flows is at a higher negative potential than is the end of the resistor at which the current leaves. Point A is thus more negative than point B. Point C, which is at the same potential as point B, is labeled negative to indicate that point C, though positive with respect to point A, is more negative than point D. To say a point is positive (or negative), without stating what it is positive with respect to has no meaning.

Kirchoff’s voltage law written as an equation is

\[ E_a + E_b + E_c + \ldots + E_n = 0 \]  \hspace{1cm} (3.13)

where \( E_a, E_b, \) etc. are the voltage drops and emf values around any closed-circuit loop.
**EXAMPLE 3.17**

*Problem:* Three resistors are connected across a 60-volt source. What is the voltage across the third resistor if the voltage drops across the first two resistors are 10 volts and 20 volts?

*Solution:* Draw a diagram like the one in Figure 3.37 and assume a direction of current as shown. Using this current, place the polarity markings at each end of each resistor and on the terminals of the source. Starting at point A, trace around the circuit in the direction of current flow, recording the voltage and polarity of each component. Starting at point A, these voltages would be as follows:

\[ E_a + E_b + E_c + \ldots + E_n = 0 \]

From the circuit:

\[ (+E_2) + (+E_3) + (+E_3) - (E_A) = 0 \]

Substituting values from circuit:

\[ E_7 + 10 + 20 - 60 = 0 \]

\[ E_7 - 30 = 0 \]

\[ E_7 = 30 \text{ volts} \]

*Note:* In much the same way, a problem can be solved in which the current is the unknown quantity.
Series Aiding and Opposing Sources

Sources of voltage that cause current to flow in the same direction are considered to be *series aiding* and their voltages add. Sources of voltage that would tend to force current in opposite directions are said to be *series opposing*, and the effective source voltage is the difference between the opposing voltages. When two opposing sources are inserted into a circuit, current flow would be in a direction determined by the larger source. Examples of series aiding and opposing sources are shown in Figure 3.38.

Kirchoff’s Law and Multiple Source Solutions

Kirchoff’s law can be used to solve multiple-source circuit problems. When applying this method, the exact same procedure is used for multiple-source circuits as for single-source circuits. This is demonstrated by the following example.

■ EXAMPLE 3.18

*Problem:* Find the amount of current in the circuit shown in Figure 3.39.

*Solution:* Start at point A:

\[ E_a + E_b + E_c + \ldots + E_n = 0 \]

**FIGURE 3.39** Solving for circuit current in a multiple source circuit.
From the circuit:
\[ E_{b2} + E_1 - E_{b1} + E_{b3} + E_2 = 0 \]
\[ 40 + 40I - 140 + 20 + 20I = 0 \]
Combining like terms:
\[ 60I - 80 = 0 \]
\[ 60I = 80 \]
\[ I = 1.33 \text{ amps} \]

**Ground**

The term *ground* is used to denote a common electrical point of zero potential. The reference point of a circuit is always considered to be at zero potential. The earth (ground) is said to be at zero potential. In Figure 3.40, point A is the zero reference or ground and is symbolized as such. Point C is 60 volts positive and point B is 20 volts positive with respect to ground. The common ground for much electrical/electronics equipment is the metal chassis. The value of ground is noted when considering its contribution to economy, simplification of schematics, and ease of measurement. When completing each electrical circuit, common points of a circuit at zero potential are connected directly to the metal chassis, thereby eliminating a large amount of connecting wire. An example of a grounded circuit is illustrated in Figure 3.41.

*Note:* Most voltage measurements used to check proper circuit operation in electronic equipment are taken with respect to ground. One meter lead is attached to ground and the other meter lead is moved to various test points.

**Open and Short Circuits**

A circuit is *open* if a break in the circuit does not provide a complete path for DC or AC current. Figure 3.42 shows an open circuit, because the fuse is blown. To protect a circuit, a fuse is placed directly into the circuit (see Figure 3.42). A fuse will open the circuit whenever a dangerously large current begins to flow. A fuse will permit currents smaller than the fuse value to flow but will melt and therefore break or open the circuit if a larger current flows. A dangerously large current will flow when a *short circuit* occurs. A short circuit is usually caused by an accidental connection between two points in a circuit that offers very little resistance and passes an abnormal amount of current (see Figure 3.43). A short circuit often occurs as a result of improper wiring or broken insulation.

**FIGURE 3.40** Use of ground symbols.

**FIGURE 3.41** Ground used as a conductor.
PARALLEL DC CIRCUITS

The principles we applied to solving simple DC series circuit calculations for determining the reactions of such quantities as voltage, current, and resistance also can be used in DC parallel and series-parallel circuits.

PARALLEL CIRCUIT CHARACTERISTICS

A parallel circuit is defined as one having two or more components connected across the same voltage source (see Figure 3.44). Recall that a series circuit has only one path for current flow. As additional loads (e.g., resistors) are added to the circuit, the total resistance increases and the total current decreases. This is not the case for a parallel circuit. In a parallel circuit, each load (or branch) is connected directly across the voltage source. In Figure 3.44, commencing at the voltage source \( E_b \) and tracing counterclockwise around the circuit, two complete and separate paths can be identified in which current can flow. One path is traced from the source through resistance \( R_1 \) and back to the source; the other, from the source through resistance \( R_2 \) and back to the source.

VOLTAGE IN PARALLEL CIRCUITS

Recall that in a series circuit the source voltage divides proportionately across each resistor in the circuit. In a parallel circuit (see Figure 3.44), the same voltage is present across all the resistors of a parallel group. This voltage is equal to the applied voltage \( E_b \) and can be expressed in equation form as

\[
E_b = E_{R_1} = E_{R_2} = E_{R_n}
\]

(3.14)
We can verify Equation 3.14 by taking voltage measurements across the resistors of a parallel circuit, as illustrated in Figure 3.45. Notice that each voltmeter indicates the same amount of voltage; that is, the voltage across each resistor is the same as the applied voltage.

*Note:* In a parallel circuit, the voltage remains the same throughout the circuit.

**Example 3.19**

*Problem:* Assume that the current through a resistor of a parallel circuit is known to be 4 milliamperes (mA) and the value of the resistor is 40,000 ohms. Determine the potential (voltage) across the resistor. The circuit is shown in Figure 3.46.

*Solution:* First find $E_{R_2}$ and then $E_b$.

Given:
- $R_2 = 40,000$ ohms
- $I_{R_2} = 4.0$ mA

Select the proper equation:

$$E = I \times R$$

Substitute known values:

$$E_{R_2} = I_{R_2} \times R_2$$

$$E_{R_2} = 4.0 \text{ mA} \times 40,000 \text{ ohms}$$

Use powers of ten:

$$E_{R_2} = (4.0 \times 10^{-3}) \times (40 \times 10^3)$$

$$E_{R_2} = 4.0 \times 40 = 160 \text{ V}$$

*Figure 3.45* Voltage comparison in a parallel circuit.

*Figure 3.46* Example 3.19.
Therefore,

\[ E_b = 160 \text{ V} \]

**Note:** Ohm’s law states that the current in a circuit is inversely proportional to the circuit resistance. This fact, important as a basic building block of electrical theory, obviously, is also important in the following explanation of current flow in parallel circuits.

**Current in Parallel Circuits**

In a series circuit, a single current flows. Its value is determined in part by the total resistance of the circuit; however, the source current in a parallel circuit divides among the available paths in relation to the value of the resistors in the circuit. Ohm’s law remains unchanged. For a given voltage, current varies inversely with resistance. The behavior of current in a parallel circuit is best illustrated by example. In Figure 3.47, the resistors \( R_1, R_2, \) and \( R_3 \) are in parallel with each other and with the battery. Each parallel path is then a branch with its own individual current. When total current \( I_T \) leaves voltage source \( E \), part \( I_1 \) of current \( I_T \) will flow through \( R_1 \), part \( I_2 \) will flow through \( R_2 \), and \( I_3 \) will flow through \( R_3 \). Branch currents \( I_1, I_2, \) and \( I_3 \) can be different; however, if a voltmeter (used for measuring the voltage of a circuit) is connected across \( R_1, R_2, \) and \( R_3 \), the respective voltages \( E_1, E_2, \) and \( E_3 \) will be equal. Therefore,

\[ E = E_1 = E_2 = E_3 \]

Total current \( I_T \) is equal to the sum of all branch currents:

\[ I_T = I_1 = I_2 = I_3 \quad (3.15) \]

This formula applies for any number of parallel branches, whether the resistances are equal or unequal.

By Ohm’s law, each branch current equals the applied voltage divided by the resistance between the two points where the voltage is applied. Hence, for each branch we have the following equations (see Figure 3.47):

**Branch 1**

\[ I_1 = E_1/R_1 = V/R_1 \]

**Branch 2**

\[ I_2 = E_2/R_2 = V/R_2 \]

**Branch 3**

\[ I_3 = E_3/R_3 = V/R_3 \]

With the same applied voltage, any branch that has less resistance allows more current through it than a branch with higher resistance.

![FIGURE 3.47 Parallel circuit.](image-url)
EXAMPLE 3.20

Problem: Two resistors, each drawing 2 amps, and a third resistor drawing 1 amp are connected in parallel across a 100-V line (see Figure 3.48). What is the total current?

Solution: The formula for total current is

\[ I_T = I_1 + I_2 + I_3 = 2 + 2 + 1 = 5 \text{ amps} \]

The total current is 5 amps.

EXAMPLE 3.21

Problem: Two branches, \( R_1 \) and \( R_2 \), across a 100-V power line draw a total line current of 20 A (Figure 3.49). Branch \( R_1 \) takes 10 A. What is current \( I_2 \) in branch \( R_2 \)?

Solution: Starting with Equation 3.15, transpose to find \( I_2 \) and then substitute the given values:

\[ I_T = I_1 + I_2 \]

\[ I_2 = I_T - I_1 = 20 - 10 = 10 \text{ A} \]

The current in branch \( R_2 \) is 10 A.

EXAMPLE 3.22

Problem: A parallel circuit consists of two 15-ohm and one 12-ohm resistors across a 120-V line (see Figure 3.50). What current will flow in each branch of the circuit and what is the total current drawn by all the resistors?

Solution: There is a 120-V potential across each resistor, so

\[ I_1 = \frac{V}{R_1} = \frac{120}{15} = 8 \text{ amps} \]

\[ I_2 = \frac{V}{R_2} = \frac{120}{15} = 8 \text{ amps} \]

\[ I_3 = \frac{V}{R_3} = \frac{120}{12} = 10 \text{ amps} \]

Now find total current:

\[ I_T = I_1 + I_2 + I_3 = 8 + 8 + 10 = 26 \text{ A} \]
The division of current in a parallel network follows a definite pattern. This pattern is described by Kirchoff’s current law: The algebraic sum of the currents entering and leaving any junction of conductors is equal to zero. This can be stated mathematically as

\[ I_a + I_b + \ldots + I_n = 0 \]  

(3.16)

where \( I_a, I_b, \) etc. are the currents entering and leaving the junction. Currents entering the junction are assumed to be positive; currents leaving the junction, negative. When solving a problem using Equation 3.16, the currents must be placed into the equation with the proper polarity.

**Example 3.23**

*Problem:* Solve for the value of \( I_3 \) in Figure 3.51.

*Solution:* First, give the currents the proper signs:

\[ I_1 = +10 \text{ amps} \quad I_3 = ? \text{ amps} \]

\[ I_2 = -3 \text{ amps} \quad I_4 = -5 \text{ amps} \]

Then, place these currents into the equation with the proper signs, as follows:

\[ I_a + I_b + \ldots + I_n = 0 \]

\[ I_1 + I_2 + I_3 + I_4 = 0 \]

\[ (+10) + (-3) + (I_3) + (-5) = 0 \]

Combining like terms:

\[ I_3 + 2 = 0 \]

\[ I_3 = -2 \text{ amps} \]

Thus, \( I_3 \) has a value of 2 amps, and the negative sign shows that it is a current leaving the junction.

**FIGURE 3.51** Example 3.23.
Parallel Resistance

Unlike series circuits where total resistance \( R_T \) is the sum of the individual resistances, in a parallel circuit the total resistance is **not** the sum of the individual resistances. In a parallel circuit, we can use Ohm’s law to find total resistance. We use the equation

\[
R = \frac{E}{I} \quad \text{or} \quad R_T = \frac{E_S}{I_T}
\]

where \( R_T \) is the total resistance of all the parallel branches across the voltage source \( E_S \), and \( I_T \) is the sum of all the branch currents.

**EXAMPLE 3.24**

**Problem:** What is the total resistance of the circuit shown in Figure 3.52?

**Solution:**

Given:

\[
E_S = 120 \text{ V} \\
I_T = 26 \text{ A}
\]

\[
R_T = \frac{E_S}{I_T} = \frac{120}{26} = 4.62 \text{ ohms}
\]

**Note:** Notice that \( R_T \) is smaller than any of the three resistances shown in Figure 3.52. This fact may surprise you—it may seem strange that the total circuit resistance is less than that of the smallest resistor (\( R_3 \), 12 ohms). However, if we refer back to the water analogy we have used previously, it makes sense. Consider water pressure and water pipes, and assume it is possible to keep the water pressure constant. A small pipe offers more resistance to the flow of water than a larger pipe, but, if we add another pipe in parallel, one of even smaller diameter, the total resistance to water flow is decreased. In an electrical circuit, even a larger resistor in another parallel branch provides an additional path for current flow, so the total resistance is less. Remember, if we add one more branch to a parallel circuit, the total resistance decreases and the total current increases.

What we essentially demonstrated in working this particular problem is that the total load connected to the 120-V line is the same as the single equivalent resistance of 4.62 ohms connected across the line. It is probably more accurate to call this total resistance the “equivalent resistance,” but by convention we use \( R_T \) or total resistance, although the terms are often used interchangeably. We illustrate the equivalent resistance in the equivalent circuit shown in Figure 3.53.

Other methods can be used to determine the equivalent resistance of parallel circuits. The most appropriate method for a particular circuit depends on the number and value of the resistors; for example, consider the parallel circuit shown in Figure 3.54. For this circuit, the following simple equation is used:

\[
R_{eq} = \frac{R}{N} \quad (3.17)
\]

**FIGURE 3.52** Example 3.24.
Principles of Basic Electricity

where

\[ R_{eq} = \frac{R}{N} \]

\[ R = \text{Ohmic value of one resistor.} \]

\[ N = \text{Number of resistors.} \]

Thus, \( R_{eq} = \frac{10 \text{ ohms}}{2} = 5 \text{ ohms} \)

When two equal value resistors are connected in parallel, they present a total resistance equivalent to a single resistor of one-half the value of either of the original resistors.

**Note:** Equation 3.17 is valid for any number of equal value parallel resistors.

### EXAMPLE 3.25

**Problem:** When five 50-ohm resistors are connected in parallel, what is the equivalent circuit resistance?

**Solution:** Using Equation 3.17:

\[ R_{eq} = \frac{R}{N} = \frac{50 \text{ ohms}}{5} = 10 \text{ ohms} \]

What about parallel circuits containing resistances of unequal value? How is equivalent resistance determined? Example 3.26 demonstrates how this is accomplished.

### EXAMPLE 3.26

**Problem:** Refer to Figure 3.55 and determine \( R_{eq} \).

**Given:**

\[ R_1 = 3 \text{ ohms} \]

\[ R_2 = 6 \text{ ohms} \]

\[ E_a = 30 \text{ volts} \]

**Known:**

\[ I_1 = 10 \text{ amps} \]

\[ I_2 = 5 \text{ amps} \]

\[ I_T = 15 \text{ amps} \]
Solution:

\[ R_{eq} = \frac{E_a}{I_T} = \frac{30 \text{ ohms}}{15} = 2 \text{ ohms} \]

In Example 3.26, the equivalent resistance of 2 ohms is less than the value of either branch resistor. Remember, in parallel circuits the equivalent resistance will always be smaller than the resistance of any branch.

**Reciprocal Method**

When circuits are encountered in which resistors of unequal value are connected in parallel, the equivalent resistance may be computed by using the *reciprocal method*.

*Note:* A *reciprocal* is an inverted fraction; the reciprocal of the fraction 3/4, for example, is 4/3. We consider a whole number to be a fraction with 1 as the denominator, so the reciprocal of a whole number is that number divided into 1; for example, the reciprocal of \( R_T \) is \( \frac{1}{R_T} \). The equivalent resistance in parallel is given by

\[
\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}
\]

where \( R_T \) is the total resistance in parallel and \( R_1, R_2, R_3, \) and \( R_n \) are the branch resistances.

**EXAMPLE 3.27**

*Problem:* Find the total resistance of 2-, 4-, and 8-ohm resistors in parallel (Figure 3.56).

*Solution:* Write the formula for three resistors in parallel:

\[
\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}
\]
Substitute the resistance values:

\[ \frac{1}{R_f} = \frac{1}{2} + \frac{1}{4} + \frac{1}{8} \]

Add fractions:

\[ \frac{1}{R_f} = \frac{4}{8} + \frac{2}{8} + \frac{1}{8} = \frac{7}{8} \]

Invert both sides of the equation:

\[ R_f = \frac{8}{7} = 1.14 \text{ ohms} \]

Note: When resistances are connected in parallel, the total resistance is always less than the smallest resistance of any single branch.

**Product-over-Sum Method**

When any two unequal resistors are in parallel, it is often easier to calculate the total resistance by multiplying the two resistances and then dividing the product by the sum of the resistances:

\[ R_f = \frac{R_1 \times R_2}{R_1 + R_2} \quad (3.19) \]

where \( R_f \) is the total resistance in parallel, and \( R_1 \) and \( R_2 \) are the two resistors in parallel.

**Example 3.28**

Problem: What is the equivalent resistance of a 20-ohm and a 30-ohm resistor connected in parallel?

Solution:

Given:
\[ R_1 = 20 \text{ ohms} \]
\[ R_2 = 30 \text{ ohms} \]

\[ R_f = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{20 \times 30}{20 + 30} = \frac{600}{50} = 12 \text{ ohms} \]

**Reduction to an Equivalent Circuit**

In the study of basic electricity, it is often necessary to resolve a complex circuit into a simpler form. Any complex circuit consisting of resistances can be reduced to a basic equivalent circuit containing the source and total resistance. This process is called reduction to an equivalent circuit. An example of circuit reduction was demonstrated in Example 3.28 and is illustrated in Figure 3.57. The circuit shown in Figure 3.57A is reduced to the simple circuit shown in Figure 3.57B.
As in the series circuit, the total power consumed in a parallel circuit is equal to the sum of the power consumed in the individual resistors:

\[ P_T = P_1 + P_2 + P_3 + \ldots + P_n \]  

(3.20)

where \( P_T \) is the total power and \( P_1, P_2, P_3, \) and \( P_n \) are the branch powers.

**Note:** Because power dissipation in resistors consists of a heat loss, power dissipations are additive regardless of how the resistors are connected in the circuit.

Total power can also be calculated by

\[ P_T = E \times I_T \]  

(3.21)

where

- \( P_T \) = Total power.
- \( E \) = Voltage source across all parallel branches.
- \( I_T \) = Total current.

The power dissipated in each branch is equal to \( EI \) and to \( V^2/R \).

**Note:** In both parallel and series arrangements, the sum of the individual values of power dissipated in the circuit equals the total power generated by the source. The circuit arrangements cannot change the fact that all power in the circuit comes from the source.

**EXAMPLE 3.29**

**Problem:** Find the total power consumed by the circuit in Figure 3.58.

**Solution:**

\[
\begin{align*}
P_{R1} &= E_b \times I_{R1} = 50 \times 5 = 250 \text{ watts} \\
P_{R2} &= E_b \times I_{R2} = 50 \times 2 = 100 \text{ watts} \\
P_{R3} &= E_b \times I_{R3} = 50 \times 1 = 50 \text{ watts} \\
P_T &= P_1 + P_2 + P_3 = 250 + 100 + 50 = 400 \text{ watts}
\end{align*}
\]

**Note:** The power dissipated in the branch circuits in Figure 3.58 is determined in the same manner as the power dissipated by individual resistors in a series circuit. The total power \( (P_T) \) is then obtained by summing up the powers dissipated in the branch resistors using Equation 3.21.
Because, in the example shown in Figure 3.58, the total current is known, we could determine the total power by the following method:

\[ P_T = E_b \times I_T = 50 \text{ V} \times 8 \text{ A} = 400 \text{ W} \]

**Rules for Solving Parallel DC Circuits**

Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is basically the same: (1) draw a circuit diagram, (2) state the values given and the values to be found, (3) state the applicable equations, and (4) substitute the given values and solve for the unknown. Along with following this problem-solving procedure, it is also important to remember to apply the rules for solving parallel DC circuits:

1. The same voltage exists across each branch of a parallel circuit and is equal to the source voltage.
2. The current through a branch of a parallel network is inversely proportional to the amount of resistance of the branch.
3. The total current of a parallel circuit is equal to the sum of the currents of the individual branches of the circuit.
4. The total resistance of a parallel circuit is equal to the reciprocal of the sum of the reciprocals of the individual resistances of the circuit.
5. The total power consumed in a parallel circuit is equal to the sum of the power consumption of the individual resistances.

**Series–Parallel Circuits**

To this point we have discussed series and parallel DC circuits; however, the maintenance operator will seldom encounter a circuit that consists solely of either type of circuit. Most circuits consist of both series and parallel elements. A circuit of this type is referred to as a series–parallel circuit, or as a combination circuit. Solving a series–parallel (combination) circuit is simply a matter of applying the laws and rules discussed up to this point.

**Solving a Series–Parallel Circuit**

At least three resistors are required to form a series–parallel circuit. An example of a series–parallel circuit is shown in Figure 3.59, where two parallel resistors, \( R_2 \) and \( R_3 \), are connected in series with resistor \( R_1 \) and voltage source \( E \). In a circuit of this type, current \( I_T \) divides after it flows through \( R_1 \); part flows through \( R_2 \), and part flows through \( R_3 \). The current then joins at the junction of the two resistors and flows back to the positive terminal of the voltage source \( (E) \) and through the voltage source to the positive terminal.
When solving for values in a series–parallel circuit (current, voltage, and resistance), follow the rules that apply to a series circuit for the series part of the circuit and follow the rules that apply to a parallel circuit for the parallel part of the circuit. Solving series–parallel circuits is simplified if all parallel and series groups are first reduced to single equivalent resistances and the circuits are redrawn in simplified form. Recall that the redrawn circuit is called an *equivalent circuit*. The procedure for developing an equivalent circuit is shown in Figure 3.60.

**FIGURE 3.59** Series–parallel circuit.

**FIGURE 3.60** Developing an equivalent circuit.
Note: There are no general formulas for the solution of series–parallel circuits because there are so many different forms of these circuits.

**EXAMPLE 3.30**

**Problem:** Find the total resistance \( R_T \), total circuit current \( I_T \), and branch currents of the circuit shown in Figure 3.61A.

**Solution:** Find the equivalent resistance of the parallel branch:

\[
R_p = \frac{R_2 \times R_3}{R_2 + R_3} = \frac{15 \times 20}{15 + 20} = \frac{300}{35} = 8.6 \text{ ohms}
\]

The equivalent circuit reduces to a series circuit (Figure 3.61B). Find the resistance of the equivalent series circuit:

\[
R_T = R_1 + R_p = 10 + 8.6 = 18.6 \text{ ohms}
\]
The equivalent circuit reduces to a single voltage source and a single resistance (Figure 3.61C). Find the actual current being supplied in the original series–parallel circuit ($I_T$):

\[ I_T = \frac{V}{R_T} = \frac{60}{18.6} = 3.3 \text{ amps} \]

Find $I_2$ and $I_3$. The voltage across $R_2$ and $R_3$ is equal to the applied voltage ($E$) less the voltage drop across $R_1$ (Figure 3.61D):

\[ V_2 = V_3 = V - (I_T \times R_1) = 60 - (3.3 \times 10) = 27 \text{ volts} \]

Then,

\[ I_2 = \frac{V_2}{R_2} = \frac{27}{15} = 1.8 \text{ amps} \]
\[ I_3 = \frac{V_3}{R_3} = \frac{27}{20} = 1.35 \text{ amps} \]

Note: The total current in the series–parallel circuit depends on the effective resistance of the parallel portion and on the other resistances.

### Example 3.31

**Problem:** Answer the following questions related to Figure 3.62:

1. The figure shows a circuit in which two resistors in series ($R_2$ and $R_3$) form one branch of a parallel circuit. The total current ($I_T$) flows into the parallel circuit, splitting into two branches at point a. At what point do the branch currents rejoin to form $I_T$?
   **Answer:** At point c.

2. Source voltage $E_S$ (30 V) drops between points a and c. The largest voltage drop is across which resistor? Why?
   **Answer:** $R_1$, because the 30 V must be divided between $R_2$ and $R_3$.

3. What is the resistance of the top branch of the circuit in Figure 3.62?
   **Answer:** $R_2 + R_3 = 14$ ohms.

4. What is the value of $R_7$?
   **Answer:**
   \[ R_7 = \frac{8 \times 14}{8 + 14} = \frac{112}{22} = 5.1 \text{ ohms} \]

5. What is the current through the top branch ($I_{2,3}$)?
   **Answer:**
   \[ I = \frac{E}{R} = \frac{30}{14} = 2.14 \text{ amps} \]

![FIGURE 3.62 Example 3.31.](image-url)
6. What is the value of $P_T$?

Answer:

\[ P_T = \frac{(E_s)^2}{R_T} = \frac{30^2}{5.1} = \frac{900}{5.1} = 176.5 \text{ watts} \]

CONDUCTORS

Recall that we pointed out earlier that electric current moves easily through some materials but with greater difficulty through others. Three good electrical conductors are copper, silver, and aluminum (generally, we can say that most metals are good conductors). At the present time, copper is the material of choice used in electrical conductors. Under special conditions, certain gases are also used as conductors; for example, neon gas, mercury vapor, and sodium vapor are used in various kinds of lamps. The function of the wire conductor is to connect a source of applied voltage to a load resistance with a minimum $IR$ voltage drop in the conductor so most of the applied voltage can produce current in the load resistance. Ideally, a conductor must have a very low resistance; a typical value for a conductor such as copper is less than 1 ohm per 10 feet. Because all electrical circuits utilize conductors of one type or another, in this section we discuss the basic features and electrical characteristics of the most common types of conductors. Moreover, because conductor splices and connections (and insulation of such connections) are also an essential part of any electric circuit, they are also discussed.

UNIT SIZE OF CONDUCTORS

A standard (or unit size) of a conductor has been established to compare the resistance and size of one conductor with another. The unit of linear measurement used with regard to the diameter of a piece of wire is the mil (0.001 of an inch). A convenient unit of wire length used is the foot. Thus, the standard unit of size in most cases is the mil-foot; a wire will have unit size if it has a diameter of 1 mil and a length of 1 foot. The resistance in ohms of a unit conductor or a given substance is called the resistivity (or specific resistance) of the substance. As a further convenience, gauge numbers are also used to compare the diameter of wires. The Brown & Sharpe (B&S) gauge was used in the past; today, the American wire gauge (AWG) is more commonly used.

SQUARE MIL

Figure 3.63 shows a square mil, which is a convenient unit of cross-sectional area for square or rectangular conductors. As shown in the figure, a square mil is the area of a square, the sides of which are 1 mil. To obtain the cross-sectional area in square mils of a square conductor, square one side measured in mils. To obtain the cross-sectional area in square mils of a rectangular conductor, multiply the length of one side by that of the other, each length being expressed in mils.

![Figure 3.63](A) Square mil; (B) circular mil; (C) comparison of circular to square mil.)
EXAMPLE 3.32

Problem: Find the cross-sectional area of a large rectangular conductor 5/8 inch thick and 5 inches wide.

Solution: The thickness may be expressed in mils as $0.625 \times 1000 = 625$ mils and the width as $5 \times 1000 = 5000$ mils. The cross-sectional area is $625 \times 5000$, or 3,125,000 square mils.

CIRCULAR MIL

The circular mil is the standard unit of wire cross-sectional area used in most wire tables. To avoid the use of decimals (because most wires used to conduct electricity may be only a small fraction of an inch), it is convenient to express these diameters in mils. For example, the diameter of a wire is expressed as 25 mils instead of 0.025 inch. A circular mil is the area of a circle having a diameter of 1 mil, as shown in Figure 3.63B. The area in circular mils of a round conductor is obtained by squaring the diameter measured in mils; thus, a wire having a diameter of 25 mils has an area of $25^2$, or 625, circular mils. By way of comparison, the basic formula for the area of a circle is

$$A = \pi \times R^2 \quad (3.22)$$

In this example, the area in square inches (in.$^2$) is

$$A = \pi \times R^2 = 3.14 \times (0.0125)^2 = 0.00049 \text{ in.}^2$$

If $D$ is the diameter of a wire in mils, the area in square mils can be determined using the following equation:

$$A = \pi(D/2)^2 \quad (3.23)$$

which translates to

$$A = 3.14/4D^2 = 0.785 \ D^2 \text{ square mils}$$

Thus, a wire 1 mil in diameter has an area of

$$A = 0.785 \times 1^2 = 0.785 \text{ square mils}$$

which is equivalent to 1 circular mil. The cross-sectional area of a wire in circular mils is therefore determined as

$$A = (0.785 \times D^2)/0.785 = D^2 \text{ circular mils}$$

where $D$ is the diameter in mils; thus, the constant $\pi/4$ is eliminated from the calculation. Note that when comparing square and round conductors that the circular mil is a smaller unit of area than the square mil, so there are more circular mils than square mils in any given area. The comparison is shown in Figure 3.63C. The area of a circular mil is equal to 0.785 of a square mil.

Note: To determine the circular-mil area when the square-mil area is given, divide the area in square mils by 0.785. Conversely, to determine the square-mil area when the circular-mil area is given, multiply the area in circular mils by 0.785.
EXAMPLE 3.33

Problem: A No. 12 wire has a diameter of 80.81 mils. (1) What is its area in circular mils? (2) What is its area in square mils?

Solution:

1. Area = \( D^2 = (80.81)^2 = 6530 \) circular mils
2. Area = \( 0.785 \times 6530 = 5126 \) square mils

EXAMPLE 3.34

Problem: A rectangular conductor is 1.5 inches wide and 0.25 inch thick. (1) What is its area in square mils? (2) What size of round conductor in circular mils is necessary to carry the same current as the rectangular bar?

Solution:

1. 1.5 in. = 1.5 \times 1000 = 1500 \text{ mils}
   0.25 in. = 0.25 \times 1000 = 250 \text{ mils}
   Area = 1500 \times 250 = 375,000 \text{ square mils}

2. To carry the same current, the cross-sectional area of the rectangular bar and the cross-sectional area of the round conductor must be equal. There are more circular mils than square mils in this area; therefore,

\[ A = \frac{375,000}{0.785} = 477,700 \text{ circular mils} \]

Note: Many electric cables are composed of stranded wires. The strands are usually single wires twisted together in sufficient numbers to make up the necessary cross-sectional area of the cable. The total area in circular mils is determined by multiplying the area of one strand in circular mils by the number of strands in the cable.

CIRCULAR-MIL-FOOT

As shown in Figure 3.64, a circular-mil-foot is actually a unit of volume. More specifically, it is a unit conductor 1 foot in length and having a cross-sectional area of 1 circular mil. Because it is considered a unit conductor, the circular-mil-foot is useful in making comparisons between wires that are made of different metals. For example, a comparison of the resistivity of various substances can be made by determining the resistance of a circular-mil-foot of each of the substances.

Note: It is sometimes more convenient to employ a different unit of volume when working with certain substances. Accordingly, unit volume may also be expressed in cubic centimeters. Cubic inches may also be used. The unit of volume employed is given in tables of specific resistances.

RESISTIVITY

All materials differ in their atomic structure and therefore in their ability to resist the flow of an electric current. As we have discussed, the measure of the ability of a specific material to resist the flow of electricity is its resistivity, or specific resistance—the resistance in ohms offered by the unit

FIGURE 3.64 Circular-mil-foot.
volume (the circular-mil-foot) of a substance to the flow of electric current. Resistivity is the reciprocal of conductivity (i.e., the ease by which current flows in a conductor). A substance that has a high resistivity will have a low conductivity, and *vice versa*. The resistance of a given length, for any conductor, depends on the resistivity of the material, the length of the wire, and the cross-sectional area of the wire according to the equation:

\[
R = \rho \times (L/A)
\]

where

- \( R \) = Resistance of the conductor (ohms).
- \( \rho \) = Specific resistance or resistivity (cm × ohms/ft).
- \( L \) = Length of the wire (ft).
- \( A \) = Cross-sectional area of the wire (cm).

The factor \( \rho \) (Greek letter rho) permits different materials to be compared for resistance according to their nature without regard to different lengths or areas. Higher values of \( \rho \) mean more resistance.

**Note:** The resistivity of a substance is the resistance of a unit volume of that substance.

Many tables of resistivity are based on the resistance in ohms of a volume of the substance 1 foot long and 1 circular mil in cross-sectional area. The temperature at which the resistance measurement is made is also specified. If the kind of metal of which the conductor is made is known, the resistivity of the metal may be obtained from a table. The resistivity, or specific resistance, values of some common substances are given in Table 3.2.

**Note:** Because silver, copper, gold, and aluminum have the lowest values of resistivity, they are the best conductors. Tungsten and iron have much higher resistivity values.

### EXAMPLE 3.35

**Problem:** What is the resistance of 1000 feet of copper wire having a cross-sectional area of 10,400 circular mils (No. 10 wire)? The wire temperature is 20°C.

**Solution:** Table 3.2 indicates that the resistivity (specific resistance) is 10.37. Substituting the known values in Equation 3.24, resistance \( R \) is determined as

\[
R = \rho \times L/A = 10.37 \times (1000/10,400) = 1 \text{ ohm (approximately)}
\]

<table>
<thead>
<tr>
<th>TABLE 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistivity (Specific Resistance)</strong></td>
</tr>
<tr>
<td>Substance</td>
</tr>
<tr>
<td>Silver</td>
</tr>
<tr>
<td>Copper (drawn)</td>
</tr>
<tr>
<td>Gold</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Tungsten</td>
</tr>
<tr>
<td>Brass</td>
</tr>
<tr>
<td>Steel (soft)</td>
</tr>
<tr>
<td>Nichrome</td>
</tr>
</tbody>
</table>
Wires are manufactured in sizes numbered according to a table known as the American wire gauge (AWG). Table 3.3 lists the standard wire sizes that correspond to the AWG. The gauge numbers specify the size of round wire in terms of its diameter and cross-sectional area. Note the following:

- As the gauge numbers increase from 1 to 40, the diameter and circular area decrease. Higher gauge numbers indicate smaller wire sizes; thus, No. 12 wire is a smaller wire than No. 4 wire.
- The circular area doubles for every three gauge sizes; for example, No 12 wire has about twice the area of No. 15 wire.
- The higher the gauge number and the smaller the wire, the greater the resistance of the wire for any given length; therefore, 1000 ft of No. 12 wire has a resistance of 1.62 ohms while 1000 ft of No. 4 wire has a resistance of 0.253 ohm.

Factors Governing Selection of Wire Size

Several factors must be considered when selecting the size of wire to be used for transmitting and distributing electric power. These factors include allowable power loss in the line, permissible voltage drop in the line, current-carrying capacity of the line, and ambient temperatures in which the wire is to be used:

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Diameter</th>
<th>Circular mils</th>
<th>Ohms/1000 ft at 25°C</th>
<th>Gauge</th>
<th>Diameter</th>
<th>Circular mils</th>
<th>Ohms/1000 ft at 25°C</th>
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<td>50.1</td>
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<td>40</td>
<td>3.1</td>
<td>9.9</td>
<td>1070.0</td>
</tr>
</tbody>
</table>
• Allowable power loss ($I^2R$) in the line—This loss represents electrical energy converted into heat. The use of large conductors will reduce the resistance and therefore the $I^2R$ loss; however, large conductors are heavier and require more substantial supports, so they are more expensive initially than small ones.

• Permissible voltage drop ($IR$ drop) in the line—If the source maintains a constant voltage at the input to the line, any variation in the load on the line will cause a variation in line current and a consequent variation in the $IR$ drop in the line. A wide variation in the $IR$ drop in the line causes poor voltage regulation at the load.

• Current-carrying capacity of the line—When current is drawn through the line, heat is generated. The temperature of the line will rise until the heat radiated, or otherwise dissipated, is equal to the heat generated by the passage of current through the line. If the conductor is insulated, the heat generated in the conductor is not so readily removed as it would be if the conductor were not insulated.

• Conductors installed in relatively high ambient temperatures—When installed in such surroundings, the heat generated by external sources constitutes an appreciable part of the total conductor heating. Due allowance must be made for the influence of external heating on the allowable conductor current, and each case has its own specific limitations.

### COPPER VS. OTHER METAL CONDUCTORS

If it were not cost prohibitive, silver, the best conductor of electron flow (electricity), would be the conductor of choice in electrical systems. Instead, silver is used only in special circuits where a substance with high conductivity is required. The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances. Likewise, each has certain disadvantages, or limitations. Copper has a higher conductivity and is more ductile (able to be drawn out into wire); it has relatively high tensile strength and can be easily soldered. It is more expensive and heavier than aluminum. Aluminum has only about 60% of the conductivity of copper, but its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona, which is the discharge of electricity from the wire when it has a high potential. The discharge is greater when smaller diameter wire is used than when larger diameter wire is used; however, aluminum conductors are not easily soldered, and aluminum’s relatively large size for a given conductance does not permit the economical use of an insulation covering. A comparison of some of the characteristics of copper and aluminum is given in Table 3.4.

**Note:** Recent practice involves using copper wiring instead of aluminum wiring in homes and some industrial applications. Aluminum connections are not as easily made as they are with copper; and, over the years, many fires have been started because of improperly connected aluminum wiring; poor connections result in high-resistance connections and excessive heat generation.

### TABLE 3.4

**Characteristics of Copper and Aluminum**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Copper</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (lb/in.²)</td>
<td>55,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Tensile strength for same conductivity (lb)</td>
<td>55,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Weight for same conductivity (lb)</td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td>Cross-section for same conductivity (cm)</td>
<td>100</td>
<td>160</td>
</tr>
<tr>
<td>Specific resistance ($Ω$/mil-ft)</td>
<td>10.6</td>
<td>17</td>
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</tbody>
</table>
**Wire Temperature Coefficients**

The resistance of pure metals (e.g., silver, copper, aluminum) increases as the temperature increases. The *temperature coefficient* of resistance, $\alpha$ (*alpha*), indicates how much the resistance changes for a change in temperature. A positive value for $\alpha$ means $R$ increases with temperature, a negative $\alpha$ means $R$ decreases, and a zero $\alpha$ means $R$ is constant, not varying with changes in temperature. Typical values of $\alpha$ are listed in Table 3.5. The amount of increase in the resistance of a 1-ohm sample of the copper conductor per degree rise in temperature (i.e., the temperature coefficient of resistance) is approximately 0.004. For pure metals, the temperature coefficient of resistance ranges between 0.004 and 0.006 ohm. Thus, a copper wire having a resistance of 50 ohms at an initial temperature of 0°C will have an increase in resistance of $50 \times 0.004$, or 0.2 ohms (approximate) for the entire length of wire for each degree of temperature rise above 0°C. At 20°C the increase in resistance is approximately $20 \times 0.2$, or 4 ohms. The total resistance at 20°C is $50 + 4$, or 54 ohms.

**Note:** As shown in Table 3.5, carbon has a negative temperature coefficient. In general, $\alpha$ is negative for all semiconductors such as germanium and silicon. A negative value for $\alpha$ means less resistance at higher temperatures; therefore, the resistance of semiconductor diodes and transistors can be reduced considerably when they become hot with normal load current. Observe, also, that constantan has a value of zero for $\alpha$. Thus, it can be used for precision wire-wound resistors that do not change resistance when the temperature increases.

**Conductor Insulation**

Electric current must be contained; it must be channeled from the power source to a useful load safely. To accomplish this, electric current must be forced to flow only where it is needed. Moreover, current-carrying conductors must not be allowed (generally) to come in contact with one another, their supporting hardware, or personnel working near them. To accomplish this, conductors are coated or wrapped with various materials. These materials have such a high resistance that they are, for all practical purposes, nonconductors. They are generally referred to as insulators or insulating materials.

Numerous types of insulated conductors are available to meet the requirements of any job; however, only the necessary minimum of insulation is applied for any particular type of cable designed to do a specific job because insulation is expensive and has a stiffening effect. Also, it is required to withstand a great variety of physical and electrical conditions. Two fundamental but distinctly different properties of insulation materials (e.g., rubber, glass, asbestos, plastics) are insulation resistance and dielectric strength:
- **Insulation resistance** is the resistance to current leakage through and over the surface of insulation materials.
- **Dielectric strength** is the ability of the insulator to withstand potential difference and is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress.

Various types of materials are used to provide insulation for electric conductors, including rubber, plastics, varnished cloth, paper, silk, cotton, and enamel.

**Conductor Splices and Terminal Connections**

When conductors join each other, or connect to a load, splices or terminals must be used. It is important that they be properly made, as any electric circuit is only as good as its weakest connection. The basic requirement of any splice or connection is that it be both mechanically and electrically as strong as the conductor or device with which it is used. High-quality workmanship and materials must be employed to ensure lasting electrical contact, physical strength, and insulation (if required).

*Note:* Conductor splices and connections are essential parts of any electric circuit.

**Soldering Operations**

Soldering operations are a vital part of electrical and electronics maintenance procedures. Soldering is a manual skill that must be learned by all personnel who work in the field of electricity. Obviously, practice is required to develop proficiency in the techniques of soldering. Both the solder and the material to be soldered (e.g., electric wire or terminal lugs) must be heated to a temperature that allows the solder to flow. If either is heated inadequately, cold solder joints result (i.e., high-resistance connections are created). Such joints do not provide either the physical strength or the electrical conductivity required. Moreover, it is necessary to select a solder that will flow at a temperature low enough to avoid damage to the part being soldered or to any other part or material in the immediate vicinity.

**Solderless Connectors**

Generally, terminal lugs and splicers that do not require solder are more widely used than those that do require solder because they are easier to mount correctly. Solderless connectors—made in a wide variety of sizes and shapes—are attached to their conductors by means of several different devices, but the principle of each is essentially the same. They are all crimped (squeezed) tightly onto their conductors. They offer adequate electrical contact, plus great mechanical strength.

**Insulation Tape**

The carpenter has his saw, the dentist his pliers, the plumber his wrench, and the electrician his insulation tape. Accordingly, one of the first things the rookie maintenance operator learns (a rookie who is also learning proper and safe techniques for performing electrical work) is the value of electrical insulation tape. Normally, the use of electrical insulating tape comes into play as the final step in completing a splice or joint, to place insulation over the bare wire at the connection point. Typically, the insulation tape used should be the same basic substance as the original insulation, usually a rubber-splicing compound. When using rubber (latex) tape as the splicing compound where the original insulation was rubber, it should be applied to the splice with a light tension so each layer presses tightly against the one underneath it. In addition to the rubber tape application (which restores the insulation to original form), restoring with friction tape is also often necessary.
In recent years, plastic electrical tape has come into wide use. It has certain advantages over rubber and friction tape; for example, it will withstand higher voltages for a given thickness. Single, thin layers of certain commercially available plastic tape will tolerate several thousand volts without breaking down.

**Note:** Be advised that, although plastic electrical tape is widely used in industrial applications, it must be applied in more layers to ensure an extra margin of safety because it is thinner than rubber or friction tape.

**ELECTROMAGNETISM**

Earlier, we discussed the fundamental theories concerning simple magnets and magnetism. That discussion dealt mainly with forms of magnetism that were not related directly to electricity—permanent magnets, for instance. Further, only brief mention was made of those forms of magnetism having a direct relation to electricity (e.g., producing electricity with magnetism). In medicine, anatomy and physiology are so closely related that the medical student cannot study one at length without involving the other. A similar relationship holds for the electrical field; that is, magnetism and basic electricity are so closely related that one cannot be studied at length without involving the other. This close fundamental relationship is continually borne out in the study of generators, transformers, battery packs, and motors. To be proficient in electricity, we must become familiar with the general relationships that exist between magnetism and electricity:

- Electric current flow will always produce some form of magnetism.
- Magnetism is by far the most commonly used means for producing or using electricity.
- The occasional peculiar behavior of electricity is caused by magnetic influences.

**Magnetic Field around a Single Conductor**

In 1819, Hans Christian Oersted, a Danish scientist, discovered that a field of magnetic force exists around a single wire conductor carrying an electric current. In Figure 3.65, a wire is passed through a piece of cardboard and connected through a switch to a dry cell. When the switch is open (no current flowing), iron filings sprinkled on the cardboard will fall back haphazardly when tapped. If we close the switch, current will begin to flow in the wire. This time, when we tap the cardboard the magnetic effect of the current in the wire will cause the filings to fall back into a definite pattern of concentric circles, with the wire as the center of the circles. Every section of the wire has this field of force around it in a plane perpendicular to the wire, as shown in Figure 3.66.
The ability of the magnetic field to attract bits of iron (as demonstrated in Figure 3.45) depends on the number of lines of force present. The strength of the magnetic field around a wire carrying a current depends on the current, as it is the current that produces the field. The greater the current, the greater the strength of the field. A large current will produce many lines of force extending far from the wire, while a small current will produce only a few lines close to the wire, as shown in Figure 3.67.

**POLARITY OF A SINGLE CONDUCTOR**

The relation between the direction of the magnetic lines of force around a conductor and the direction of current flow along the conductor may be determined by means of the left-hand rule for a conductor. If the conductor is grasped in the left hand with the thumb extended in the direction of electron flow (− to +), the fingers will point in the direction of the magnetic lines of force. This is the same direction that the north pole of a compass would point to if the compass were placed in the magnetic field.

*Note:* Arrows are generally used in electric diagrams to denote the direction of current flow along the length of wire. Where cross-sections of wire are shown, a special view of the arrow is used. A cross-sectional view of a conductor that is carrying current toward the observer is illustrated in Figure 3.68A. The direction of current is indicated by a dot, which represents the head of the arrow. A conductor that is carrying current away from the observer is illustrated in Figure 3.68B. The direction of current is indicated by a cross, which represents the tail of the arrow.

**MAGNETIC FIELD AROUND TWO PARALLEL CONDUCTORS**

When two parallel conductors carry current in the same direction, the magnetic fields tend to encircle both conductors, drawing them together with a force of attraction, as shown in Figure 3.69A. Two parallel conductors carrying currents in opposite directions are shown in Figure 3.69B. The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force are crowded together in the space between the wires and tend to push the wires apart; two parallel adjacent conductors carrying currents in the same direction attract each other, and two parallel conductors carrying currents in opposite directions repel each other.
The magnetic field around a current-carrying wire exists at all points along its length. Bending the current-carrying wire into the form of a single loop has two results. First, the magnetic field consists of more dense concentric circles in a plane perpendicular to the wire (see Figure 3.66), although the total number of lines is the same as for the straight conductor. Second, all the lines inside the loop are in the same direction. When this straight wire is wound around a core, as is shown in Figure 3.70, it becomes a coil and the magnetic field assumes a different shape. When current is passed through the coiled conductor, the magnetic field of each turn of wire links with the fields of adjacent turns. The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil will be a north pole and the other end will be a south pole.
Figure 3.70 Current-carrying coil.

**Polarity of an Electromagnetic Coil**

In Figure 3.67, it was shown that the direction of the magnetic field around a straight conductor depends on the direction of current flow through that conductor; thus, a reversal of current flow through a conductor causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current flow through a coil also causes a reversal of its two-pole field. This occurs because that field is the product of the linkage between the individual turns of wire on the coil; therefore, if the field of each turn is reversed, it follows that the total field (coils’ field) is also reversed. When the direction of electron flow through a coil is known, its polarity may be determined by use of the left-hand rule for coils. This rule is illustrated in Figure 3.70 and can be stated as follows: When the coil is grasped in the left hand, with the fingers wrapped around in the direction of electron flow, the thumb will point toward the north pole.

**Strength of an Electromagnetic Field**

The strength, or intensity, of the magnetic field of a coil depends on a number of factors:

- Number of turns of the conductor
- Amount of current flow through the coil
- Ratio of the coil length to its width
- Type of material in the core

**Magnetic Units**

The law of current flow in the electric circuit is similar to the law for establishing flux in the magnetic circuit. The magnetic flux, $\phi$ (phi), is similar to current in the Ohm’s law formula and is comprised of the total number of lines of force existing in the magnetic circuit. The maxwell is the unit of flux; 1 line of force is equal to 1 maxwell. 

*Note:* The maxwell is often referred to as simply a line of force, line of induction, or line.

The strength of a magnetic field in a coil of wire depends on how much current flows in the turns of the coil. The more current, the stronger the magnetic field. Also, the more turns, the more concentrated are the lines of force. The force that produces the flux in the magnetic circuit (comparable to electromotive force in Ohm’s law) is known as magnetomotive force (m.m.f). The practical unit of magnetomotive force is the ampere-turn (At). In equation form:

$$F \, \text{(ampere-turns)} = N \times I \quad (3.25)$$

where

- $F$ = Magnetomotive force (At).
- $N$ = Number of turns.
- $I$ = Current (A).
EXAMPLE 3.36

Problem: Calculate the ampere-turns for a coil with 2000 turns and a 5-mA current.

Solution: Use Equation 3.25 and substitute \( N = 2000 \) and \( I = 5 \times 10^{-3} \) A:

\[
N \times I = 2000 \times (5 \times 10^{-3}) = 10 \text{ At}
\]

The unit of intensity of magnetizing force per unit of length is designated as \( H \) and is sometimes expressed as Gilberts per centimeter of length. Expressed as an equation:

\[
H = \frac{(N \times I)}{L} \tag{3.26}
\]

where

- \( H \) = Magnetic field intensity (ampere-turns per meter, At/m).
- \( N \times I \) = Number of turns \times current (ampere-turns, At).
- \( L \) = Length between poles of the coil (meters, m).

Note: Equation 3.26 is for a solenoid, and \( H \) is the intensity of an air core. With an iron core, \( H \) is the intensity through the entire core, and \( L \) is the length of or distance between poles of the iron core.

PROPERTIES OF MAGNETIC MATERIALS

In this section, we discuss two important properties of magnetic materials: permeability and hysteresis.

Permeability

When the core of an electromagnet is made of annealed sheet steel it produces a stronger magnet than if a cast iron core is used because annealed sheet steel is more readily acted upon by the magnetizing force of the coil than is the hard cast iron. Simply put, soft sheet steel is said to have greater permeability because of the greater ease with which magnetic lines are established in it. Recall that permeability is the relative ease with which a substance conducts magnetic lines of force. The permeability of air is arbitrarily set at 1. The permeability of other substances is the ratio of their ability to conduct magnetic lines compared to that of air. The permeability of nonmagnetic materials, such as aluminum, copper, wood, and brass, is essentially unity, or the same as for air.

Note: The permeability of magnetic materials varies with the degree of magnetization, being smaller for high values of flux density. Reluctance, which is analogous to resistance and is the opposition to the production of flux in a material, is inversely proportional to permeability. Iron has high permeability and, therefore, low reluctance. Air has low permeability and hence high reluctance.

Hysteresis

When the current in a coil of wire reverses thousands of times per second, a considerable loss of energy can occur. This loss of energy is caused by hysteresis. Hysteresis means “a lagging behind”; that is, the magnetic flux in an iron core lags behind the increases or decreases of the magnetizing force. The simplest method of illustrating the property of hysteresis is by graphical means, such as the hysteresis loop for a magnetic material shown in Figure 3.71. The hysteresis loop is a series of curves that show the characteristics of a magnetic material. Opposite directions of current result in the opposite directions of \(+H\) and \(-H\) for field intensity. Similarly, the range of flux density is indicated by \(+B\) and \(-B\). The current starts at the center 0 (zero) when the material is unmagnetized. Positive \( H \) values increase \( B \) to saturation at \(+B_{\text{max}}\). Next \( H \) decreases to zero, but \( B \) drops only to the value of \( B_r \) because of hysteresis. The current that produced the original magnetization now is reversed so \( H \) becomes negative. \( B \) drops to zero and continues to \(-B_{\text{max}}\). As the \(-H \) values decrease,
B is reduced to \(-B\), when \(H\) is zero. Now, with a positive swing of current, \(H\) becomes positive, producing saturation at \(+B_{\text{max}}\) again. The hysteresis loop is now complete. The curve does not return to zero at the center because of hysteresis.

**Electromagnets**

An electromagnet is composed of a coil of wire wound around a core that is normally soft iron, because of its high permeability and low hysteresis. When direct current flows through the coil, the core will become magnetized with the same polarity that the coil would have without the core. If the current is reversed, the polarities of the coil and core are reversed. The electromagnet is of great importance in electricity simply because the magnetism can be turned on or turned off at will. The starter solenoid (an electromagnet) in automobiles and power boats is a good example. In an automobile or boat, an electromagnet is part of a relay that connects the battery to the induction coil and generates the very high voltage required to start the engine. The starter solenoid isolates this high voltage from the ignition switch. When no current flows in the coil, it is an air core, but when the coil is energized, a movable soft-iron core does two things. First, the magnetic flux is increased because the soft-iron core is more permeable than the air core. Second, the flux is more highly concentrated. All of this concentration of magnetic lines of force in the soft-iron core results in a very good magnet when current flows in the coil, but soft iron loses its magnetism quickly when the current is shut off. The effect of the soft iron is, of course, the same whether it is movable, as in some solenoids, or permanently installed in the coil. An electromagnet, then, consists basically of a coil and a core; it becomes a magnet when current flows through the coil. The ability to control the action of magnetic force makes an electromagnet very useful in many circuit applications. Many applications of electromagnets are discussed throughout this manual.

**AC THEORY**

Because voltage is induced in a conductor when lines of force are cut, the amount of the induced electromotive force (emf) depends on the number of lines cut in a unit time. To induce an emf of 1 volt, a conductor must cut 100,000,000 lines of force per second. To obtain this great number of cuttings, the conductor is formed into a loop and rotated on an axis at great speed (see Figure 3.72). The two sides of the loop become individual conductors in series, each side of the loop cutting lines of force and inducing twice the voltage than a single conductor would induce. In commercial generators, the number of cuttings and the resulting emf are increased by (1) increasing the number of lines of force by using more magnets or stronger electromagnets, (2) using more conductors or loops, or (3) rotating the loops faster. (Both AC and DC generators are covered later.)
Principles of Basic Electricity

How an AC generator operates to produce an AC voltage and current is a basic concept taught in elementary and middle-school science classes. Of course, today we accept technological advances as commonplace—we surf the Internet, text our friends, watch cable television, use our cell phones, and take outer space flight as a given. We consider the production of electricity, which makes all of these technologies possible, to be a right. These technologies are bottom shelf to us today; they are readily available to us so we use them—no big deal, right? Not worth thinking about. This point of view, though, surely was not typical of those who broke ground in developing technology and electricity.

During the groundbreaking years of electric technology development, the geniuses of the science of electricity (including George Simon Ohm) performed their technological breakthroughs in faltering steps. We tend to forget that those first faltering steps of scientific achievement in the field of electricity were achieved with crude and, for the most part, homemade apparatus. (Does this sound something like the more contemporary garage and basement inventors who came up with the first basic user-friendly microcomputer and software packages and perhaps will come up with the renewable energy innovations of tomorrow?)

Indeed, the innovators of electricity had to fabricate nearly all of the laboratory equipment used in their experiments. At the time, the only convenient source of electrical energy available to these early scientists was the voltaic cell, invented some years earlier. Because of the fact that cells and batteries were the only sources of power available, some of the early electrical devices were designed to operate from direct current (DC); thus, direct current was used extensively at the time. When the use of electricity became widespread, certain disadvantages in the use of direct current became apparent. In a direct-current system, the supply voltage must be generated at the level required by the load. To operate a 240-volt lamp, for example, the generator must deliver 240 volts. A 120-volt lamp could not be operated from the same generator by any convenient means. A resistor could be placed in series with the 120-volt lamp to drop the extra 120 volts, but the resistor would waste an amount of power equal to that consumed by the lamp.

Another disadvantage of direct-current systems is the large amount of power lost due to the resistance of the transmission wires used to carry current from the generating station to the consumer. This loss could be greatly reduced by operating the transmission line at a very high voltage and low current. This is not a practical solution in a DC system, however, because the load would also have to operate at high voltage. As a result of the difficulties encountered with direct current, practically all modern power distribution systems use alternating current (AC).

Unlike DC voltage, AC voltage can be stepped up or down by a device called a transformer. Transformers allow the transmission lines to be operated at high voltage and low current for maximum efficiency. Then, at the consumer end, the voltage is stepped down to whatever value the load requires by using a transformer. Due to its inherent advantages and versatility, alternating current has replaced direct current in all but a few commercial power distribution systems.
**Basic AC Generator**

As shown in Figure 3.72, an AC voltage and current can be produced when a conductor loop rotates through a magnetic field and cuts lines of force to generate an induced AC voltage across its terminals. This describes the basic principle of operation of an alternating current generator, or alternator. An alternator converts mechanical energy into electrical energy. It does this by utilizing the principle of *electromagnetic induction*. The basic components of an alternator are an armature, around which many turns of conductor are wound and which rotates in a magnetic field, as well as some means of delivering the resulting alternating current to an external circuit. (We will cover generator construction in more detail later; in this section, we concentrate on the theory of operation.)

**Cycle**

An AC voltage is one that continually changes in magnitude and periodically reverses in polarity (see Figure 3.73). The zero axis is a horizontal line across the center. The vertical variations on the voltage wave show the changes in magnitude. The voltages above the horizontal axis have positive (+) polarity, while voltages below the horizontal axis have negative (−) polarity. Figure 3.74 shows a suspended loop of wire (conductor or armature) being rotated (moved) in a counterclockwise direction through the magnetic field between the poles of a permanent magnet. For ease of explanation, the loop has been divided into a thick and thin half. Notice that in Figure 3.74A the thick half is moving along (parallel to) the lines of force; consequently, it is cutting none of these lines. The same is true of the thin half, moving in the opposite direction. Because the conductors are not cutting any lines of force, no emf is induced. As the loop rotates toward the position shown in Figure 3.74B, it cuts more and more lines of force per second because it is cutting more directly across the field (lines of force) as it approaches the position shown in Figure 3.74B. At the position shown in Figure 3.74B, the induced voltage is greatest because the conductor is cutting directly across the field.

As the loop continues to be rotated toward the position shown in Figure 3.74C, it cuts fewer and fewer lines of force per second. The induced voltage decreases from its peak value. Eventually, the loop is once again moving in a plane parallel to the magnetic field, and no voltage (zero voltage) is induced. The loop has now been rotated through half a circle (one alternation, or 180°). The sine curve shown in the lower part of Figure 3.74 shows the induced voltage at every instant of rotation of the loop. Notice that this curve contains 360°, or two alternations. In Figure 3.74, if the loop is rotated at a steady rate and if the strength of the magnetic field is uniform, the number of cycles per second (cps), or *hertz*, and the voltage will remain at fixed values. Continuous rotation will produce a series of sine-wave voltage cycles or, in other words, an AC voltage. In this way, mechanical energy is converted into electrical energy.

*Note:* Two complete alternations in a period of time is called a *cycle.*

**FIGURE 3.73** AC voltage waveform.
The frequency of an alternating voltage or current is the number of complete cycles occurring in each second of time. It is indicated by the symbol $f$ and is expressed in hertz (Hz). One cycle per second equals 1 hertz. Thus, 60 cycles per second (cps) equals 60 Hz. A frequency of 2 Hz (Figure 3.75B) is twice the frequency of 1 Hz (Figure 3.75A). The amount of time for the completion of 1 cycle is the period. It is indicated by the symbol $T$ for time and is expressed in seconds. Frequency and period are reciprocals of each other:

$$f = \frac{1}{T} \quad (3.27)$$

$$T = \frac{1}{f} \quad (3.28)$$

Note: The higher the frequency, the shorter the period.

**FIGURE 3.74** Basic alternating current generator.

**FIGURE 3.75** Comparison of frequencies.
The angle of 360° represents the time for 1 cycle, or the period $T$. So, we can show the horizontal axis of the sine wave in units of either electrical degrees or seconds (see Figure 3.76). The wavelength is the length of one complete wave or cycle. It depends upon the frequency of the periodic variation and its velocity of transmission. It is indicated by the symbol $\lambda$ (Greek lowercase lambda). Expressed as a formula:

$$\lambda = \text{Velocity}/\text{Frequency}$$

(3.29)

**CHARACTERISTIC VALUES OF AC VOLTAGE AND CURRENT**

Because an AC sine wave voltage or current has many instantaneous values throughout the cycle, it is convenient to specify magnitudes to compare one wave with another. The peak, average, or root-mean-square (RMS) value can be specified (see Figure 3.77). These values apply to current or voltage.

**Peak Amplitude**

One of the most frequently measured characteristics of a sine wave is its amplitude. Unlike DC measurement, the amount of alternating current or voltage present in a circuit can be measured in various ways. In one method of measurement, the maximum amplitude of either the positive or the negative alternation is measured. The value of current or voltage obtained is called the peak voltage or the peak current. An oscilloscope is used to measure the peak value of current or voltage. The peak value is illustrated in Figure 3.77.
**Peak-to-Peak Amplitude**

A second method of indicating the amplitude of a sine wave consists of determining the total voltage or current between the positive and negative peaks. This value of current or voltage is the peak-to-peak value (see Figure 3.77). Because both alternations of a pure sine wave are identical, the peak-to-peak value is twice the peak value. Peak-to-peak voltage is usually measured with an oscilloscope, although some voltmeters have a special scale calibrated in peak-to-peak volts.

**Instantaneous Amplitude**

The *instantaneous value* of a sine wave of voltage for any angle of rotation is expressed by the formula:

\[ e = E_m \times \sin(\theta) \quad (3.30) \]

where
- \( e \) = Instantaneous voltage.
- \( E_m \) = Maximum or peak voltage.
- \( \sin(\theta) \) = Sine of the angle at which \( e \) is desired.

Similarly, the equation for the instantaneous value of a sine wave of current would be

\[ i = I_m \times \sin(\theta) \quad (3.31) \]

where
- \( i \) = Instantaneous current.
- \( I_m \) = Maximum or peak current.
- \( \sin(\theta) \) = Sine of the angle at which \( i \) is desired.

*Note:* The instantaneous value of voltage constantly changes as the armature of an alternator moves through a complete rotation. Because current varies directly with voltage, according to Ohm's law, the instantaneous changes in current also result in a sine wave for which the positive and negative peaks and intermediate values can be plotted exactly as we plotted the voltage sine wave. However, instantaneous values are not useful in solving most AC problems, so an *effective* value is used.

**Effective or RMS Value**

The effective value of an AC voltage or current of sine waveform is defined in terms of an equivalent heating effect of a direct current. Heating effect is independent of the direction of current flow. The alternating current of a sine waveform having a maximum value of 14.14 amps produces the same amount of heat in a circuit having a resistance of 1 ohm as a direct current of 10 amps. Knowing this, we can work out a constant value for converting any peak value to a corresponding effective value. This constant is represented by \( x \) in the simple equation below. Solve for \( x \) to three decimal places:

\[ 14.14x = 10 \]

\[ x = 0.707 \]

*Note:* Because all instantaneous values of induced voltage are somewhere between zero and \( E_m \) (maximum or peak voltage), the effective value of a sine wave voltage or current must be greater than zero and less than \( E_m \).
The effective value is also called the root-mean-square (RMS) value because it is the square root of the average of the squared values between zero and maximum. The effective value of an alternating current is stated in terms of an equivalent direct current. The phenomenon that is used as the standard comparison is the heating effect of the current. In many instances, it is necessary to convert from effective to peak or vice versa using a standard equation. Figure 3.77 shows that the peak value of a sine wave is 1.414 times the effective value; therefore, the equation we use is

**Note:** Anytime an AC voltage or current is stated without any qualifications, it is assumed to be an effective value.

\[ E_m = E \times 1.414 \]  \hspace{1cm} (3.32)  

where

- \( E_m \) = Maximum or peak voltage.
- \( E \) = Effective or RMS voltage.

and

\[ I_m = I \times 1.414 \]  \hspace{1cm} (3.33)  

where

- \( I_m \) = Maximum or peak current.
- \( I \) = Effective or RMS current.

Occasionally it is necessary to convert a peak value of current or voltage to an effective value. This is accomplished by using the following equations:

\[ E = E_m \times 0.707 \]  \hspace{1cm} (3.34)  

where

- \( E \) = Effective voltage.
- \( E_m \) = Maximum or peak voltage.

\[ I = I_m \times 0.707 \]  \hspace{1cm} (3.35)  

where

- \( I \) = Effective current.
- \( I_m \) = Maximum or peak current.

**Average Value**

Because the positive alternation is identical to the negative alternation, the average value of a complete cycle of a sine wave is zero. In certain types of circuits, however, it is necessary to compute the average value of one alternation. Figure 3.77 shows that the average value of a sine wave is 0.637 \times peak value; therefore,

\[ \text{Average value} = 0.637 \times \text{peak value} \]  \hspace{1cm} (3.36)  

or

\[ E_{avg} = E_m \times 0.637 \]  

where

- \( E_{avg} \) = Average voltage of one alternation.
- \( E_m \) = Maximum or peak voltage.
Similarly,

\[ I_{\text{avg}} = I_m \times 0.637 \]  \hspace{1cm} (3.37)

where

\[ I_{\text{avg}} = \text{Average current in one alternation.} \]
\[ I_m = \text{Maximum or peak current.} \]

Table 3.6 lists various sine wave amplitude values used to convert AC sine wave voltage and current.

### RESISTANCE IN AC CIRCUITS

If a sine wave of voltage is applied to a resistance, the resulting current will also be a sine wave. This follows Ohm’s law, which states that the current is directly proportional to the applied voltage. Figure 3.78 shows a sine wave of voltage and the resulting sine wave of current superimposed on the same time axis. Notice that as the voltage increases in a positive direction the current increases along with it. When the voltage reverses direction, the current reverses direction. At all times the voltage and current pass through the same relative parts of their respective cycles at the same time. When two waves, such as those shown in Figure 3.78, are precisely in step with one another they are said to be in phase. To be in phase, the two waves must go through their maximum and minimum points at the same time and in the same direction. In some circuits, several sine waves can be in phase with each other. Thus, it is possible to have two or more voltage drops in phase with each other and in phase with the circuit current.

![FIGURE 3.78 Voltage and current waves in phase.](image-url)
Note: It is important to remember that Ohm's law for DC circuits is applicable to AC circuits with resistance only.

Voltage waves are not always in phase; for example, Figure 3.79 shows voltage wave $E_1$, which starts at $0^\circ$ (time 1). As voltage wave $E_1$ reaches its positive peak, a second voltage wave, $E_2$, begins to rise (time 2). Because these waves do not go through their maximum and minimum points at the same instant of time, a phase difference exists between the two waves, and the two waves are said to be out of phase. For the two waves in Figure 3.79, this phase difference is $90^\circ$.

**Phase Relationships**

In the preceding section, we discussed the important concepts of being in phase and phase difference. Another important phase concept is phase angle. The phase angle between two waveforms of the same frequency is the angular difference at a given instant of time. As an example, the phase angle between waves B and A (see Figure 3.80) is $90^\circ$. Take the instant of time at $90^\circ$. The horizontal axis is shown in angular units of time. Wave B starts at maximum value and reduces to zero value at $90^\circ$, while wave A starts at zero and increases to maximum value at $90^\circ$. Wave B reaches its maximum value $90^\circ$ ahead of wave A, so wave B leads wave A by $90^\circ$ (and wave A lags wave B by $90^\circ$).
This 90° phase angle between waves B and A is maintained throughout the complete cycle and all successive cycles. At any instant of time, wave B has the value that wave A will have 90° later. Wave B is a cosine wave because it is displaced 90° from wave A, which is a sine wave.

**Note:** The amount by which one wave leads or lags another is measured in degrees.

To compare phase angles or phases of alternating voltages or currents, it is more convenient to use vector diagrams corresponding to the voltage and current waveforms. A vector is a straight line used to denote the magnitude and direction of a given quantity. Magnitude is denoted by the length of the line drawn to scale, and the direction is indicated by the arrow at one end of the line, together with the angle that the vector makes with a horizontal reference vector.

**Note:** In electricity, because different directions really represent time expressed as a phase relationship, an electrical vector is called a phasor. In an AC circuit containing only resistance, the voltage and current occur at the same time; that is, they are in phase. To indicate this condition by means of phasors all that is necessary is to draw the phasors for the voltage and current in the same direction. The value of each is indicated by the length of the phasor.

A vector, or phasor, diagram is shown in Figure 3.81, where vector $V_B$ is vertical to show the phase angle of 90° with respect to vector $V_A$, which is the reference. Because lead angles are shown in the counterclockwise direction from the reference vector, $V_B$ leads $V_A$ by 90°.

**INDUCTANCE**

To this point we have learned the following key points about magnetic fields:

- A field of force exists around a wire carrying a current.
- This field has the form of concentric circles around the wire, in planes perpendicular to the wire and with the wire at the center of the circles.
- The strength of the field depends on the current. Large currents produce large fields; small currents produce small fields.
- When lines of force cut across a conductor, a voltage is induced in the conductor.

Moreover, to this point we have studied circuits that have been resistive (i.e., resistors presented the only opposition to current flow). Two other phenomena, inductance and capacitance, exist in DC circuits to some extent, but they are major players in AC circuits. Both inductance and capacitance present a kind of opposition to current flow that is called reactance, which we will cover later. Before we examine reactance, however, we must first study inductance and capacitance.

**WHAT IS INDUCTANCE?**

Inductance is the characteristic of an electrical circuit that makes itself evident by opposing the starting, stopping, or changing of current flow. A simple analogy can be used to explain inductance. We are all familiar with how difficult it is to push a heavy load (a cart full of heavy items, for example). It takes more work to start the load moving than it does to keep it moving. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change...
in velocity; therefore, inertia can hinder us in some ways and help us in others. Inductance exhibits the same effect on current in an electric circuit as inertia does on velocity of a mechanical object. The effects of inductance are sometimes desirable, sometimes undesirable.

**Note:** Simply put, inductance is the characteristic of an electrical conductor that opposes a change in current flow.

Because inductance is the property of an electric circuit that opposes any change in the current through that circuit, if the current increases then a self-induced voltage opposes this change and delays the increase. On the other hand, if the current decreases then a self-induced voltage tends to aid (or prolong) the current flow, delaying the decrease. Thus, current can neither increase nor decrease as fast in an inductive circuit as it can in a purely resistive circuit. In AC circuits, this effect becomes very important because it affects the phase relationships between voltage and current. When inductance is a factor in a circuit, the voltage and current generated by the same armature are out of phase. We will examine these phase relationships later. Our objective now is to understand the nature and effects of inductance in an electric circuit.

**Unit of Inductance**

The unit for measuring inductance (\(L\)) is the *henry* (named for the American physicist Joseph Henry), which is abbreviated as h. Figure 3.82 shows the schematic symbol for an inductor. An inductor has an inductance of 1 henry if an emf of 1 volt is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. The relation among the induced voltage, inductance, and rate of change of current with respect to time can be stated mathematically as

\[
E = L \times \Delta I / \Delta t
\]

(3.38)

where

- \(E\) = Induced emf (volts).
- \(L\) = Inductance (henrys).
- \(\Delta I\) = Change in amperes occurring in \(\Delta t\) seconds.

**Note:** The symbol \(\Delta\) (Delta) means “change in.”

The henry is a large unit of inductance that is used with relatively large inductors. The unit employed with small inductors is the millihenry (mH). For still smaller inductors, the unit of inductance is the microhenry (\(\mu\)H).

**Self-Inductance**

As previously explained, current flow in a conductor always produces a magnetic field surrounding, or linking with, the conductor. When the current changes, the magnetic field changes, and an emf is induced in the conductor. This emf is called a *self-induced emf* because it is induced in the conductor carrying the current.

**Note:** Even a perfectly straight length of conductor has some inductance.

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**FIGURE 3.82** Schematic symbol for an inductor.
The direction of the induced emf has a definite relation to the direction in which the field that induces the emf varies. When the current in a circuit is increasing, the flux linking with the circuit is increasing. This flux cuts across the conductor and induces an emf in the conductor in such a direction as to oppose the increase in current and flux. This emf is sometimes referred to as **counterelectromotive force** (cemf). The two terms are used synonymously throughout this manual. Likewise, when the current is decreasing, an emf is induced in the opposite direction and opposes the decrease in current.

**Note:** The effects described here are summarized by **Lenz’s law**, which states that the induced emf in any circuit is always in a direction opposite that of the effect that produced it.

Shaping a conductor so the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor increases the inductance. This is shown in its simplest form in Figure 3.83A. A loop of conductor is looped so two portions of the conductor lie adjacent and parallel to one another. These portions are labeled Conductor 1 and Conductor 2. When the switch is closed, electron flow through the conductor establishes a typical concentric field around all portions of the conductor. The field is shown in a single plane (for simplicity) that is perpendicular to both conductors. Although the field originates simultaneously in both conductors, it is considered as originating in Conductor 1, and its effect on Conductor 2 will be noted. With increasing current, the field expands outward, cutting across a portion of Conductor 2. The resultant induced emf in Conductor 2 is shown by the dashed arrow. Note that it is in opposition to the battery current and
voltage, according to Lenz’s law. In Figure 3.83B, the same section of Conductor 2 is shown, but with the switch open and the flux collapsing. Four major factors affect the self-inductance of a conductor, or circuit:

**Note:** From Figure 3.83, the important point to note is that the voltage of self-induction opposes both changes in current. It delays the initial buildup of current by opposing the battery voltage and delays the breakdown of current by exerting an induced voltage in the same direction in which the battery voltage acted.

1. **Number of turns**—Inductance depends on the number of wire turns. Wind more turns to increase inductance. Take turns off to decrease the inductance. Figure 3.84 compares the inductance of two coils made with different numbers of turns.

2. **Spacing between turns**—Inductance depends on the spacing between turns, or the length of the inductor. Figure 3.85 shows two inductors with the same number of turns. The turns of the first inductor have a wide spacing. The turns of the second inductor are closer together. The second coil, though shorter, has a larger inductance value because of its close spacing between turns.

3. **Coil diameter**—Coil diameter, or cross-sectional area, is highlighted in Figure 3.86. The larger diameter inductor has higher inductance. Both coils shown have the same number of turns, and the spacing between turns is the same, but the first inductor has a smaller diameter than the second one. The inductance of the second inductor is greater than that for the first inductor.

4. **Type of core material**—Permeability, as pointed out earlier, is a measure of how easily a magnetic field goes through a material. Permeability also tells us how much stronger the magnetic field will be with the material inside the coil. Figure 3.87 shows three identical coils. One has an air core, one has a powdered iron core in the center, and the other has a

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**FIGURE 3.84** (A) Few turns, low inductance; (B) more turns, higher inductance.

**FIGURE 3.85** (A) Wide spacing between turns, low inductance; (B) close spacing between turns, higher inductance.

**FIGURE 3.86** (A) Small diameter, low inductance; (B) larger diameter, higher inductance.

**FIGURE 3.87** (A) air core, low inductance; (B) powdered iron core, higher inductance; (C) soft iron core, highest inductance.
soft iron core. This figure illustrates the effects of core material on inductance. The inductance of a coil is affected by the magnitude of current when the core is a magnetic material. When the core is air, the inductance is independent of the current.

**Note:** The inductance of a coil increases very rapidly as the number of turns is increased. It also increases as the coil is made shorter, the cross-sectional area is made larger, or the permeability of the core is increased.

**GROWTH AND DECAY OF CURRENT IN AN RL SERIES CIRCUIT**

If a battery is connected across a pure inductance, the current builds up to its final value at a rate that is determined by the battery voltage and the internal resistance of the battery. The current buildup is gradual because of the counter emf (cemf) generated by the self-inductance of the coil. When the current starts to flow, the magnetic lines of force move out, cut the turns of wire on the inductor, and build up a cemf that opposes the emf of the battery. This opposition causes a delay in the time it takes the current to build up to a steady value. When the battery is disconnected, the lines of force collapse, again cutting the turns of the inductor and building up an emf that tends to prolong the current flow.

Although the analogy is not exact, electrical inductance is somewhat like mechanical inertia. A boat begins to move on the surface of water at the instant a constant force is applied to it. At this instant, its rate of change of speed (acceleration) is greatest, and all the applied force is used to overcome the inertia of the boat. After a while, the speed of the boat increases but its acceleration decreases; the applied force is used up overcoming the friction of the water against the hull. As the speed levels off and acceleration drops to zero, the applied force equals the opposing friction force at this speed and the inertia effect disappears. In the case of inductance, it is electrical inertia that must be overcome.

Figure 3.88 shows a circuit that includes two switches, a battery, and a voltage divider containing a resistor (R) and an inductor (L). Switches S₁ and S₂ are mechanically interlocked (“ganged”), as indicated by the dashed line; when one closes, the other opens at exactly the same instant. Such an arrangement is an RL (resistive–inductive) series circuit. The source voltage of the battery is applied across the resistor and inductor when S₁ is closed. As S₁ is closed, as shown in Figure 3.88, a voltage (E) appears across the resistor and inductor. A current attempts to flow, but the inductor opposes this current by building up a cemf. At the first instant S₁ is closed, the cemf exactly equals the battery emf, and its polarity is opposite. Under this condition, no current will flow in resistor R. Because no current can flow when the cemf is exactly equal to the battery voltage, no voltage is dropped across R. As time goes on, more of the battery voltage appears across the resistor and less across the inductor. The rate of change of current is less and the induced emf is less. As the steady-state condition of the current flow is approached, the drop across the inductor approaches zero, and all the battery voltage is used to overcome the resistance of the circuit.

**FIGURE 3.88** Growth and decay of current in an RL circuit.
When \( S_2 \) is closed (source voltage \( E \) is removed from the circuit), the flux that has been established around \( L \) collapses through the windings and induces voltage \( E_L \) in \( L \) which has a polarity opposite that of \( E \) and is essentially equal to it in magnitude. The induced voltage, \( E_L \), causes current \( I \) to flow through \( R \) in the same direction that it was flowing when \( S_1 \) was closed. Voltage \( E_R \), which is initially equal to \( E \), is developed across \( R \). It rapidly falls to zero as voltage \( E_L \) across \( L \) falls to zero due to the collapsing flux.

**Note:** When a switch is first closed to complete a circuit, inductance opposes the buildup of current in the circuit.

**Note:** In many electronic circuits, the time required for the growth or decay of current is important, but these applications are beyond the scope of this manual; however, you need to learn the fundamentals of the \( L/R \) time constant, which are discussed in the following section.

### \( L/R \) Time Constant

The time required for the current through an inductor to increase to 63.2% (63%) of the maximum current or to decrease to 36.7% (37%) is known as the *time constant* of the circuit. An \( RL \) circuit is shown in Figure 3.89. The value of the time constant in seconds is equal to the inductance in henrys divided by the circuit resistance in ohms. One set of values is given in Figure 3.89. \( L/R \) is the symbol used for this time constant. If \( L \) is in henrys and \( R \) is in ohms, \( t \) (time) is in seconds. If \( L \) is in microhenrys and \( R \) is in ohms, \( t \) is in microseconds. If \( L \) is in millihenrys and \( R \) is in ohms, \( t \) is in milliseconds. \( R \) in the \( L/R \) equation is always in ohms, and the time constant is on the same order of magnitude as \( L \). Two useful relations used in calculating \( L/R \) time constants are as follows:

\[
\frac{L}{R} \text{ (henrys)/R (ohms)} = t \text{ (seconds)} \tag{3.39}
\]

\[
\frac{L}{R} \text{ (microhenrys)/R (ohms)} = t \text{ (microseconds)} \tag{3.40}
\]

**Note:** The time constant of an \( RL \) circuit is always expressed as a ratio between inductance \( (L) \) and resistance \( (R) \).

### Mutual Inductance

When the current in a conductor or coil changes, the varying flux can cut across any other conductor or coil located nearby, thus inducing voltages in both. A varying current in \( L_1 \), therefore, induces voltage across \( L_1 \) and across \( L_2 \) (Figure 3.90); see Figure 3.91 for the schematic symbol for two coils with mutual inductance. When the induced voltage \( (E_{L2}) \) produces current in \( L_2 \), its varying magnetic field induces voltage in \( L_1 \); hence, the two coils \( L_1 \) and \( L_2 \) have *mutual inductance* because

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**FIGURE 3.89** \( L/R \) time constant.
current change in one coil can induce voltage in the other. The unit of mutual inductance is the henry, and the symbol is $L_M$. Two coils have a mutual inductance of 1 henry when a current change of 1 A/sec in one coil induces 1 volt in the other coil. The factors affecting the mutual inductance of two adjacent coils are dependent on

- Physical dimensions of the two coils
- Number of turns in each coil
- Distance between the two coils
- Relative positions of the axes of the two coils
- Permeability of the cores

*Note:* The amount of mutual inductance depends on the relative position of the two coils. If the coils are separated a considerable distance, the amount of flux common to both coils is small and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flow of one coil links the turns of the other, then mutual inductance is high. The mutual inductance can be increased greatly by mounting the coils on a common iron core.

**Calculation of Total Inductance**

In the study of advanced electrical theory, it is necessary to know the effect of mutual inductance in solving for total inductance in both series and parallel circuits; however, for our purposes in this manual, we do not attempt to make these calculations. Instead, we discuss the basic total inductance calculations that the maintenance operator should be familiar with. If inductors in series are located far enough apart, or well shielded to make the effects of mutual inductance negligible, the total inductance is calculated in the same manner as for resistances in series; we merely add them:

$$L_T = L_1 + L_2 + L_3 + \ldots + L_n$$  \hspace{1cm} (3.41)
EXAMPLE 3.37

Problem: If a series circuit contains three inductors with values of 40, 50, and 20 µh, what is the total inductance?
Solution:

\[ L_T = 40 + 50 + 20 = 110 \, \mu h \]

In a parallel circuit containing inductors (without mutual inductance), the total inductance is calculated in the same manner as for resistances in parallel:

\[ \frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n} \]  \hspace{2cm} (3.42)

EXAMPLE 3.38

Problem: A circuit contains three totally shielded inductors in parallel. The values of the three inductances are 4, 5, and 10 mh. What is the total inductance?
Solution:

\[ \frac{1}{L_T} = \frac{1}{4} + \frac{1}{5} + \frac{1}{10} = 0.25 + 0.2 + 0.1 = 0.55 \]

\[ L_T = \frac{1}{0.55} = 1.8 \, mh \]

CAPACITANCE

No matter how complex the electrical circuit, it is composed of no more than three basic electrical properties: resistance, inductance, and capacitance. Accordingly, gaining a thorough understanding of these three basic properties is a necessary step toward the understanding of electrical equipment. We have covered resistance and inductance, and the last of the basic three, capacitance, is covered in this section. Earlier, we learned that inductance opposes any change in current. Capacitance is the property of an electric circuit that opposes any change of voltage in a circuit. If applied voltage is increased, capacitance opposes the change and delays the voltage increase across the circuit. If applied voltage is decreased, capacitance tends to maintain the higher original voltage across the circuit, thus delaying the decrease. Capacitance is also defined as that property of a circuit that enables energy to be stored in an electric field. Natural capacitance exists in many electric circuits; however, in this manual, we are concerned only with the capacitance that is designed into the circuit by means of devices called capacitors.

Note: The most noticeable effect of capacitance in a circuit is that voltage can neither increase nor decrease as rapidly in a capacitive circuit as it can in a circuit that does not include capacitance.

CAPACITORS

A capacitor, or condenser, is a manufactured electrical device that consists of two conducting plates of metal separated by an insulating material called a dielectric (see Figure 3.92). (The prefix \textit{di}- means “through” or “across.”) When a capacitor is connected to a voltage source, there is a short current pulse. A capacitor stores this electric charge in the dielectric (it can be charged and
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discharged, as we shall see later). To form a capacitor of any appreciable value, however, the area of the metal pieces must be quite large and the thickness of the dielectric must be quite small. The symbol used to designate a capacitor is \( C \); the unit of capacitance is the farad (F). The farad is that capacitance that will store 1 coulomb of charge in the dielectric when the voltage applied across the capacitor terminals is 1 volt. The schematic symbols for capacitors are shown in Figure 3.93.

Note: A capacitor is essentially a device that stores electrical energy.

The capacitor is used in a number of ways in electrical circuits. It may block DC portions of a circuit, as it is effectively a barrier to direct current (but not to alternating current). It may be part of a tuned circuit—one such application is in the tuning of a radio to a particular station. It may be used to filter AC out of a DC circuit. Most of these are advanced applications that are beyond the scope of this presentation; however, a basic understanding of capacitance is necessary to the fundamentals of AC theory.

Note: A capacitor does not conduct direct current. The insulation between the capacitor plates blocks the flow of electrons. We learned earlier that there is a short current pulse when we first connect the capacitor to a voltage source. The capacitor quickly charges to the supply voltage, and then the current stops.

The two plates of the capacitor shown in Figure 3.94 are electrically neutral because each plate has as many protons (positive charge) as electrons (negative charge); thus, the capacitor has no charge. Now connect a battery across the plates (Figure 3.95A). When the switch is closed (Figure 3.95B), the negative charge on plate A is attracted to the positive terminal of the battery. This movement of charges will continue until the difference in charge between plates A and B is equal to the electromotive force (voltage) of the battery. The capacitor is now charged. Because almost none of the charge can cross the space between the plates, the capacitor will remain in this condition even if the battery is removed (Figure 3.96A); however, if a conductor is placed across the plates (Figure 3.96B), the electrons find a path back to plate A and the charges on each plate are again neutralized. The capacitor is now discharged.
FIGURE 3.94  Two plates of a capacitor with a neutral charge.

FIGURE 3.95  (A) Neutral capacitor; (B) charged capacitor.

FIGURE 3.96  (A) Charged capacitor; (B) discharging a capacitor.
Note: In a capacitor, electrons cannot flow through the dielectric, because it is an insulator. Because it takes a definite quantity of electrons to charge a capacitor, it is said to have \textit{capacity}. This characteristic is referred to as \textit{capacitance}.

**Dielectric Materials**

Somewhat similar to the phenomenon of permeability in magnetic circuits, various materials differ in their ability to support electric flux (lines of force) or to serve as dielectric material for capacitors. Materials are rated in their ability to support electric flux in terms of a number called a \textit{dielectric constant}. Other factors being equal, the higher the value of the dielectric constant, the better the dielectric material. Dry air is the reference against which all other materials are rated. Dielectric constants for some common materials are given in Table 3.7.

Note: From Table 3.7 it is obvious that pure water is the best dielectric. Keep in mind that the key word here is “pure." Water capacitors are used today in some high-energy applications, in which differences in potential are measured in thousands of volts.

**Unit of Capacitance**

Capacitance is equal to the amount of charge that can be stored in a capacitor divided by the voltage applied across the plates:

\[
C = \frac{Q}{E} \tag{3.43}
\]

where
- \(C\) = Capacitance (farads, F).
- \(Q\) = Amount of charge (coulombs, C).
- \(E\) = Voltage (volts, V).

**Example 3.39**

**Problem:** What is the capacitance of two metal plates separated by 1 centimeter of air if 0.001 coulomb of charge is stored when a potential of 300 volts is applied to the capacitor?

**Solution:** Given that \(Q = 0.001\) coulomb, \(E = 200\) volts, and

\[
C = \frac{Q}{E}
\]

Convert to the power of ten:

\[
C = \frac{(10 \times 10^{-4})}{(2 \times 10^2)} = 5 \times 10^{-6} = 0.000005\text{ farads}
\]
**Note:** Although the capacitance value obtained in Example 3.39 appears small, many electronic circuits require much smaller capacitors. The farad is a cumbersome unit that is far too large for many applications. The microfarad (µF) is one millionth of a farad (1 × 10⁻⁶ farad) and is a more convenient unit.

Equation 3.43 can be rewritten as follows:

\[ Q = C \times E \]  
\[ E = \frac{Q}{C} \]  

**Note:** From Equation 3.44, do not get the mistaken idea that capacitance is dependent on charge and voltage. Capacitance is determined entirely by physical factors, which are covered later.

**Factors Affecting Value of Capacitance**

The capacitance of a capacitor depends on three main factors: plate surface area, distance between plates, and dielectric constant of the insulating material:

- **Plate surface area**—Capacitance varies directly with plate surface area. We can double the capacitance value by doubling the plate surface area of the capacitor. Figure 3.97 shows a capacitor with a small surface area and another one with a large surface area. Adding more capacitor plates can increase the plate surface area. Figure 3.98 shows alternate plates connecting to opposite capacitor terminals.

- **Distance between plates**—Capacitance varies inversely with the distance between plate surfaces. The capacitance increases when the plates are closer together. Figure 3.99 shows capacitors with the same plate surface area but different spacing.

![FIGURE 3.97](A) Small plates, small capacitance; (B) larger plates, higher capacitance.

![FIGURE 3.98](Se veral sets of plates connected to produce a capacitor with greater surface area.)
• **Dielectric constant of the insulating material**—An insulating material with a higher dielectric constant produces a higher capacitance rating. Figure 3.100 shows two capacitors. Both have the same plate surface area and spacing. Air is the dielectric in the first capacitor, and mica is the dielectric in the second one. The dielectric constant of mica is 5.4 times greater than the dielectric constant of air, so the mica capacitor has 5.4 times more capacitance than the other capacitor.

**Voltage Rating of Capacitors**

There is a limit to the voltage that may be applied across any capacitor. If too large a voltage is applied, it will overcome the resistance of the dielectric and a current will be forced through it from one plate to the other, sometimes burning a hole in the dielectric. In this event, a short circuit exists and the capacitor must be discarded. The maximum voltage that may be applied to a capacitor is known as the **working voltage** and must never be exceeded. The working voltage of a capacitor depends on (1) the type of material used as the dielectric, and (2) the thickness of the dielectric. As a margin of safety, the capacitor should be selected so its working voltage is at least 50% greater than the highest voltage to be applied to it; for example, if a capacitor is expected to have a maximum of 200 volts applied to it, its working voltage should be at least 300 volts.

**Charge and Discharge of an RC Series Circuit**

According to Ohm’s law, the voltage across a resistance is equal to the current through it times the value of the resistance. This means that a voltage will be developed across a resistance only when current flows through it. As previously stated, a capacitor is capable of storing or holding a charge of electrons. When uncharged, both plates contain the same number of free electrons. When charged, one plate contains more free electrons than the other. The difference in the number of electrons is a measure of the charge on the capacitor. The accumulation of this charge builds up a voltage across the terminals of the capacitor, and the charge continues to increase until this voltage equals the
applied voltage. The greater the voltage, the greater the charge on the capacitor. Unless a discharge path is provided, a capacitor keeps its charge indefinitely. Any practical capacitor, however, has some leakage through the dielectric so the voltage will gradually leak off. A voltage divider with resistance and capacitance may be connected in a circuit by means of a switch, as shown in Figure 3.101. Such a series arrangement is called an RC series circuit.

If \( S_1 \) is closed, electrons flow counterclockwise around the circuit containing the battery, capacitor, and resistor. This flow of electrons ceases when \( C \) is charged to the battery voltage. At the instant current begins to flow, there is no voltage on the capacitor and the drop across \( R \) is equal to the battery voltage. The initial charging current \( (I) \) is therefore equal to \( E_S/R \). The current flowing in the circuit soon charges the capacitor. Because the voltage on the capacitor is proportional to its charge, a voltage \( (E_C) \) will appear across the capacitor. This voltage opposes the battery voltage—that is, these two voltages buck each other. As a result, voltage \( E_R \) across the resistor is equal to \( E_S - E_C \), which is equal to the voltage drop \( (I_C R) \) across the resistor. Because \( E_S \) is fixed, \( I_C \) decreases as \( E_C \) increases. The charging process continues until the capacitor is fully charged and the voltage across it is equal to the battery voltage. At this instant, the voltage across \( R \) is zero and no current flows through it. In Figure 3.101, if \( S_2 \) is closed (\( S_1 \) opened), a discharge current \( (I_D) \) will discharge the capacitor. Because \( I_D \) is opposite in direction to \( I_C \), the voltage across the resistor will have a polarity opposite to the polarity during the charging time; however, this voltage will have the same magnitude and will vary in the same manner. During discharge the voltage across the capacitor is equal and opposite to the drop across the resistor. The voltage drops rapidly from its initial value and then approaches zero slowly. The actual time it takes to charge or discharge is important in advanced electricity and electronics. Because the charge or discharge time depends on the values of resistance and capacitance, an RC circuit can be designed for the proper timing of certain electrical events. The RC time constant is covered in the next section.

**RC Time Constant**

The time required to charge a capacitor to 63% of maximum voltage or to discharge it to 37% of its final voltage is known as the time constant of the current. An RC circuit is shown in Figure 3.102. The time constant \( T \) for an RC circuit is

\[
T = R \times C
\]

The time constant of an RC circuit is usually very short because the capacitance of a circuit may be only a few microfarads or even picofarads.

*Note:* An RC time constant expresses the charge and discharge times for a capacitor.
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Capacitors in Series and Parallel

Like resistors or inductors, capacitors may be connected in series, in parallel, or in a series–parallel combination. Unlike resistors or inductors, however, total capacitance in series, parallel, or series–parallel combinations is found in a different manner. Simply put, the rules are not the same for the calculation of total capacitance. This difference is explained as follows: Parallel capacitance is calculated like series resistance, and series capacitance is calculated like parallel resistance:

- When capacitors are connected in series (see Figure 3.103), the total capacitance \( C_T \) is

\[
\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{C_n}
\]  

(3.47)

**EXAMPLE 3.40**

**Problem:** Find the total capacitance of a 3-µF, a 5-µF, and a 15-µF capacitor in series.

**Solution:** Write Equation 3.47 for three capacitors in series:

\[
\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{1}{3} + \frac{1}{5} + \frac{1}{15} = \frac{5}{15} = \frac{5}{3} \quad C_T = \frac{5}{3} = 1.7 \text{ µF}
\]

- When capacitors are connected in parallel (see Figure 3.104), the total capacitance \( C_T \) is the sum of the individual capacitances:

\[
C_T = C_1 + C_2 + C_3 + \ldots + C_n
\]  

(3.48)

**FIGURE 3.102**  
*RC circuit.*

**FIGURE 3.103**  
*Series capacitive circuit.*
EXAMPLE 3.41

Problem: Determine the total capacitance in a parallel capacitive circuit, given:

\[ C_1 = 2 \mu F \]
\[ C_2 = 3 \mu F \]
\[ C_3 = 0.25 \mu F \]

Solution: Write Equation 3.48 for three capacitors in parallel:

\[ C_T = C_1 + C_2 + C_3 = 2 + 3 + 0.25 = 5.25 \mu F \]

- If capacitors are connected in a combination of series and parallel (see Figure 3.105), the total capacitance is found by applying Equations 3.47 and 3.48 to the individual branches.

TYPES OF CAPACITORS

Capacitors used for commercial applications are divided into two major groups—fixed and variable—and are named according to their dielectric. Most common are air, mica, paper, and ceramic capacitors, plus the electrolytic type. These types are compared in Table 3.8. The fixed capacitor has a set value of capacitances that is determined by its construction. The construction of the variable capacitor allows a range of capacitances. Within this range, the desired value of capacitance is obtained by some mechanical means, such as by turning a shaft (as in turning a radio tuner knob, for example) or adjusting a screw to adjust the distance between the plates. The electrolytic capacitor consists of two metal plates separated by an electrolyte. The electrolyte, either paste or liquid, is in contact with the negative terminal, and this combination forms the negative electrode. The dielectric is a very thin film of oxide deposited on the positive electrode, which is aluminum sheet. Electrolytic capacitors are polarity sensitive (i.e., they must be connected in a circuit according to their polarity markings) and are used where a large amount of capacitance is required.
Like batteries, ultracapacitors, also known as supercapacitors, pseudocapacitors, electric double-layer capacitors, or electrochemical double-layer capacitors (EDLCs), are energy storage devices (NREL, 2009). To meet the power, energy, and voltage requirements for a wide range of applications, they use electrolytes and various-sized cells configured into modules. As storage devices, however, they differ from batteries in that ultracapacitors (which are true capacitors in that energy is stored via charge separation at the electrode–electrolyte interface) store energy electrostatically, but batteries store energy chemically. Ultracapacitors provide quick bursts of energy and also offer an improvement of about two to three orders of magnitude in capacitance (as compared to an average capacitor), but with a lower working voltage. Moreover, they can withstand hundreds of thousands of charge/discharge cycles without degrading. As an alternative energy source, ultracapacitors have proven themselves as reliable energy storage components that can be used to power a variety of electronic and portable devices such as radios, flashlights, cell phones, and emergency kits. As ultracapacitor technology matures they are being developed to function as batteries; for example, the vehicle industry is deploying ultracapacitors as a replacement for chemical batteries.

Ultracapacitor Operation

An ultracapacitor polarizes an electrolytic solution to store energy electrostatically. Though it is an electrochemical device, no chemical reactions are involved in its energy storage mechanism. This mechanism is highly reversible and allows the ultracapacitor to be charged and discharged hundreds of thousands of times. As shown in Figure 3.106, an ultracapacitor is comprised of two nonreactive porous plates, or collectors, suspended within an electrolyte, with a voltage potential applied across

---

**TABLE 3.8**

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Construction</th>
<th>Capacitance Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Meshed plates</td>
<td>10–400 pF</td>
</tr>
<tr>
<td>Mica</td>
<td>Stacked plates</td>
<td>10–5000 pF</td>
</tr>
<tr>
<td>Paper</td>
<td>Rolled foil</td>
<td>0.001–1 µF</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Tubular</td>
<td>0.5–1600 pF</td>
</tr>
<tr>
<td></td>
<td>Disk</td>
<td>0.002–0.1 µF</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>Aluminum</td>
<td>5–1000 µF</td>
</tr>
<tr>
<td></td>
<td>Tantalum</td>
<td>0.01–300 µF</td>
</tr>
</tbody>
</table>

---

**FIGURE 3.106** Ultracapacitor.
the collectors. In an individual ultracapacitor cell, the applied potential on the positive electrode attracts the negative ions in the electrolyte, while the potential on the negative electrode attracts the positive ions. A dielectric separator between the two electrodes prevents the charge from moving between the two electrodes. Once the ultracapacitor is charged and energy stored, a load can use this energy. The amount of energy stored is very large compared to a standard capacitor because of the enormous surface area created by the porous carbon electrodes and the small separation (10 angstroms) created by the dielectric separate; however, it stores a much smaller amount of energy than does a battery. Because the rates of charge and discharge are determined solely by is physical properties, the ultracapacitor can release energy much faster (with more power) than a battery that relies on slow chemical reactions.

**INDUCTIVE AND CAPACITIVE REACTANCE**

Earlier, we learned that the inductance of a circuit acts to oppose any change of current flow in that circuit and that capacitance acts to oppose any change of voltage. In DC circuits these reactions are not important, because they are momentary and occur only when a circuit is first closed or opened. In AC circuits, these effects become very important because the direction of current flow is reversed many times each second, and the opposition presented by inductance and capacitance is, for practical purposes, constant. In purely resistive circuits, either DC or AC, the term for opposition to current flow is resistance. When the effects of capacitance or inductance are present, as they often are in AC circuits, the opposition to current flow is called reactance. The total opposition to current flow in circuits that have both resistance and reactance is called impedance. In this section, we cover the calculation of inductive and capacitive reactance and impedance; the phase relationships of resistance, inductive, and capacitive circuits; and power in reactive circuits.

**INDUCTIVE REACTANCE**

In order to gain an understanding of the reactance of a typical coil, we need to review exactly what occurs when AC voltage is impressed across the coil. The AC voltage produces an alternating current. When a current flows in a wire, lines of force are produced around the wire. Large currents produce many lines of force; small currents produce only a few lines of force. As the current changes, the number of lines of force will change. The field of force will seem to expand and contract as the current increases and decreases, as shown in Figure 3.107. As the field expands and contracts, the lines of force must cut across the wires that form the turns of the coil.

These cuttings induce an emf in the coil. This emf acts in the direction so as to oppose the original voltage and is called a counter (or back) emf. The effect of this counter emf is to reduce the original voltage impressed on the coil. The net effect will be to reduce the current below that which would flow if there were no cuttings or counter emf. In this sense, the counter emf is acting as a

![Expanding lines of force](image1.png) ![Contracting lines of force](image2.png)

**FIGURE 3.107** AC current producing a moving (expanding and collapsing) field; in a coil, this moving field cuts the wires of the coil.
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resistance in reducing the current. Although it would be more convenient to consider the current-reducing effect of a counter emf as a number of ohms of effective resistance, we don’t do this. Instead, because a counter emf is not actually a resistance but merely acts as a resistance, we use the term reactance to describe this effect.

**Note:** The reactance of a coil is the number of ohms of resistance that the coil seems to offer as a result of a counter emf induced in it. Its symbol is \( X \) to differentiate it from the DC resistance \( R \).

The inductive reactance of a coil depends primarily on (1) the inductance of the coil, and (2) the frequency of the current flowing through the coil. The value of the reactance of a coil is therefore proportional to its inductance and the frequency of the AC circuit in which it is used. The formula for inductive reactance is

\[
X_L = 2\pi fL \tag{3.49}
\]

Because \( 2\pi = 2 \times 3.14 = 6.28 \), Equation 3.49 becomes

\[
X_L = 6.28fL
\]

where
- \( X_L \) = Inductive reactance (ohms).
- \( f \) = Frequency (Hz).
- \( L \) = Inductance (h).

If any two quantities are known in Equation 3.49, the third can be found:

\[
L = \frac{X_L}{6.28f} \tag{3.50}
\]

\[
f = \frac{X_L}{6.28L} \tag{3.51}
\]

**EXAMPLE 3.42**

**Problem:** The frequency of a circuit is 60 Hz and the inductance is 20 mh. What is \( X_L \)?

**Solution:**

\[
X_L = 2\pi fL = 6.28 \times 60 \times 0.02 = 7.5 \text{ ohms}
\]

**EXAMPLE 3.43**

**Problem:** A 30-mh coil is in a circuit operating at a frequency of 1400 kHz. Find its inductive reactance.

**Solution:** Given that \( L = 30 \text{ mh} \) and \( f = 1400 \text{ kHz} \), find \( X_L \). First, change the units of measurement:

\[
30 \text{ mh} = 30 \times 10^{-3} \text{ h}
\]

\[
1400 \text{ kHz} = 1400 \times 10^3
\]

Now find the inductive reactance:

\[
X_L = 6.28fL
\]

\[
X_L = 6.28 \times (1400 \times 10^3) \times (30 \times 10^{-3}) = 263,760 \text{ ohms}
\]
■ EXAMPLE 3.44

*Problem:* Given \( L = 400 \, \mu \text{H} \) and \( f = 1500 \, \text{Hz} \), find \( X_L \).

*Solution:*

\[
X_L = 2\pi f L = 6.28 \times 1500 \times 0.0004 = 3.78 \, \text{ohms}
\]

*Note:* If frequency or inductance varies, inductive reactance must also vary. The inductance of a coil does not vary appreciably after the coil is manufactured, unless it is designed as a variable inductor; thus, frequency is generally the only variable factor affecting the inductive reactance of a coil. The inductive reactance of the coil will vary directly with the applied frequency.

**CAPACITIVE REACTANCE**

Previously, we learned that as a capacitor is charged electrons are drawn from one plate and deposited on the other. As more and more electrons accumulate on the second plate, they begin to act as an opposing voltage, which attempts to stop the flow of electrons just as a resistor would do. This opposing effect is called the *reactance* of the capacitor and is measured in ohms. As noted earlier, the basic symbol for reactance is \( X \), and the subscript defines the type of reactance. Earlier, we used \( X_L \) to represent inductive reactance; the subscript \( L \) refers to inductance. Following the same pattern, we use \( X_C \) to represent capacitive reactance. The two factors affecting capacitive reactance \( (X_C) \) are:

- Size of the capacitor
- Frequency

*Note:* Capacitive reactance, \( X_C \), is the opposition to the flow of AC current due to capacitance in the circuit.

The larger the capacitor, the greater the number of electrons that may be accumulated on its plates. When the plate area is large, the electrons do not accumulate in one spot but spread out over the entire area of the plate and do not impede the flow of new electrons onto the plate; therefore, a large capacitor offers a small reactance. In a capacitor with a small plate area, the electrons cannot spread out, and they attempt to stop the flow of electrons coming onto the plate; therefore, a small capacitor offers a large reactance. The reactance, therefore, is *inversely* proportional to the capacitance.

If an AC voltage is impressed across the capacitor, electrons are accumulated first on one plate and then on the other. If the frequency of the changes in polarity is low, the time available to accumulate electrons is large. This means that a large number of electrons will be able to accumulate, which will result in a large opposing effect, or a large reactance. If the frequency is high, the time available to accumulate electrons will be small. This means that only a few electrons will accumulate on the plates, which will result in a small opposing effect, or a small reactance. The reactance, therefore, is *inversely* proportional to the frequency. The formula for capacitive reactance is

\[
X_C = \frac{1}{2\pi f C}
\]  

(3.52)

where

- \( X_C = \) Capacitive reactance (ohms).
- \( f = \) Frequency (Hz).
- \( C = \) Capacitance (F).

■ EXAMPLE 3.45

*Problem:* What is the capacitive reactance of a circuit operating at a frequency of 60 Hz, if the total capacitance is 130 \( \mu \text{F} \)?

*Solution:*

\[
X_C = \frac{1}{2\pi f C} = \frac{1}{(6.28 \times 60 \times 0.00013)} = 20.4 \, \text{ohms}
\]
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Phase relationships for $R$, $L$, and $C$ circuits

Unlike a purely resistive circuit, where current rises and falls with the voltage (i.e., it neither leads nor lags; current and voltage are in phase), current and voltage are not in phase in inductive and capacitive circuits. This is the case, of course, because events are not quite instantaneous in circuits that have either inductive or capacitive components. In the case of an inductor, voltage is first applied to the circuit, then the magnetic field begins to expand, and self-induction causes a countercurrent to flow in the circuit, opposing the original circuit current. In this case, voltage leads current by 90° (Figure 3.108). When a circuit includes a capacitor, a charge current begins to flow and then a difference in potential appears between the plates of the capacitor. In this case, current leads voltage by 90° (Figure 3.109).

Note: In an inductive circuit, voltage leads current by 90°; in a capacitive circuit, current leads voltage by 90°.

Impedance

Impedance is the total opposition to the flow of alternating current in a circuit that contains resistance and reactance. In the case of pure inductance, inductive reactance ($X_L$) is the total opposition to the flow of current through it. In the case of pure resistance, $R$ represents the total opposition. The combined opposition of $R$ and $X_L$ in series or in parallel to current flow is the impedance. The symbol for impedance is $Z$. The impedance of resistance in series with inductance is

$$\frac{1}{R_I} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

(3.53)
where
\[ Z = \text{Impedance (ohms)}. \]
\[ R = \text{Resistance (ohms)}. \]
\[ X_L = \text{Inductive reactance (ohms)}. \]

The impedance of resistance in series with capacitance is
\[ Z = \sqrt{R^2 + X_L^2} \]  
(3.54)

where
\[ Z = \text{Impedance (ohms)}. \]
\[ R = \text{Resistance (ohms)}. \]
\[ X_C = \text{Inductive capacitance (ohms)}. \]

When the impedance of a circuit includes \( R \), \( X_L \), and \( X_C \), both resistance and net reactance must be taken into account. The equation for impedance that includes both \( X_L \) and \( X_C \) is
\[ Z = \sqrt{R^2 + X_C^2} \]  
(3.55)

POWER IN REACTIVE CIRCUITS

The power in a DC circuit is equal to the product of volts and amps, but in an AC circuit this is true only when the load is resistive and has no reactance. In a circuit possessing inductance only, the true power is zero. The current lags the applied voltage by 90°. The true power in a capacitive circuit is also zero. True power is the average power actually consumed by the circuit, the average being taken over one complete cycle of alternating current. The apparent power is the product of the RMS volts and RMS amps. The ratio of true power to apparent power in an AC circuit is called the power factor. It may be expressed as a percent or as a decimal.

AC CIRCUIT THEORY

To this point, we have pointed out how combinations of inductance and resistance and then capacitance and resistance behave in an AC circuit, and we saw how \( RL \) and \( RC \) combinations affect the current, voltages, power, and power factor of a circuit:

1. The voltage drop across a resistor is **in phase** with the current through it.
2. The voltage drop across an inductor **leads** the current through it by 90°.
3. The voltage drop across a capacitor **lags** the current through it by 90°.
4. The voltage drops across inductors and capacitors are **180° out of phase**.

Solving AC problems is complicated by the fact that current varies with time as the AC output of an alternator goes through a complete cycle. The various voltage drops in the circuit vary in phase—they are not at their maximum or minimum values at the same time. AC circuits frequently include all three circuit elements: resistance, inductance, and capacitance. In this section, all three of these fundamental circuit parameters are combined and their effect on circuit values studied.

**Series RLC Circuit**

Figure 3.110 shows both the sine waveforms and the vectors for purely resistive, inductive, and capacitive circuits. Only the vectors show the direction, because the magnitudes are dependent on the values chosen for a given circuit. (We are only interested in the effective root-mean-square
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(A) Pure Resistive Circuit (voltage and current are in phase)

(B) Pure Inductive Circuit (voltage leads current by 90°).

(C) Pure Capacitive Circuit (voltage lags current by 90°).

FIGURE 3.110 Sine waveforms and vectorial representation of $R$, $L$, and $C$ circuits.
values.) If the individual resistances and reactances are known, Ohm’s law may be applied to find
the voltage drops. For example, we know that \( E_R = I \times R \) and \( E_C = I \times X_C \). Then, according to Ohm’s
law, \( E_L = I \times X_L \). In AC circuits, current varies with time, and the voltage drops across the vari-
ous elements also vary with time; however, the same variation is not always present in each at the
same time (except in purely resistive circuits) because current and voltage are not in phase. We are
primarily concerned, in practical terms, with effective values of current and voltage; however, to
understand basic AC theory, we need to know what occurs from instant to instant. In Figure 3.111,
note first that current is the common reference for all three element voltages, because there is only
one current in a series circuit, and it is common to all elements. The dashed line in Figure 3.111A
represents the common series current. Voltage vectors for each element are provided to demonstrate
their individual relationships to the common current. The total source voltage (\( E \)) is the vector sum
of the individual voltages of \( IR \), \( IX_L \), and \( IX_C \). The arrangement of these three voltages is sum-
marized in Figure 3.111B. Because \( IX_L \) and \( IX_C \) are each 90° away from \( I \), they are 180° from each
other. Vectors in direct opposition (180° out of phase) may be subtracted directly. The total reactive
voltage (\( EX \)) is the difference of \( IX_L \) and \( IX_C \); for example, \( EX = IX_L - IX_C = 45 - 15 = 30 \) volts. The
final relationship of line voltage and current, as seen from the source, is shown in Figure 3.111C.
Had \( X_C \) been larger than \( X_L \), the voltage would lag, rather than lead. When \( X_C \) and \( X_L \) are of equal
value, the line voltage and current will be in phase.

**Note:** In a resistive circuit, the phase difference between voltage and current is zero.
Note: The voltage across a single reactive element in a series circuit can have a greater effective value than that of the applied voltage.

Note: One of the most important characteristics of an RLC circuit is that it can be made to respond most effectively to a single given frequency. When operated in this condition, the circuit is said to be in resonance with or resonant to the operating frequency. A circuit is at resonance when the inductive reactance ($X_L$) is equal to the capacitive reactance ($X_C$). At resonance, impedance ($Z$) equals resistance ($R$).

In summary, the series RLC circuit illustrates three important points:

- The current in a series RLC circuit either leads or lags the applied voltage, depending on whether $X_C$ is greater or less than $X_L$.
- A capacitive voltage drop in a series circuit always subtracts directly from an inductive voltage drop.
- The voltage across a single reactive element in a series circuit can have a greater effective value than that of the applied voltage.

**Parallel RLC Circuits**

The true power of a circuit is $P = E \times I \times \cos(\theta)$. For any given amount of power to be transmitted, the current ($I$) varies inversely with the power factor, $\cos(\theta)$. The addition of capacitance in parallel with inductance will, under the proper conditions, improve the power factor of the circuit and make possible the transmission of electric power with reduced line loss and improved voltage regulation. Figure 3.112A shows a three-branch, parallel AC circuit with a resistance in one branch, inductance in the second branch, and capacitance in the third branch. The voltage is the same across each parallel branch, so $V_T = V_R = V_L = V_C$. The applied voltage ($V_T$) is used as the reference line to measure phase angle $\theta$. The total current ($I_T$) is the vector sum of $I_R$, $I_L$, and $I_C$. The current in the resistance ($I_R$) is in phase with the applied voltage ($V_T$) (Figure 3.112B). The current in the capacitor ($I_C$) leads total voltage $V_T$ by 90°. $I_L$ and $I_C$ are exactly 180° out of phase and thus acting in opposite directions (Figure 3.112B). When $I_L > I_C$, $I_T$ lags $V_T$ (Figure 3.112C), so the parallel RLC circuit is considered inductive.

![Parallel RLC circuit diagram](A) Parallel RLC circuit diagram  
![Vector diagram, $I_L > I_C$](B) Vector diagram, $I_L > I_C$  
![Current-vector triangle, $I_L > I_C$](C) Current-vector triangle, $I_L > I_C$

**FIGURE 3.112** $R$, $X_L$, and $X_C$ in parallel.
Power in AC Circuits

In circuits that have only resistance, but no reactance, the amount of power absorbed in the circuit is easily calculated by \( P = I^2 \times R \). However, in dealing with circuits that include inductance and capacitance (or both), which is often the case in AC circuits, the calculation of power is a more complicated process. Earlier, we explained that power is a measure of the rate at which work is done. The work of a resistor is to limit current flow to the correct, safe level. In accomplishing this, the resistor dissipates heat, and we say that power is consumed or absorbed by the resistor. Inductors and capacitors also oppose current flow, but they do so by producing current that opposes the line current. In either inductive or capacitive circuits, instantaneous values of power may be very large, but the power actually absorbed is essentially zero, since only resistance dissipates heat (absorbs power). Both inductance and capacitance return the power to the source.

Any component that has resistance, such as a resistor or the wiring of an inductor, consumes power. Such power is not returned to the source, because it is dissipated as heat. Previously, we stated that power consumed in the circuit is called true power, or average power. The two terms are interchangeable, but we generally use the term average power, because the overall value is more meaningful than the instantaneous values of power appearing in the circuit during a complete cycle. Not all apparent power is consumed by the circuit; however, because the alternator does deliver the power, it must be considered in the design. The average power consumption may be small, but instantaneous values of voltage and current are often very large. Apparent power is an important design consideration, especially in assessing the amount of insulation necessary. In an AC circuit that includes both reactance and resistance, some power is consumed by the load and some is returned to the source. How much of each depends on the phase angle, because current normally leads or lags voltage by some angle.

Note: In terms of the dissipation of power as heat in a circuit, average power is the power that is dissipated as heat, but apparent power includes both power that is dissipated as heat and power that is returned to the source.

Note: Recall that in a purely reactive circuit, current and voltage are 90° out of phase.

In an RLC circuit, the \( R/Z \) ratio is the cosine of the phase angle, \( \theta \); therefore, it is easy to calculate average power in an RLC circuit:

\[
P = E \times I \times \cos(\theta)
\]  

(3.56)

where

- \( P \) = Average power absorbed by the circuit.
- \( E \) = Effective value of the voltage across the circuit.
- \( I \) = Effective value of current in the circuit.
- \( \theta \) = Phase angle between voltage and current.

Note: Recall that the equation for average power in a purely resistive circuit is \( P = E \times I \). In a resistive circuit, \( P = E \times I \) because the \( \cos(\theta) \) is 1 and need not be considered. In most cases, the phase angle will be neither 90° nor zero, but somewhere between those extremes.

**Example 3.46**

Problem: An RLC circuit has a source voltage of 500 volts, line current is 2 amps, and current leads voltage by 60°. What is the average power?

Solution: The cosine of 60° = 0.5, so

\[
\text{Average power} = 500 \, \text{V} \times 2 \, \text{A} \times 0.5 = 500 \, \text{W}
\]
EXAMPLE 3.47

Problem: An RLC circuit has a source voltage of 300 volts, line current is 2 amps, and current lags voltage by 31.8°. What is the average power?

Solution: The cosine of 31.8° = 0.8499, so

\[ \text{Average power} = 300 \text{ V} \times 2 \text{ A} \times 0.8499 = 509.9 \text{ W} \]

EXAMPLE 3.48

Problem: Given \( E = 100 \) volts, \( I = 4 \) amps, and \( \theta = 58.4° \), what is the average power?

Solution: The cosine of 58.4° = 0.5240, so

\[ \text{Average power} = 100 \text{ V} \times 4 \text{ A} \times 0.5240 = 209.6 \text{ W} \]

GENERATORS

DC GENERATORS

A DC generator is a rotating machine that converts mechanical energy into electrical energy. This conversion is accomplished by rotating an armature, which carries conductors, in a magnetic field, thus inducing an emf in the conductors. As stated previously, in order for an emf to be induced in the conductors, a relative motion must always exist between the conductors and the magnetic field in such a manner that conductors cut through the field. In most DC generators, the armature is the rotating member and the field is the stationary member. A mechanical force is applied to the shaft of the rotating member to cause the relative motion. Thus, when mechanical energy is put into the machine in the form of a mechanical force or twist on the shaft, causing the shaft to turn at a certain speed, electrical energy in the form of voltage and current is delivered to the external load circuit.

Note: Mechanical power must be applied to the shaft constantly as long as the generator is supplying electrical energy to the external load circuit.

To gain a basic understanding of the operation of a DC generator, consider the following explanation. A simple DC generator consists of an armature coil with a single turn of wire (Figure 3.113A,B). (The armature coils used in large DC machines are usually wound in their final shape before being put on the armature, and the sides of the preformed coil are placed in the slots of the laminated armature core.) This armature coil cuts across the magnetic field to produce voltage. If a complete
path is present, current will move through the circuit in the direction shown by the arrows in Figure 3.113A. In this position of the coil, commutator segment 1 is in contact with brush 1, while commutator segment 2 is in contact with brush 2. As the armature rotates a half turn in a clockwise direction, the contacts between the commutator segments and the brushes are reversed (Figure 3.113B). At this moment, segment 1 is in contact with brush 2 and segment 2 is in contact with brush 1. Because of this commutator action, that side of the armature coil that is in contact with either of the brushes is always cutting across the magnetic field in the same direction. Thus, brushes 1 and 2 have constant polarity, and a pulsating DC current is delivered to the external load circuit.

**Note:** In DC generators, voltage induced in individual conductors is AC. It is converted to DC (rectified) by the commutator, which rotates in contact with carbon brushes so current generated is in one direction (i.e., direct current).

The several different types of DC generators take their names from the type of field excitation used; that is, they are classified according to the manner in which the field windings are connected to the armature circuit. When the field of the generator is excited (or supplied) from a separate DC source (such as a battery) other than its own armature, it is called a separately excited DC generator (Figure 3.114). The field windings of a shunt generator (self-excited) are connected in series with a rheostat, across the armature in shunt with the load, as shown in Figure 3.115; the shunt generator is widely used in industry. The field windings of a series generator (self-excited) are connected in series with the armature and load, as shown in Figure 3.116. Series generators are seldom used. Compound generators (self-excited) contain both series and shunt field windings, as shown in Figure 3.117; compound generators are widely used in industry.
Note: As central generating stations increased in size along with number and power distribution distances, DC generating systems, because of the high power losses in long DC transmission lines, were replaced by AC generating systems to reduce power transmission costs.

AC Generators

Most electric power utilized today is generated by alternating-current generators (also called alternators). They are made in many different sizes, depending on their intended use. Regardless of size, however, all generators operate on the same basic principle—a magnetic field cutting through conductors or conductors passing through a magnetic field. They include (1) a group of conductors in which the output voltage is generated, and (2) a second group of conductors through which direct current is passed to obtain an electromagnetic field of fixed polarity. The conductors in which the electromagnetic field originates are always referred to as the field windings.

In addition to the armature and field, there must also be motion between the two. To provide this motion, AC generators are built in two major assemblies, the stator and the rotor. The rotor rotates inside the stator. The revolving-field AC generator (see Figure 3.118) is the most widely used type. In this type of generator, direct current from a separate source is passed through windings on the rotor by means of slip rings and brushes. (Slip rings and brushes are adequate for the DC field supply because the power level in the field is much smaller than in the armature circuit.) This maintains a rotating electromagnetic field of fixed polarity. The rotating magnetic field, following the rotor, extends outward and cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, AC voltages are induced in the windings because magnetic fields of first one polarity and then the other cut through them. The output power is taken from the
stationary windings and may be connected through fixed output terminals (T1 and T2 in Figure 3.118). This is advantageous, in that there are no sliding contacts and the entire output circuit is continuously insulated.

**Note:** In AC generators, frequency and electromagnetic wave cycles per second depend on how fast the rotor turns and the number of electromagnetic field poles. The voltage generated depends on the rotor speed, number of coils in the armature, and strength of the magnetic field.

**ELECTRIC MOTORS**

There is an almost endless variety of tasks that electric motors perform in the operation of industrial and domestic equipment. An *electric motor* is a machine used to change electrical energy to mechanical energy to do the work. (Recall that a generator does just the opposite; that is, a generator changes mechanical energy to electrical energy.) Previously, we pointed out that when a current passes through a wire a magnetic field is produced around the wire. If this magnetic field passes through a stationary magnetic field, the fields either repel or attract, depending on their relative polarity. If both are positive or negative, they repel. If they have opposite polarities, they attract. Applying this basic information to motor design, an electromagnetic coil, the armature, rotates on a shaft. The armature and shaft assembly are called the *rotor*. The rotor is assembled between the poles of a permanent magnet and each end of the rotor coil (armature) is connected to a commutator also mounted on the shaft. A commutator is composed of copper segments insulated from the shaft and from each other by an insulating material. As like poles of the electromagnet in the rotating armature pass the stationary permanent magnet poles, they are repelled, continuing the motion. As the opposite poles near each other, they attract, continuing the motion.

**DC MOTORS**

The construction of a DC motor is essentially the same as that of a DC generator; however, it is important to remember that the DC generator converts mechanical energy into the electrical energy back into mechanical energy. A DC generator may be made to function as a motor by applying a suitable source of DC voltage across the normal output electrical terminals. The various types of DC motors differ in the way their field coils are connected. Each has characteristics that are advantageous under given load conditions. *Shunt motors* (see Figure 3.119) have field coils connected in parallel with the armature circuit. This type of motor, with constant potential applied, develops variable torque at an essentially constant speed, even under changing load conditions. Such loads are found in machine-shop equipment, such as lathes, shapes, drills, milling machines, and so forth. *Series motors* (see Figure 3.120) have field coils connected in series with the armature circuit. This
type of motor, with constant potential applied, develops variable torque but its speed varies widely under changing load conditions. The speed is low under heavy loads but becomes excessively high under light loads. Series motors are commonly used to drive electric hoists, winches, cranes, and certain types of vehicles (e.g., electric trucks). Also, series motors are used extensively to start internal combustion engines. Compound motors (see Figure 3.121) have one set of field coils in parallel with the armature circuit and another set of field coils in series with the armature circuit. This type of motor is a compromise between shunt and series motors. It develops an increased starting torque over that of the shunt motor and has less variation in speed than the series motor. The speed of a DC motor is variable. It is increased or decreased by a rheostat connected in series with the field or in parallel with the rotor. Interchanging either the rotor or field winding connections reverses direction.

**Brushless DC Motor**

Brushless DC motors can be deployed in any area currently utilizing brushed DC motors. In renewable energy applications, the brushless DC motor can be found in such high-power applications as electric vehicles, hybrid vehicles, and some industrial machinery. The Segway® scooter and the Vectrix™ maxi-scooter use brushless DC motors. They are more commonly found in consumer devices, such as computer hard drives, CD/DVD players, and PC cooling fans. The brushless DC motor is a synchronous motor powered by DC current that has permanent magnets (usually rare-earth-type magnets) mounted on the spinning rotor; instead of a mechanical commutation system based on brushes, it has a commutation system that is electronically controlled by a solid-state controller. The commutator and brush system form a set of electrical switches, each opening and closing in sequence, such that electrical power always flows through the armature coil closest to the stationary stator.

**AC Motors**

Alternating current voltage can easily be transformed from low voltages to high voltages, or *vice versa*, and can be moved over a much greater distance without too much loss in efficiency. Most of the power-generating systems today, therefore, produce alternating current. Thus, it logically follows that a great majority of the electrical motors utilized today are designed to operate on alternating current. AC motors offer other advantages, though, in addition to the wide availability of AC power. In general, AC motors are less expensive than DC motors. Most types of AC motors do not employ brushes and commutators which eliminates many problems of maintenance and wear and eliminates dangerous sparking. AC motors are manufactured in many different sizes, shapes, and ratings for use on an even greater number of jobs. They are designed for use with either polyphase or single-phase power systems. This text cannot possibly cover all aspects of the subject of AC motors; consequently, it deals mainly with the operating principles of the two most common types—the induction motor and the synchronous motor.

**Induction Motors (Polyphase)**

The induction motor is the most common AC motor because of its simple, rugged construction and good operating characteristics. It consists of two parts: the *stator* (stationary part) and the *rotor* (rotating part). The most important type of polyphase induction motor is the three-phase motor.
**Note:** A three-phase system \((3\theta)\) is a combination of three single-phase \((1\theta)\) systems. In a three-phase, balanced system, the power comes from an AC generator that produces three separate but equal voltages, each of which is out of phase with the other voltages by 120°. Although single-phase circuits are widely used in electrical systems, most generation and distribution of AC current are three phase.

The driving torque of both DC and AC motors is derived from the reaction of current-carrying conductors in a magnetic field. In the DC motor, the magnetic field is stationary and the armature, with its current-carrying conductors, rotates. The current is supplied to the armature through a commutator and brushes. In induction motors, the rotor currents are supplied by electromagnet induction. The stator windings, connected to the AC supply, contain two or more out-of-time-phase currents, which produce corresponding magnetomotive force (mmf), establishing a rotating magnetic field across the air gap. This magnetic field rotates continuously at constant speed regardless of the load on the motor. The stator winding corresponds to the armature winding of a DC motor or to the primary winding of a transformer. The rotor is not connected electrically to the power supply. The induction motor derives its name from the fact that mutual induction (or transformer action) takes place between the stator and the rotor under operating conditions. The magnetic revolving field produced by the stator cuts across the rotor conductors, inducing a voltage in the conductors. This induced voltage causes rotor current to flow. Hence, motor torque is developed by the interaction of the rotor current and the magnetic revolving field.

**Synchronous Motors**

Like induction motors, synchronous motors have stator windings that produce a rotating magnetic field, but, unlike the induction motor, the synchronous motor requires a separate source of direct current from the field. It also requires special starting components, including a salient-pole field with starting grid winding. The rotor of the conventional type synchronous motor is essentially the same as that of the salient-pole AC generator. The stator windings of induction and synchronous motors are essentially the same. In operation, the synchronous motor rotor locks into step with the rotating magnetic field and rotates at the same speed. If the rotor is pulled out of step with the rotating stator field, no torque is developed and the motor stops. Because a synchronous motor develops torque only when running at synchronous speed, it is not self-starting and hence needs some device to bring the rotor to synchronous speed. A synchronous motor may be started by a DC motor on a common shaft. After the motor is brought to synchronous speed, AC current is applied to the stator windings. The DC starting motor now acts as a DC generator, which supplies DC field excitation for the rotor. The load then can be coupled to the motor.

**Single-Phase Motors**

Single-phase motors are so called because their field windings are connected directly to a single-phase source. These motors are used extensively in fractional horsepower sizes in commercial and domestic applications. The advantages of using single-phase motors in small sizes are that they are less expensive to manufacture than other types, and they eliminate the need for three-phase AC lines. Single-phase motors are used in fans, refrigerators, portable drills, grinders, and so forth. A single-phase induction motor with only one stator winding and a cage rotor is like a three-phase induction motor with a cage rotor except that the single-phase motor has no magnetic revolving field at start and hence no starting torque. However, if the rotor is brought up to speed by external means, the induced currents in the rotor will cooperate with the stator currents to produce a revolving field, which causes the rotor to continue to run in the direction in which it was started. Several methods are used to provide the single-phase induction motor with starting torque. These methods categorize the motor as split-phase, capacitor, shaded-pole, or repulsion-start. Another class of single-phase motors is the AC series (universal) type.
Principles of Basic Electricity

Split-Phase Motor

The split-phase motor (Figure 3.122), has a stator composed of slotted lamination that contains a starting winding and a running winding. The starting winding has fewer turns and smaller wire than the running winding, hence higher resistance and less reactance. The main winding occupies the lower half of the slots and the starting winding occupies the upper half. When the same voltage is applied to both windings, the current in the main winding lags behind the current in the starting winding. The angle ($\theta$) between the main winding and the starting winding is enough phase difference to provide a weak rotating magnetic field that produces a starting torque. When the motor reaches a predetermined speed, usually 75% of synchronous speed, a centrifugal switch mounted on the motor shaft opens, thereby disconnecting the starting winding. Because of their low starting torque, fractional-horsepower, split-phase motors are used in a wide variety of equipment, such as washers, oil burners, ventilating fans, and woodworking machines. The direction of rotation of the split-phase motor can be reversed by interchanging the starting winding leads.

Note: If two stator windings of unequal impedance are spaced 90° apart but connected in parallel to a single-phase source, the field produced will appear to rotate. This is the principle of phase splitting.

Capacitor Motor

The capacitor motor is a modified form of split-phase motor. Its capacitor is in series with the starting winding (Figure 3.123). The capacitor motor operates with an auxiliary winding and series capacitor permanently connected to the line (Figure 3.123). The capacitance in series may be of one value for starting and another value for running. As the motor approaches synchronous speed, the centrifugal switch disconnects one section of the capacitor. If the starting winding is cut out after the motor has increased in speed, the motor is a capacitor-start motor. If the starting winding and capacitor are designed to be left in the circuit continuously, the motor is a capacitor-run motor. Capacitor motors are used to drive grinders, drill presses, refrigerator compressors, and other loads that require relatively high starting torque. The direction of rotation of the capacitor motor can be reversed by interchanging the starting winding leads.

FIGURE 3.122 Split-phase motor.

FIGURE 3.123 Capacitor motor.
Shaded-Pole Motor
A shaded-pole motor employs a salient-pole stator and a cage rotor. The projecting poles on the stator resemble those of DC machines except that the entire magnetic circuit is laminated and a portion of each pole is split to accommodate a short-circuited coil called a shading coil (Figure 3.124). The coil is usually a single band or strap of copper. The effect of the coil is to produce a small sweeping motion of the field flux from one side of the pole piece to the other as the field pulsates. This slight shift in the magnetic field produces a small starting torque. Thus, shaded-pole motors are self-starting. This motor is generally manufactured in very small sizes, up to 1/20 horsepower, for driving small fans, small appliances, and clocks.

In operation, during that part of the cycle when the main pole flux is increasing, the shading coil is cut by the flux, and the resulting induced emf and current in the shading coil tend to prevent the flux from rising readily through it. Thus, the greater portion of the flux rises in that portion of the pole that is not in the vicinity of the shading coil. When the flux reaches its maximum value, the rate of change of flux is zero, and the voltage and current in the shading coil are also zero. At this time, the flux is distributed more uniformly over the entire pole face. Then, as the main flux decreases toward zero, the induced voltage and current in the shading coil reverse their polarity, and the resulting mmf tends to prevent the flux from collapsing through the iron in the region of the shading coil. The result is that the main flux first rises in the unshaded portion of the pole and later in the shaded portion. This action is equivalent to a sweeping movement of the field across the pole face in the direction of the shaded pole. The rotor conductors are cut by this moving field, and the force exerted on them causes the rotor to turn in the direction of the sweeping field. The shaded-pole method of starting is used in very small motors, up to about 1/25 hp, for driving small fans, small appliances, and clocks.

Repulsion-Start Motor
Like a DC motor, the repulsion-start motor has a form-wound rotor with commutator and brushes. The stator is laminated and contains a distributed single-phase winding. In its simplest form, the stator resembles that of the single-phase motor. In addition, the motor has a centrifugal device that removes the brushes from the commutator and places a short-circuiting ring around the commutator. This action occurs at about 75% of synchronous speed. Thereafter, the motor operates with the characteristics of the single-phase induction motor. This type of motor is made in sizes ranging from 1/2 to 15 hp and is used in applications requiring a high starting torque.

AC Series Motor
The AC series motor operates on either AC or DC circuits. When an ordinary DC series motor is connected to an AC supply, the current drawn by the motor is low due to the high series-field impedance. The result is low running torque. To reduce the field reactance to a minimum, AC series motors are built with as few turns as possible. Armature reaction is overcome by using compensating windings (see Figure 3.125) in the pole pieces. As in DC series motors, the speed in AC series
motors increases to a high value with a decrease in load. The torque is high for high armature currents, so the motor has a good starting torque. AC series motors operate more efficiently at low frequencies. Fractional horsepower AC series motors are called universal motors. They do not have compensating windings. They are used extensively to operate fans and portable tools, such as drills, grinders, and saws.

**TRANSFORMERS**

A transformer is an electric control device (with no moving parts) that raises or lowers voltage or current in an electric distribution system. The basic transformer consists of two coils electrically insulated from each other and wound on a common core (Figure 3.126). Magnetic coupling is used to transfer electric energy from one coil to another. The coil that receives energy from AC sources is the primary coil. The coil that delivers energy to AC loads is the secondary coil. The core of transformers used at low frequencies is generally made of magnetic material, usually laminated sheet steel. Cores of transformers used at higher frequencies are made of powdered iron and ceramics, or nonmagnetic materials. Some coils are simply wound on nonmagnetic hollow forms such as cardboard or plastic so the core material is actually air.

In operation, an alternating current will flow when an AC voltage is applied to the primary coil of a transformer. This current produces a field of force that changes as the current changes. The changing magnetic field is carried by the magnetic core to the secondary coil, where it cuts across the turns of that coil. In this way, an AC voltage in one coil is transferred to another coil, even though there is no electrical connection between them. The number of lines of force available in the primary is determined by the primary voltage and the number of turns on the primary, with each turn producing a given number of lines. If there are many turns on the secondary, each line of force will cut many turns of wire and induce a high voltage. If the secondary contains only a few turns, there will be few cuttings and low induced voltage. The secondary voltage, then, depends on the number of secondary turns as compared with the number of primary turns. If the secondary has twice as many turns as the primary, the secondary voltage will be twice as large as the primary voltage. If the secondary has half as many turns as the primary, the secondary voltage will be one-half as large as the primary voltage. A voltage ratio of 1:4 means that for each volt on the primary there are 4 volts on the secondary. This is called a *step-up* transformer. A step-up transformer receives a low voltage on the primary coil and delivers a high voltage from the secondary coil. In contrast, a voltage ratio of 4:1 means that for 4 volts on the primary coil there is only 1 volt on the secondary. This is called a *step-down transformer*. A step-down transformer receives a high voltage on the primary coil and delivers a low voltage from the secondary.

*Note:* The voltage on the coils of a transformer is directly proportional to the number of turns on the coils.

![Basic transformer diagram](image-url)
POWER DISTRIBUTION SYSTEM PROTECTION

Interruptions are very rare in a power distribution system that has been properly designed. Still, protective devices are necessary because of the load diversity. Most installations are quite complex. In addition, externally caused variations might overload them or endanger personnel. Figure 3.127 shows the general relationship between protective devices and different components of a complete system. Each part of the circuit has its own protective device or devices that protect not only the load but also the wiring and control devices themselves. These disconnect and protective devices are described in the following sections.

FUSES

The passage of an electric current produces heat. The larger the current, the more heat is produced. To prevent large currents from accidentally flowing through expensive apparatus and burning it up, a fuse is placed directly into the circuit, as in Figure 3.127, so as to form a part of the circuit through which all the current must flow. The fuse will permit currents smaller than the fuse value to flow but will melt and therefore break the circuit if a larger, dangerous current ever appears; for example, a dangerously large current will flow when a short circuit occurs. A short circuit is usually caused by an accidental connection between two points in a circuit which offer very little resistance to the flow of electrons. If the resistance is small, there will be nothing to stop the flow of the current, and the current will increase enormously. The resulting heat generated might cause a fire. If the circuit is protected by a fuse, the heat caused by the short-circuit current will melt the fuse wire, thus breaking the circuit and reducing the current to zero.

Note: A fuse is a thin strip of easily melted material. It protects a circuit from large currents by melting quickly, thereby breaking the circuit.

FIGURE 3.127 Motor power distribution system.
Fuses are rated by the number of amps of current that can flow through them before they melt and break the circuit; thus, a fuse can be, for example, 10, 15, 20, or 30 amps. We must be sure that any fuse inserted in a circuit is rated low enough to melt, or “blow,” before the apparatus is damaged. In a plant building wired to carry a current of 10 A, it is best to use a fuse no larger than 10 A so a current larger than 10 A could never flow. Some equipment, such as an electric motor, requires more current during starting than for normal running; fast-time or medium-time fuses that provide running protection might blow during the initial period when high starting current is required. Delayed-action fuses are used to handle these situations.

CIRCUIT BREAKERS

Circuit breakers are protective devices that open automatically at a preset ampere rating to interrupt an overload or short circuit. Unlike fuses, they do not require replacement when they are activated. They are simply reset to restore power after the overload has been cleared. Circuit breakers are made in both plug-in and bolt-on designs. Plug-in breakers are used in load centers. Bolt-on breakers are used in panelboards and exclusively for high interrupting current applications. Circuit breakers are rated according to current and voltage, as well as short-circuit-interrupting current. A single handle opens or closes contacts between two or more conductors. Breakers are single pole, but single-pole units can be ganged to form double- or triple-pole devices opened with a single handle.

Note: A circuit breaker is designed to break the circuit and stop the current flow when the current exceeds a predetermined value.

Several types of circuit breakers are commonly used. They may be thermal or magnetic, or a combination of the two. Thermal breakers are tripped when the temperature rises because of heat created by the overcurrent condition. Bimetallic strips provide the time delay for overload protection. Magnetic breakers operate on the principle that a sudden current rise will create enough magnetic field to turn an armature, tripping the breaker and opening the circuit. Magnetic breakers provide the instantaneous action needed for short-circuit protection. Magnetic breakers are also used where ambient temperatures might adversely affect the action of a thermal breaker. Thermal–magnetic breakers combine features of both types. An important feature of the circuit breaker is its arc chutes, which allow the breaker to extinguish very hot arcs harmlessly. Some circuit breakers must be reset by hand, while others reset themselves automatically. If the overload condition still exists when the circuit breaker is reset, the circuit breaker will trip again to prevent damage to the circuit.

CONTROL DEVICES

Control devices are electrical accessories (switches and relays) that govern the power delivered to any electrical load. In its simplest form, the control applies voltage to, or removes it from, a single load. In more complex control systems, the initial switch may set into action other control devices (relays) that govern motor speeds, servomechanisms, temperatures, and numerous other pieces of equipment. In fact, all electrical systems and equipment are controlled in some manner by one or more controls. A controller is a device or group of devices that serves to govern, in some predetermined manner, the device to which it is connected. In large electrical systems, it is necessary to have a variety of controls for operation of the equipment. These controls range from simple push buttons to heavy-duty contactors that are designed to control the operation of large motors. The push button is manually operated; a contactor is electrically operated.
ELECTRICAL DRAWINGS

Working drawings for the fabrication and troubleshooting of electrical machinery, switching devices, and chassis for electronic equipment, cabinets, housings, and other mechanical elements associated with electrical equipment are based on the same principles as given earlier. Those qualified to operate, maintain, and repair electrical equipment must understand electrical systems. The electrician or student of electricity must be able to read electrical drawings to understand the system and to determine what is wrong when electrical equipment fails to run properly. This section introduces electrical drawings, and the functions of important electrical components and how they are shown on drawings are explained.

ELECTRICAL SYMBOLS

Figure 3.128 shows some of the most common symbols used on electrical drawings. It is not necessary to memorize these symbols, but the maintenance operator should be familiar with them as an aid to reading electrical drawings.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Symbol" /></td>
<td>Ceiling fixture</td>
</tr>
<tr>
<td><img src="image2" alt="Symbol" /></td>
<td>Power transformer</td>
</tr>
<tr>
<td><img src="image3" alt="Symbol" /></td>
<td>Wall fixture</td>
</tr>
<tr>
<td><img src="image4" alt="Symbol" /></td>
<td>Branch circuit concealed in ceiling or wall</td>
</tr>
<tr>
<td><img src="image5" alt="Symbol" /></td>
<td>Duplex outlet (grounded)</td>
</tr>
<tr>
<td><img src="image6" alt="Symbol" /></td>
<td>Branch circuit concealed in floor</td>
</tr>
<tr>
<td><img src="image7" alt="Symbol" /></td>
<td>Single receptacle floor outlet (ungrounded)</td>
</tr>
<tr>
<td><img src="image8" alt="Symbol" /></td>
<td>Branch circuit exposed</td>
</tr>
<tr>
<td><img src="image9" alt="Symbol" /></td>
<td>Street light</td>
</tr>
<tr>
<td><img src="image10" alt="Symbol" /></td>
<td>Feeders (note heavy line)</td>
</tr>
<tr>
<td><img src="image11" alt="Symbol" /></td>
<td>Motor</td>
</tr>
<tr>
<td><img src="image12" alt="Symbol" /></td>
<td>Number of wires in conduit (3)</td>
</tr>
<tr>
<td><img src="image13" alt="Symbol" /></td>
<td>Single-pole switch</td>
</tr>
<tr>
<td><img src="image14" alt="Symbol" /></td>
<td>Fuse</td>
</tr>
<tr>
<td><img src="image15" alt="Symbol" /></td>
<td>Three-way switch</td>
</tr>
<tr>
<td><img src="image16" alt="Symbol" /></td>
<td>Transformer</td>
</tr>
<tr>
<td><img src="image17" alt="Symbol" /></td>
<td>Circuit breaker</td>
</tr>
<tr>
<td><img src="image18" alt="Symbol" /></td>
<td>Ground</td>
</tr>
<tr>
<td><img src="image19" alt="Symbol" /></td>
<td>Panel board and cabinet</td>
</tr>
<tr>
<td><img src="image20" alt="Symbol" /></td>
<td>Normally open contacts</td>
</tr>
<tr>
<td><img src="image21" alt="Symbol" /></td>
<td>Power panel</td>
</tr>
<tr>
<td><img src="image22" alt="Symbol" /></td>
<td>Normally closed contacts</td>
</tr>
<tr>
<td><img src="image23" alt="Symbol" /></td>
<td>Motor controller</td>
</tr>
</tbody>
</table>

FIGURE 3.128 Common electrical symbols.
Types of Electrical Drawings

The two kinds of electrical drawings used for troubleshooting operations are *architectural drawings* and *circuit drawings*. An architectural drawing shows the physical locations of the electric lines in a plant building or between buildings. A circuit drawing shows the electrical loads served by each circuit.

*Note:* A circuit drawing does not indicate the physical location of any load or circuit.

Architectural Drawings

Figure 3.129 shows three types of architectural drawings. The *plot plan* shows the electric distribution to all the plant buildings. The *floor plan* shows where branch circuits are located in one building or pumping station, where equipment is located, and where outside and inside tie-ins to water, heat, and electric power are located. The *riser diagram* shows how the wiring goes to each floor of the building.

Circuit Drawings

A circuit drawing shows how a single circuit distributes electricity to various loads (e.g., pump motors, grinders, bar screens, mixers). Unlike an architectural drawing, a circuit drawing does not show the location of these loads. Figure 3.130 depicts a typical single-line circuit drawing and shows the power distribution to 11 loads. The number in each circle indicates the power rating of the loads in horsepower.

*Note:* Electrical loads in all plants can be divided into two categories: critical and noncritical. Critical loads are essential to the operation of the plant and cannot be turned off (e.g., critical unit processes). Noncritical loads include pieces of equipment that would not disrupt the operation of the plant or pumping station or compromise safety if they were turned off for a short period of time (e.g., air conditioners, fan systems, electric water heaters, certain lighting systems).

The numbers in the rectangles show the current ratings of circuit breakers. The upper number is the current in amps the circuit breaker will allow as a momentary surge.

*Note:* Circuit breakers are typically equipped with surge protection for three-phase motors and other devices. When a three-phase motor is started, current demand is six to ten times normal value. After start, current flow decreases to its normal rated value. Surge protection is also provided to allow slight increases in current flow when the load varies or increases slightly. The lower number is the maximum current the circuit breaker will allow to flow continuously. Most circuit breakers are also equipped with an instantaneous trip value for protection against short circuits.
A ladder drawing is a type of schematic diagram that shows a control circuit. The parts of the control circuit lie on horizontal lines, like the rungs of a ladder. Figure 3.131 is an example of a ladder diagram. The purpose of a ladder drawing, such as the one shown in Figure 3.131, is to cut maintenance and troubleshooting time. This is accomplished when the designer follows certain guidelines when making electrical drawings and layouts. Let’s take a closer look at the ladder drawing for a control circuit shown in Figure 3.131. Note the numbering of elementary circuit lines. Normally, closed contacts are indicated by a bar under the line number. Moreover, note that the line numbers are enclosed in a geometric figure to prevent mistaking the line numbers for circuit numbers. All contacts and the conductors connected to them are properly numbered. Typically, numbering is carried throughout the entire electrical system. This may involve going through one or more terminal blocks. The incoming and outgoing conductors as well as the terminal blocks carry the proper electrical circuit numbers. When possible, connections to all electrical components are taken back to one common checkpoint. All electrical elements on a machine should be correctly identified with the same markings as shown on the ladder drawing in Figure 3.131; for example, if a given solenoid is marked “Solenoid A2” on the drawing, the actual solenoid on the machine should carry the marking “Solenoid A2.”

Note: The size of electrical drawings is important. This can be understood first in the problem of storing drawings. If every size and shape were allowed, the task of systematic and protective filing of drawings could be tremendous. Pages that are 8-1/2 × 11 or 9 × 12 inches and multiples thereof are generally accepted. The drawing size can also be a problem for the troubleshooter or maintenance operator. If the drawing is too large, it is unwieldy to handle at the machine. If it is too small, it is difficult to read the schematic.
DISCUSSION AND REVIEW QUESTIONS

1. Explain the difference between a series and a parallel circuit.
2. What is the sum of all voltages in a series circuit equal to?
3. For any total voltage rise in a circuit, there must be an equal total _______.

Refer to the figure to the right for questions 4 through 8.

4. Is the direction of current flow clockwise or counterclockwise?
5. $I_T =$ ?
6. $E$ dropped across $R_1 =$ ?
7. What is the power absorbed by $R_2$?
8. $P_T =$ ?
9. The equivalent resistance \((R_f)\) of parallel branches is ________ than the smallest branch resistance because all of the branches must take ________ current from the source than any one branch.

10. A short circuit has ________ resistance, resulting in ________ current.

11. What is the total resistance of four 30-ohm resistors connected in parallel?

12. There is only ________ voltage across all components in parallel.

13. The sum of the ________ values of power dissipated in parallel resistances equals the ________ power produced by the source.

Refer to the figure to the right for questions 14 through 16.

14. \(R_f = ?\)
15. \(I_f = ?\)
16. \(P_f = ?\)

Refer to the figure to the right for questions 17 through 20.

17. What is the total resistance \((R_T)\) of the circuit?
18. What is the total current \((I_T)\) in the circuit?
19. What is the voltage across \(R_3\)?
20. What is the total power consumed in the circuit?

Answers

1. A series circuit has only one path for current flow, whereas a parallel circuit has more than one path.
2. Source voltage
3. Voltage drop
4. Counterclockwise
5. 2 amps
6. 12 volts
7. 16 volts
8. 80 watts
9. Less, more
10. Zero, excessive
11. 120 ohms
12. One
13. Individual, total
14. \(R_f = 10\) ohms
15. \(I_f = 2\) amps
16. \(P_f = 40\) watts
17. 12 ohms
18. 1 amp (rounded)
19. 1.5 volts
20. 12 watts (rounded)
REFERENCES AND RECOMMENDED READING


