3

Electrical Fundamentals

LEARNING OBJECTIVES

Upon completion and review of this chapter, you should be able to:

- Explain the terms conductor, insulator, and semiconductor, and differentiate between their functions.
- Identify and explain the basic electrical concepts of resistance, voltage, current, voltage drop, and conductance.
- Define the two theories of current flow (conventional and electron) and explain the difference between DC and AC current.
- Explain the cause-and-effect relationship in Ohm's law between voltage, current, resistance, and voltage drop.
- Define electrical power and its Ohm's law relationship.
- Define capacitance and describe the function of a capacitor in an automotive electrical circuit.

KEY TERMS

Ampere
Capacitance
Capacitor
Circuit
Conductors
Conventional Theory
Current
Ground
Insulators
Ohm
Ohm's Law
Resistance
Resistors
Semiconductors
Voltage
Voltage Drop
Watt

INTRODUCTION

This chapter reviews all of the basic electrical principles required to understand electronics and the automotive electrical/electronic systems in the later chapters. An automotive technician must have a thorough grasp of the basis of electricity and electronics. Electronics has become the single most important subject area and the days when many technicians could avoid working on an electrical circuit through an entire career are long past. This course of electrical study will cover conductors and insulators, characteristics of electricity, the complete electrical circuit, Ohm's Law, and finally capacitance and capacitors.

CONDUCTORS AND INSULATORS

- **Conductors.** Conductors are materials with fewer than four electrons in their atom's outer orbit that allow easy movement of electrons through them. Copper is an excellent conductor because it has only one electron in its outer orbit. This orbit is far enough away from the nucleus of the copper atom that the pull or force holding the outermost electron in orbit is relatively weak. See Figure 3-1. Copper is the conductor most used in vehicles because the price of copper is reasonable compared to the relative cost of other conductors with similar properties.
- **Insulators.** The protons and neutrons in the nucleus are held together very tightly. Normally the nucleus does not change. But some of the outer electrons are held very loosely, and they can move from one atom to another. An atom that loses electrons has more positive charges (protons) than negative charges (electrons); it is positively charged. An atom that gains electrons has more negative than positive particles; is negatively charged. A charged atom is called an ion. Some materials hold their electrons very tightly; therefore, electrons do not move through them very well. These materials are called insulators. **Insulators** are materials with more than four electrons in their atom's outer orbit. Because they have more than four electrons in their outer orbit, it becomes easier for these materials to acquire (gain) electrons than to release electrons. Examples of insulators include plastics, wood, glass, rubber, ceramics (spark plugs), and varnish for covering (insulating) copper wires in alternators and starters.
- **Semiconductors.** Materials with exactly four electrons in their outer orbit are neither conductors nor insulators and are called *semiconductor* materials.

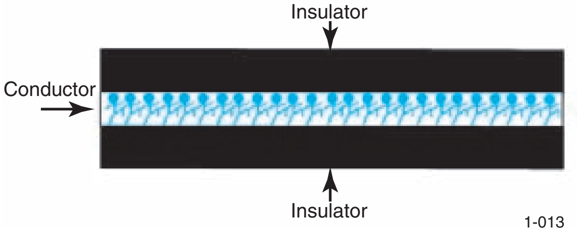

Figure 3-1. Conductors and insulators.

Wires

A wire in a wiring harness is made up of a conductor and an insulator. The metal core of the wire, typically made of copper, is the conductor. The outer jacket (made of plastic or other material) coating the core is the insulator. Under normal circumstances, electrons move a few inches per second. Yet when an electrical potential is applied to one end of a wire, the effect is felt almost immediately at the other end of that wire. This is so because the electrons in the conductor affect one another, much like billiard balls in a line.

CHARACTERISTICS OF ELECTRICITY

Voltage

We have said that a number of electrons gathered in one place effect an electrical charge. We call this charge an electrical potential or "voltage." **Voltage** is measured in volts (V). Since it is used to "move electrons," an externally applied electrical potential is sometimes called an "electromotive force" or EMF. Potential, voltage, and EMF all mean the same thing. You can think of voltage as the electrical "pressure" (Figure 3-2) that drives electron flow or current, similar to water pressure contained in a tank. When voltage is applied to a disconnected length of wire (open circuit), there is no sustained movement of electrons. No current flows in the wire, because current flows only when there is a difference in potential (Figure 3-3). Check the voltage with a meter, and you will find that it is the same at both ends of the wire. (See the section on "DMM Operating Principles" in Chapter 3 of the *Shop Manual*.)

If voltage is applied to one end of a conductor, a different potential must be connected to the other end of that conductor for current to flow. In a typical automotive circuit, the positive terminal of the vehicle battery is the potential at one

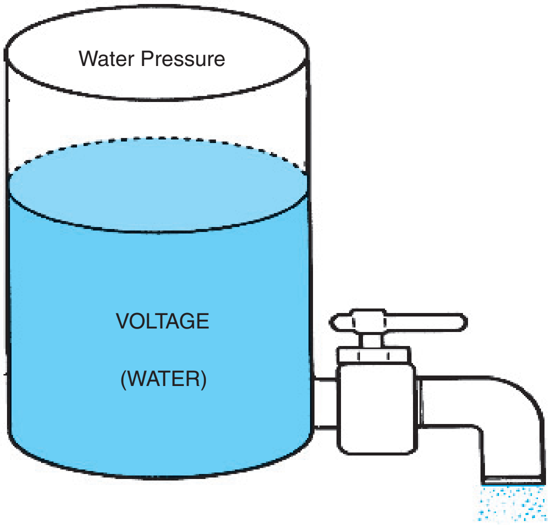

Figure 3-2. Voltage and water pressure.

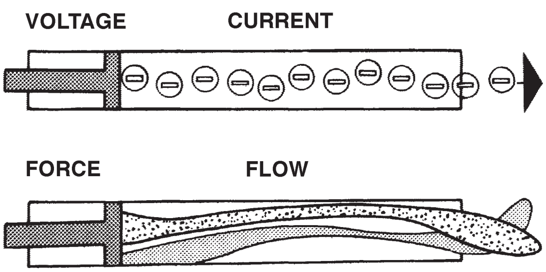

Figure 3-3. Voltage pushes current flow like force pushes water flow.

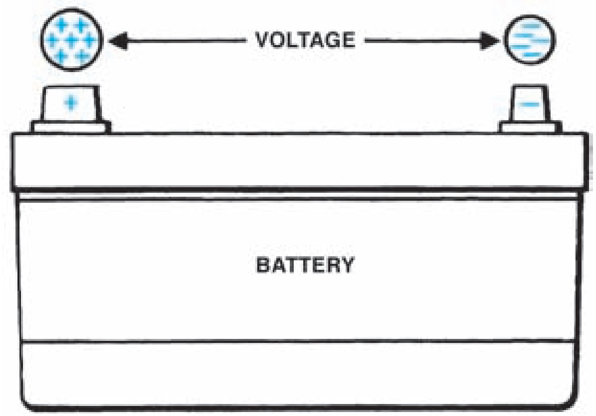

Figure 3-4. Voltage is a potential difference in electromotive force.

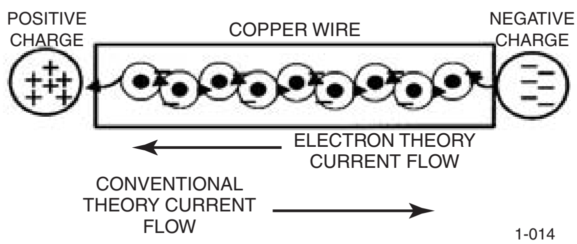

Figure 3-5. Current flow.

end of a conductor, and the negative terminal is the potential at the other end (Figure 3-4).

Current

The movement of electrons in a circuit is the flow of electricity, or current flow (Figure 3-5), which is measured in **amperes** (A). This unit expresses how many electrons move through a circuit in one second. A current flow of 6.25×10^{18} electrons per second is equal to one ampere. A coulomb is 6.281×10^{18} electrons per second. 1 coulomb/sec=1 ampere.

Current Flow

Current flow will occur only if there is a path and a difference in electrical potential; this difference is known as *charge differential* and is measured in voltage. Charge differential exists when the electrical source has a deficit of electrons and therefore is positively charged. Electrons are negatively charged and unlike charges attract, so electrons flow toward the positive source.

See the section on "DMM Operating Principles" in Chapter 3 of the *Shop Manual.*

Conventional Current Flow and Electron Theory

In automotive service literature, current flow is usually shown as flowing from the positive terminal to the negative terminal. This way of describing current flow is called the **conventional theory.** Another way of describing current flow is called the *electron theory,* and it states that current flows from the negative terminal to the positive terminal. The conventional theory and electron theory are two different ways of describing the same current flow.

Essentially, both theories are correct. The electron theory follows the logic that electrons move from an area of many electrons (negative charge) to one of few electrons (positive charge). However, in describing the behavior of semiconductors, we often describe current as moving from positive to negative. The important thing to know is which theory is being used by the service literature you

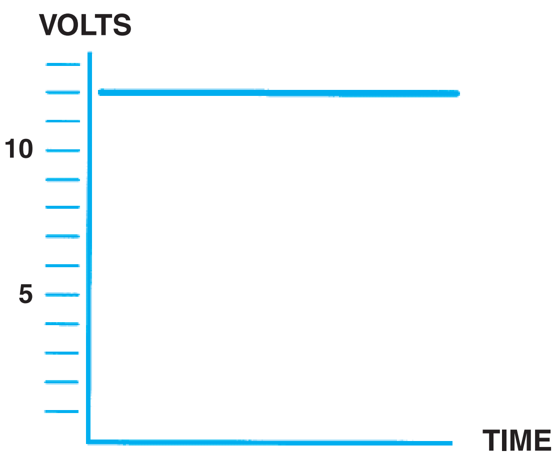

Figure 3-6. Direct current.

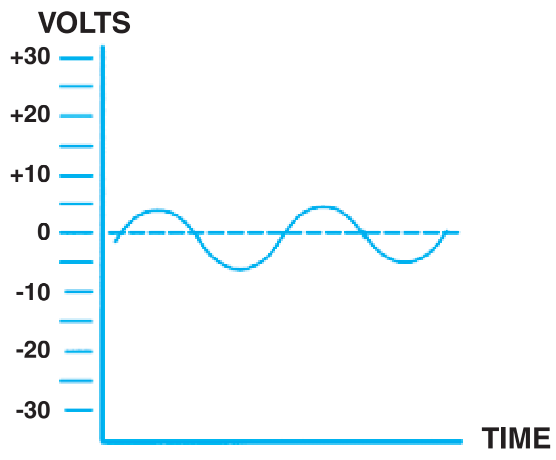

Figure 3-7. Alternating current.

happen to be using; most schematics use conventional current flow theory.

A conductor, such as a piece of copper wire, contains billions of neutral atoms whose electrons move randomly from atom to atom, vibrating at high frequencies. When an external power source such as a battery is connected to the conductor, a deficit of electrons occurs at one end of the conductor and an excess of electrons occurs at the other end, the negative terminal will have the effect of repelling free electrons from the conductor's atoms while the positive terminal will attract free electrons. This results in a flow of electrons through the conductor from the negative charge to the positive charge. The rate of flow will depend on the charge differential (or potential difference/voltage). The charge differential or voltage is a measure of electrical pressure. The role of a battery, for instance, is to act as a sort of electron pump. In a closed electrical circuit, electrons move through a conductor, producing a displacement effect close to the speed of light.

The physical dimensions of a conductor are also a factor. The larger the cross-sectional area (measured by wire gauge size) the more atoms there are over a given sectional area, therefore the more free electrons; therefore, as wire size increases, so does the ability to flow more electrical current through the wire.

Direct Current

When a steady-state electrical potential is applied to a circuit, the resulting current flows in one direction. We call that *direct current* or DC (Figure 3-6). Batteries produce a steady-state, or DC, potential. The advantage of using DC is it can be stored electro-chemically in a battery.

Alternating Current

The electrical potential created by a generator is not steady state, it fluctuates between positive and negative. When such a potential is applied to a circuit, it causes a current that first flows in one direction, then reverses itself and flows in the other direction. In residential electrical systems, this direction reversal happens 60 times a second. This type of current is called *alternating current* or AC (Figure 3-7). Rotating a coil in a magnetic field usually produces alternating current. Alternating current describes a flow of electrical charge that cyclically reverses, due to a reversal in polarity at the voltage source.

Automotive generators produce AC potential. Alternating current is easier to produce in a generator, due to the laws of magnetism, but it is extremely difficult to store. Generators incorporate special circuits that convert the AC to DC before it is used in the vehicle's electrical systems. (Alternating current is also better suited than DC for transmission through power lines.) The frequency at which the current alternates is measured in cycles. A *cycle* is one complete reversal of current from zero though positive to negative and back to the zero point. Frequency is usually measured in cycles per second or hertz.

Resistance

More vehicles can travel on a four-lane superhighway in a given amount of time than on a two-lane country road. A large-diameter pipe can flow more fluid than a small-diameter pipe. A similar characteristic applies to electricity. A large wire can carry

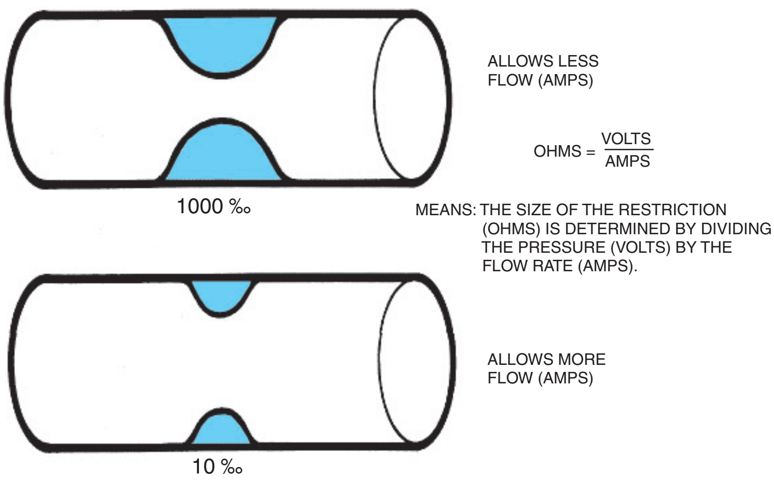

Figure 3-8. Resistance.

more current than a small wire. The reason the large wire carries more current is that it offers less *resistance* to current flow. All materials contain some resistance. For information about measuring resistance, see the section on "DMM Operating Principles" in Chapter 3 of the *Shop Manual.*

Resistance opposes the movement of electrons, or current flow. All electrical devices and wires have some resistance. Materials with very low resistance are called conductors; materials with very high resistance are called insulators. As resistance works to oppose current flow, it changes electrical energy into some other form of energy, such as heat, light, or motion.

Resistance factors (Figure 3-8) determine the resistance of a conductor by a combination of the following:

- **Atomic structure (how many free electrons):** The more free electrons a material has, the less resistance it offers to current flow. Example: copper versus aluminum wire.
- **Length:** The longer a conductor, the higher the resistance.
- **Width (cross-sectional area):** The larger the cross-sectional area of a conductor, the lower the resistance. For example: 12-gauge versus 20-gauge wire.
- **Temperature:** For most materials, the higher the temperature, the higher the resistance. There are a few materials whose resistance goes down as temperature goes up.

The condition of a conductor can also have a large affect on its resistance (Figure 3-9). Broken strands of wire, corrosion, and loose connections can cause the resistance of a conductor to increase.

Wanted and Unwanted Resistance

Resistance is useful in electrical circuits. We use it to produce heat, make light, limit current, and regulate voltage. However, resistance in the wrong place can cause circuit trouble. Sometimes you can predict that high (unwanted) resistance is present by just looking at an electrical connection or component. Expect resistance to be high if the material is discolored or if a connection appears loose. Resistance can also be affected by the physical condition of a conductor. For example, battery terminals are made of lead, ordinarily an excellent conductor. However, when a battery terminal is covered with corrosion, resistance is substantially increased. This makes the terminal a less effective conductor.

Ohms

The basic unit of measurement for resistance is the **ohm.** The symbol for ohms is the Greek letter omega (Ω). If the resistance of a material is high (close to infinite ohms), it is an insulator. If the resistance of a material is low (close to zero ohms), it is a conductor.

Resistors

Resistors are devices used to provide specific values of resistance in electrical circuits. A common type is the carbon-composition resistor, which is available in many specific resistance values. They

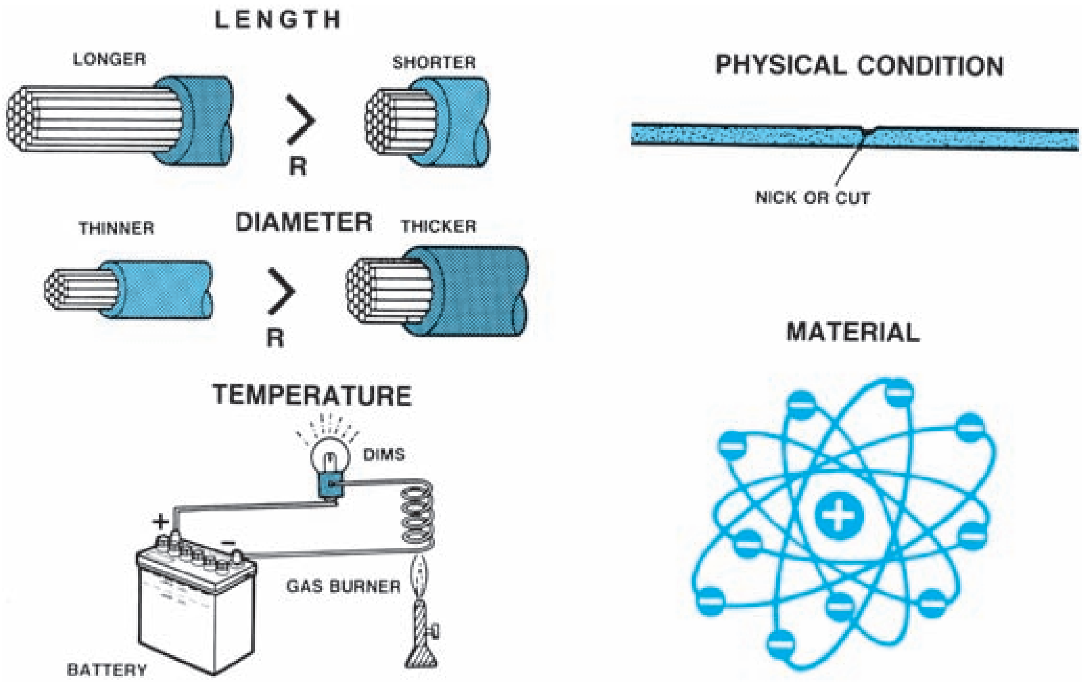

Figure 3-9. Resistance factors.

are generally marked with colored bands that make up a code expressing each resistor's value. The size of the resistor determines how much heat the device can dissipate, and therefore how much power it can handle.

COMPLETE ELECTRICAL CIRCUIT

For current to flow continuously from a voltage supply, such as a battery, there must be a complete circuit, as shown in Figure 3-10. A **circuit** is a path for electric current. Current flows from one end of a circuit to the other when the ends are connected to opposite charges (positive and negative) We usually call these ends *power* and *ground.* Current flows only in a closed or completed circuit. If there is a break somewhere in the circuit, current cannot flow. We usually call a break in a circuit an open. Most protection circuits contain a source of power, conductive material (wires) load, controls, and a ground. These elements are connected to each other with conductors, such as a copper wire. The primary power source in a car or truck is the battery. As long as there is no external connection between the positive and negative sides, there is no flow of electricity. Once an external connection is made between them, the free electrons have a path to flow on, and the entire electrical system is connected between the positive and negative sides.

Power (Voltage Source)

The 12-volt battery is the most common voltage source in automotive circuits. The battery is an electrochemical device; In other words, it uses chemicals to create electricity. It has a positive side and a negative side, separated by plates. Typically, the positive (+) part of the battery is made up of lead peroxide. The negative (−) part of the battery is made up of sponge lead. A pasty chemical called electrolyte is used as a conductor between the positive and negative parts. Electrolyte is made from water and sulfuric acid. So, within the battery there exists an electrical potential. The operation of the alternator continuously replenishes the electrical potential of the battery to prevent it from "draining."

Load

The load is any device in a circuit that uses electricity to do its job. For example, the loads in a circuit could include a motor, a solenoid, a relay, and

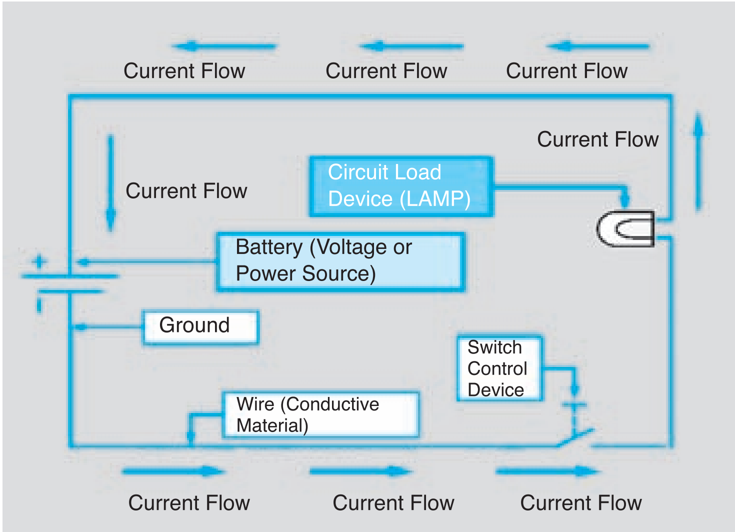

Figure 3-10. The complete electrical circuit.

a light bulb. All loads offer some resistance to current flow.

Controls

Control devices perform many different jobs, such as turning lights on and off, dimming lights, and controlling the speed of motors. Control devices work by completely stopping current flow or by varying the rate of flow. Controls used to stop current flow include switches, relays, and transistors. Controls used to vary the rate include rheostats, transistors, and other solid-state devices. Control devices can be on the positive or negative side of the circuit.

Ground

In a closed circuit, electrons flow from one side of the voltage source, through the circuit, and then return to the other side of the source. We usually call the return side of the source the **ground.** A circuit may be connected to ground with a wire or through the case of a component. When a component is case-grounded, current flows through its metal case to ground. In an automobile, one battery terminal is connected to the vehicle chassis with a conductor. As a result, the chassis is at the same electrical potential as the battery terminal. It can act as the ground for circuits throughout the vehicle. If the chassis didn't act as a ground, the return sides of vehicle circuits would have to reach all the way back to the ground terminal of the battery.

Conductive Material

Conductive materials, such as copper wire with an insulator, readily permit this flow of electrons from atom to atom and connect the elements of the circuit: power source, load, controls, and ground.

Negative or Positive Ground

Circuits can use a negative or a positive ground. Most vehicles today use a negative ground system. In this system, the negative battery terminal is connected to the chassis.

Voltage Drop

In an electrical circuit, resistance behaves somewhat like an orifice restriction in a refrigerant circuit. In a refrigerant circuit, pressure upstream of the orifice is higher than that downstream of the orifice. Similarly, voltage is higher before the resistance than it is after the resistance. The voltage change across the resistance is called a **voltage drop** (Figure 3-11).

Voltage drop is the voltage lost or consumed as current moves through resistance. Voltage is highest where the conductor connects to the voltage source, but decreases slightly as it moves through the conductor. If you measure voltage before it

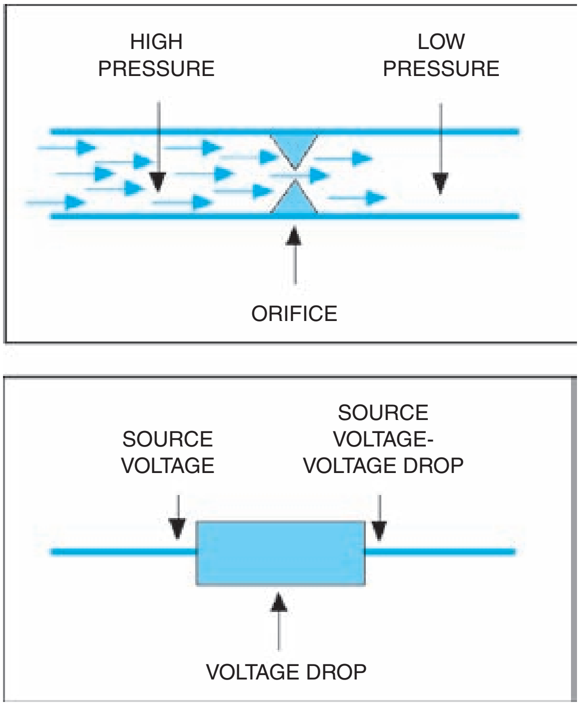

Figure 3-11. Voltage drop. (GM Service and Parts Operations)

goes into a conductor and measure it again on the other side of a conductor, you will find that the voltage has decreased. This is voltage drop. When you connect several conductors to each other, the voltage will drop each time the current passes through another conductor.

Voltage drop is the result of a total applied voltage that is not equal at both ends of a single load circuit. Whenever the voltage applied to a device (a load) is less than the source voltage there is a resistance between the two components. The resistance in a circuit opposes the electron flow, with a resulting voltage loss applied to the load. This loss is voltage drop. Kirchhoff's Voltage Law states that the sum of the voltage drops in any circuit will equal the source or applied voltage. For more information about measuring voltage, See the section on "DMM Operating Principles" in Chapter 3 of the *Shop Manual*.

OHM'S LAW

The German physicist, George Simon Ohm, established that electric pressure in volts, electrical resistance in ohms, and the amount of current in amperes flowing through any circuit are all related. **Ohm's Law** states that voltage equals current times resistance, and is expressed as E=IR. Ohm's Law is based on the fact that it takes 1 volt of electrical potential to push 1 ampere of current through 1 ohm of resistance, as demonstrated in Figure 3-12.

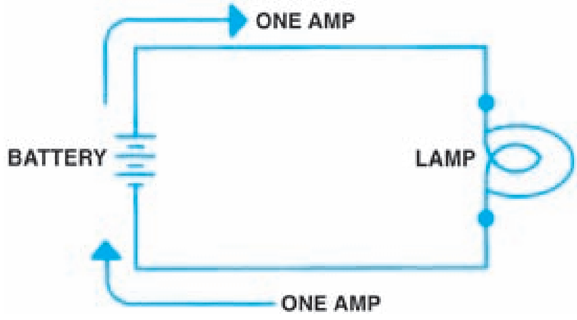

Figure 3-12. If this battery provides 1 volt of pressure, the resistance of the lamp must be 1 ohm.

Ohm's Law Units

Electricity is difficult to understand because it cannot be seen or felt. Illustrating electrical units water makes the units of electricity easier to understand.

Voltage

Voltage is the unit of electrical pressure. This is the same as water pressure is measured in pounds per square inch or psi. Just as water pressure is available at a faucet, there can be water pressure or voltage without water or current flow. In the Ohm's Law equation, voltage is represented by the letter *E* for *electromotive force*. One ampere is equal to 6.28×10^{18} electrons (1 columb) passing a given point in an electrical circuit in one second.

Current

Electrical current is measured in amperes. An ampere is a unit of the amount of current flow. This unit would be the same as gallons per minute (gpm) of water flow if compared to water from a faucet. In the Ohm's Law equation, current is represented by the letter *I* for *intensity* or amperage. The equation is

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

Resistance

The unit of electrical resistance is the ohm, named by George Ohm. An ohm is the unit of electrical resistance. Resistance in the flow of water is usually associated with the size of the water pipe. A small water pipe can only allow so much water, whereas a larger pipe or hose can allow more water to flow. A large fire hose, for example, allows more water in gallons per minute than a garden hose. Resistance in an electrical circuit creates heat because the increased number of collisions that occur between the free electrons and the vibrating atoms. When these collisions create heat, the resistance continues to increase. In the Ohm's Law equation, resistance is represented by the letter *R*, for resistance. The equation is:

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

In a complete electrical circuit, the resistance in ohms is higher if the voltage (E) is higher and/or if the current in amperes (I) is lower. A **closed circuit** is a circuit that is complete and current is flowing. An **open circuit** has a break somewhere and no current flows.

Here is an easy way to remember how to solve for any part of the equation: To use the "solving circle" in Figure 3-13, cover the letter you don't know. The remaining letters give the equation for determining the unknown quantity.

In the circuit in Figure 3-14, the source voltage is unknown. The resistance of the load in the circuit is 2 ohms. The current flow through the circuit is 6 amps. Since the volts are missing, the correct equation to solve for voltage is volts = amps × ohms. If the known units are inserted into the equation, the current can be calculated. Performing the multiplication in the equation yeilds in 12 volts. volts = 6 × 2 as the source voltage in the circuit.

In the circuit in Figure 3-15, the current is unknown. The resistance of the load in the circuit is 2 ohms. The source voltage is 12 volts. Since the amps are missing, the correct equation to solve for current is as follows:

$$Amps\ (I) = \frac{Volts}{Ohms} = \frac{E}{R} = \frac{12}{2} = 6\ amps$$

If the known units are inserted into the equation, the current can be calculated. Performing the division in the equation yields in 6 amps as the current flow in the circuit.

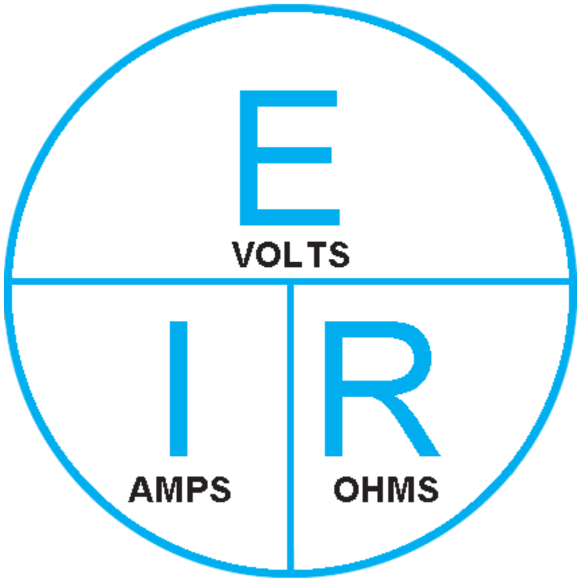

Figure 3-13. Ohm's Law solving circle.

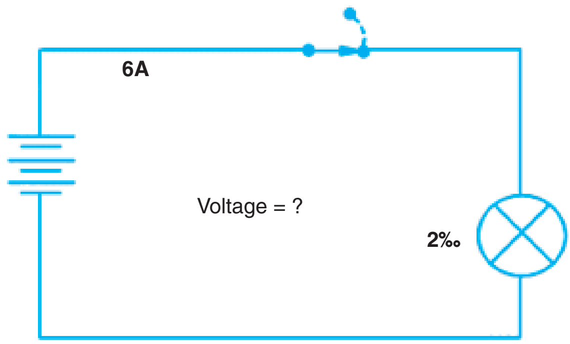

Figure 3-14. Solving for voltage.

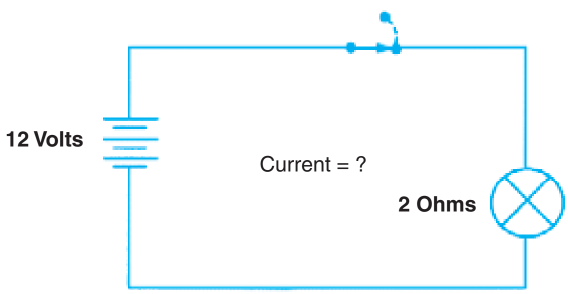

Figure 3-15. Solving for current.

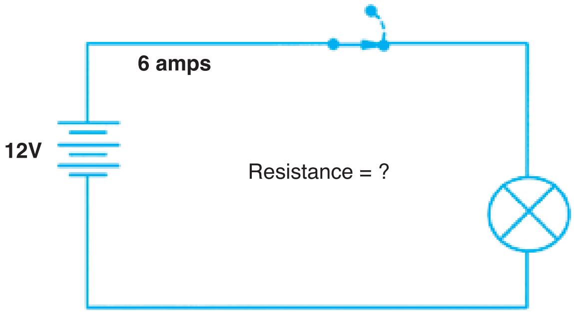

Figure 3-16. Solving for resistance.

In the circuit in Figure 3-16, the resistance is unknown. The current flow through the circuit is 6 amps. The source voltage is 12 volts. Since the ohms are missing, the correct equation to solve for resistance is as follows:

$$Ohms\ (R) = \frac{Volts}{Amps} = \frac{E}{I} = \frac{12}{6} = 2\ ohms$$

If the known units are inserted into the equation, the resistance can be calculated. Performing the division in the equation yields 2 ohms as the resistance in the circuit.

Ohm's Law General Rules

Ohm's Law shows that both voltage and resistance affect current. Current never changes on its own—it changes only if voltage or resistance changes. Current cannot change on its own because voltage causes current through a conductor and all conductors have resistance. The amount of current can change only if the voltage or the conductor changes. Ohm's Law says if the voltage in a conductor increases or decreases, the current will increase or decrease. If the resistance in a conductor increases or decreases, the current will decrease or increase. The general Ohm's Law rule, assuming the resistance doesn't change, is as follows:

- As voltage increases, current increases
- As voltage decreases, current decreases

For more information about measuring voltage, resistance, and current, see the section on "DMM Operating" in Chapter 3 of the *Shop Manual.*

Ohm's Law Chart

The table in (Figure 3-17) summarizes the relationship between voltage, resistance, and current. This table can predict the *effect of changes* in voltage and resistance or it can predict the *cause of changes* in current. In addition to showing what happens to current if voltage or resistance changes, the chart also tells you the most likely result if both voltage and resistance change.

If the voltage increases (Column 2), the current increases (Column 1)—*provided the resistance stays the same* (Column 3). If the voltage decreases (Column 2), the current decreases (Column 1)—*provided the resistance stays the same* (Column 3). For example: Solving the three columns mathematically, if 12 volts ÷ 4 ohms = 3 amps, and the voltage increases to 14 volts/4 ohms = 3.5 amps, the current will increase with the resistance staying at 4 ohms. Decrease the voltage to 10 volts: 10 volts/4 ohms = 2.5 amps, or a decrease in current. In both cases, the resistance stays the same.

If the resistance increases (Column 3), the current decreases (Column 1)—*provided the voltage stays the same* (Column 2). If the resistance decreases (Column 3), the current increases (Column 1)—*provided the voltage stays the same* (Column 2). For example: solving the three columns mathematically, 12 volts ÷ 4 ohms = 3 amps; increase resistance to 5 ohms and keep the voltage at 12 volts: 12 volts/5 ohms = 2.4 amps, a decrease in current. Decrease the resistance to 3 ohms and keep the voltage at 12 volts:12 volts/3 ohms = 4 amps, or an increase in current. In both cases, the voltage stays the same.

POWER

Power is the name we give to the rate of work done by any sort of machine. The output of automotive engines is usually expressed in horsepower; so is the output of electric motors. Many electrical devices are rated by how much electrical power they consume, rather than by how much power they produce. Power consumption is expressed in **watts:** 746 watts = 1 horsepower.

Power Formula

We describe the relationships among power, voltage, and current with the Power Formula. The basic equation for the Power Formula is as follows:

	I-Current (Amps)	E-Voltage (Volts)	R-Resistance (Ohms)
IF VOLTAGE INCREASES or DECREASES	Increases ⇑	Increases ⇑	Stays Same
	Increases ⇑	Increases ⇑	Decreases ⇓
	Stays Same	Increases ⇑	Increases ⇑
	Decreases ⇓	Decreases ⇓	Stays Same
	Stays Same	Decreases ⇓	Decreases ⇓
	Decreases ⇓	Decreases ⇓	Increases ⇑
	Decreases ⇓	Stays Same	Increases ⇑
If RESISTANCE INCREASES or DECREASES	Decreases ⇓	Decreases ⇓	Increases ⇑
	Stays Same	Increases ⇑	Increases ⇑
	Increases ⇑	Stays Same	Decreases ⇓
	Stays Same	Decreases ⇓	Decreases ⇓
	Increases ⇑	Increases ⇑	Decreases ⇓
	Increases ⇑	Stays Same	Decreases ⇓
CURRENT will INCREASE or DECREASE	Increases ⇑	Increases ⇑	Stays Same
	Increases ⇑	Increases ⇑	Decreases ⇓
	Decreases ⇓	Stays Same	Increases ⇑
	Decreases ⇓	Decreases ⇓	Stays Same
	Decreases ⇓	Decreases ⇓	Increases ⇑

Figure 3-17. Ohm's Law relationship table.

$$P = I \times E \text{ or watts } = \text{ amps} \times \text{volts}$$

Power is the product of current multiplied times voltage. In a circuit, if voltage or current increases, then power increases. If voltage or current decreases, then the power decreases.

The most common applications of ratings in watts are probably light bulbs, resistors, audio speakers, and home appliances. Here's an example of how we determine power in watts: If the total current (I) is equal to 10 amps, and the voltage (E) is equal to 120 volts, then

$$P = 120 \times 10 = 1200 \text{ watts}$$

You can multiply the voltage times the current in any circuit and find how much power is consumed. For example, a typical hair dryer can draw almost 10 amps of current. You know that the voltage in your home is about 120. Multiply these two values and you get 1200 watts.

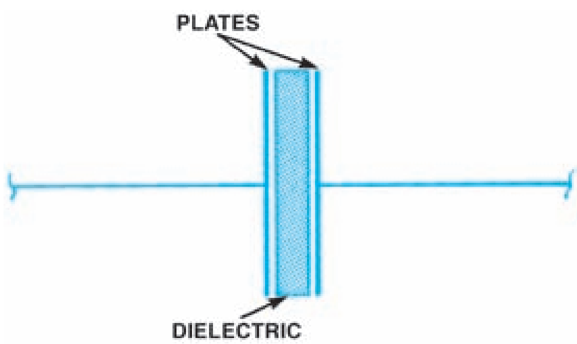

Figure 3-18. A simple capacitor.

CAPACITANCE

Earlier, you learned that a resistor is any device that opposes current flow. A **capacitor** (Figure 3-18) is a device that opposes a change in voltage. The property of opposing voltage change is called **capacitance,** which is also used to describe the electron storage capability of a capacitor. Capacitors are sometimes referred to as condensers because they do the same thing; that is, they store electrons.

There are many uses for capacitors. In automotive electrical systems, capacitors are used to store energy, to make up timer circuits, and as filters. Actual construction methods vary, but a simple capacitor can be made from two plates of conductive material separated by an insulating material called a *dielectric*. Typical dielectric materials are air, mica, paper, plastic, and ceramic. The greater the dielectric properties of the material used in a capacitor, the greater the resistance to voltage leakage.

Energy Storage

When the capacitor (Figure 3-19) is charged to the same potential as the voltage source, current flow stops. The capacitor can then hold its charge when it is disconnected from the voltage source. With the two plates separated by a dielectric, there is nowhere for the electrons to go. The negative plate retains its accumulation of electrons, and the positive plate still has a deficit of electrons. This is how the capacitor stores energy.

When a capacitor is connected to an electrical power source, it is capable of storing electrons from that power source (Figure 3-20). When the capacitor's charge capability is reached, it will cease to accept electrons from the power source. An electrostatic field exists between the capacitor plates and no current flows in the circuit. The charge is retained in the capacitor until the plates are connected to a lower-voltage electrical circuit; at this point, the stored electrons are discharged from the capacitor into the lower-potential (lower-voltage) electrical circuit.

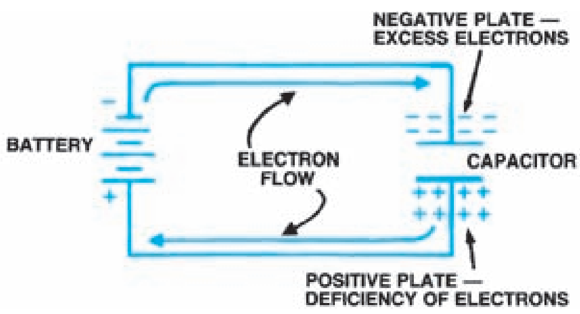

Figure 3-19. As the capacitor is charging, the battery forces electrons through the circuit.

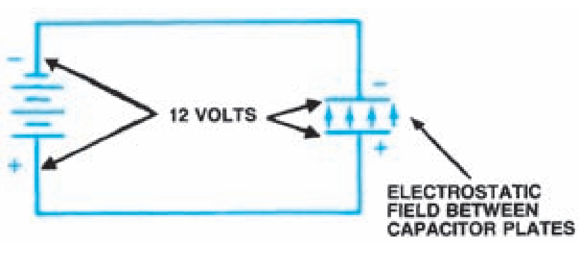

Figure 3-20. When the capacitor is charged, there is equal voltage across the capacitor and the battery. An electrostatic field exists between the capacitor plates. No current flows in the circuit.

Capacitor Discharge

A charged capacitor can deliver its stored energy just like a battery. When capacitors provide electricity, we say they *Discharge*. Used to deliver small currents, a capacitor can power a circuit for a short time (Figure 3-21).

In some circuits, a capacitor can take the place of a battery. Electrons can be stored on the surface of a capacitor plate. If a capacitor is placed in a circuit with a voltage source, current flows in the circuit briefly while the capacitor "charges"; that is, electrons accumulate on the surface of the plate connected to the negative terminal and move away from the plate connected to the positive terminal. Electrons move in this way until the electrical charge of the capacitor is equal to that of the voltage source. How fast this happens depends on several factors, including the voltage applied and the size of the capacitor; generally speaking, it happens very quickly.

A **capacitor** is a device that opposes a change in voltage. The property of opposing voltage

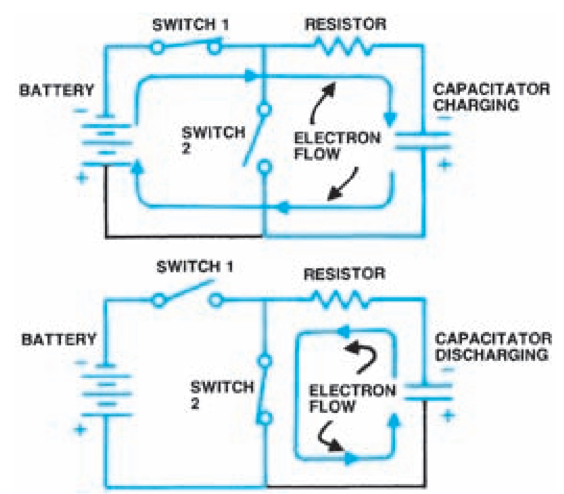

Figure 3-21. The capacitor is charged through one circuit (top) and discharged through another.

change is called “**capacitance**,” which is also used to describe the electron storage capability of a capacitor. Capacitors are sometimes referred to as condensers because they do the same thing, that is, they store electrons.

There are many uses for capacitors. In an automotive electrical system, capacitors are used to store energy, to make up timer circuits, and as filters. Actual construction methods vary, but a simple capacitor can be made from two plates of conductive material separated by an insulating material called a “dielectric.” Typical dielectric materials are air, mica, paper, plastic, and ceramic. The greater the dielectric properties of the material used in a capacitor the greater the resistance to voltage leakage.

Capacitance is measured in **farads**, which is named after Michael Faraday (1791–1867). The symbol for farads is F. If a charge of 1 coulomb is placed on the plates of a capacitor and the potential difference between them is 1 volt, the capacitance is then defined to be 1 farad. One coulomb is equal to the charge of 6.25×10^{18} electrons. One farad is an extremely large quantity of capacitance. Microfarads (0.000001 farad) or μF are more commonly used.

Capacitors are manufactured using many different types of materials and can be various shapes and sizes. Capacitors are used in many automotive electronic circuits and perform the role of an AC/DC filter. A filter is used to reduce high-voltage pulses that could damage electronic circuits. A capacitor can also help reduce the surge (voltage spike) that can occur when circuits containing a coil are turned off.

Types of Capacitors

Capacitors, also called **condensers**, come in a variety of sizes, shapes, and construction. All capacitors are rated in farads or microfarads as well as the voltage rating. See Figure 3-22.

- **Resistor-capacitor circuits (R-C circuits):** A common use of an RC circuit is in the power lead to a radio or sound system where the combination of the two components is used to eliminate alternating voltage interference. The capacitor can pass AC voltage signals, which are used to take these signals to ground through a resistor so that these signals do not travel to the radio.

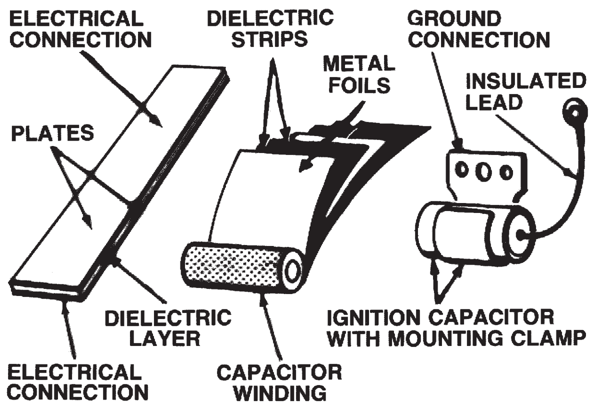

Figure 3-22. Types of capacitors.

Calculating Total Capacitance

The total capacitance of a circuit (Figure 3-23) is dependent on how the capacitors are designed in the circuit. When capacitors are in parallel, total capacitance is determined by the following equation:

$$C_T = C_1 + C_2 + C_3$$

When capacitors are in series, total capacitance is determined by the following equation:

$$C_t = \frac{1}{\frac{1}{C_t} + \frac{1}{C_t}}$$

Future Trends in Voltage: The 42-Volt System

The voltage of the automotive electrical system was not always at today’s 12 volts. It was raised once from 6 volts to 12 volts around 1955. The reason was that a higher ignition energy was required for the higher-compression V8 engines being introduced, prompting the need for a higher-voltage electrical system. Occurring almost simultaneously with this ignition issue were new automotive features such as radios, higher-power headlamps, and more powerful electric starting motors, all of which were stretching the capabilities of the existing 6-volt system. A pressing need for more reliable ignition drove the implementation of a single higher-energy 12-volt battery (with 14-volt regulation). The transition took about two years.

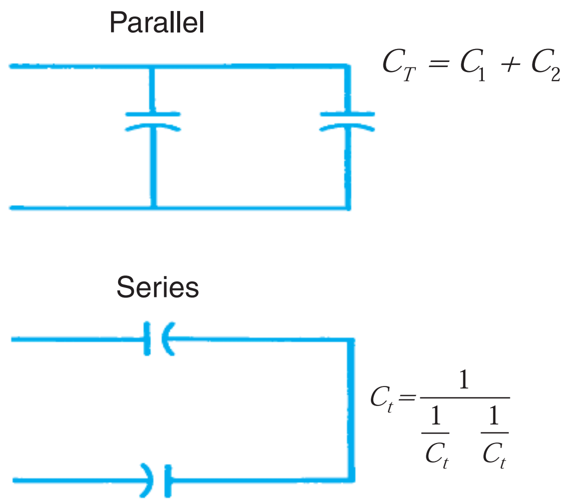

Figure 3-23. Calculating total capacitance here.

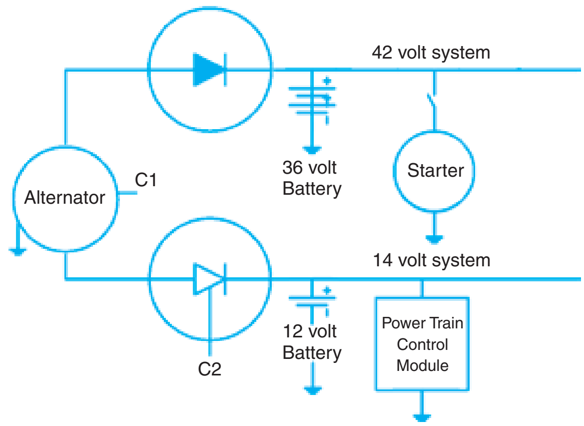

Figure 3-24. Dual 42-volt /14-volt system.

Today's automobile industry is now faced with a similar situation. Many new electronic features are emerging. Some of them are to meet tighter emission and fuel economy regulations, such as electromechanical (EM) engine valve actuators and convenience items such as in-vehicle information technology systems; some are to satisfy increased desires for safety and comfort with features such as electronic brakes and steering. Many of these cannot be practically introduced using the currently available 14-volt power supply, and a higher-voltage supply would definitely be beneficial to some of the existing automotive components. The comparative complexity of today's 14-volt electrical system and the large number of different components designed to operate at 14 volts make the prospect of changing to any new voltage more difficult. Moreover, there are some specific components, such as light bulbs and low-power electronic control modules, that still require 12- to 14-volt operation.

Before the entire electrical system is transferred to a higher voltage, a dual-voltage electrical system will most likely appear. In a dual-voltage system, a new higher-voltage system is introduced to accommodate desired higher power components and features while simultaneously preserving the present 14-volt system for some interim period and for those components that require the present lower voltage.

42-Volt/14-Volt Electrical System Design

Due to the use of hybrid and mybrid vehicles, it is very likely there will be a dual-voltage electrical architecture before a complete single 42-volt system. In a 42/14-volt dual-voltage system, the governing partitioning philosophy is that high-power loads will generally be allocated to the 42-volt bus, while the low-power electronic loads, including most key-off loads, will be allocated to the 14-volt bus.

Figure 3-24 shows a dual system, including a complicated alternator with two sets of stator windings to deliver power separately to the 42- and 14-volt buses, combined with an integral starter motor. This design is often referred to as an Integrated Starter Alternator (ISA). The dual-stator/starter motor version uses a standard field control (labeled C1) to regulate the 42-volt bus voltage and a phase-controlled converter (C2) to regulate the 14-volt bus voltage. Here again, high-power loads, including the cranking motor, are allocated to the 42-volt bus, while the 14-volt bus supplies the low-power electronic control modules. Separate batteries are used for each bus. There are some difficulties in controlling individual stator windings for optimal outputs in this dual-stator winding architecture.

SUMMARY

A conductor is a metallic element that contains fewer than four electrons in its outer shell. An insulator is a non-metallic substance that contains more than four electrons in the outer shell. Semiconductors are a group of materials that cannot be classified either as conductors or insulators; they have exactly four electrons in their outer shell. Current flow is measured by the number of free electrons passing a given point in an electrical circuit per second. Electrical pressure or charge differential is measured in *volts,* resistance in *ohms* and current in *amperes*. If a hydraulic circuit analogy is used to describe an electrical circuit, *voltage* is equivalent to fluid pressure, *current* to the flow in gpm, and *resistance* to flow restriction.

Capacitors are used to store electrons: this consists of conductor plates separated by a dielectric. Capacitance is measured in farads: capacitors are rated by voltage and by capacitance.

Review Questions

1. Which of the following methods can calculate circuit current?
   a. Multiplying amps times ohms
   b. Dividing ohms by volts
   c. Dividing volts by ohms
   d. Multiplying volts times watts
2. Which of the following methods can calculate circuit resistance?
   a. Dividing amps into volts
   b. Dividing volts into amps
   c. Multiplying volts times amps
   d. Multiplying amps times ohms
3. Which of the following causes voltage drop in a circuit?
   a. Increase in wire size
   b. Increase in resistance
   c. Increase in insulation
   d. Decrease in current
4. Which of the following describes a function of a capacitor in an electrical circuit?
   a. Timing device
   b. Rectification
   c. DC-to-AC conversion
   d. Inductance
5. Which of the following is a measure of electrical current?
   a. Amperes
   b. Ohms
   c. Voltage
   d. Watts
6. A material with many free electrons is a good
   a. Compound
   b. Conductor
   c. Insulator
   d. Semiconductor
7. A material with four electrons in the valence ring is which of these:
   a. Compound
   b. Insulator
   c. Semiconductor
   d. Conductor
8. The conventional theory of current flow says that current flows
   a. Randomly
   b. Positive to negative
   c. Negative to positive
   d. At 60 cycles per second
9. Voltage is which of these items:
   a. Applied to a circuit
   b. Flowing in a circuit
   c. Built into a circuit
   d. Flowing out of a circuit
10. The unit that represents resistance to current flow is which of these items:
    a. Ampere
    b. Volt
    c. Ohm
    d. Watt
11. In automotive systems, voltage is supplied by which of these components:
    a. Alternator
    b. ECM
    c. DC Generator
    d. Voltage Regulator
12. Which of the following characteristic does *not* affect resistance?
    a. Diameter of the conductor
    b. Temperature of the conductor
    c. Atomic structure of the conductor
    d. Direction of current flow in the conductor
13. The resistance in a longer piece of wire is which of these:
    a. Higher
    b. Lower
    c. Unchanged
    d. Higher, then lower
14. According to Ohm's Law, when one volt pushes one ampere of current through a conductor, the resistance is:
    a. Zero
    b. One ohm
    c. One watt
    d. One coulomb
15. The sum of the voltage drops in a circuit equals which of these:
    a. Amperage
    b. Resistance
    c. Source voltage
    d. Shunt circuit voltage
16. Which of the following is a measure of electrical pressure?
    a. Amperes
    b. Ohms
    c. Voltage
    d. Watts

17. Which of the following causes voltage drop in a circuit?
    a. Increase in wire size
    b. Increase in resistance
    c. Increase in insulation
    d. Decrease in current

18. Where E = volts, I = amperes, and R = resistance, Ohm's Law is written as which of these formulas:
    a. $I = E \times R$
    b. $E = I \times R$
    c. $R = E \times I$
    d. $E = 12 \times R$

19. In a closed circuit with a capacitor, current will continue to flow until the voltage charge across the capacitor plates becomes which of these:
    a. Less than the source voltage
    b. Equal to the source voltage
    c. Greater than the source voltage
    d. Equal to the resistance of the plates

20. Capacitors are also called which of these items:
    a. Diodes
    b. Resistors
    c. Condensers
    d. Dielectrics

21. Capacitors are rated in
    a. Microcoulombs
    b. Megawatts
    c. Microfarads
    d. Milliohms