

Ohm's Law, Power, AND ENERGY

4

OBJECTIVES

- *Understand the importance of Ohm's law and how to apply it to a variety of situations.*
- *Be able to plot Ohm's law and understand how to "read" a graphical plot of voltage versus current.*
- *Become aware of the differences between power and energy levels and how to solve for each.*
- *Understand the power and energy flow of a system, including how the flow impacts on the efficiency of operation.*
- *Become aware of the operation of a variety of fuses and circuit breakers and where each is employed.*

4.1 INTRODUCTION

Now that the three important quantities of an electric circuit have been introduced, this chapter reveals how they are interrelated. The most important equation in the study of electric circuits is introduced, and various other equations that allow us to find power and energy levels are discussed in detail. It is the first chapter where we tie things together and develop a feeling for the way an electric circuit behaves and what affects its response. For the first time, the data provided on the labels of household appliances and the manner in which your electric bill is calculated will have some meaning. It is indeed a chapter that should open your eyes to a wide array of past experiences with electrical systems.

4.2 OHM'S LAW

As mentioned above, the first equation to be described is without question one of the most important to be learned in this field. It is not particularly difficult mathematically, but it is very powerful because it can be applied to any network in any time frame. That is, it is applicable to dc circuits, ac circuits, digital and microwave circuits, and, in fact, any type of applied signal. In addition, it can be applied over a period of time or for instantaneous responses. The equation can be derived directly from the following basic equation for all physical systems:

$$\text{Effect} = \frac{\text{cause}}{\text{opposition}} \quad (4.1)$$

Every conversion of energy from one form to another can be related to this equation. In electric circuits, the *effect* we are trying to establish is the flow of charge, or *current*. The *potential difference*, or voltage, between two points is the *cause* ("pressure"), and the opposition is the *resistance* encountered.

An excellent analogy for the simplest of electrical circuits is the water in a hose connected to a pressure valve, as discussed in Chapter 2. Think of the electrons in the copper wire as the water in the hose, the pressure valve as the applied voltage, and the size of the hose as the factor that determines the resistance. If the pressure valve is closed, the water simply sits in the





FIG. 4.1
George Simon Ohm.
 Courtesy of the Smithsonian
 Institution. Photo No. 51,145.

German (Erlangen, Cologne)
 (1789–1854)

Physicist and Mathematician
Professor of Physics, University of Cologne

In 1827, developed one of the most important laws of electric circuits: *Ohm's law*. When the law was first introduced, the supporting documentation was considered lacking and foolish, causing him to lose his teaching position and search for a living doing odd jobs and some tutoring. It took some 22 years for his work to be recognized as a major contribution to the field. He was then awarded a chair at the University of Munich and received the Copley Medal of the Royal Society in 1841. His research also extended into the areas of molecular physics, acoustics, and telegraphic communication.

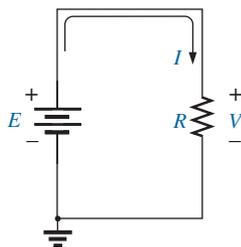


FIG. 4.2
Basic circuit.

hose without a general direction, much like the oscillating electrons in a conductor without an applied voltage. When we open the pressure valve, water will flow through the hose much like the electrons in a copper wire when the voltage is applied. In other words, the absence of the “pressure” in one case and the voltage in the other simply results in a system without direction or reaction. The rate at which the water will flow in the hose is a function of the size of the hose. A hose with a very small diameter will limit the rate at which water can flow through the hose, just as a copper wire with a small diameter will have a high resistance and will limit the current.

In summary, therefore, the absence of an applied “pressure” such as voltage in an electric circuit will result in no reaction in the system and no current in the electric circuit. Current is a reaction to the applied voltage and not the factor that gets the system in motion. To continue with the analogy, the more the pressure at the spigot, the greater the rate of water flow through the hose, just as applying a higher voltage to the same circuit results in a higher current.

Substituting the terms introduced above into Eq. (4.1) results in

$$\text{Current} = \frac{\text{potential difference}}{\text{resistance}}$$

and

$$I = \frac{E}{R} \quad (\text{amperes, A}) \quad (4.2)$$

Eq. (4.2) is known as **Ohm's law** in honor of Georg Simon Ohm (Fig. 4.1). The law states that for a fixed resistance, the greater the voltage (or pressure) across a resistor, the more the current, and the more the resistance for the same voltage, the less the current. In other words, the current is proportional to the applied voltage and inversely proportional to the resistance.

By simple mathematical manipulations, the voltage and resistance can be found in terms of the other two quantities:

$$E = IR \quad (\text{volts, V}) \quad (4.3)$$

and

$$R = \frac{E}{I} \quad (\text{ohms, } \Omega) \quad (4.4)$$

All the quantities of Eq. (4.2) appear in the simple electrical circuit in Fig. 4.2. A resistor has been connected directly across a battery to establish a current through the resistor and supply. Note that

the symbol E is applied to all sources of voltage

and

the symbol V is applied to all voltage drops across components of the network.

Both are measured in volts and can be applied interchangeably in Eqs. (4.2) through (4.4).

Since the battery in Fig. 4.2 is connected directly across the resistor, the voltage V_R across the resistor must be equal to that of the supply. Applying Ohm's law:

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

Note in Fig. 4.2 that the voltage source “pressures” current (conventional current) in a direction that leaves the positive terminal of the supply and



returns to the negative terminal of the battery. *This will always be the case for single-source networks.* (The effect of more than one source in the same network is investigated in a later chapter.) Note also that the current enters the positive terminal and leaves the negative terminal for the load resistor R .

For any resistor, in any network, the direction of current through a resistor will define the polarity of the voltage drop across the resistor

as shown in Fig. 4.3 for two directions of current. Polarities as established by current direction become increasingly important in the analyses to follow.

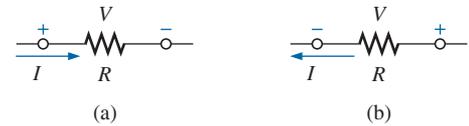


FIG. 4.3
Defining polarities.

EXAMPLE 4.1 Determine the current resulting from the application of a 9 V battery across a network with a resistance of 2.2 Ω .

Solution: Eq. (4.2):

$$I = \frac{V_R}{R} = \frac{E}{R} = \frac{9 \text{ V}}{2.2 \Omega} = \mathbf{4.09 \text{ A}}$$

EXAMPLE 4.2 Calculate the resistance of a 60 W bulb if a current of 500 mA results from an applied voltage of 120 V.

Solution: Eq. (4.4):

$$R = \frac{V_R}{I} = \frac{E}{I} = \frac{120 \text{ V}}{500 \times 10^{-3} \text{ A}} = \mathbf{240 \Omega}$$

EXAMPLE 4.3 Calculate the current through the 2 k Ω resistor in Fig. 4.4 if the voltage drop across it is 16 V.

Solution:

$$I = \frac{V}{R} = \frac{16 \text{ V}}{2 \times 10^3 \Omega} = \mathbf{8 \text{ mA}}$$

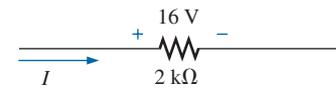


FIG. 4.4
Example 4.3.

EXAMPLE 4.4 Calculate the voltage that must be applied across the soldering iron in Fig. 4.5 to establish a current of 1.5 A through the iron if its internal resistance is 80 Ω .

Solution:

$$E = V_R = IR = (1.5 \text{ A})(80 \Omega) = \mathbf{120 \text{ V}}$$

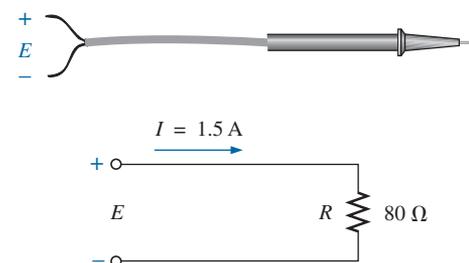


FIG. 4.5
Example 4.4.

In a number of the examples in this chapter, such as Example 4.4, the voltage applied is actually that obtained from an ac outlet in the home, office, or laboratory. This approach was used to provide an opportunity for the student to relate to real-world situations as soon as possible and to demonstrate that a number of the equations derived in this chapter are applicable to ac networks also. Chapter 13 will provide a direct relationship between ac and dc voltages that permits the mathematical substitutions used in this chapter. In other words, don't be concerned that some of the voltages and currents appearing in the examples of this chapter are actually ac voltages, because the equations for dc



networks have exactly the same format, and all the solutions will be correct.

4.3 PLOTTING OHM'S LAW

Graphs, characteristics, plots, and the like, play an important role in every technical field as a mode through which the broad picture of the behavior or response of a system can be conveniently displayed. It is therefore critical to develop the skills necessary both to read data and to plot them in such a manner that they can be interpreted easily.

For most sets of characteristics of electronic devices, the current is represented by the vertical axis (ordinate), and the voltage by the horizontal axis (abscissa), as shown in Fig. 4.6. First note that the vertical axis is in amperes and the horizontal axis is in volts. For some plots, I may be in milliamperes (mA), microamperes (μA), or whatever is appropriate for the range of interest. The same is true for the levels of voltage on the horizontal axis. Note also that the chosen parameters require that the spacing between numerical values of the vertical axis be different from that of the horizontal axis. The linear (straight-line) graph reveals that the resistance is not changing with current or voltage level; rather, it is a fixed quantity throughout. The current direction and the voltage polarity appearing at the top of Fig. 4.6 are the defined direction and polarity for the provided plot. If the current direction is opposite to the defined direction, the region below the horizontal axis is the region of interest for the current I . If the voltage polarity is opposite to that defined, the region to the left of the current axis is the region of interest. For the standard fixed resistor, the first quadrant, or region, of Fig. 4.6 is the only region of interest. However, you will encounter many devices in your electronics courses that use the other quadrants of a graph.

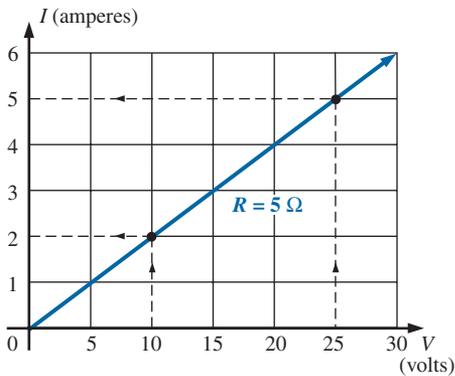
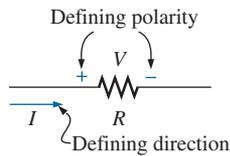


FIG. 4.6
Plotting Ohm's law.

Once a graph such as Fig. 4.6 is developed, the current or voltage at any level can be found from the other quantity by simply using the resulting plot. For instance, at $V = 25 \text{ V}$, if a vertical line is drawn on Fig. 4.6 to the curve as shown, the resulting current can be found by drawing a horizontal line over to the current axis, where a result of 5 A is obtained. Similarly, at $V = 10 \text{ V}$, a vertical line to the plot and a horizontal line to the current axis results in a current of 2 A, as determined by Ohm's law.

If the resistance of a plot is unknown, it can be determined at any point on the plot since a straight line indicates a fixed resistance. At any point on the plot, find the resulting current and voltage, and simply substitute into the following equation:

$$R_{dc} = \frac{V}{I} \tag{4.5}$$

To test Eq. (4.5), consider a point on the plot where $V = 20 \text{ V}$ and $I = 4 \text{ A}$. The resulting resistance is $R_{dc} = 20 \text{ V}/4 \text{ A} = 5 \Omega$. For comparison purposes, a 1Ω and a 10Ω resistor were plotted on the graph in Fig. 4.7. Note that the less the resistance, the steeper the slope (closer to the vertical axis) of the curve.

If we write Ohm's law in the following manner and relate it to the basic straight-line equation

$$I = \frac{1}{R} \cdot E + 0$$

$$\downarrow \quad \downarrow \quad \downarrow \quad \downarrow$$

$$y = m \cdot x + b$$

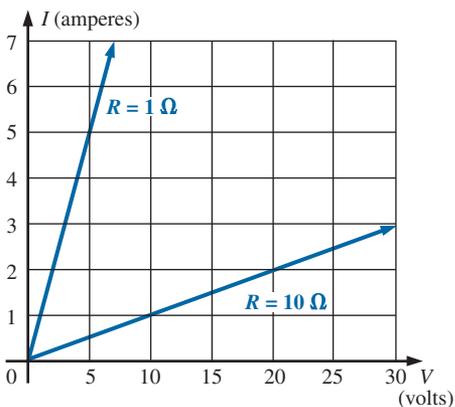


FIG. 4.7
Demonstrating on an I-V plot that the less the resistance, the steeper the slope.



we find that the slope is equal to 1 divided by the resistance value, as indicated by the following:

$$m = \text{slope} = \frac{\Delta y}{\Delta x} = \frac{\Delta I}{\Delta V} = \frac{1}{R} \quad (4.6)$$

where Δ signifies a small, finite change in the variable.

Eq. (4.6) reveals that the greater the resistance, the less the slope. If written in the following form, Eq. (4.6) can be used to determine the resistance from the linear curve:

$$R = \frac{\Delta V}{\Delta I} \quad (\text{ohms}) \quad (4.7)$$

The equation states that by choosing a particular ΔV (or ΔI), you can obtain the corresponding ΔI (or ΔV , respectively) from the graph, as shown in Fig. 4.8, and then determine the resistance. If the plot is a straight line, Eq. (4.7) will provide the same result no matter where the equation is applied. However, if the plot curves at all, the resistance will change.

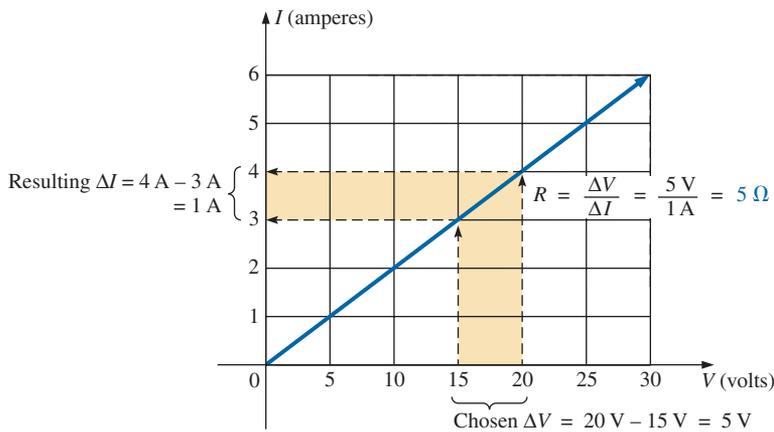


FIG. 4.8
Applying Eq. (4.7)

EXAMPLE 4.5 Determine the resistance associated with the curve in Fig. 4.9 using Eqs. (4.5) and (4.7), and compare results.

Solution: At $V = 6 \text{ V}$, $I = 3 \text{ mA}$, and

$$R_{dc} = \frac{V}{I} = \frac{6 \text{ V}}{3 \text{ mA}} = 2 \text{ k}\Omega$$

For the interval between 6 V and 8 V ,

$$R = \frac{\Delta V}{\Delta I} = \frac{2 \text{ V}}{1 \text{ mA}} = 2 \text{ k}\Omega$$

The results are equivalent.

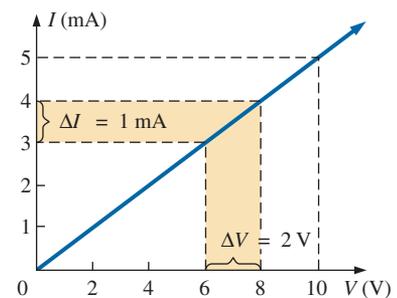


FIG. 4.9
Example 4.5.

Before leaving the subject, let us first investigate the characteristics of a very important semiconductor device called the **diode**, which will be examined in detail in basic electronics courses. This device ideally acts

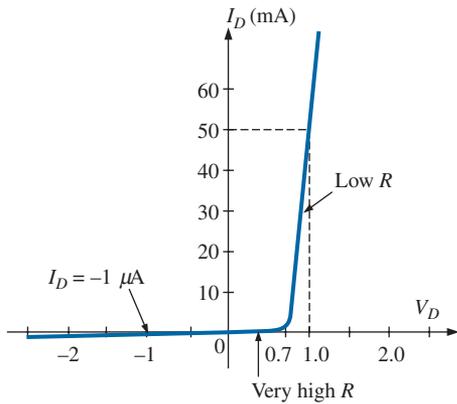


FIG. 4.10

Semiconductor diode characteristics.

as a low-resistance path to current in one direction and a high-resistance path to current in the reverse direction, much like a switch that passes current in only one direction. A typical set of characteristics appears in Fig. 4.10. Without any mathematical calculations, the closeness of the characteristic to the voltage axis for negative values of applied voltage indicates that this is the low-conductance (high resistance, switch opened) region. Note that this region extends to approximately 0.7 V positive. However, for values of applied voltage greater than 0.7 V, the vertical rise in the characteristics indicates a high-conductivity (low resistance, switch closed) region. Application of Ohm's law will now verify the above conclusions.

At $V_D = +1\text{ V}$,

$$R_{\text{diode}} = \frac{V_D}{I_D} = \frac{1\text{ V}}{50\text{ mA}} = \frac{1\text{ V}}{50 \times 10^{-3}\text{ A}} = 20\ \Omega$$

(a relatively low value for most applications)

At $V_D = -1\text{ V}$,

$$R_{\text{diode}} = \frac{V_D}{I_D} = \frac{1\text{ V}}{1\ \mu\text{A}} = 1\ \text{M}\Omega$$

(which is often represented by an open-circuit equivalent)

4.4 POWER

In general,

the term power is applied to provide an indication of how much work (energy conversion) can be accomplished in a specified amount of time; that is, power is a rate of doing work.

For instance, a large motor has more power than a smaller motor because it has the ability to convert more electrical energy into mechanical energy in the same period of time. Since energy is measured in joules (J) and time in seconds (s), power is measured in joules/second (J/s). The electrical unit of measurement for power is the watt (W) defined by

$$1\text{ watt (W)} = 1\text{ joule/second (J/s)} \tag{4.8}$$

In equation form, power is determined by

$$P = \frac{W}{t} \tag{4.9}$$

(watts, W, or joules/second, J/s)

with the **energy** (W) measured in joules and the time t in seconds.

The unit of measurement—the watt—is derived from the surname of James Watt (Fig. 4.11), who was instrumental in establishing the standards for power measurements. He introduced the **horsepower** (hp) as a measure of the average power of a strong dray horse over a full working day. It is approximately 50% more than can be expected from the average horse. The horsepower and watt are related in the following manner:

$$1\text{ horsepower} \cong 746\text{ watts}$$



FIG. 4.11

James Watt.

Courtesy of the Smithsonian Institution. Photo No. 30,391.

Scottish (Greenock, Birmingham)
(1736–1819)

Instrument Maker and Inventor
Elected Fellow of the Royal Society
of London in 1785

In 1757, at the age of 21, used his innovative talents to design mathematical instruments such as the *quadrant*, *compass*, and various *scales*. In 1765, introduced the use of a separate *condenser* to increase the efficiency of steam engines. In the following years, he received a number of important patents on improved engine design, including a rotary motion for the steam engine (versus the reciprocating action) and a double-action engine, in which the piston pulled as well as pushed in its cyclic motion. Introduced the term **horsepower** as the average power of a strong dray (small cart) horse over a full working day.



The power delivered to, or absorbed by, an electrical device or system can be found in terms of the current and voltage by first substituting Eq. (2.5) into Eq. (4.9):

$$P = \frac{W}{t} = \frac{QV}{t} = V\frac{Q}{t}$$

But

$$I = \frac{Q}{t}$$

so that

$$\boxed{P = VI} \quad (\text{watts, W}) \quad (4.10)$$

By direct substitution of Ohm's law, the equation for power can be obtained in two other forms:

$$P = VI = V\left(\frac{V}{R}\right)$$

and

$$\boxed{P = \frac{V^2}{R}} \quad (\text{watts, W}) \quad (4.11)$$

or

$$P = VI = (IR)I$$

and

$$\boxed{P = I^2R} \quad (\text{watts, W}) \quad (4.12)$$

The result is that the power absorbed by the resistor in Fig. 4.12 can be found directly, depending on the information available. In other words, if the current and resistance are known, it pays to use Eq. (4.12) directly, and if V and I are known, use of Eq. (4.10) is appropriate. It saves having to apply Ohm's law before determining the power.

The power supplied by a battery can be determined by simply inserting the supply voltage into Eq. (4.10) to produce

$$\boxed{P = EI} \quad (\text{watts, W}) \quad (4.13)$$

The importance of Eq. (4.13) cannot be overstated. It clearly states the following:

The power associated with any supply is not simply a function of the supply voltage. It is determined by the product of the supply voltage and its maximum current rating.

The simplest example is the car battery—a battery that is large, difficult to handle, and relatively heavy. It is only 12 V, a voltage level that could be supplied by a battery slightly larger than the small 9 V portable radio battery. However, to provide the **power** necessary to start a car, the battery must be able to supply the high surge current required at starting—a component that requires size and mass. In total, therefore, it is not the voltage or current rating of a supply that determines its power capabilities; it is the product of the two.

Throughout the text, the abbreviation for energy (W) can be distinguished from that for the watt (W) because the one for energy is in italics while the one for watt is in roman. In fact, all variables in the dc section appear in italics while the units appear in roman.

EXAMPLE 4.6 Find the power delivered to the dc motor of Fig. 4.13.

Solution: $P = EI = (120 \text{ V})(5 \text{ A}) = 600 \text{ W} = \mathbf{0.6 \text{ kW}}$

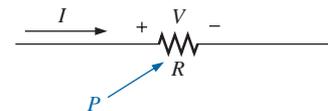


FIG. 4.12

Defining the power to a resistive element.

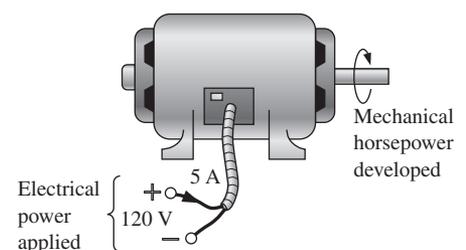


FIG. 4.13

Example 4.6.

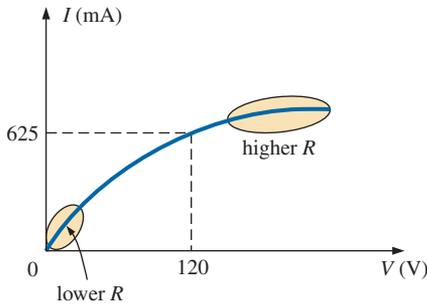


FIG. 4.14

The nonlinear I - V characteristics of a 75 W light bulb (Example 4.8).

EXAMPLE 4.7 What is the power dissipated by a $5\ \Omega$ resistor if the current is $4\ \text{A}$?

Solution:

$$P = I^2R = (4\ \text{A})^2(5\ \Omega) = \mathbf{80\ \text{W}}$$

EXAMPLE 4.8 The I - V characteristics of a light bulb are provided in Fig. 4.14. Note the nonlinearity of the curve, indicating a wide range in resistance of the bulb with applied voltage. If the rated voltage is $120\ \text{V}$, find the wattage rating of the bulb. Also calculate the resistance of the bulb under rated conditions.

Solution: At $120\ \text{V}$,

$$I = 0.625\ \text{A}$$

and

$$P = VI = (120\ \text{V})(0.625\ \text{A}) = \mathbf{75\ \text{W}}$$

At $120\ \text{V}$,

$$R = \frac{V}{I} = \frac{120\ \text{V}}{0.625\ \text{A}} = \mathbf{192\ \Omega}$$

Sometimes the power is given and the current or voltage must be determined. Through algebraic manipulations, an equation for each variable is derived as follows:

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

and

$$I = \sqrt{\frac{P}{R}} \quad (\text{amperes, A}) \quad (4.14)$$

$$P = \frac{V^2}{R} \Rightarrow V^2 = PR$$

and

$$V = \sqrt{PR} \quad (\text{volts, V}) \quad (4.15)$$

EXAMPLE 4.9 Determine the current through a $5\ \text{k}\Omega$ resistor when the power dissipated by the element is $20\ \text{mW}$.

Solution: Eq. (4.14):

$$\begin{aligned} I &= \sqrt{\frac{P}{R}} = \sqrt{\frac{20 \times 10^{-3}\ \text{W}}{5 \times 10^3\ \Omega}} = \sqrt{4 \times 10^{-6}} = 2 \times 10^{-3}\ \text{A} \\ &= \mathbf{2\ \text{mA}} \end{aligned}$$

4.5 ENERGY

For power, which is the rate of doing work, to produce an energy conversion of any form, it must be *used over a period of time*. For example, a motor may have the horsepower to run a heavy load, but unless the motor is *used* over a period of time, there will be no energy conversion. In addition, the longer the motor is used to drive the load, the greater will be the energy expended.



The **energy** (W) lost or gained by any system is therefore determined by

$$W = Pt \quad (\text{wattseconds, Ws, or joules}) \quad (4.16)$$

Since power is measured in watts (or joules per second) and time in seconds, the unit of energy is the *wattsecond* or *joule* (note Fig. 4.15). The wattsecond, however, is too small a quantity for most practical purposes, so the *watthour* (Wh) and the *kilowatthour* (kWh) are defined, as follows:

$$\text{Energy (Wh)} = \text{power (W)} \times \text{time (h)} \quad (4.17)$$

$$\text{Energy (kWh)} = \frac{\text{power (W)} \times \text{time (h)}}{1000} \quad (4.18)$$

Note that the energy in kilowatthours is simply the energy in watthours divided by 1000. To develop some sense for the kilowatthour energy level, consider that *1 kWh is the energy dissipated by a 100 W bulb in 10 h*.

The **kilowatthour meter** is an instrument for measuring the energy supplied to the residential or commercial user of electricity. It is normally connected directly to the lines at a point just prior to entering the power distribution panel of the building. A typical set of dials is shown in Fig. 4.16, along with a photograph of an analog kilowatthour meter. As indicated, each power of ten below a dial is in kilowatthours. The more rapidly the aluminum disc rotates, the greater the energy demand. The dials are connected through a set of gears to the rotation of this disc. A solid-state digital meter with an extended range of capabilities also appears in Fig. 4.16.



FIG. 4.16

Kilowatthour meters: (a) analog; (b) digital.
(Courtesy of ABB Electric Metering Systems.)

EXAMPLE 4.10 For the dial positions in Fig. 4.16(a), calculate the electricity bill if the previous reading was 4650 kWh and the average cost in your area is 9¢ per kilowatthour.

Solution:

$$5360 \text{ kWh} - 4650 \text{ kWh} = 710 \text{ kWh used}$$

$$710 \text{ kWh} \left(\frac{9¢}{\text{kWh}} \right) = \$63.90$$

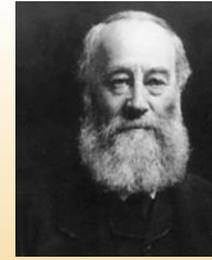


FIG. 4.15

James Prescott Joule.

© Hulton-Deutsch Collection/Corbis

British (Salford, Manchester)

(1818–89)

Physicist

Honorary Doctorates from the Universities of Dublin and Oxford

Contributed to the important fundamental *law of conservation of energy* by establishing that various forms of energy, whether electrical, mechanical, or heat, are in the same family and can be exchanged from one form to another. In 1841 introduced *Joule's law*, which stated that the heat developed by electric current in a wire is proportional to the product of the current squared and the resistance of the wire (I^2R). He further determined that the heat emitted was equivalent to the power absorbed and therefore heat is a form of energy.



EXAMPLE 4.11 How much energy (in kilowatt-hours) is required to light a 60 W bulb continuously for 1 year (365 days)?

Solution:

$$W = \frac{Pt}{1000} = \frac{(60 \text{ W})(24 \text{ h/day})(365 \text{ days})}{1000} = \frac{525,600 \text{ Wh}}{1000} \\ = \mathbf{525.60 \text{ kWh}}$$

EXAMPLE 4.12 How long can a 205 W television set be on before using more than 4 kWh of energy?

Solution:

$$W = \frac{Pt}{1000} \Rightarrow t \text{ (hours)} = \frac{(W)(1000)}{P} = \frac{(4 \text{ kWh})(1000)}{205 \text{ W}} = \mathbf{19.51 \text{ h}}$$

EXAMPLE 4.13 What is the cost of using a 5 hp motor for 2 h if the rate is 9¢ per kilowatt-hour?

Solution:

$$W \text{ (kilowatt-hours)} = \frac{Pt}{1000} = \frac{(5 \text{ hp} \times 746 \text{ W/hp})(2 \text{ h})}{1000} = 7.46 \text{ kWh} \\ \text{Cost} = (7.46 \text{ kWh})(9¢/\text{kWh}) = \mathbf{67.14¢}$$

EXAMPLE 4.14 What is the total cost of using all of the following at 9¢ per kilowatt-hour?

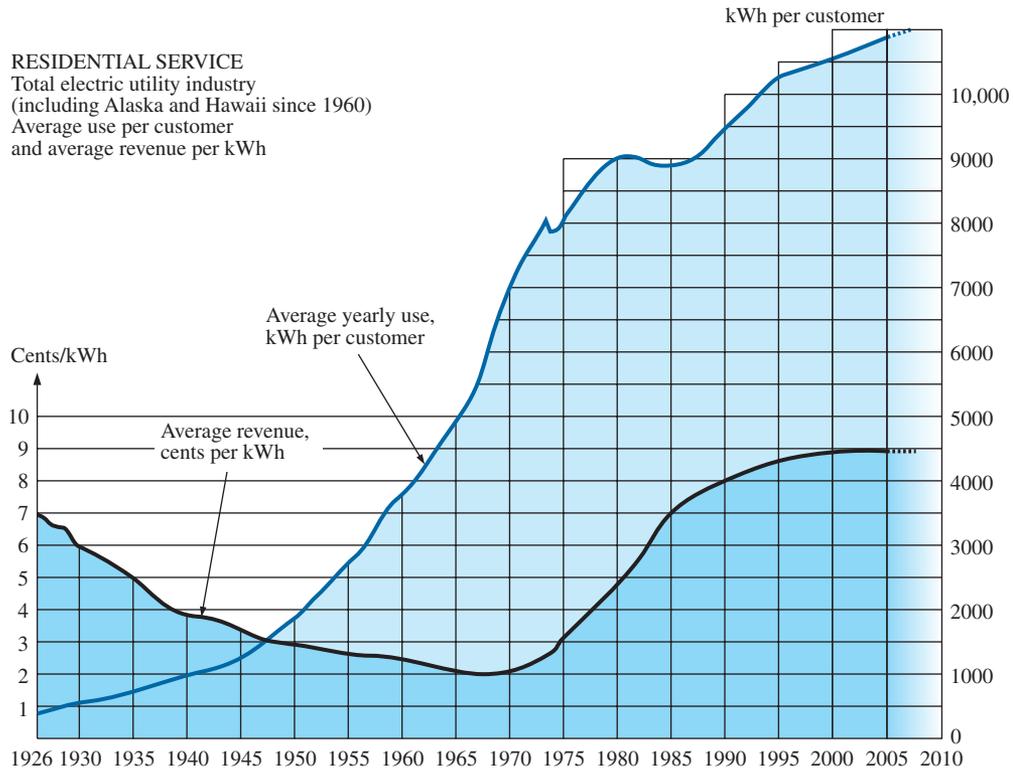
- A 1200 W toaster for 30 min
- Six 50 W bulbs for 4 h
- A 400 W washing machine for 45 min
- A 4800 W electric clothes dryer for 20 min

Solution:

$$W = \frac{(1200 \text{ W})(\frac{1}{2} \text{ h}) + (6)(50 \text{ W})(4 \text{ h}) + (400 \text{ W})(\frac{3}{4} \text{ h}) + (4800 \text{ W})(\frac{1}{3} \text{ h})}{1000} \\ = \frac{600 \text{ Wh} + 1200 \text{ Wh} + 300 \text{ Wh} + 1600 \text{ Wh}}{1000} = \frac{3700 \text{ Wh}}{1000} \\ W = 3.7 \text{ kWh} \\ \text{Cost} = (3.7 \text{ kWh})(9¢/\text{kWh}) = \mathbf{33.3¢}$$

The chart in Fig. 4.17 shows the national average cost per kilowatt-hour compared to the kilowatt-hours used per customer. Note that the cost today is just above the level of 1926, but the average customer uses more than 20 times as much electrical energy in a year. Keep in mind that the chart in Fig. 4.17 is the average cost across the nation. Some states have average rates close to 6¢ per kilowatt-hour, whereas others approach 18¢ per kilowatt-hour.

Table 4.1 lists some common household appliances with their typical wattage ratings. You might find it interesting to calculate the cost of


FIG. 4.17

Cost per kWh and average kWh per customer versus time.
 (Based on data from Edison Electric Institute.)

TABLE 4.1

Typical wattage ratings of some common household items.

Appliance	Wattage Rating	Appliance	Wattage Rating
Air conditioner	860	Laptop computer:	
Blow dryer	1300	Sleep	<1 W (Typically 0.3 W to 0.5 W)
Cassette player/recorder	5	Normal	10–20 W
Cellular phone:		High	25–35 W
Standby	≅35 mW	Microwave oven	1200
Talk	≅4.3 W	Pager	1–2 mW
Clock	2	Radio	70
Clothes dryer (electric)	4800	Range (self-cleaning)	12,200
Coffee maker	900	Refrigerator (automatic defrost)	1800
Dishwasher	1200	Shaver	15
Fan:		Stereo equipment	110
Portable	90	Sun lamp	280
Window	200	Toaster	1200
Heater	1322	Trash compactor	400
Heating equipment:		TV (color)	200
Furnace fan	320	Videocassette recorder	110
Oil-burner motor	230	Washing machine	500
Iron, dry or steam	1100	Water heater	4500



operating some of these appliances over a period of time using the chart in Fig. 4.17 to find the cost per kilowatt-hour.

4.6 EFFICIENCY

A flowchart for the energy levels associated with any system that converts energy from one form to another is provided in Fig. 4.18. Note that the output energy level must always be less than the applied energy due to losses and storage within the system. The best one can hope for is that W_{out} and W_{in} are relatively close in magnitude.

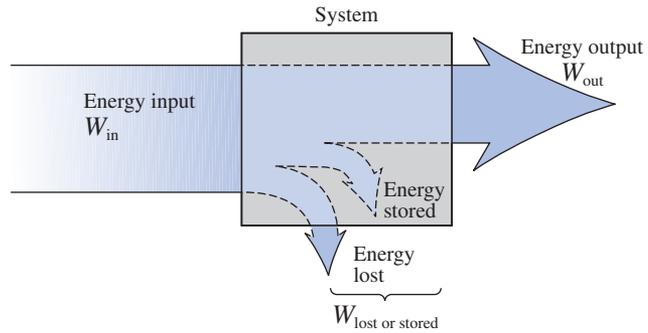


FIG. 4.18
Energy flow through a system.

Conservation of energy requires that

$$\text{Energy input} = \text{energy output} + \text{energy lost or stored by the system}$$

Dividing both sides of the relationship by t gives

$$\frac{W_{in}}{t} = \frac{W_{out}}{t} + \frac{W_{\text{lost or stored by the system}}}{t}$$

Since $P = W/t$, we have the following:

$$P_i = P_o + P_{\text{lost or stored}} \quad (W) \quad (4.19)$$

The **efficiency** (η) of the system is then determined by the following equation:

$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}}$$

and
$$\eta = \frac{P_o}{P_i} \quad (\text{decimal number}) \quad (4.20)$$

where η (the lowercase Greek letter *eta*) is a decimal number. Expressed as a percentage,

$$\eta\% = \frac{P_o}{P_i} \times 100\% \quad (\text{percent}) \quad (4.21)$$

In terms of the input and output energy, the efficiency in percent is given by



$$\eta\% = \frac{W_o}{W_i} \times 100\% \quad (\text{percent}) \quad (4.22)$$

The maximum possible efficiency is 100%, which occurs when $P_o = P_i$, or when the power lost or stored in the system is zero. Obviously, the greater the internal losses of the system in generating the necessary output power or energy, the lower the net efficiency.

EXAMPLE 4.15 A 2 hp motor operates at an efficiency of 75%. What is the power input in watts? If the applied voltage is 220 V, what is the input current?

Solution:

$$\eta\% = \frac{P_o}{P_i} \times 100\%$$
$$0.75 = \frac{(2 \text{ hp})(746 \text{ W/hp})}{P_i}$$

and $P_i = \frac{1492 \text{ W}}{0.75} = \mathbf{1989.33 \text{ W}}$

$$P_i = EI \quad \text{or} \quad I = \frac{P_i}{E} = \frac{1989.33 \text{ W}}{220 \text{ V}} = \mathbf{9.04 \text{ A}}$$

EXAMPLE 4.16 What is the output in horsepower of a motor with an efficiency of 80% and an input current of 8 A at 120 V?

Solution:

$$\eta\% = \frac{P_o}{P_i} \times 100\%$$
$$0.80 = \frac{P_o}{(120 \text{ V})(8 \text{ A})}$$

and $P_o = (0.80)(120 \text{ V})(8 \text{ A}) = 768 \text{ W}$

with $768 \text{ W} \left(\frac{1 \text{ hp}}{746 \text{ W}} \right) = \mathbf{1.03 \text{ hp}}$

EXAMPLE 4.17 If $\eta = 0.85$, determine the output energy level if the applied energy is 50 J.

Solution:

$$\eta = \frac{W_o}{W_i} \Rightarrow W_o = \eta W_i = (0.85)(50 \text{ J}) = \mathbf{42.5 \text{ J}}$$

The very basic components of a generating (voltage) system are depicted in Fig. 4.19. The source of mechanical power is a structure such as a paddlewheel that is turned by water rushing over the dam. The gear train ensures that the rotating member of the generator is turning at rated speed. The output voltage must then be fed through a transmission system to the load. For each component of the system, an input and

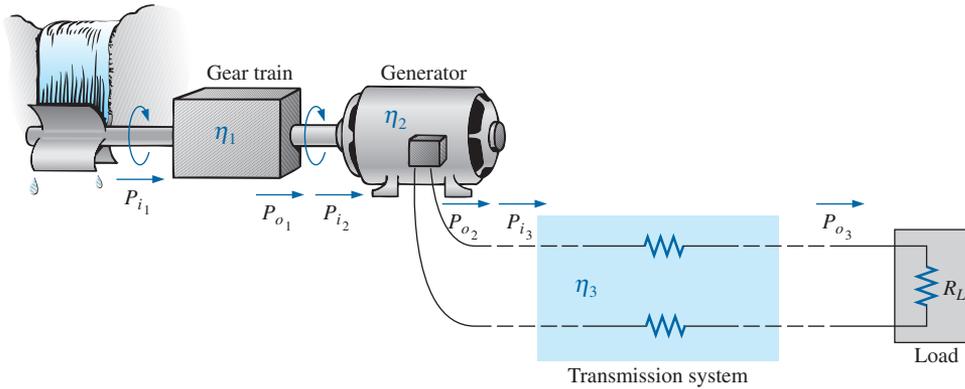


FIG. 4.19
Basic components of a generating system.

output power have been indicated. The efficiency of each system is given by

$$\eta_1 = \frac{P_{o1}}{P_{i1}} \quad \eta_2 = \frac{P_{o2}}{P_{i2}} \quad \eta_3 = \frac{P_{o3}}{P_{i3}}$$

If we form the product of these three efficiencies,

$$\eta_1 \cdot \eta_2 \cdot \eta_3 = \frac{P_{o1}}{P_{i1}} \cdot \frac{P_{o2}}{P_{i2}} \cdot \frac{P_{o3}}{P_{i3}} = \frac{P_{o3}}{P_{i1}}$$

and substitute the fact that $P_{i2} = P_{o1}$ and $P_{i3} = P_{o2}$, we find that the quantities indicated above will cancel, resulting in P_{o3}/P_{i1} , which is a measure of the efficiency of the entire system.

In general, for the representative cascaded system in Fig. 4.20,

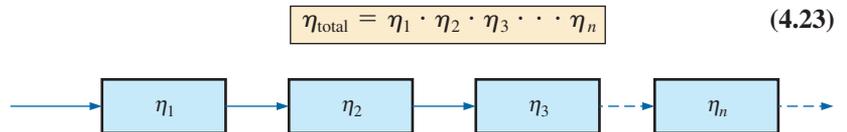


FIG. 4.20
Cascaded system.

EXAMPLE 4.18 Find the overall efficiency of the system in Fig. 4.19 if $\eta_1 = 90\%$, $\eta_2 = 85\%$, and $\eta_3 = 95\%$.

Solution:

$$\eta_T = \eta_1 \cdot \eta_2 \cdot \eta_3 = (0.90)(0.85)(0.95) = 0.727, \text{ or } \mathbf{72.7\%}$$

EXAMPLE 4.19 If the efficiency η_1 drops to 40%, find the new overall efficiency and compare the result with that obtained in Example 4.18.

Solution:

$$\eta_T = \eta_1 \cdot \eta_2 \cdot \eta_3 = (0.40)(0.85)(0.95) = 0.323, \text{ or } \mathbf{32.3\%}$$

Certainly 32.3% is noticeably less than 72.7%. The total efficiency of a cascaded system is therefore determined primarily by the lowest efficiency (weakest link) and is less than (or equal to if the remaining efficiencies are 100%) the least efficient link of the system.

4.7 CIRCUIT BREAKERS, GFCIs, AND FUSES

The incoming power to any large industrial plant, heavy equipment, simple circuit in the home, or to meters used in the laboratory must be limited to ensure that the current through the lines is not above the rated value. Otherwise, the conductors or the electrical or electronic equipment may be damaged, and dangerous side effects such as fire or smoke may result.

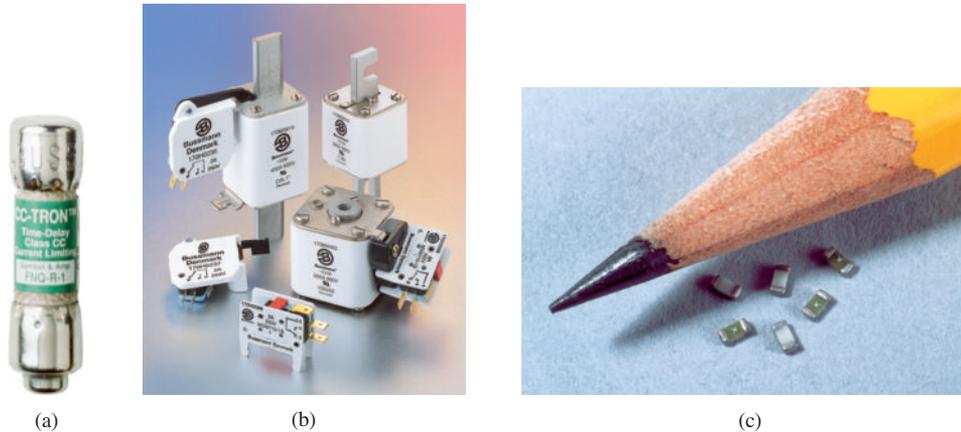


FIG. 4.21

Fuses: (a) CC-TRON® (0–10 A); (b) Semitron (0–600 A); (c) subminiature surface-mount chip fuses.
(Courtesy of Cooper Bussmann.)

To limit the current level, **fuses** or **circuit breakers** are installed where the power enters the installation, such as in the panel in the basement of most homes at the point where the outside feeder lines enter the dwelling. The fuses in Fig. 4.21 have an internal metallic conductor through which the current passes; a fuse begins to melt if the current through the system exceeds the rated value printed on the casing. Of course, if the fuse melts, the current path is broken and the load in its path is protected.

In homes built in recent years, fuses have been replaced by circuit breakers such as those appearing in Fig. 4.22. When the current exceeds rated conditions, an electromagnet in the device will have sufficient strength to draw the connecting metallic link in the breaker out of the circuit and open the current path. When conditions have been corrected, the breaker can be reset and used again.

The most recent National Electrical Code requires that outlets in the bathroom and other sensitive areas be of the ground fault circuit interrupt (GFCI) variety; GFCIs (often abbreviated GFI) are designed to trip more quickly than the standard circuit breaker. The commercial unit in Fig. 4.23 trips in 5 ms. It has been determined that 6 mA is the maximum level that most individuals can be exposed to for a short period of time without the risk of serious injury. A current higher than 11 mA can cause involuntary muscle contractions that could prevent a person from letting go of the conductor and possibly cause him or her to enter a state of shock. Higher currents lasting more than a second can cause the heart to go into fibrillation and possibly cause death in a few minutes. The GFCI is able to react as quickly as it does by sensing the difference between the input and output currents to the outlet; the currents should be the same if everything is working properly. An errant path, such as through an individual, establishes a difference in the two current levels and causes the breaker to trip and disconnect the power source.



FIG. 4.22

Circuit breakers.
(Courtesy of Potter and Brumfield Division, AMF, Inc.)



FIG. 4.23

Ground fault circuit interrupter (GFCI): 125 V ac, 60 Hz, 15 A outlet.
(Reprinted with permission of the Leviton Manufacturing Company. Leviton SmartLock™ GFCI.)



4.8 APPLICATIONS

Microwave Oven

It is probably safe to say that most homes today have a microwave oven (see Fig. 4.24). Most users are not concerned with its operating efficiency. However, it is interesting to learn how the units operate and apply some of the theory presented in this chapter.

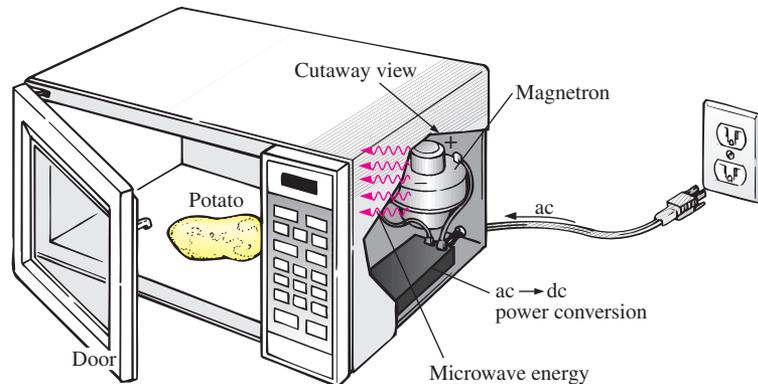


FIG. 4.24
Microwave oven.

First, some general comments. Most microwaves are rated at 500 W to 1200 W at a frequency of 2.45 GHz (almost 2.5 billion cycles per second compared to the 60 cycles per second for the ac voltage at the typical home outlet—details in Chapter 13). The heating occurs because the water molecules in the food are vibrated at such a high frequency that the friction with neighboring molecules causes the heating effect. Since it is the high frequency of vibration that heats the food, there is no need for the material to be a conductor of electricity. However, any metal placed in the microwave can act as an antenna (especially if it has any points or sharp edges) that will attract the microwave energy and reach very high temperatures. In fact, a browning skillet is now made for microwaves that has some metal embedded in the bottom and sides to attract the microwave energy and raise the temperature at the surface between the food and skillet to give the food a brown color and a crisp texture. Even if the metal did not act as an antenna, it is a good conductor of heat and could get quite hot as it draws heat from the food.

Any container with low moisture content can be used to heat foods in a microwave. Because of this requirement, manufacturers have developed a whole line of microwave cookware that is very low in moisture content. Theoretically, glass and plastic have very little moisture content, but even so when heated in the oven for a minute or so, they do get warm. It could be the moisture in the air that clings to the surface of each or perhaps the lead used in good crystal. In any case, microwaves should be used only to prepare food. They were not designed to be dryers or evaporators.

The instructions with every microwave specify that the oven should not be turned on when empty. Even though the oven may be empty, microwave energy will be generated and will make every effort to find a channel for absorption. If the oven is empty, the energy might be attracted to the oven itself and could do some damage. To demonstrate that a dry empty glass or plastic container will not attract a significant amount of microwave energy, place two glasses in an oven, one with water and the other empty. After one minute, you will find the glass with the water quite



warm due to the heating effect of the hot water while the other is close to its original temperature. In other words, the water created a heat sink for the majority of the microwave energy, leaving the empty glass as a less attractive path for heat conduction. Dry paper towels and plastic wrap can be used in the oven to cover dishes since they initially have low water molecule content, and paper and plastic are not good conductors of heat. However, it would be very unsafe to place a paper towel in an oven alone because, as said above, the microwave energy will look for an absorbing medium and could set the paper on fire.

The cooking of food by a conventional oven is from the outside in. The same is true for microwave ovens, but they have the additional advantage of being able to penetrate the outside few centimeters of the food, reducing the cooking time substantially. The cooking time with a microwave oven is related to the amount of food in the oven. Two cups of water will take longer to heat than one cup, although it is not a linear relationship so it won't take twice as long—perhaps 75% to 90% longer. Eventually, if you place enough food in the microwave oven and compare the longer cooking time to that with a conventional oven, you will reach a crossover point where it would be just as wise to use a conventional oven and get the texture in the food you might prefer.

The basic construction of the microwave is depicted in Fig. 4.24. It uses a 120 V ac supply which is then converted through a high-voltage transformer to one having peak values approaching 5000 V (at substantial current levels)—sufficient warning to leave microwave repair to the local service location. Through the rectifying process briefly described in Chapter 2, a high dc voltage of a few thousand volts is generated that appears across a magnetron. The magnetron, through its very special design (currently the same design as in WW II when it was invented by the British for their high-power radar units), generates the required 2.45 GHz signal for the oven. It should be pointed out also that the magnetron has a specific power level of operation that cannot be controlled—once it's on, it's on at a set power level. One may then wonder how the cooking temperature and duration can be controlled. This is accomplished through a controlling network that determines the amount of off and on time during the input cycle of the 120 V supply. Higher temperatures are achieved by setting a high ratio of on to off time, while low temperatures are set by the reverse action.

One unfortunate characteristic of the magnetron is that in the conversion process, it generates a great deal of heat that does not go toward the heating of the food and that must be absorbed by heat sinks or dispersed by a cooling fan. Typical conversion efficiencies are between 55% and 75%. Considering other losses inherent in any operating system, it is reasonable to assume that most microwaves are between 50% and 60% efficient. However, the conventional oven with its continually operating exhaust fan and heating of the oven, cookware, surrounding air, and so on, also has significant losses, even if it is less sensitive to the amount of food to be cooked. All in all, the convenience factor is probably the other factor that weighs the heaviest in this discussion. It also leaves the question of how our time is figured into the efficiency equation.

For specific numbers, let us consider the energy associated with baking a 5-oz potato in a 1200 W microwave oven for 5 min if the conversion efficiency is an average value of 55%. First, it is important to realize that when a unit is rated as 1200 W, that is the rated power drawn from the line during the cooking process. If the microwave is plugged into a 120 V outlet, the current drawn is

$$I = P/V = 1200 \text{ W}/120 \text{ V} = 10.0 \text{ A}$$



which is a significant level of current. Next, we can determine the amount of power dedicated solely to the cooking process by using the efficiency level. That is,

$$P_o = \eta P_i = (0.55)(1200 \text{ W}) = 660 \text{ W}$$

The energy transferred to the potato over a period of 5 min can then be determined from

$$W = Pt = (660 \text{ W})(5 \text{ min})(60 \text{ s/1 min}) = 198 \text{ kJ}$$

which is about half of the energy (nutritional value) derived from eating a 5-oz potato. The number of kilowatthours drawn by the unit is determined from

$$W = Pt/1000 = (1200 \text{ W})(5/60 \text{ h})/1000 = 0.1 \text{ kWh}$$

At a rate of 10¢/kWh we find that we can cook the potato for 1 penny—relatively speaking, pretty cheap. A typical 1550 W toaster oven would take an hour to heat the same potato, using 1.55 kWh and costing 15.5 cents—a significant increase in cost.

Household Wiring

A number of facets of household wiring can be discussed without examining the manner in which they are physically connected. In the following chapters, additional coverage is provided to ensure that you develop a solid fundamental understanding of the overall household wiring system. At the very least you will establish a background that will permit you to answer questions that you should be able to answer as a student of this field.

The one specification that defines the overall system is the maximum current that can be drawn from the power lines since the voltage is fixed at 120 V or 240 V (sometimes 208 V). For most older homes with a heating system other than electric, a 100 A service is the norm. Today, with all the electronic systems becoming commonplace in the home, many people are opting for the 200 A service even if they don't have electric heat. A 100 A service specifies that the maximum current that can be drawn through the power lines into your home is 100 A. Using the line-to-line rated voltage and the full-service current (and assuming all resistive-type loads), we can determine the maximum power that can be delivered using the basic power equation:

$$P = EI = (240 \text{ V})(100 \text{ A}) = 24,000 \text{ W} = 24 \text{ kW}$$

This rating reveals that the total rating of all the units turned on in the home cannot exceed 24 kW at any one time. If it did, we could expect the main breaker at the top of the power panel to open. Initially, 24 kW may seem like quite a large rating, but when you consider that a self-cleaning electric oven may draw 12.2 kW, a dryer 4.8 kW, a water heater 4.5 kW, and a dishwasher 1.2 kW, we are already at 22.7 kW (if all the units are operating at peak demand), and we haven't turned the lights or TV on yet. Obviously, the use of an electric oven alone may strongly suggest considering a 200 A service. However, be aware that seldom are all the burners of a stove used at once, and the oven incorporates a thermostat to control the temperature so that it is not on all the time. The same is true for the water heater and dishwasher, so the chances of all the units in a home demanding full service at the same time is very slim. Certainly, a typical home with electric heat that may draw 16 kW just for heating in cold weather must consider a 200 A service. You must also understand that there is some leeway in maximum ratings for safety purposes. In

other words, a system designed for a maximum load of 100 A can accept a slightly higher current for short periods of time without significant damage. For the long term, however, it should not be exceeded.

Changing the service to 200 A is not simply a matter of changing the panel in the basement—a new, heavier line must be run from the road to the house. In some areas feeder cables are aluminum because of the reduced cost and weight. In other areas, aluminum is not permitted because of its temperature sensitivity (expansion and contraction), and copper must be used. In any event, when aluminum is used, the contractor must be absolutely sure that the connections at both ends are very secure. The National Electric Code specifies that 100 A service must use a #4 AWG copper conductor or #2 aluminum conductor. For 200 A service, a 2/0 copper wire or a 4/0 aluminum conductor must be used as shown in Fig. 4.25(a). A 100 A or 200 A service must have two lines and a service neutral as shown in Fig. 4.25(b). Note in Fig. 4.25(b) that the lines are coated and insulated from each other, and the service neutral is spread around the inside of the wire coating. At the terminal point, all the strands of the service neutral are gathered together and securely attached to the panel. It is fairly obvious that the cables of Fig. 4.25(a) are stranded for added flexibility.



FIG. 4.25

200 A service conductors: (a) 4/0 aluminum and 2/0 copper; (b) three-wire 4/0 aluminum service.

Within the system, the incoming power is broken down into a number of circuits with lower current ratings utilizing 15 A, 20 A, 30 A, and 40 A protective breakers. Since the load on each breaker should not exceed 80% of its rating, in a 15 A breaker the maximum current should be limited to 80% of 15 A, or 12 A, with 16 A for a 20 A breaker, 24 A for a 30 A breaker, and 32 A for a 40 A breaker. The result is that a home with 200 A service can theoretically have a maximum of 12 circuits ($200 \text{ A} / 16 \text{ A} = 12.5$) utilizing the 16 A maximum current ratings associated with 20 A breakers. However, if aware of the loads on each circuit, electricians can install as many circuits as they feel appropriate. The code further specifies that a #14 wire should not carry a current in excess of 15 A, a #12 in excess of 20 A, and a #10 in excess of 30 A. Thus, #12 wire is now the most common for general home wiring to ensure that it can handle any excursions beyond 15 A on the 20 A breaker (the most common breaker size). The #14 wire is often used in conjunction with the #12 wire in areas where it is known that the current levels are limited. The #10 wire is typically used for high-demand appliances such as dryers and ovens.

The circuits themselves are usually broken down into those that provide lighting, outlets, and so on. Some circuits (such as ovens and dryers)



require a higher voltage of 240 V, obtained by using two power lines and the neutral. The higher voltage reduces the current requirement for the same power rating, with the net result that the appliance can usually be smaller. For example, the size of an air conditioner with the same cooling ability is measurably smaller when designed for a 240 V line than when designed for 120 V. Most 240 V lines, however, demand a current level that requires 30 A or 40 A breakers and special outlets to ensure that appliances rated at 120 V are not connected to the same outlet. If time permits, check the panel in your home and take note of the number of circuits—in particular, the rating of each breaker and the number of 240 V lines indicated by breakers requiring two slots of the panel. Total the current ratings of all the breakers in your panel, and explain, using the above information, why the total exceeds your feed level.

For safety sake, grounding is a very important part of the electrical system in your home. The National Electric Code requires that the neutral wire of a system be grounded to an earth-driven rod, a metallic water piping system of 10 ft or more, or a buried metal plate. That ground is then passed on through the electrical circuits of the home for further protection. In a later chapter, the details of the connections and grounding methods are discussed.

4.9 COMPUTER ANALYSIS

Now that a complete circuit has been introduced and examined in detail, we can begin the application of computer methods. As mentioned in Chapter 1, three software packages will be introduced to demonstrate the options available with each and the differences that exist. All have a broad range of support in the educational and industrial communities. The student version of PSpice (OrCAD Release 10 from Cadence Design Systems) receives the most attention, followed by Multisim. Each approach has its own characteristics with procedures that must be followed exactly; otherwise, error messages will appear. Do not assume that you can “force” the system to respond the way you would prefer—every step is well defined, and one error on the input side can result in results of a meaningless nature. At times you may believe that the system is in error because you are absolutely sure you followed every step correctly. In such cases, accept the fact that something was entered incorrectly, and review all your work very carefully. All it takes is a comma instead of a period or a decimal point to generate incorrect results.

Be patient with the learning process; keep notes of specific maneuvers that you learn; and don't be afraid to ask for help when you need it. For each approach, there is always the initial concern about how to start and proceed through the first phases of the analysis. However, be assured that with time and exposure you will work through the required maneuvers at a speed you never would have expected. In time you will be absolutely delighted with the results you can obtain using computer methods.

In this section, Ohm's law is investigated using the software packages PSpice and Multisim to analyze the circuit in Fig. 4.26. Both require that the circuit first be “drawn” on the computer screen and then analyzed (simulated) to obtain the desired results. As mentioned above, the analysis program cannot be changed by the user. The proficient user is one who can draw the most out of a computer software package.

Although the author feels that there is sufficient material in the text to carry a new student of the material through the programs provided, be aware that this is not a computer text. Rather, it is one whose primary pur-

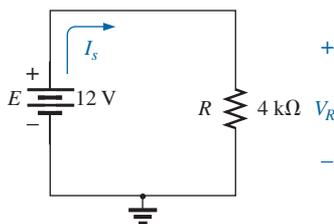


FIG. 4.26

Circuit to be analyzed using PSpice and Multisim.



pose is simply to introduce the different approaches and how they can be applied effectively. Today, some excellent texts and manuals are available that cover the material in a great deal more detail and perhaps at a slower pace. In fact, the quality of the available literature has improved dramatically in recent years.

PSpice

Readers who were familiar with older versions of PSpice such as Versions 8 and 9.2 will find that the changes in Version 10 are primarily in the front end and the simulation process. After executing a few programs, you will find that most of the procedures you learned from older versions will be applicable here also—at least the sequential process has a number of strong similarities.

Once OrCAD Version 10 has been installed, you must first open a **Folder** in the **C:** drive for storage of the circuit files that result from the analysis. Be aware, however, that

once the folder has been defined, it does not have to be defined for each new project unless you choose to do so. If you are satisfied with one location (folder) for all your projects, this is a one-time operation that does not have to be repeated with each network.

To establish the **Folder**, simply right-click the mouse on **Start** at the bottom left of the screen to obtain a listing that includes **Explore**. Select **Explore** to obtain the **Start Menu** dialog box and then use the sequence **File-New Folder** to open a new folder. Type in **PSpice** (the author's choice) and left-click to install. Then exit (using the **X** at the top right of the screen). The folder **PSpice** will be used for all the projects you plan to work on in this text.

Our first project can now be initiated by double-clicking on the **OrCAD 10.0 Demo** icon on the screen, or you can use the sequence **Start All Programs-CAPTURE CIS DEMO**. The resulting screen has only a few active keys on the top toolbar. The first keypad at the top left is the **Create document** key (or you can use the sequence **File-New Project**). A **New Project** dialog box opens in which you must enter the **Name** of the project. For our purposes we will choose **PSpice 4-1** as shown in the **SCHEMATIC** listing in Fig. 4.27 and select **Analog or Mixed A/D** (to be used for all the analyses of this text). Note at the bottom of the dialog box that the **Location** appears as **C:\PSpice** as set above. Click **OK**, and another dialog box appears titled **Create PSpice Project**. Select **Create a blank project** (again, for all the analyses to be performed in this text). Click **OK**, and a third toolbar appears at the top of the screen with some of the keys enabled. An additional toolbar can be established along the right edge of the screen by left-clicking anywhere on the **SCHEMATIC 1: PAGE 1** screen. A **Project Manager Window** appears with **PSpice 4-1** next to an icon and an associated + sign in a small square. Clicking on the + sign will take the listing a step further to **SCHEMATIC1**. Click + again, and **PAGE1** appears; clicking on a – sign reverses the process. Double-clicking on **PAGE1** creates a working window titled **SCHEMATIC1: PAGE1**, revealing that a project can have more than one schematic file and more than one associated page. The width and height of the window can be adjusted by grabbing an edge until you see a double-headed arrow and dragging the border to the desired location. Either window on the screen can be moved by clicking on the top heading to make it dark blue and then dragging it to any location.

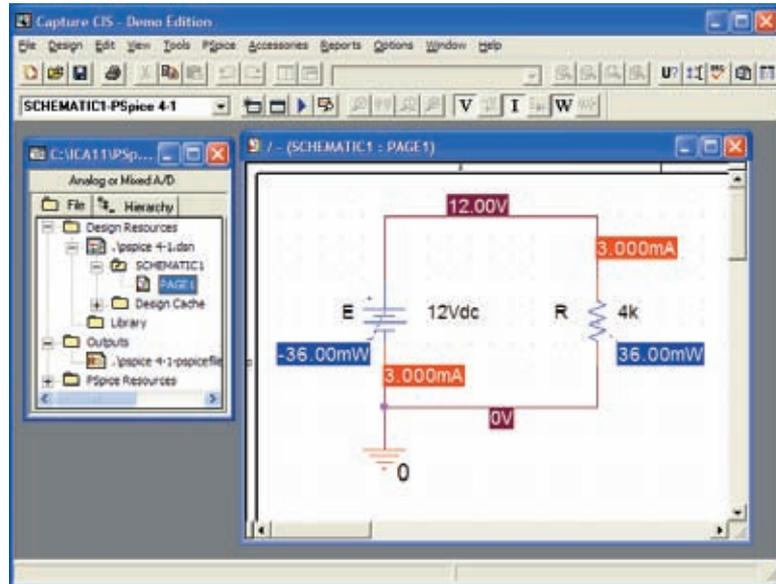


FIG. 4.27

Using PSpice to determine the voltage, current, and power levels for the circuit in Fig. 4.26.

Now you are ready to build the simple circuit in Fig. 4.26. Select the **Place a part** key (the second key from the top of the toolbar on the right) to obtain the **Place Part** dialog box. Since this is the first circuit to be constructed, you must ensure that the parts appear in the list of active libraries. Select **Add Library-Browse File**, and select **analog.olb**, and when it appears under the **File name** heading, select **Open**. It will now appear in the **Libraries** listing at the bottom left of the dialog box. Repeat for the **eval.olb** and **source.olb** libraries. All three files are required to build the networks appearing in this text. However, it is important to realize that

once the library files have been selected, they will appear in the active listing for each new project without having to add them each time—a step, such as the Folder step above, that does not have to be repeated with each similar project.

Click **OK**, and you can now place components on the screen. For the dc voltage source, first select the **Place a part** key and then select **SOURCE** in the library listing. Under **Part List**, a list of available sources appears; select **VDC** for this project. Once **VDC** has been selected, its symbol, label, and value appears on the picture window at the bottom right of the dialog box. Click **OK**, and the **VDC** source follows the cursor across the screen. Move it to a convenient location, left-click the mouse, and it will be set in place as shown in Fig. 4.27. Since only one source is required, right-clicking results in a list of options, in which **End Mode** appears at the top. Choosing this option ends the procedure, leaving the source in a red dashed box. If it is red, it is an active mode and can be operated on. Left-clicking puts the source in place and removes the red active status.

One of the most important steps in the procedure is to ensure that a 0 V ground potential is defined for the network so that voltages at any point in the network have a reference point. *The result is a requirement that every network must have a ground defined.* For our purposes, the **0/SOURCE**



option will be our choice when the **GND** key is selected. It ensures that one side of the source is defined as 0 V. It is obtained by selecting the ground symbol from the toolbar at the right edge of the screen. A **Place Ground** dialog box appears under which **0/SOURCE** can be selected. Finally, you need to add a resistor to the network by selecting the **Place a part** key again and then selecting the **ANALOG** library. Scrolling the options, note that **R** appears and should be selected. Click **OK**, and the resistor appears next to the cursor on the screen. Move it to the desired location and click it in place. Then right-click and **End Mode**, and the resistor has been entered into the schematic's memory. Unfortunately, the resistor ended up in the horizontal position, and the circuit of Fig. 4.26 has the resistor in the vertical position. No problem: Simply select the resistor again to make it red, and right-click. A listing appears in which **Rotate** is an option. It turns the resistor 90° in the counterclockwise direction. It can also be rotated 90° by simultaneously selecting **Ctrl-R**.

All the required elements are on the screen, but they need to be connected. To accomplish this, select the **Place a wire** key that looks like a step in the right toolbar. The result is a crosshair with the center that should be placed at the point to be connected. Place the crosshair at the top of the voltage source, and left-click it once to connect it to that point. Then draw a line to the end of the next element, and click again when the crosshair is at the correct point. A red line results with a square at each end to confirm that the connection has been made. Then move the crosshair to the other elements, and build the circuit. Once everything is connected, right-clicking provides the **End Mode** option. Don't forget to connect the source to ground as shown in Fig. 4.27.

Now you have all the elements in place, but their labels and values are wrong. To change any parameter, simply double-click on the parameter (the label or the value) to obtain the **Display Properties** dialog box. Type in the correct label or value, click **OK**, and the quantity is changed on the screen. The labels and values can be moved by simply clicking on the center of the parameter until it is closely surrounded by the four small squares and then dragging it to the new location. Left-clicking again deposits it in its new location.

Finally, you can initiate the analysis process, called **Simulation**, by selecting the **Create a new simulation profile** key at the far left of the second toolbar down—it resembles a data page with a star in the top left corner. A **New Simulation** dialog box opens that first asks for the **Name** of the simulation. The **New Simulation** dialog box can also be obtained by using the sequence **PSpice-New Simulation Profile**. **Bias Point** is entered for a dc solution, and **none** is left in the **Inherit From** request. Then select **Create**, and a **Simulation Settings** dialog box appears in which **Analysis-Analysis Type-Bias Point** is sequentially selected. Click **OK**, and select the **Run** key (which looks like an isolated blue arrowhead) or choose **PSpice-Run** from the menu bar. An **Output Window** opens that appears to be somewhat inactive. It will not be used in the current analysis, so close (**X**) the window, and the circuit in Fig. 4.27 appears with the voltage, current, and power levels of the network. The voltage, current, or power levels can be removed (or replaced) from the display by simply selecting the **V**, **I**, or **W** in the third toolbar from the top. Individual values can be removed by simply selecting the value and pressing the **Delete** key or the scissors key in the top menu bar. Resulting values can be moved by simply left-clicking the value and dragging it to the desired location.

Note in Fig. 4.27 that the current is 3 mA (as expected) at each point in the network, and the power delivered by the source and dissipated by



the resistor is the same, or 36 mW. There are also 12 V across the resistor as required by the configuration.

There is no question that this procedure seems long for such a simple circuit. However, keep in mind that we needed to introduce many new facets of using PSpice that are not discussed again. By the time you finish analyzing your third or fourth network, the procedure will be routine and easy to do.

Multisim

For comparison purposes, Multisim is also used to analyze the circuit in Fig. 4.26. Although there are differences between PSpice and Multisim, such as initiating the process, constructing the networks, making the measurements, and setting up the simulation procedure, there are sufficient similarities between the two approaches to make it easier to learn one if you are already familiar with the other. The similarities will be obvious only if you make an attempt to learn both. One of the major differences between the two is the option to use actual instruments in Multisim to make the measurements—a positive trait in preparation for the laboratory experience. However, in Multisim, you may not find the extensive list of options available with PSpice. In general, however, both software packages are well prepared to take us through the types of analyses to be encountered in this text.

When the **Multisim** icon is selected from the opening window, a screen appears with the heading **Circuit 1-Multisim**. A menu bar appears across the top of the screen, with a **Standard toolbar** directly below as shown in Fig. 4.28. Initially, the third level includes the

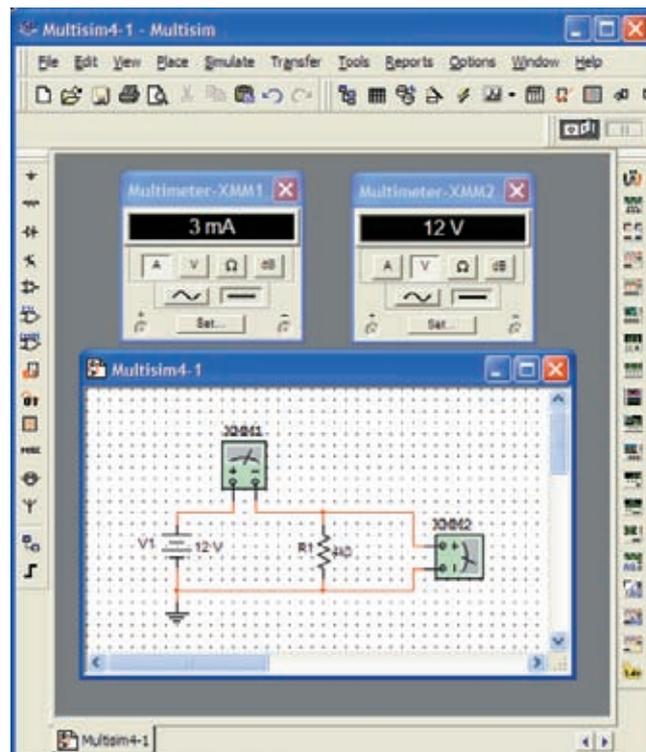


FIG. 4.28

Using Multisim to determine the voltage and current levels for the circuit of Fig. 4.26.



Component toolbar, Ladder diagram toolbar and Virtual toolbar. For our purposes, the **Ladder diagram toolbar** and **Virtual toolbar** were deleted. You do this by selecting **View** from the top menu bar and then **Toolbars**. By removing the check next to **Ladder diagram** and **Virtual**, both toolbars are deleted. The remaining **Component toolbar** can be moved to the left edge by grabbing an edge of the toolbar and moving to the left edge as shown in Fig. 4.28. Some users of Multisim prefer to leave the **Virtual toolbar** and use it more than the **Component toolbar**. Either approach is simply a matter of preference. The **Virtual toolbar** provides a list of components for which the value must be set. The **Components list** includes the same list under **Basic** but also includes a list of standard values. The heading can be changed to **Multisim 4-1** by selecting **File-Save As** to open the **Save As** dialog box. Enter **Multisim 4-1** as the **File name** to obtain the listing of Fig. 4.28.

For the placement of components, **View-Show Grid** was selected so that a grid would appear on the screen. As you place an element, it will automatically be placed in a relationship specific to the grid structure.

To build the circuit in Fig. 4.26, first take the cursor and place it on the battery symbol at the top of the component toolbar at the left of the screen. Left-click and a list of sources will appear. Under **Component**, select **DC-POWER**. The symbol appears in the adjoining box area. Click **OK**. The battery symbol appears on the screen next to the location of the cursor. Move the cursor to the desired location, and left-click to set the battery symbol in place. The operation is complete. If you want to delete the source, simply left-click on the symbol again to create a dashed rectangle around the source. These rectangles indicate that the source is in the active mode and can be operated on. If you want to delete it, click on the **Delete** key or select the scissor keypad on the top toolbar. If you want to modify the source, right-click *outside* the rectangle, and you get one list. Right-click *within* the rectangle, and you have a different set of options. At any time, if you want to remove the active state, left-click anywhere on the screen. If you want to move the source, click on the source symbol to create the rectangle, but do not release the mouse. Hold it down and drag the source to the preferred location. When the source is in place, release the mouse. Click again to remove the active state. *From now on, whenever possible, the word click means a left-click.* The need for a right click will continue to be spelled out.

For the simple circuit in Fig. 4.28, you need to place a resistor across the source. Select the second keypad down that looks like a resistor symbol. A dialog box opens with a **Family** listing. Selecting **RESISTOR** results in a list of standard values that can be quickly selected for the deposited resistor. However, in this case, you want to use a 4 k Ω resistor, which is not a standard value, so you must choose the **BASIC_VIRTUAL** option. Recall that the term *virtual* indicates that we can set the parameters of the component. When **BASIC_VIRTUAL** is selected, a **Component** list appears under which **RESISTOR_VIRTUAL** is chosen resulting in the resistor symbol in the symbol box. Select **OK** to place the resistor on the grid structure which can then be deposited as described for the supply. Because it is the first resistor to be placed, the resistor is labeled **R1**, has a value of 1 k Ω as its initial value, and appears in the horizontal position.

In Fig. 4.26, the resistor is in the vertical position, so a rotation must be made. Click on the resistor to obtain the active state and then right-click within the rectangle. A number of options appear, including **Cut**, **Delete**, **Flip**, **Rotate**, **Font**, and **Color**. To rotate 90° counterclockwise, select that option, and the resistor is automatically rotated 90°. Now, as with the battery, to place the resistor in position, click on the resistor symbol to create the rectangle and then, holding it down, drag the resistor



to the desired position. When the resistor is in place, release the mouse, and click again to remove the rectangle—the resistor is in place.

Finally, you need a ground for all networks. Going back to the **Sources** parts bin, find **GROUND**, which is the fourth option down under **Component**. Select **GROUND** and place it on the screen below the voltage source as shown in Fig. 4.28. Now, before connecting the components together, move the labels and the value of each component to the relative positions shown in Fig. 4.28. Do this by clicking on the label or value to create a small set of squares around the element and then dragging the element to the desired location. Release the mouse, and then click again to set the element in place. To change the label or value, double-click on the label (such as **V1**) to open a **POWER_SOURCES** dialog box. Select **Label** and enter **E** as the **Reference Designation (Ref Des)**. Then, before leaving the dialog box, go to **Value** and change the value if necessary. It is very important to realize that you cannot type in the units where the **V** now appears to the right of the value. The prefix is controlled by the scroll keys at the left of the unit of measure. For practice, try the scroll keys, and you will find that you can go from **pV** to **TV**. For now, leave it as **V**. Click **OK**, and both have been changed on the screen. The same process can be applied to the resistive element to obtain the label and value appearing in Fig. 4.28.

Next, you need to tell the system which results should be generated and how they should be displayed. For this example, we use a multimeter to measure both the current and the voltage of the circuit. The **Multimeter** is the first option in the list of instruments appearing in the toolbar to the right of the screen. When selected, it appears on the screen and can be placed anywhere using the same procedure defined for the components above. The voltmeter was turned clockwise using the procedure described above for the elements. Double-click on the meter symbol, and a **Multimeter** dialog box opens in which the function of the meter must be defined. Since the meter **XMM1** will be used as an ammeter, select the letter **A** and the horizontal line to indicate dc level. There is no need to select **Set** for the default values since they have been chosen for the broad range of applications. The dialog meters can be moved to any location by clicking on their heading bar to make it dark blue and then dragging the meter to the preferred position. For the voltmeter, **V** and the horizontal bar were selected as shown in Fig. 4.28.

Finally, the elements need to be connected. To do this, bring the cursor to one end of an element, say, the top of the voltage source. A small dot and a crosshair appears at the top end of the element. Click once, follow the path you want, and place the crosshair over the positive terminal of the ammeter. Click again, and the wire appears in place.

At this point, you should be aware that the software package has its preferences about how it wants the elements to be connected. That is, you may try to draw it one way, but the computer generation may be a different path. Eventually, you will learn these preferences and can set up the network to your liking. Now continue making the connections appearing in Fig. 4.28, moving elements or adjusting lines as necessary. Be sure that the small dot appears at any point where you want a connection. Its absence suggests that the connection has not been made and the software program has not accepted the entry.

You are now ready to run the program and view the solution. The analysis can be initiated in a number of ways. One option is to select **Simulate** from the top toolbar, followed by **RUN**. Another is to select the **Simulate** key in the design bar grouping in the top toolbar. It appears as a sharp, jagged lightning bolt on a black background. The last option, and



the one we use the most, requires an **OFF/ON, 0/1** switch on the screen. It is obtained through **VIEW>Show Simulate Switch** and appears as shown in the top right corner of Fig. 4.28. Using this last option, the analysis (called **Simulation**) is initiated by placing the cursor on the 1 of the switch and left-clicking. The analysis is performed, and the current and voltage appear on the meter as shown in Fig. 4.28. Note that both provide the expected results.

One of the most important things to learn about applying Multisim:

Always stop or end the simulation (clicking on 0 or choosing OFF) before making any changes in the network. When the simulation is initiated, it stays in that mode until turned off.

There was obviously a great deal of material to learn in this first exercise using Multisim. Be assured, however, that as we continue with more examples, you will find the procedure quite straightforward and actually enjoyable to apply.

PROBLEMS

SECTION 4.2 Ohm's Law

1. What is the voltage across a $47\ \Omega$ resistor if the current through it is $2.5\ \text{A}$?
2. What is the current through a $6.8\ \Omega$ resistor if the voltage drop across it is $12\ \text{V}$?
3. How much resistance is required to limit the current to $1.5\ \text{mA}$ if the potential drop across the resistor is $6\ \text{V}$?
4. At starting, what is the current drain on a $12\ \text{V}$ car battery if the resistance of the starting motor is $40\ \text{M}\Omega$?
5. If the current through a $0.02\ \text{M}\Omega$ resistor is $3.6\ \mu\text{A}$, what is the voltage drop across the resistor?
6. If a voltmeter has an internal resistance of $15\ \text{k}\Omega$, find the current through the meter when it reads $62\ \text{V}$.
7. If a refrigerator draws $2.2\ \text{A}$ at $120\ \text{V}$, what is its resistance?
8. If a clock has an internal resistance of $7.5\ \text{k}\Omega$, find the current through the clock if it is plugged into a $120\ \text{V}$ outlet.
9. A washing machine is rated at $4.2\ \text{A}$ at $120\ \text{V}$. What is its internal resistance?
10. A CD player draws $125\ \text{mA}$ when $4.5\ \text{V}$ is applied. What is the internal resistance?
11. The input current to a transistor is $20\ \mu\text{A}$. If the applied (input) voltage is $24\ \text{mV}$, determine the input resistance of the transistor.
12. The internal resistance of a dc generator is $0.5\ \Omega$. Determine the loss in terminal voltage across this internal resistance if the current is $15\ \text{A}$.
- *13.
 - a. If an electric heater draws $9.5\ \text{A}$ when connected to a $120\ \text{V}$ supply, what is the internal resistance of the heater?
 - b. Using the basic relationships of Chapter 2, how much energy is converted in $1\ \text{h}$?
14. In a TV camera, a current of $2.4\ \mu\text{A}$ passes through a resistor of $3.3\ \text{M}\Omega$. What is the voltage drop across the resistor?

SECTION 4.3 Plotting Ohm's Law

15.
 - a. Plot the curve of I (vertical axis) versus V (horizontal axis) for a $120\ \Omega$ resistor. Use a horizontal scale of 0 to $100\ \text{V}$ and a vertical scale of 0 to $1\ \text{A}$.
 - b. Using the graph of part (a), find the current at a voltage of $20\ \text{V}$ and $50\ \text{V}$.
16.
 - a. Plot the I - V curve for a $5\ \Omega$ and a $20\ \Omega$ resistor on the same graph. Use a horizontal scale of 0 to $40\ \text{V}$ and a vertical scale of 0 to $2\ \text{A}$.
 - b. Which is the steeper curve? Can you offer any general conclusions based on results?
 - c. If the horizontal and vertical scales were interchanged, which would be the steeper curve?
17.
 - a. Plot the I - V characteristics of a $1\ \Omega$, $100\ \Omega$, and $1000\ \Omega$ resistor on the same graph. Use a horizontal axis of 0 to $100\ \text{V}$ and a vertical axis of 0 to $100\ \text{A}$.
 - b. Comment on the steepness of a curve with increasing levels of resistance.
- *18. Sketch the internal resistance characteristics of a device that has an internal resistance of $20\ \Omega$ from 0 to $10\ \text{V}$, an internal resistance of $4\ \Omega$ from $10\ \text{V}$ to $15\ \text{V}$, and an internal resistance of $1\ \Omega$ for any voltage greater than $15\ \text{V}$. Use a horizontal scale that extends from 0 to $20\ \text{V}$ and a vertical scale that permits plotting the current for all values of voltage from 0 to $20\ \text{V}$.
- *19.
 - a. Plot the I - V characteristics of a $2\ \text{k}\Omega$, $1\ \text{M}\Omega$, and a $100\ \Omega$ resistor on the same graph. Use a horizontal axis of 0 to $20\ \text{V}$ and a vertical axis of 0 to $10\ \text{mA}$.
 - b. Comment on the steepness of the curve with decreasing levels of resistance.
 - c. Are the curves linear or nonlinear? Why?

SECTION 4.4 Power

20. If $420\ \text{J}$ of energy are absorbed by a resistor in $4\ \text{min}$, what is the power to the resistor?
21. The power to a device is $40\ \text{joules per second (J/s)}$. How long will it take to deliver $640\ \text{J}$?



22. a. How many joules of energy does a 2 W nightlight dissipate in 8 h?
b. How many kilowatt-hours does it dissipate?
23. A resistor of $10\ \Omega$ has charge flowing through it at the rate of 300 coulombs per minute (C/min). How much power is dissipated?
24. How long must a steady current of 1.4 A exist in a resistor that has 3 V across it to dissipate 12 J of energy?
25. What is the power delivered by a 6 V battery if the charge flows at the rate of 48 C/min?
26. The current through a $4\ \text{k}\Omega$ resistor is 7.2 mA. What is the power delivered to the resistor?
27. The power consumed by a $2.2\ \text{k}\Omega$ resistor is 240 mW. What is the current level through the resistor?
28. What is the maximum permissible current in a $120\ \Omega$, 2 W resistor? What is the maximum voltage that can be applied across the resistor?
29. The voltage drop across a transistor network is 12 V. If the total resistance is $5.6\ \text{k}\Omega$, what is the current level? What is the power delivered? How much energy is dissipated in 1 h?
30. If the power applied to a system is 324 W, what is the voltage across the line if the current is 2.7 A?
31. A 1 W resistor has a resistance of $4.7\ \text{M}\Omega$. What is the maximum current level for the resistor? If the wattage rating is increased to 2 W, will the current rating double?
32. A $2.2\ \text{k}\Omega$ resistor in a stereo system dissipates 42 mW of power. What is the voltage across the resistor?
33. A dc battery can deliver 45 mA at 9 V. What is the power rating?
34. What are the "hot" resistance level and current rating of a 120 V, 100 W bulb?
35. What are the internal resistance and voltage rating of a 450 W automatic washer that draws 3.75 A?
36. A calculator with an internal 3 V battery draws 0.4 mW when fully functional.
a. What is the current demand from the supply?
b. If the calculator is rated to operate 500 h on the same battery, what is the ampere-hour rating of the battery?
37. A $20\ \text{k}\Omega$ resistor has a rating of 100 W. What are the maximum current and the maximum voltage that can be applied to the resistor?
42. a. In 10 h an electrical system converts 1200 kWh of electrical energy into heat. What is the power level of the system?
b. If the applied voltage is 208 V, what is the current drawn from the supply?
c. If the efficiency of the system is 82%, how much energy is lost or stored in 10 h?
43. At 9¢ per kilowatt-hour, how long can you play a 250 W color television for \$1?
44. A 60 W bulb is on for one hour. Find the energy converted in
a. watt-hours
b. watt-seconds
c. joules
d. kilowatt-hours
- *45. A small, portable black-and-white television draws 0.455 A at 9 V.
a. What is the power rating of the television?
b. What is the internal resistance of the television?
c. What is the energy converted in 6 h of typical battery life?
- *46. a. If a house is supplied with 120 V, 100 A service, find the maximum power capability.
b. Can the homeowner safely operate the following loads at the same time?
5 hp motor
3000 W clothes dryer
2400 W electric range
1000 W steam iron
c. If all the appliances are used for 2 hours, how much energy is converted in kWh?
- *47. What is the total cost of using the following at 9¢ per kilowatt-hour?
a. 860 W air conditioner for 6 h
b. 4800 W clothes dryer for 30 min
c. 900 W coffee maker for 20 min
d. 110 W stereo for 3.5 h
- *48. What is the total cost of using the following at 9¢ per kilowatt-hour?
a. 200 W fan for 4 h
b. 1200 W dryer for 20 min
c. 70 W radio for 1.5 h
d. 150 W color television set for 2 h 10 min

SECTION 4.5 Energy

38. A $10\ \Omega$ resistor is connected across a 12 V battery.
a. How many joules of energy will it dissipate in 1 min?
b. If the resistor is left connected for 2 min instead of 1 min, will the energy used increase? Will the power dissipation level increase?
39. How much energy in kilowatt-hours is required to keep a 230 W oil-burner motor running 12 h a week for 5 months? (Use $4\frac{1}{2}$ weeks = 1 month.)
40. How long can a 1500 W heater be on before using more than 12 kWh of energy?
41. How much does it cost to use a 24 W radio for 3 h at 9¢ per kilowatt-hour?

SECTION 4.6 Efficiency

49. What is the efficiency of a motor that has an output of 0.5 hp with an input of 395 W?
50. The motor of a power saw is rated 68.5% efficient. If 1.8 hp are required to cut a particular piece of lumber, what is the current drawn from a 120 V supply?
51. What is the efficiency of a dryer motor that delivers 1 hp when the input current and voltage are 4 A and 220 V, respectively?
52. A stereo system draws 2.4 A at 120 V. The audio output power is 50 W.
a. How much power is lost in the form of heat in the system?
b. What is the efficiency of the system?



53. If an electric motor having an efficiency of 76% and operating off a 220 V line delivers 3.6 hp, what input current does the motor draw?
54. A motor is rated to deliver 2 hp.
- If it runs on 110 V and is 90% efficient, how many watts does it draw from the power line?
 - What is the input current?
 - What is the input current if the motor is only 70% efficient?
55. An electric motor used in an elevator system has an efficiency of 90%. If the input voltage is 220 V, what is the input current when the motor is delivering 15 hp?
56. The motor used on a conveyor belt is 85% efficient. If the overall efficiency is 75%, what is the efficiency of the conveyor belt assembly?
57. A 2 hp motor drives a sanding belt. If the efficiency of the motor is 87% and that of the sanding belt is 75% due to slippage, what is the overall efficiency of the system?
58. If two systems in cascade each have an efficiency of 80% and the input energy is 60 J, what is the output energy?
59. The overall efficiency of two systems in cascade is 72%. If the efficiency of one is 0.9, what is the efficiency in percent of the other?
60.
 - What is the total efficiency of three systems in cascade with efficiencies of 98%, 87%, and 21%?
 - If the system with the least efficiency (21%) were removed and replaced by one with an efficiency of 90%, what would be the percentage increase in total efficiency?
- *61. If the total input and output power of two systems in cascade are 400 W and 128 W, respectively, what is the efficiency of each system if one has twice the efficiency of the other?

SECTION 4.9 Computer Analysis

62. Using PSpice or Multisim, repeat the analysis of the circuit in Fig. 4.26 with $E = 400$ mV and $R = 0.04$ M Ω .
63. Using PSpice or Multisim, repeat the analysis of the circuit in Fig. 4.26, but reverse the polarity of the battery and use $E = 0.02$ V and $R = 240$ Ω .

GLOSSARY

- Circuit breaker** A two-terminal device designed to ensure that current levels do not exceed safe levels. If “tripped,” it can be reset with a switch or a reset button.
- Diode** A semiconductor device whose behavior is much like that of a simple switch; that is, it will pass current ideally in only one direction when operating within specified limits.
- Efficiency (η)** A ratio of output to input power that provides immediate information about the energy-converting characteristics of a system.
- Energy (W)** A quantity whose change in state is determined by the product of the rate of conversion (P) and the period involved (t). It is measured in joules (J) or wattseconds (Ws).
- Fuse** A two-terminal device whose sole purpose is to ensure that current levels in a circuit do not exceed safe levels.
- Horsepower (hp)** Equivalent to 746 watts in the electrical system.
- Kilowatthour meter** An instrument for measuring kilowatthours of energy supplied to a residential or commercial user of electricity.
- Ohm’s law** An equation that establishes a relationship among the current, voltage, and resistance of an electrical system.
- Power** An indication of how much work can be done in a specified amount of time; a *rate* of doing work. It is measured in joules/second (J/s) or watts (W).