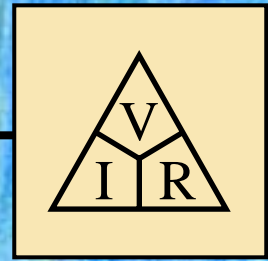


4



Ohm's Law, Power, and Energy

4.1 OHM'S LAW

Consider the following relationship:

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

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. 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 hose without motion, much like the 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 will simply result in a system without motion 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 more the rate





German (Erlangen,
Cologne)
(1789–1854)
Physicist and
Mathematician
Professor of Physics,
University of
Cologne



Courtesy of the
Smithsonian Institution
Photo No. 51,145

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. 4.1
Georg Simon Ohm.

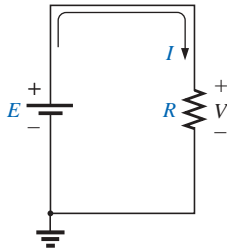


FIG. 4.2
Basic circuit.

of water flow through the hose, just as applying a higher voltage to the same circuit will result in a higher current.

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

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

and

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

Equation (4.2) is known as **Ohm's law** in honor of Georg Simon Ohm (Fig. 4.1). The law clearly reveals 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

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

The three quantities of Eqs. (4.2) through (4.4) are defined by the simple circuit of Fig. 4.2. The current I of Eq. (4.2) results from applying a dc supply of E volts across a network having a resistance R . Equation (4.3) determines the voltage E required to establish a current I through a network with a total resistance R , and Equation (4.4) provides the resistance of a network that results in a current I due to an impressed voltage E .

Note in Fig. 4.2 that the voltage source “pressures” current in a direction that passes from the negative to the positive terminal of the battery. This will always be the case for single-source circuits. The effect of more than one source in the network will be examined in the chapters to follow. The symbol for the voltage of the battery (a source of electrical energy) is the uppercase letter E , whereas the loss in potential energy across the resistor is given the symbol V . The polarity of the voltage drop across the resistor is as defined by the applied source because the two terminals of the battery are connected directly across the resistive element.

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):

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

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):

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

For an isolated resistive element, the polarity of the voltage drop is as shown in Fig. 4.3(a) for the indicated current direction. A reversal in current will reverse the polarity, as shown in Fig. 4.3(b). In general, the flow of charge is from a high (+) to a low (-) potential. Polarities as established by current direction will become increasingly important in the analysis to follow.

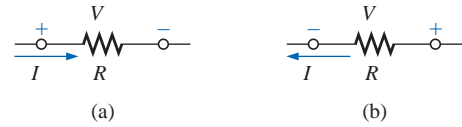


FIG. 4.3
Defining polarities.

EXAMPLE 4.3 Calculate the current through the 2-kΩ resistor of Fig. 4.4 if the voltage drop across it is 16 V.

Solution:

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

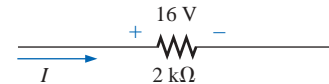


FIG. 4.4
Example 4.3.

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

Solution:

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

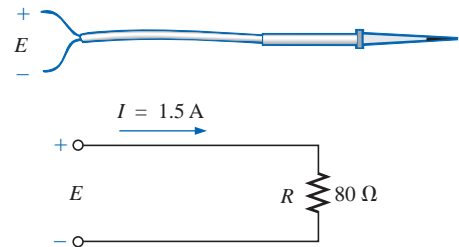


FIG. 4.5
Example 4.4.

In a number of the examples in this chapter, such as Example 4.4 above, 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 about the fact 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.

4.2 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

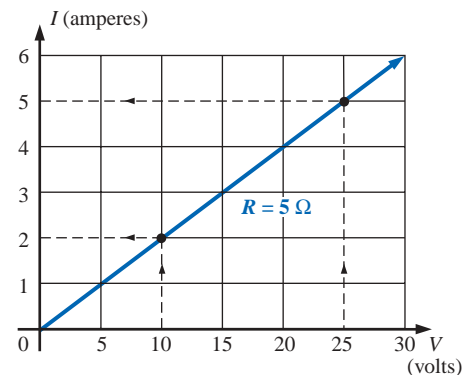
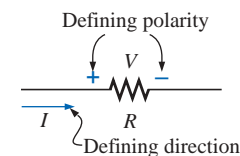


FIG. 4.6
Plotting Ohm's law.



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 will use the other quadrants of a graph.

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 will result 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:

$$R_{dc} = \frac{V}{I} \quad (4.5)$$

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 $R_{dc} = V/I = 20\text{ V}/4\text{ A} = 5\ \Omega$. For comparison purposes, a $1\text{-}\Omega$ and $10\text{-}\Omega$ resistor were plotted on the graph of 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

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

$$\begin{array}{cccc} \downarrow & \downarrow & \downarrow & \downarrow \\ y = m \cdot x + b \end{array}$$

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.

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

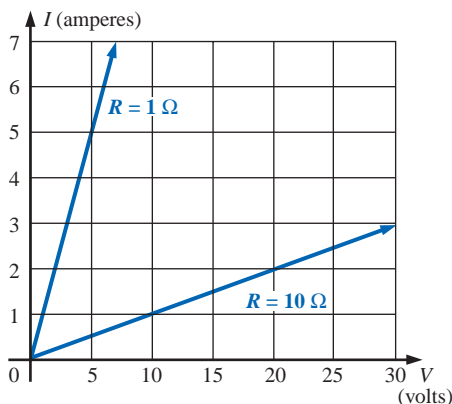


FIG. 4.7

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



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

The equation states that by choosing a particular ΔV (or ΔI), one 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, Equation (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.

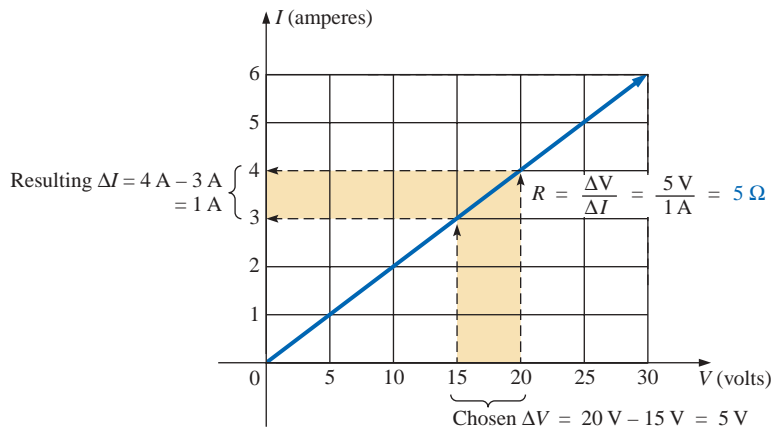


FIG. 4.8
Applying Eq. (4.6).

EXAMPLE 4.5 Determine the resistance associated with the curve of 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.

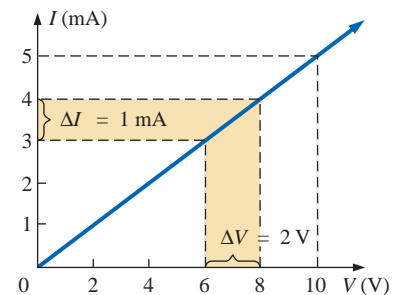


FIG. 4.9
Example 4.5.

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 will ideally act like 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 will pass 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.

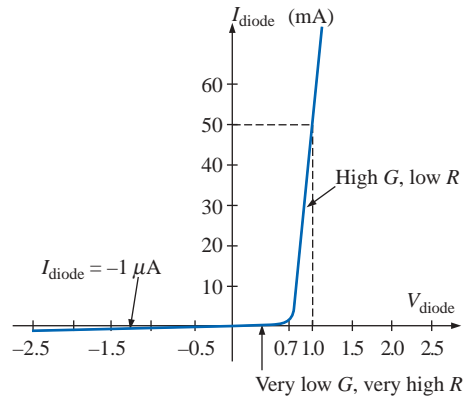


FIG. 4.10
Semiconductor diode characteristic.

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

$$\begin{aligned} R_{\text{diode}} &= \frac{V}{I} = \frac{1 \text{ V}}{50 \text{ mA}} = \frac{1 \text{ V}}{50 \times 10^{-3} \text{ A}} \\ &= 20 \Omega \\ &\text{(a relatively low value for most applications)} \end{aligned}$$

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

$$\begin{aligned} R_{\text{diode}} &= \frac{V}{I} = \frac{1 \text{ V}}{1 \mu\text{A}} \\ &= 1 \text{ M}\Omega \\ &\text{(which is often represented by an open-circuit equivalent)} \end{aligned}$$

4.3 POWER

Power is an indication of how much work (the conversion of energy from one form to another) can be done in a specified amount of time, that is, a *rate* of doing work. For instance, a large motor has more power than a small motor because it can convert more electrical energy into mechanical energy in the same period of time. Since converted 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

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

In equation form, power is determined by

$$\boxed{P = \frac{W}{t}} \quad \text{(watts, W, or joules/second, J/s)} \quad (4.9)$$

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

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



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:

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

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. (2.7) into Eq. (4.9):

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

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

so that
$$P = VI \quad (\text{watts}) \quad (4.10)$$

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

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

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

The result is that the power absorbed by the resistor of 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.

Power can be delivered or absorbed as defined by the polarity of the voltage and the direction of the current. For all dc voltage sources, power is being *delivered* by the source if the current has the direction appearing in Fig. 4.13(a). Note that the current has the same direction as established by the source in a single-source network. If the current direction and polarity are as shown in Fig. 4.13(b) due to a multisource network, the battery is absorbing power much as when a battery is being charged.

For resistive elements, all the power delivered is dissipated in the form of heat because the voltage polarity is defined by the current direction (and vice versa), and current will always enter the terminal of higher potential corresponding with the absorbing state of Fig. 4.13(b). A reversal of the current direction in Fig. 4.12 will also reverse the polarity of the voltage across the resistor and match the conditions of Fig. 4.13(b).

Scottish (Greenock, Birmingham) (1736-1819) Instrument Maker and Inventor Elected Fellow of the Royal Society of London in 1785



Courtesy of the Smithsonian Institution Photo No. 30,391

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 years to follow 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.

FIG. 4.11 James Watt.

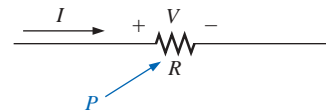


FIG. 4.12 Defining the power to a resistive element.

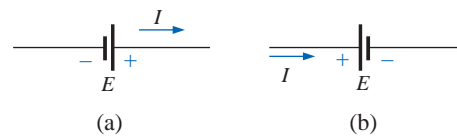


FIG. 4.13 Battery power: (a) supplied; (b) absorbed.



The magnitude of the power delivered or absorbed by a battery is given by

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

with E the battery terminal voltage and I the current through the source.

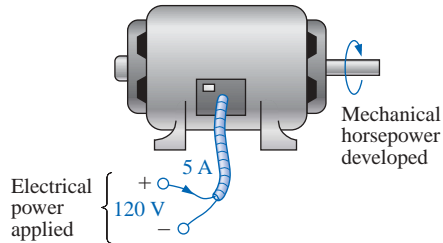


FIG. 4.14
Example 4.6.

EXAMPLE 4.6 Find the power delivered to the dc motor of Fig. 4.14.

Solution:

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

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

Solution:

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

EXAMPLE 4.8 The I - V characteristics of a light bulb are provided in Fig. 4.15. Note the nonlinearity of the curve, indicating a wide range in resistance of the bulb with applied voltage as defined by the discussion of Section 4.2. If the rated voltage is 120 V , find the wattage rating of the bulb. Also calculate the resistance of the bulb under rated conditions.

Solution: At 120 V ,

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

and

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

At 120 V ,

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

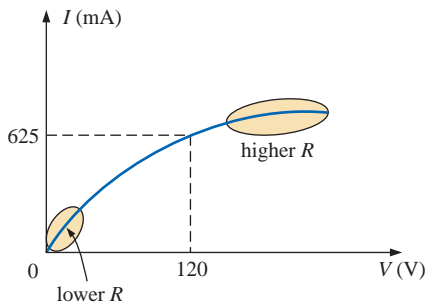


FIG. 4.15
The nonlinear I - V characteristics of a 75-W light bulb.

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

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

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

and

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

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



Solution: Eq. (4.14):

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

4.4 WATTMETERS

As one might expect, there are instruments that can measure the power delivered by a source and to a dissipative element. One such instrument, the **wattmeter**, appears in Fig. 4.16. Since power is a function of both the current and the voltage levels, four terminals must be connected as shown in Fig. 4.17 to measure the power to the resistor R .

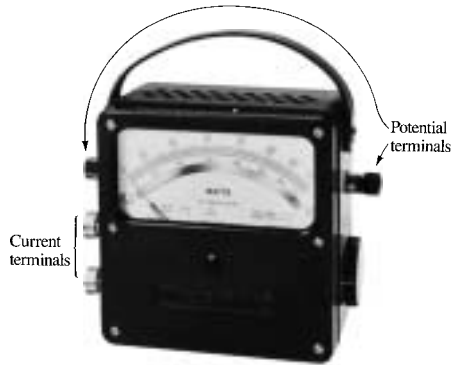


FIG. 4.16
Wattmeter. (Courtesy of Electrical Instrument Service, Inc.)

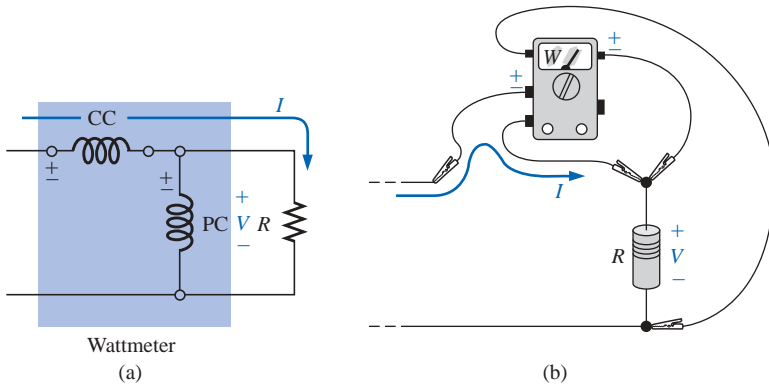


FIG. 4.17
Wattmeter connections.

If the current coils (CC) and potential coils (PC) of the wattmeter are connected as shown in Fig. 4.17, there will be an up-scale reading on the wattmeter. A reversal of either coil will result in a below-zero indication. Three voltage terminals may be available on the voltage side to permit a choice of voltage levels. On most wattmeters, the current terminals are physically larger than the voltage terminals to provide safety and to ensure a solid connection.

4.5 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. Take particular note of the fact 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_o and W_i are relatively close in magnitude.

Conservation of energy requires that

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

Dividing both sides of the relationship by t gives

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

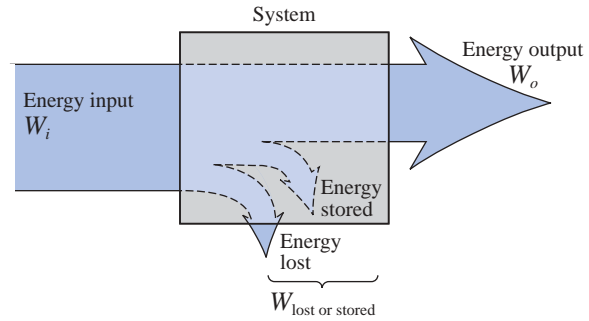


FIG. 4.18
Energy flow through a system.

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

$$P_i = P_o + P_{\text{lost or stored}} \quad (\text{W}) \quad (4.16)$$

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

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

and

$$\eta = \frac{P_o}{P_i} \quad (\text{decimal number}) \quad (4.17)$$

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

$$\eta\% = \frac{P_o}{P_i} \times 100\% \quad (\text{percent}) \quad (4.18)$$

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

$$\eta\% = \frac{W_o}{W_i} \times 100\% \quad (\text{percent}) \quad (4.19)$$

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 4.10 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 4.11 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

$$768 \text{ W} \left(\frac{1 \text{ hp}}{746 \text{ W}} \right) = \mathbf{1.029 \text{ hp}}$$

EXAMPLE 4.12 If $\eta = 0.85$, determine the output energy level if the applied energy is 50 J.

Solution:

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

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 will then ensure 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

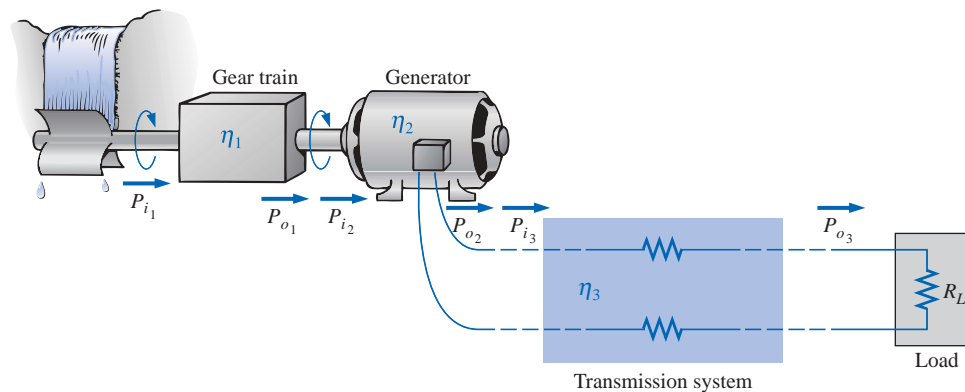


FIG. 4.19

Basic components of a generating system.



input and 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,

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

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 of Fig. 4.20,

$$\eta_{\text{total}} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdots \eta_n \quad (4.20)$$

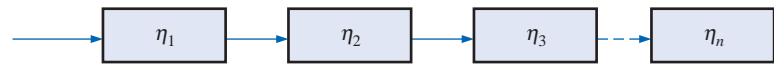


FIG. 4.20
Cascaded system.

EXAMPLE 4.13 Find the overall efficiency of the system of 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 4.14 If the efficiency η_1 drops to 40%, find the new overall efficiency and compare the result with that obtained in Example 4.13.

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.

4.6 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

$$W = Pt \quad (\text{wattseconds, Ws, or joules}) \quad (4.21)$$



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. 4.21) as indicated above. The wattsecond, however, is too small a quantity for most practical purposes, so the *watthour* (Wh) and *kilowatthour* (kWh) were defined, as follows:

$$\text{Energy (Wh)} = \text{power (W)} \times \text{time (h)} \quad (4.22)$$

$$\text{Energy (kWh)} = \frac{\text{power (W)} \times \text{time (h)}}{1000} \quad (4.23)$$

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. 4.22(a) 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 appears in Fig. 4.22(b).

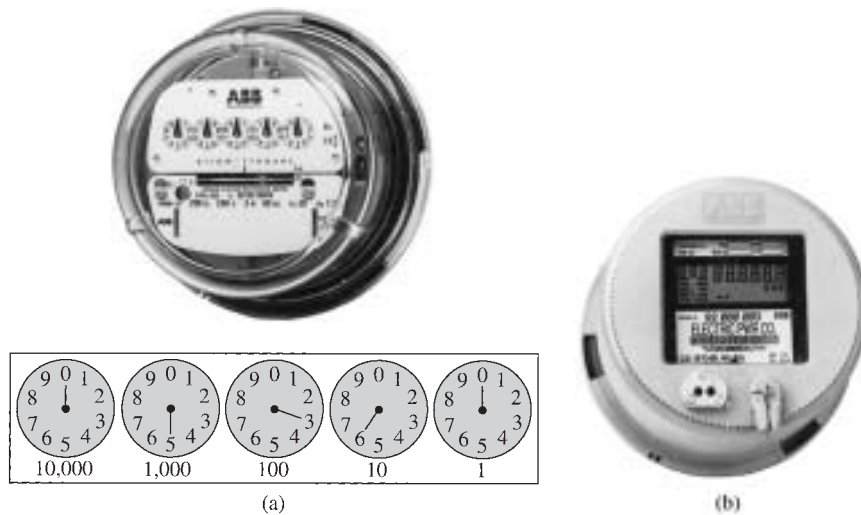


FIG. 4.22
 Kilowatthour meters: (a) analog; (b) digital. (Courtesy of ABB Electric Metering Systems.)

EXAMPLE 4.15 For the dial positions of Fig. 4.22(a), calculate the electricity bill if the previous reading was 4650 kWh and the average cost is 9¢ per kilowatthour.

Solution:

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

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

British (Salford, Manchester) (1818–89)
 Physicist
 Honorary Doctorates from the Universities of Dublin and Oxford



Bettmann Archive Photo Number 076800P

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.

FIG. 4.21
 James Prescott Joule.



EXAMPLE 4.16 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 4.17 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 4.18 What is the cost of using a 5-hp motor for 2 h if the rate is 9¢ per kilowatt-hour?

Solution:

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

$$\text{Cost} = (7.46 \text{ kWh})(9\text{¢/kWh}) = \mathbf{67.14\text{¢}}$$

EXAMPLE 4.19 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:

$$W = \frac{(1200 \text{ W})(\frac{1}{2} \text{ h}) + (6)(50 \text{ W})(4 \text{ h}) + (400 \text{ W})(\frac{3}{4} \text{ h}) + (4800 \text{ W})(\frac{1}{3} \text{ h})}{1000}$$

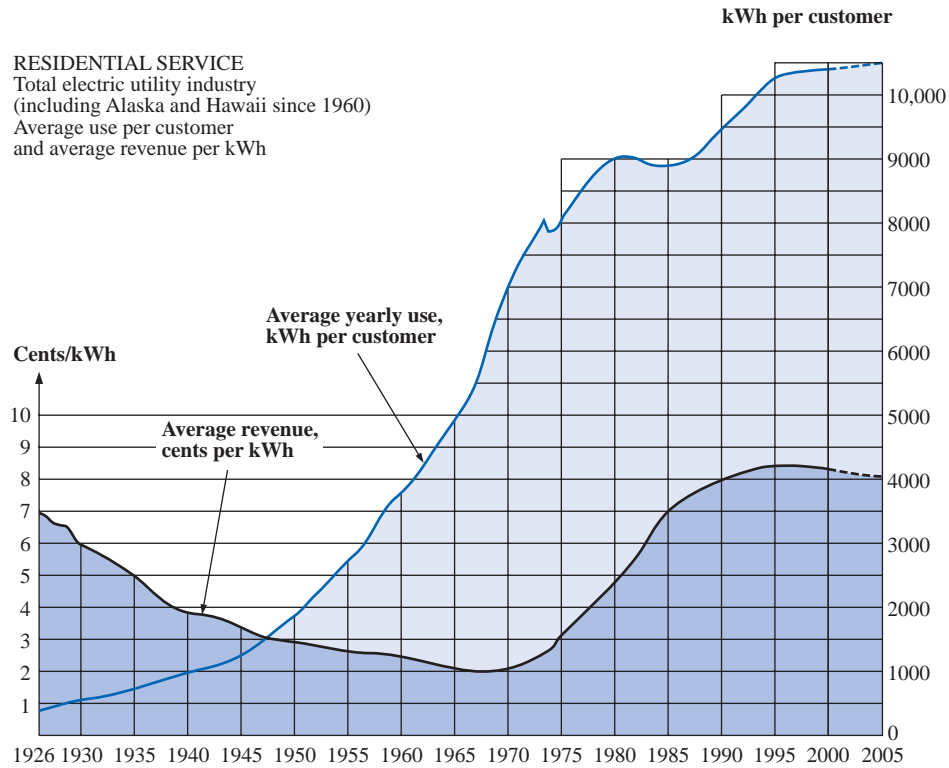
$$= \frac{600 \text{ Wh} + 1200 \text{ Wh} + 300 \text{ Wh} + 1600 \text{ Wh}}{1000} = \frac{3700 \text{ Wh}}{1000}$$

$$W = 3.7 \text{ kWh}$$

$$\text{Cost} = (3.7 \text{ kWh})(9\text{¢/kWh}) = \mathbf{33.3\text{¢}}$$

The chart in Fig. 4.23 shows the average cost per kilowatt-hour compared to the kilowatt-hours used per customer. Note that the cost today is above the level of 1926 and the average customer uses more than 20 times as much electrical energy in a year. Keep in mind that the chart of Fig. 4.23 is the average cost across the nation. Some states have average rates close to 5¢ per kilowatt-hour, whereas others approach 12¢ per kilowatt-hour.

Table 4.1 lists some common household appliances with their typical wattage ratings. It might prove interesting for the reader to calculate the cost of operating some of these appliances over a period of time using the chart in Fig. 4.23 to find the cost per kilowatt-hour.


FIG. 4.23

Cost per kWh and average kWh per customer versus time. (Courtesy of Edison Electric Institute.)

TABLE 4.1

Typical wattage ratings of some common household items.

| Appliance | Wattage Rating | Appliance | Wattage Rating |
|--------------------------|----------------|----------------------------------|----------------------------------|
| Air conditioner | 860 | Lap-top computer: | |
| Blow dryer | 1,300 | 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 | 1,200 |
| Talk | ≅ 4.3 W | Pager | 1–2 mW |
| Clock | 2 | Phonograph | 75 |
| Clothes dryer (electric) | 4,800 | Projector | 1,200 |
| Coffee maker | 900 | Radio | 70 |
| Dishwasher | 1,200 | Range (self-cleaning) | 12,200 |
| Fan: | | Refrigerator (automatic defrost) | 1,800 |
| Portable | 90 | Shaver | 15 |
| Window | 200 | Stereo equipment | 110 |
| Heater | 1,322 | Sun lamp | 280 |
| Heating equipment: | | Toaster | 1,200 |
| Furnace fan | 320 | Trash compactor | 400 |
| Oil-burner motor | 230 | TV (color) | 200 |
| Iron, dry or steam | 1,100 | Videocassette recorder | 110 |
| | | Washing machine | 500 |
| | | Water heater | 4,500 |



(a)



(b)



(c)

FIG. 4.24
Fuses: (a) CC-TRON[®] (0–10 A); (b) subminiature solid matrix; (c) Semitron (0–600 A). (Courtesy of Bussman Manufacturing Co.)

4.7 CIRCUIT BREAKERS, GFCIs, AND FUSES

The incoming power to any large industrial plant, heavy equipment, simple circuit in the home, or 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, or dangerous side effects such as fire or smoke may result. 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 of Fig. 4.24 have an internal metallic conductor through which the current will pass; a fuse will begin to melt if the current through the system exceeds the rated value printed on the casing. Of course, if the fuse melts through, 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. 4.25. 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.

**FIG. 4.25**

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

The most recent National Electrical Code requires that outlets in the bathroom and other sensitive areas be of the ground fault current interrupt (GFCI) variety; GFCIs are designed to trip more quickly than the standard circuit breaker. The commercial unit of Fig. 4.26 trips in 5 ns. 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

**FIG. 4.26**

*Ground fault current interrupter (GFCI)
125-V ac, 60-Hz, 15-A outlet. (Courtesy of Leviton, Inc.)*

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.

4.8 APPLICATIONS

Microwave Oven

It is probably safe to say that most modern homeowners have a microwave oven such as appearing in Fig. 4.27(a)—even those of us who went through the phase of worrying about whether it was safe and whether it was a proper way to prepare food. Now we use the oven so often during the day that we wonder how we ever did without it before. For most users, its operating efficiency is not the biggest concern, probably because its impact on the monthly bill is not that easy to define with so many appliances in the home. However, it might be of some interest to examine the unit in more detail and apply some of the theory presented in this chapter.

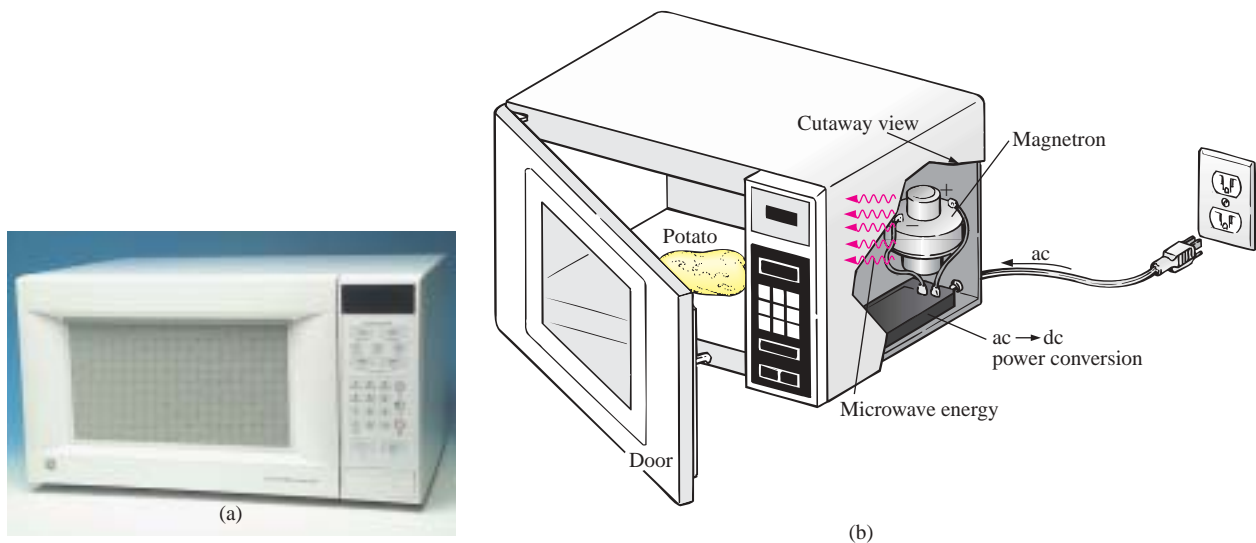


FIG. 4.27

Microwave oven: (a) photo; (b) basic construction.

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 (espe-



cially 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 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. 4.27(b). 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 will be generated that will appear 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), will generate the required 2.45-GHz signal for the oven. It should be pointed out also that the magnetron has a specific power level of oper-



ation 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

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

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, resulting in 1.55 kWh and a cost of 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 chapters to follow, additional coverage will be 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 208 V (depending on how the power lines are utilized). 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:

$$P = EI = (208 \text{ V})(100 \text{ A}) = 20,800 \text{ W} = 20.8 \text{ kW}$$

This rating reveals that the total rating of all the units turned on in the home cannot exceed 20.8 kW at any one time. If it did, we could expect the main breaker at the top of the power panel to open. Initially, 20.8 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, one must 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. One 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. 4.28(a). A 100-A or 200-A service must have two lines and a service neutral as shown in Fig. 4.28(b). Note in Fig. 4.28(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. 4.28(a) are stranded for added flexibility.

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


FIG. 4.28

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

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, the electrician can install as many circuits as he feels appropriate. The code further specifies that a #14 wire shall 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 208 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 208-V line than when designed for 120 V. Most 208-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 208-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 the above 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 will be introduced.



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 9.2 from Cadence Design Systems) will receive the most attention, followed by Electronics Workbench from Multisim and then a few sample programs using a programming language called C++. 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 will be investigated using the software packages PSpice and Electronics Workbench (EWB) to analyze the circuit in Fig. 4.29. 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 is fixed in stone and cannot be changed by the user. The proficient user is one who can draw the most out of a computer software package. In a later chapter, the C++ programming language will be introduced in some detail to demonstrate how a user can control the analysis procedure and how the results are displayed.

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 purpose 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 version 8 will find that the major changes in this latest 9.2 version 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.

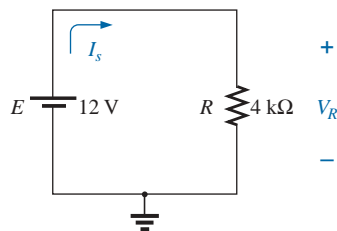


FIG. 4.29

Circuit to be analyzed using PSpice and Electronics Workbench.

Once 9.2 OrCAD Lite has been installed, the first required procedure is to open a **Folder** in the **C:** drive for storage of the circuit files that will 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** to obtain a listing that includes **Explore**. Select **Explore**, and then use the sequence **File-New Folder** to obtain a new folder on the screen waiting for a name. Type in **PSpice** (the author's choice) followed by a left click of the mouse to install. Then exit (using the **X** at the top right of the screen) the **Exploring-Start Menu**, and the first step is complete—you're on your way. The folder **PSpice** has been established 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 Lite Edition** icon on the screen, or you can use the sequence **Start-Programs-Orcad Family Release 9.2 Lite Edition**. The resulting screen has only a few active keys on the top toolbar. The first at the top left is the **Create new document** key (or you can use the sequence **File-New Project**). Selecting the key will result in a **New Project** dialog box in which the **Name** of the project must be entered. For our purposes we will choose **Ohmslaw** as shown in the heading of Fig. 4.30 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 will appear

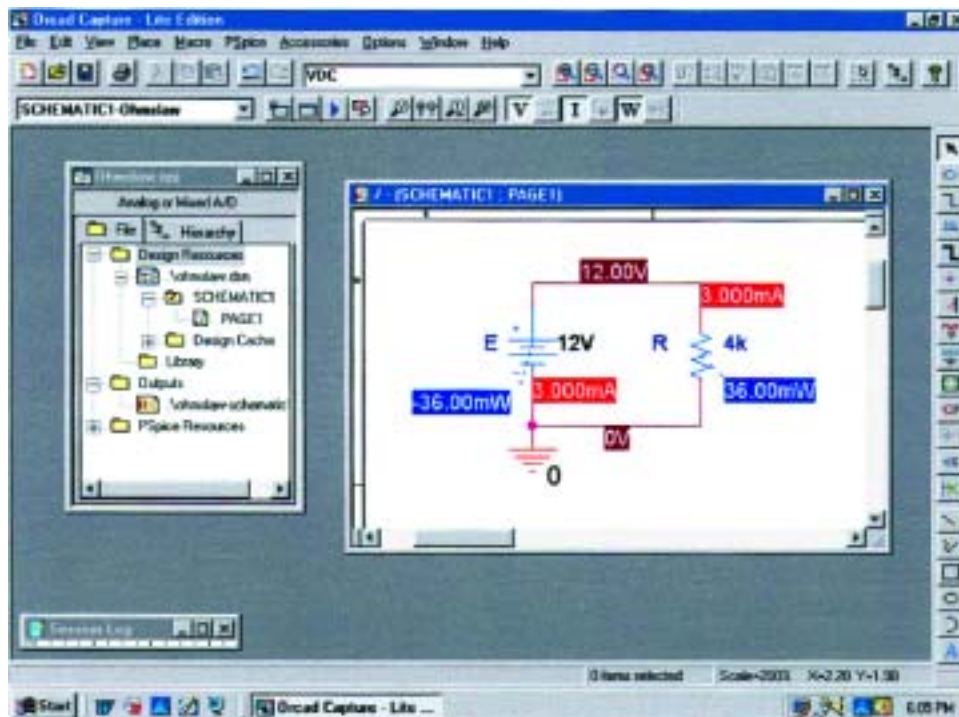


FIG. 4.30

Using PSpice to determine the voltage, current, and power levels for the circuit of Fig. 4.29.



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 will appear at the top of the screen with some of the keys enabled. A **Project Manager Window** will appear with **Ohmslaw** as its heading. The new project listing will appear with 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** will appear; clicking on a – sign will reverse the process. Double-clicking on **PAGE1** will create 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 to obtain 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.

Now we are ready to build the simple circuit of Fig. 4.29. 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, we must ensure that the parts appear in the list of active libraries. Select **Add Library-Browse File**, and select **analog.olb**, **eval.olb**, and **source.olb**. When each appears under the **File name** heading, select **Open**. All three files will be 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 we 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 will appear; select **VDC** for this project. Once **VDC** has been selected, its symbol, label, and value will appear on the picture window at the bottom right of the dialog box. Click **OK**, and the **VDC** source will follow 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. 4.30. Since only one source is required, a right click of the mouse will result in a list of options, in which **End Mode** appears at the top. Choosing this option will end the procedure, leaving the source in a red dashed box. The fact that it is red indicates that it is an active mode and can be operated on. One more left click of the mouse, and the source will be in place and the red active status removed.

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 will ensure that one side of the source is defined as 0 V. Finally, we 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** will appear and should be selected. Click **OK**, and the resistor will appear next to the cursor on the screen. Move it to the desired location and click it in place. Then right-click the mouse 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. 4.29 has the resistor in the vertical position. No problem: Simply select the resistor again to make it red, and right-click the mouse. A listing will appear in which **Rotate** is an option. It will turn 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. This is accomplished by selecting 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 the mouse again when the crosshair is at the correct point. A red line will result 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, a right click will provide the **End Mode** option. Don't forget to connect the source to ground as shown in Fig. 4.30.

Now we 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. Another left click, and it is deposited in its new location.

Finally, we can initiate the analysis process, called **Simulation**, by selecting the **Create a new simulation profile** key near the top left of the display—it resembles a data page with a star in the top left corner. A **New Simulation** dialog box will result that first asks for the **Name** of the simulation. **Bias Point** is selected for a dc solution, and **none** is left in the **Inherit From** request. Then select **Create**, and a **Simulation Setting** dialog box will appear 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** will result that appears to be somewhat inactive. It will not be used in the current analysis, so close (**X**) the window, and the circuit of Fig. 4.30 will appear 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. 4.30 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 the description above was long for such a trivial circuit. However, keep in mind that we needed to introduce many new facets of using PSpice that will not be touched on again in the future. By the time you finish analyzing your third or fourth network, the above procedure will appear routine and will move rather quickly. You will once again be looking for new challenges.



Electronics Workbench (EWB)

For comparison purposes, Electronics Workbench will be used to analyze the circuit in Fig. 4.29. Although there are differences between PSpice and EWB, such as the initiation 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 EWB to make the measurements—a positive trait in preparation for the laboratory experience. However, in EWB 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 2001** icon is selected from the opening window, a screen will appear with the heading **Multisim-Circuit 1**. A menu bar appears across the top of the screen, with one toolbar below the menu bar and one to each side of the screen. The toolbars appearing can be controlled by the sequence **View-Toolbars** followed by a selection of which toolbars you want to appear. For the analysis of this text, all the toolbars were selected. 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.

Now to build the circuit of Fig. 4.29. First take the cursor and place it on the battery symbol at the top of the component toolbar at the left of the screen. One left click of the mouse, and a list of sources will appear. Place the cursor on any one of the sources, and text will appear on the screen defining the type of source. Placing the cursor on the third key pad down will result in **DC VOLTAGE SOURCE**. Left-click again, and the battery symbol will appear on the screen next to the location of the cursor. Move the cursor to the desired location, and with a single left click of the mouse the battery symbol can be set in place. The operation is complete. If you want to delete the source, simply click on the symbol again with a left click of the mouse to create four small squares around the source. These squares indicate that the source is in the active mode and can be operated on. If you want to delete it, simply click on the **Delete** key or select the scissor key pad on the top toolbar. If you want to modify the source, perform a right click of the mouse *outside* the four small squares, and you get one list. Perform the right click *within* the four squares, and you have a different set of options. At any time, if you want to remove the active state, simply perform a left click anywhere on the screen. If you want to move the source, simply click on the source symbol to create the four squares, but do not release the clicker. Hold it down and drag the source to the preferred location. When the source is in place, release the clicker, and one more click will remove the active state. To remove the **SOURCES** toolbar, simply click on the **X** in the top right corner of the toolbar.

The next key down from the source key that looks like a resistor controls the display of the **Basic** passive components of a network. Click once on the symbol, and two columns of components will appear. *From now on, whenever possible, the word click will imply a left click of the mouse.* The need for a right click will continue to be spelled out.



For the circuit of Fig. 4.29 we need a resistor. When you place the cursor over the left resistor, the text **RESISTOR** will appear. When you place it over the right resistor, the text **RESISTOR_VIRTUAL** will appear. For all the analyses in this text using EWB, the virtual resistor will be used. The term **RESISTOR** is used for all resistors of a standard commercial value—the values typically made commercially. The term **VIRTUAL** is applied to any component in which you, the user, can define the value you want. Click once on the virtual resistor, and it will appear on the screen next to the cursor in the horizontal position. In Fig. 4.29 it is in the vertical position, so a rotation must be made. This can be done by clicking on the resistor to obtain the active state and then performing a right click of the mouse within the four squares. A number of options appear, including deleting (**Cut**) the component, copy, change position, and color. Since we want to rotate 90° clockwise, we select that option, and the resistor will automatically be rotated 90°. Now, as with the battery, to place the resistor in position, simply click on the resistor symbol to create the four small squares, and then, holding the left clicker down, drag the resistor to the desired position. When the resistor is in place, release the clicker, and click again to remove the four squares—the resistor is in place.

Finally, we need a ground for all networks. Going back to the **SOURCES** parts bin, we find that a ground is the first option at the top of the toolbar. Select the **GROUND** on the left, and place it on the screen below the voltage source as shown in Fig. 4.31. Now, before connecting the components together, move the labels and the value of each component to the relative positions shown in Fig. 4.31. This is accomplished by simply clicking on the label or value to create a small

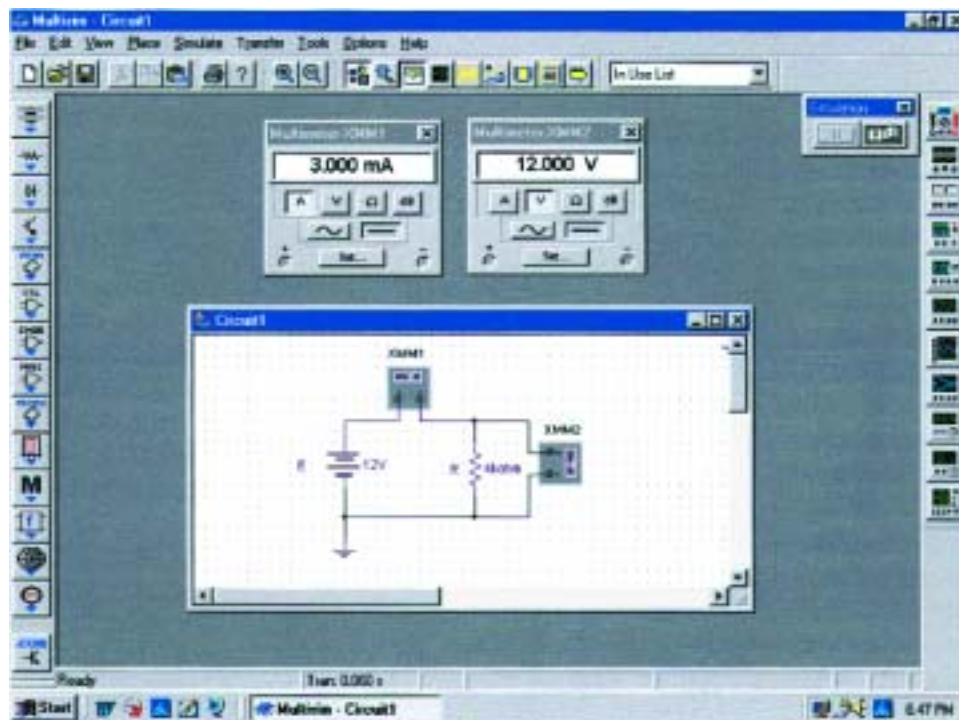


FIG. 4.31

Using Electronics Workbench to determine the voltage and current level for the circuit of Fig. 4.29.



set of squares around the element and then dragging the element to the desired location. Release the clicker, and then click again to set the element in place. To change the label or value, simply double-click on the label (such as **V1**), and a **Battery** dialog box will appear. Select **Label** and enter **E** as the **Reference ID**. 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. 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 simply **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. 4.31.

Next, we should tell the system which results should be generated and how they should be displayed. For this example we will 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 will appear on the screen and 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 either meter symbol, and a **Multimeter** dialog box will appear in which the function of the meter must be defined. Since the meter **XMM1** will be used as an ammeter, the letter **A** will be selected 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 simply 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. 4.31.

Finally, the elements need to be connected. This is accomplished by simply bringing the cursor to one end of an element, say, the top of the voltage source, with the result that a small dot and a crosshair will appear at the top end of the element. Click the mouse once, follow the path you want, and place the crosshair over the positive terminal of the ammeter. Then click again and the wire will appear 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. In time you will be aware of those preferences and will be able to set up the network to your liking. Now continue making the connections appearing in Fig. 4.31, moving elements of 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.

Now we are 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/STOP**. Another is to select the **Simulate** key in the design bar grouping in the top toolbar. It appears as a sharp, jagged, green plot on a black background. The last option, and the one we will use the most, requires an **OFF/ON, 0/1** switch on the screen. It is obtained through **VIEW>Show Simulate Switch** and will appear as shown in the top right corner of Fig. 4.31. Using this last option, the analysis (called **Simulation**) is initiated by placing the cursor on the 1 of the switch and left-clicking the mouse. The analysis will be performed, and the current and voltage will appear



on the meter as shown in Fig. 4.31. Note that both are providing the expected results.

Now for one of the most important things to learn about applying EWB:

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 will stay in that mode until turned off.

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

PROBLEMS

SECTION 4.1 Ohm's Law

1. What is the potential drop across a $6\text{-}\Omega$ resistor if the current through it is 2.5 A ?
2. What is the current through a $72\text{-}\Omega$ resistor if the voltage drop across it is 12 V ?
3. How much resistance is required to limit the current to 1.5 mA if the potential drop across the resistor is 6 V ?
4. At starting, what is the current drain on a 12-V car battery if the resistance of the starting motor is $0.056\text{ }\Omega$?
5. If the current through a $0.02\text{-M}\Omega$ resistor is $3.6\text{ }\mu\text{A}$, 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 V .
7. If a refrigerator draws 2.2 A at 120 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-V outlet.
9. A washing machine is rated at 4.2 A at 120 V . What is its internal resistance?
10. If a soldering iron draws 0.76 A at 120 V , what is its resistance?
11. The input current to a transistor is $20\text{ }\mu\text{A}$. If the applied (input) voltage is 24 mV , determine the input resistance of the transistor.
12. The internal resistance of a dc generator is $0.5\text{ }\Omega$. Determine the loss in terminal voltage across this internal resistance if the current is 15 A .
- *13. a. If an electric heater draws 9.5 A when connected to a 120-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 h ?

SECTION 4.2 Plotting Ohm's Law

14. Plot the linear curves of a $100\text{-}\Omega$ and a $0.5\text{-}\Omega$ resistor on the graph of Fig. 4.6. If necessary, reproduce the graph.
15. Sketch the characteristics of a device that has an internal resistance of $20\text{ }\Omega$ from 0 to 10 V and an internal resis-

tance of $2\text{ }\Omega$ for higher voltages. Use the axes of Fig. 4.6. If necessary, reproduce the graph.

16. Plot the linear curves of a $2\text{-k}\Omega$ and a $50\text{-k}\Omega$ resistor on the graph of Fig. 4.6. Use a horizontal scale that extends from 0 to 20 V and a vertical axis scaled off in milliamperes. If necessary, reproduce the graph.
17. What is the change in voltage across a $2\text{-k}\Omega$ resistor established by a change in current of 400 mA through the resistor?
- *18. a. Using the axes of Fig. 4.10, sketch the characteristics of a device that has an internal resistance of $500\text{ }\Omega$ from 0 to 1 V and $50\text{ }\Omega$ between 1 V and 2 V . Its resistance then changes to $-20\text{ }\Omega$ for higher voltages. The result is a set of characteristics very similar to those of an electronic device called a *tunnel diode*.
b. Using the above characteristics, determine the resulting current at voltages of 0.7 V , 1.5 V , and 2.5 V .

SECTION 4.3 Power

19. If 420 J of energy are absorbed by a resistor in 7 min , what is the power to the resistor?
20. The power to a device is $40\text{ joules per second (J/s)}$. How long will it take to deliver 640 J ?
21. a. How many joules of energy does a 2-W nightlight dissipate in 8 h ?
b. How many kilowatthours does it dissipate?
22. A resistor of $10\text{ }\Omega$ has charge flowing through it at the rate of $300\text{ coulombs per minute (C/min)}$. How much power is dissipated?
23. How long must a steady current of 2 A exist in a resistor that has 3 V across it to dissipate 12 J of energy?
24. What is the power delivered by a 6-V battery if the charge flows at the rate of 48 C/min ?
25. The current through a $4\text{-}\Omega$ resistor is 7 mA . What is the power delivered to the resistor?
26. The voltage drop across a $3\text{-}\Omega$ resistor is 9 mV . What is the power input to the resistor?
27. If the power input to a $4\text{-}\Omega$ resistor is 64 W , what is the current through the resistor?
28. A $1/2\text{-W}$ resistor has a resistance of $1000\text{ }\Omega$. What is the maximum current that it can safely handle?



29. A 2.2-k Ω resistor in a stereo system dissipates 42 mW of power. What is the voltage across the resistor?
30. A dc battery can deliver 45 mA at 9 V. What is the power rating?
31. What are the "hot" resistance level and current rating of a 120-V, 100-W bulb?
32. What are the internal resistance and voltage rating of a 450-W automatic washer that draws 3.75 A?
33. A calculator with an internal 3-V battery draws 0.4 mW when fully functional.
- What is the current demand from the supply?
 - If the calculator is rated to operate 500 h on the same battery, what is the ampere-hour rating of the battery?
34. A 20-k Ω resistor has a rating of 100 W. What are the maximum current and the maximum voltage that can be applied to the resistor?
- *35. a. Plot power versus current for a 100- Ω resistor. Use a power scale from 0 to 1 W and a current scale from 0 to 100 mA with divisions of 0.1 W and 10 mA, respectively.
- Is the curve linear or nonlinear?
 - Using the resulting plot, determine the current at a power level of 500 mW.
- *36. A small, portable black-and-white television draws 0.455 A at 9 V.
- What is the power rating of the television?
 - What is the internal resistance of the television?
 - What is the energy converted in 6 h of typical battery life?
- *37. a. If a home is supplied with a 120-V, 100-A service, find the maximum power capability.
- 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
43. 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?
44. 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?
45. A 2-hp motor drives a sanding belt. If the efficiency of the motor is 87% and that of the sanding belt 75% due to slippage, what is the overall efficiency of the system?
46. If two systems in cascade each have an efficiency of 80% and the input energy is 60 J, what is the output energy?
47. 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?
- *48. 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?
49. a. 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?
50. a. Perform the following conversions:
 - 1 Wh to joules
 - 1 kWh to joules
- Based on the results of part (a), discuss when it is more appropriate to use one unit versus the other.

SECTION 4.5 Efficiency

38. What is the efficiency of a motor that has an output of 0.5 hp with an input of 450 W?
39. 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?
40. 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?
41. A stereo system draws 2.4 A at 120 V. The audio output power is 50 W.
- How much power is lost in the form of heat in the system?
 - What is the efficiency of the system?
42. If an electric motor having an efficiency of 87% and operating off a 220-V line delivers 3.6 hp, what input current does the motor draw?
- SECTION 4.6 Energy
51. A 10- Ω resistor is connected across a 15-V battery.
- How many joules of energy will it dissipate in 1 min?
 - If the resistor is left connected for 2 min instead of 1 min, will the energy used increase? Will the power dissipation level increase?
52. 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 $4\frac{1}{3}$ weeks = 1 month.)
53. How long can a 1500-W heater be on before using more than 10 kWh of energy?
54. How much does it cost to use a 30-W radio for 3 h at 9¢ per kilowatt-hour?
55. a. In 10 h an electrical system converts 500 kWh of electrical energy into heat. What is the power level of the system?
- If the applied voltage is 208 V, what is the current drawn from the supply?
 - If the efficiency of the system is 82%, how much energy is lost or stored in 10 h?
56. a. At 9¢ per kilowatt-hour, how long can one play a 250-W color television for \$1?



- b. For \$1, how long can one use a 4.8-kW dryer?
c. Compare the results of parts (a) and (b), and comment on the effect of the wattage level on the relative cost of using an appliance.
57. What is the total cost of using the following at 9¢ per kilowatthour?
860-W air conditioner for 24 h
4800-W clothes dryer for 30 min
400-W washing machine for 1 h
1200-W dishwasher for 45 min
- *58. What is the total cost of using the following at 9¢ per kilowatthour?
110-W stereo set for 4 h
1200-W projector for 20 min
60-W tape recorder for 1.5 h
150-W color television set for 3 h 45 min

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.

SECTION 4.9 Computer Analysis PSpice or Electronics Workbench

59. Repeat the analysis of the circuit of Fig. 4.29 with $E = 400$ mV and $R = 0.04$ M Ω .
60. Repeat the analysis of the circuit of Fig. 4.29, but reverse the polarity of the battery and use $E = 0.02$ V and $R = 240$ Ω .

Programming Language (C++, QBASIC, Pascal, etc.)

61. Write a program to calculate the cost of using five different appliances for varying lengths of time if the cost is 9¢ per kilowatthour.
62. Request I , R , and t and determine V , P , and W . Print out the results with the proper units.

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).

Wattmeter An instrument capable of measuring the power delivered to an element by sensing both the voltage across the element and the current through the element.

