chapter 3

Ohm's Law

The mathematical relationship between voltage, current, and resistance was discovered in 1826 by Georg Simon Ohm. The relationship, known as Ohm's law, is the basic foundation for all circuit analysis in electronics. Ohm's law, which is the basis of this chapter, states that the amount of current, I, is directly proportional to the voltage, V, and inversely proportional to the resistance, R. Expressed mathematically, Ohm's law is stated as

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

Besides the coverage of Ohm's law, this chapter also introduces you to the concept of power. Power can be defined as the time rate of doing work. The symbol for power is P and the unit is the watt. All the mathematical relationships that exist between V, I, R, and P are covered in this chapter.

In addition to Ohm's law and power, this chapter also discusses electric shock and open- and short-circuit troubles.

Chapter Objectives

After studying this chapter you should be able to

- *List* the three forms of Ohm's law.
- *Use* Ohm's law to calculate the current, voltage, or resistance in a circuit.
- *List* the multiple and submultiple units of voltage, current, and resistance.
- *Explain* the difference between a linear and a nonlinear resistance.
- *Explain* the difference between work and power and list the units of each.
- *Calculate* the power in a circuit when the voltage and current, current and resistance, or voltage and resistance are known.
- *Determine* the required resistance and appropriate wattage rating of a resistor.
- *Identify* the shock hazards associated with working with electricity.
- *Explain* the difference between an open circuit and short circuit.

Chapter Outline

Important Terms

ampere
electron volt (eV)
horsepower (hp)
inverse relation
joule
kilowatt-hour (kWh)
linear proportion
linear resistance
maximum working voltage rating
nonlinear resistance
ohm
open circuit
power
short circuit
volt
volt-ampere characteristic
watt

Online Learning Center

Additional study aids for this chapter are available at the Online Learning Center: **www.mhhe.com/grob11e**.

GOOD TO KNOW

A piece of equipment known as a power supply can provide a variable dc output voltage to electronic circuits under test. A red-colored jack provides connection to the positive (+) side of the dc voltage whereas a black-colored jack provides connection to the negative (−) side.

3–1 The Current $I = V/R$

If we keep the same resistance in a circuit but vary the voltage, the current will vary. The circuit in Fig. 3–1 demonstrates this idea. The applied voltage *V* can be varied from 0 to 12 V, as an example. The bulb has a 12-V filament, which requires this much voltage for its normal current to light with normal intensity. The meter *I* indicates the amount of current in the circuit for the bulb.

With 12 V applied, the bulb lights, indicating normal current. When *V* is reduced to 10 V, there is less light because of less *I*. As *V* decreases, the bulb becomes dimmer. For zero volts applied, there is no current and the bulb cannot light. In summary, the changing brilliance of the bulb shows that the current varies with the changes in applied voltage.

For the general case of any *V* and *R*, Ohm's law is

$$I = \frac{V}{R} \quad \textbf{(3–1)}$$

where *I* is the amount of current through the resistance *R* connected across the source of potential difference *V*. With volts as the practical unit for *V* and ohms for *R*, the amount of current *I* is in amperes. Therefore,

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}$$

This formula says simply to divide the voltage across *R* by the ohms of resistance between the two points of potential difference to calculate the amperes of current through *R*. In Fig. 3–2, for instance, with 6 V applied across a 3-Ω resistance, by Ohm's law, the amount of current *I* equals $6/3$ or 2 A.

High Voltage but Low Current

It is important to realize that with high voltage, the current can have a low value when there is a very high resistance in the circuit. For example, 1000 V applied across 1,000,000 Ω results in a current of only $1/1000$ A. By Ohm's law,

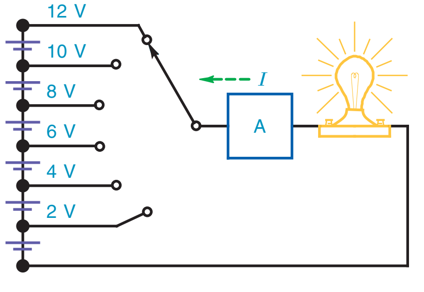
$$I = \frac{V}{R}$$

$$= \frac{1000\ \text{V}}{1{,}000{,}000\ \Omega} = \frac{1}{1000}$$

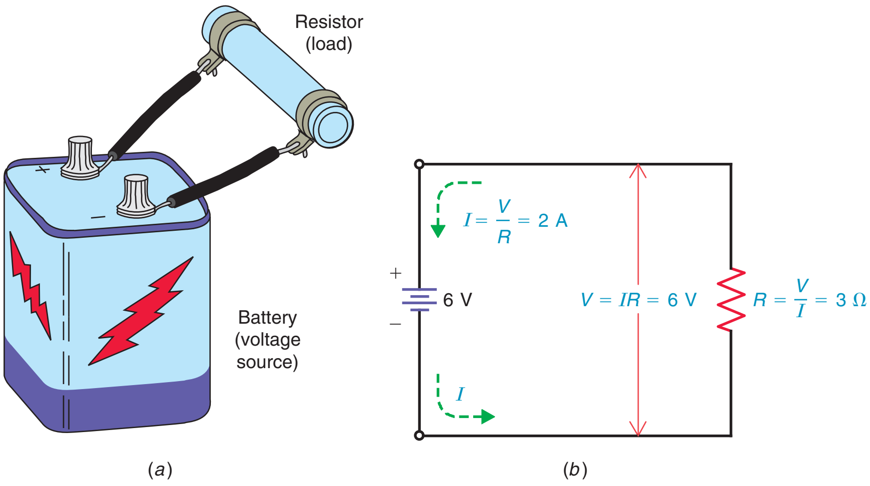
$$I = 0.001\ \text{A}$$

The practical fact is that high-voltage circuits usually do have small values of current in electronic equipment. Otherwise, tremendous amounts of power would be necessary.

Figure 3–1 Increasing the applied voltage *V* produces more current *I* to light the bulb with more intensity.



MultiSim **Figure 3–2** Example of using Ohm's law. (*a*) Wiring diagram of a circuit with a 6-V battery for *V* applied across a load *R*. (*b*) Schematic diagram of the circuit with values for *I* and *R* calculated by Ohm's law.



Low Voltage but High Current

At the opposite extreme, a low value of voltage in a very low resistance circuit can produce a very high current. A 6-V battery connected across a resistance of 0.01 Ω produces 600 A of current:

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

$$= \frac{6\ \text{V}}{0.01\ \Omega}$$

$$I = 600\ \text{A}$$

Less *I* with More *R*

Note the values of *I* in the following two examples also.

CALCULATOR

To do a division problem like *V*/*R* in Example 3–1 on the calculator, punch in the number 120 for the numerator, then press the ÷ key for division before punching in 8 for the denominator. Finally, press the = key for the answer of 15 on the display. The numerator must be punched in first.

Example 3–1

A heater with the resistance of 8 Ω is connected across the 120-V power line. How much is current *I*?

ANSWER

$$I = \frac{V}{R} = \frac{120\ \text{V}}{8\ \Omega}$$

$$I = 15\ \text{A}$$

Example 3–2

A small lightbulb with a resistance of 2400 Ω is connected across the same 120-V power line. How much is current *I*?

ANSWER

$$I = \frac{V}{R} = \frac{120\ \text{V}}{2400\ \Omega}$$

$$I = 0.05\ \text{A}$$

Although both cases have the same 120 V applied, the current is much less in Example 3–2 because of the higher resistance.

Typical *V* and *I*

Transistors and integrated circuits generally operate with a dc supply of 5, 6, 9, 12, 15, 24, or 50 V. The current is usually in millionths or thousandths of one ampere up to about 5 A.

3-1 Self-Review

Answers at end of chapter.

a. **Calculate *I* for 24 V applied across 8 Ω.**
b. **Calculate *I* for 12 V applied across 8 Ω.**
c. **Calculate *I* for 24 V applied across 12 Ω.**
d. **Calculate *I* for 6 V applied across 1 Ω.**

3–2 The Voltage *V* = *IR*

Referring back to Fig. 3–2, the voltage across *R* must be the same as the source *V* because the resistance is connected directly across the battery. The numerical value of this *V* is equal to the product $I \times R$. For instance, the *IR* voltage in Fig. 3–2 is 2 A × 3 Ω, which equals the 6 V of the applied voltage. The formula is

$$V = IR \tag{3–2}$$

CALCULATOR

To do a multiplication problem like $I \times R$ in Example 3–3 on the calculator, punch in the factor 2.5, then press the ⊗ key for multiplication before punching in 12 for the other factor. Finally, press the ⊜ key for the answer of 30 on the display. The factors can be multiplied in any order.

Example 3–3

If a 12-Ω resistor is carrying a current of 2.5 A, how much is its voltage?

ANSWER

$$V = IR$$
$$= 2.5\ \text{A} \times 12\ \Omega$$
$$= 30\ \text{V}$$

With I in ampere units and R in ohms, their product V is in volts. Actually, this must be so because the I value equal to V/R is the amount that allows the IR product to be the same as the voltage across R.

Beside the numerical calculations possible with the IR formula, it is useful to consider that the IR product means voltage. Whenever there is current through a resistance, it must have a potential difference across its two ends equal to the IR product. If there were no potential difference, no electrons could flow to produce the current.

3–2 Self-Review

Answers at end of chapter.

a. Calculate V for 0.002 A through 1000 Ω.
b. Calculate V for 0.004 A through 1000 Ω.
c. Calculate V for 0.002 A through 2000 Ω.

GOOD TO KNOW

Since R and G are reciprocals of each other, the conductance, G, of a circuit can be calculated as $G = \frac{I}{V}$.

3–3 The Resistance $R = V/I$

As the third and final version of Ohm's law, the three factors V, I, and R are related by the formula

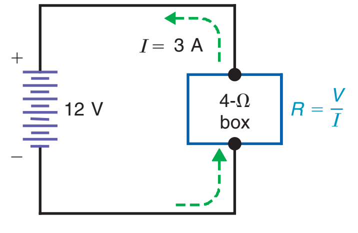
$$R = \frac{V}{I} \qquad (3\text{–}3)$$

In Fig. 3–2, R is 3 Ω because 6 V applied across the resistance produces 2 A through it. Whenever V and I are known, the resistance can be calculated as the voltage across R divided by the current through it.

Physically, a resistance can be considered some material whose elements have an atomic structure that allows free electrons to drift through it with more or less force applied. Electrically, though, a more practical way of considering resistance is simply as a V/I ratio. Anything that allows 1 A of current with 10 V applied has a resistance of 10 Ω. This V/I ratio of 10 Ω is its characteristic. If the voltage is doubled to 20 V, the current will also double to 2 A, providing the same V/I ratio of a 10-Ω resistance.

Furthermore, we do not need to know the physical construction of a resistance to analyze its effect in a circuit, so long as we know its V/I ratio. This idea is illustrated in Fig. 3–3. Here, a box with some unknown material in it is connected in a circuit where we can measure the 12 V applied across the box and the 3 A of current through it. The resistance is 12V/3A, or 4 Ω. There may be liquid, gas, metal, powder, or any other material in the box; but electrically the box is just a 4-Ω resistance because its V/I ratio is 4.

Figure 3–3 The resistance R of any component is its V/I ratio.



Example 3–4

How much is the resistance of a lightbulb if it draws 0.16 A from a 12-V battery?

ANSWER

$$R = \frac{V}{I} = \frac{12\ \text{V}}{0.16\ \text{A}} = 75\ \Omega$$

3–3 Self-Review

Answers at end of chapter.

a. **Calculate R for 12 V with 0.003 A.**
b. **Calculate R for 12 V with 0.006 A.**
c. **Calculate R for 12 V with 0.001 A.**

3–4 Practical Units

The three forms of Ohm's law can be used to define the practical units of current, potential difference, and resistance as follows:

$$1 \text{ ampere} = \frac{1 \text{ volt}}{1 \text{ ohm}}$$

$$1 \text{ volt} = 1 \text{ ampere} \times 1 \text{ ohm}$$

$$1 \text{ ohm} = \frac{1 \text{ volt}}{1 \text{ ampere}}$$

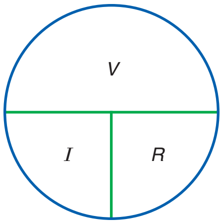


Figure 3–4 A circle diagram to help in memorizing the Ohm's law formulas $V = IR$, $I = V/R$, and $R = V/I$. The V is always at the top.

One **ampere** is the amount of current through a one-ohm resistance that has one volt of potential difference applied across it.

One **volt** is the potential difference across a one-ohm resistance that has one ampere of current through it.

One **ohm** is the amount of opposition in a resistance that has a V/I ratio of 1, allowing one ampere of current with one volt applied.

In summary, the circle diagram in Fig. 3–4 for $V = IR$ can be helpful in using Ohm's law. Put your finger on the unknown quantity and the desired formula remains. The three possibilities are

Cover V and you have IR.
Cover I and you have V/R.
Cover R and you have V/I.

3–4 Self-Review

Answers at end of chapter.

a. **Calculate V for 0.007 A through 5000 Ω.**
b. **Calculate the amount of I for 12,000 V across 6,000,000 Ω.**
c. **Calculate R for 8 V with 0.004 A.**

3–5 Multiple and Submultiple Units

The basic units—ampere, volt, and ohm—are practical values in most electric power circuits, but in many electronics applications, these units are either too small or too big. As examples, resistances can be a few million ohms, the output of a high-voltage supply in a computer monitor is about 20,000 V, and the current in transistors is generally thousandths or millionths of an ampere.

In such cases, it is often helpful to use multiples and submultiples of the basic units. These multiple and submultiple values are based on the metric system of units discussed earlier. The common conversions for V, I, and R are summarized at the end of this chapter, but a complete listing of all metric prefixes is in Table A–2 in Appendix A.

Example 3–5

MultiSim

The I of 8 mA flows through a 5-kΩ R. How much is the IR voltage?

ANSWER

$$V = IR = 8 \times 10^{-3} \times 5 \times 10^{3} = 8 \times 5$$
$$V = 40 \text{ V}$$

In general, milliamperes multiplied by kilohms results in volts for the answer, as 10^{-3} and 10^{3} cancel.

Example 3–6

MultiSim

How much current is produced by 60 V across 12 kΩ?

ANSWER

$$I = \frac{V}{R} = \frac{60}{12 \times 10^{3}}$$
$$= 5 \times 10^{-3} = 5 \text{ mA}$$

Note that volts across kilohms produces milliamperes of current. Similarly, volts across megohms produces microamperes.

In summary, common combinations to calculate the current I are

$$\frac{\text{V}}{\text{k}\Omega} = \text{mA} \quad \text{and} \quad \frac{\text{V}}{\text{M}\Omega} = \mu\text{A}$$

Also, common combinations to calculate IR voltage are

$$\text{mA} \times \text{k}\Omega = \text{V}$$
$$\mu\text{A} \times \text{M}\Omega = \text{V}$$

These relationships occur often in electronic circuits because the current is generally in units of milliamperes or microamperes. A useful relationship to remember is that 1 mA is equal to 1000 μA.

3–5 Self-Review

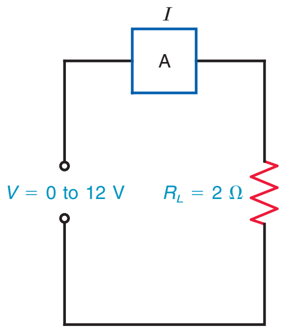
Answers at end of chapter.

a. Change the following to basic units with powers of 10 instead of metric prefixes: 6 mA, 5 kΩ, and 3 μA.
b. Change the following powers of 10 to units with metric prefixes: 6×10^{-3} A, 5×10^{3} Ω, and 3×10^{-6} A.
c. Which is larger, 2 mA or 20 μA?
d. How much current flows in a 560-kΩ resistor if the voltage is 70 V?

3–6 The Linear Proportion between *V* and *I*

The Ohm's law formula $I = V/R$ states that V and I are directly proportional for any one value of R. This relation between V and I can be analyzed by using a fixed resistance of 2 Ω for R_L, as in Fig. 3–5. Then when V is varied, the meter shows I values directly proportional to V. For instance, with 12 V, I equals 6 A; for 10 V, the current is 5 A; an 8-V potential difference produces 4 A.

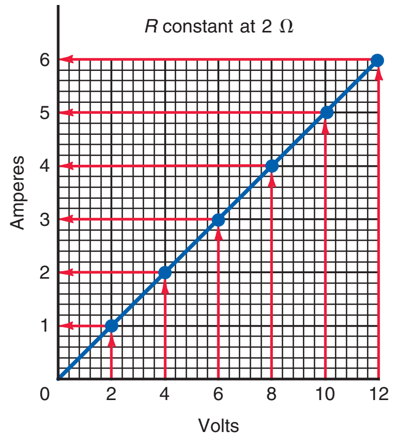
MultiSim **Figure 3–5** Experiment to show that *I* increases in direct proportion to *V* with the same *R*. (*a*) Circuit with variable *V* but constant *R*. (*b*) Table of increasing *I* for higher *V*. (*c*) Graph of *V* and *I* values. This is a linear volt-ampere characteristic. It shows a direct proportion between *V* and *I*.



(*a*)

Volts V	Ohms Ω	Amperes A
0	2	0
2	2	1
4	2	2
6	2	3
8	2	4
10	2	5
12	2	6

(*b*)



(*c*)

All the values of *V* and *I* are listed in the table in Fig. 3–5*b* and plotted in the graph in Fig. 3–5*c*. The *I* values are one-half the *V* values because *R* is 2 Ω. However, *I* is zero with zero volts applied.

Plotting the Graph

The voltage values for *V* are marked on the horizontal axis, called the *x axis* or *abscissa.* The current values *I* are on the vertical axis, called the *y axis* or *ordinate.*

Because the values for *V* and *I* depend on each other, they are variable factors. The independent variable here is *V* because we assign values of voltage and note the resulting current. Generally, the independent variable is plotted on the *x* axis, which is why the *V* values are shown here horizontally and the *I* values are on the ordinate.

The two scales need not be the same. The only requirement is that equal distances on each scale represent equal changes in magnitude. On the *x* axis here, 2-V steps are chosen, whereas the *y* axis has 1-A scale divisions. The zero point at the origin is the reference.

The plotted points in the graph show the values in the table. For instance, the lowest point is 2 V horizontally from the origin, and 1 A up. Similarly, the next point is at the intersection of the 4-V mark and the 2-A mark.

A line joining these plotted points includes all values of *I*, for any value of *V*, with *R* constant at 2 Ω. This also applies to values not listed in the table. For instance, if we take the value of 7 V up to the straight line and over to the *I* axis, the graph shows 3.5 A for *I*.

GOOD TO KNOW

In Fig. 3–5c, the slope of the straight line increases as *R* decreases. Conversely, the slope decreases as *R* increases. For any value of *R*, the slope of the straight line can be calculated as $\Delta I/\Delta V$ or $\frac{1}{R}$.

Volt-Ampere Characteristic

The graph in Fig. 3–5*c* is called the *volt-ampere characteristic* of *R*. It shows how much current the resistor allows for different voltages. Multiple and submultiple units of *V* and *I* can be used, though. For transistors, the units of *I* are often milliamperes or microamperes.

Linear Resistance

The *straight-line (linear) graph* in Fig. 3–5 shows that *R* is a linear resistor. A linear resistance has a constant value of ohms. Its *R* does not change with the applied voltage. Then V and I are directly proportional. Doubling the value of V from 4 to 8 V results in twice the current, from 2 to 4 A. Similarly, three or four times the value of V will produce three or four times I, for a proportional increase in current.

Nonlinear Resistance

This type of resistance has a nonlinear volt-ampere characteristic. As an example, the resistance of the tungsten filament in a lightbulb is nonlinear. The reason is that R increases with more current as the filament becomes hotter. Increasing the applied voltage does produce more current, but I does not increase in the same proportion as the increase in V. Another example of a nonlinear resistor is a thermistor.

Inverse Relation between *I* and *R*

Whether R is linear or not, the current I is less for more R, with the applied voltage constant. This is an inverse relation, that is, I goes down as R goes up. Remember that in the formula $I = V/R$, the resistance is in the denominator. A higher value of R actually lowers the value of the complete fraction.

As an example, let V be constant at 1 V. Then I is equal to the fraction $1/R$. As R increases, the values of I decrease. For R of 2 Ω, I is ½ or 0.5 A. For a higher R of 10 Ω, I will be lower at $\frac{1}{10}$ or 0.1 A.

GOOD TO KNOW

When the voltage, *V*, is constant, the relationship between *I* and *R* is not linear. This means that equal changes in *R* do not produce equal changes in *I*. A graph of *I* versus *R* with *V* constant is called a hyperbola.

3–6 Self-Review

Answers at end of chapter.

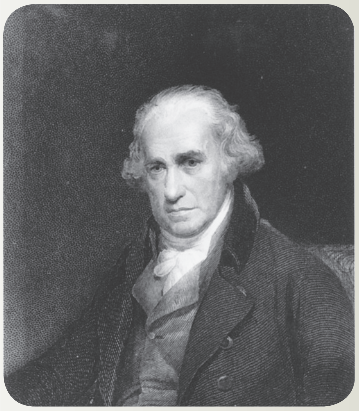
Refer to the graph in Fig. 3–5*c*.

a. Are the values of *I* on the *y* or *x* axis?

b. Is this *R* linear or nonlinear?

c. If the voltage across a 5-Ω resistor increases from 10 V to 20 V, what happens to *I*?

d. The voltage across a 5-Ω resistor is 10 V. If *R* is doubled to 10 Ω, what happens to *I*?



PIONEERS IN ELECTRONICS

The unit of electric power, the watt, is named for Scottish inventor and engineer *James Watt (1736–1819)*. One watt equals one joule of energy transferred in one second.

3–7 Electric Power

The unit of electric *power* is the *watt* (W), named after James Watt (1736–1819). One watt of power equals the work done in one second by one volt of potential difference in moving one coulomb of charge.

Remember that one coulomb per second is an ampere. Therefore power in watts equals the product of volts times amperes.

$$\text{Power in watts} = \text{volts} \times \text{amperes}$$

$$P = V \times I \qquad (3\text{–}4)$$

When a 6-V battery produces 2 A in a circuit, for example, the battery is generating 12 W of power.

The power formula can be used in three ways:

$$P = V \times I$$

$$I = P \div V \quad \text{or} \quad \frac{P}{V}$$

$$V = P \div I \quad \text{or} \quad \frac{P}{I}$$

Which formula to use depends on whether you want to calculate P, I, or V. Note the following examples.

Example 3–7

A toaster takes 10 A from the 120-V power line. How much power is used?

ANSWER

$$P = V \times I = 120\text{ V} \times 10\text{ A}$$
$$P = 1200\text{ W} \quad \text{or} \quad 1.2\text{ kW}$$

Example 3–8

How much current flows in the filament of a 300-W bulb connected to the 120-V power line?

ANSWER

$$I = \frac{P}{V} = \frac{300\text{ W}}{120\text{ V}}$$
$$I = 2.5\text{ A}$$

Example 3–9

How much current flows in the filament of a 60-W bulb connected to the 120-V power line?

ANSWER

$$I = \frac{P}{V} = \frac{60\text{ W}}{120\text{ V}}$$
$$I = 0.5\text{ A} \quad \text{or} \quad 500\text{ mA}$$

Note that the lower wattage bulb uses less current.

GOOD TO KNOW

Since $V = \frac{W}{Q}$ then $W = V \times Q$.
Therefore, $P = \frac{V \times Q}{T}$ or $P = V \times \frac{Q}{T}$.
Since $I = \frac{Q}{T}$ then $P = V \times I$.

Work and Power

Work and energy are essentially the same with identical units. Power is different, however, because it is the time rate of doing work.

As an example of work, if you move 100 lb a distance of 10 ft, the work is 100 lb × 10 ft or 1000 ft·lb, regardless of how fast or how slowly the work is done. Note that the unit of work is foot-pounds, without any reference to time.

However, power equals the work divided by the time it takes to do the work. If it takes 1 s, the power in this example is 1000 ft·lb/s; if the work takes 2 s, the power is 1000 ft·lb in 2 s, or 500 ft·lb/s.

Similarly, electric power is the rate at which charge is forced to move by voltage. This is why power in watts is the product of volts and amperes. The voltage states the amount of work per unit of charge; the current value includes the rate at which the charge is moved.

Watts and Horsepower Units

A further example of how electric power corresponds to mechanical power is the fact that

$$746 \text{ W} = 1 \text{ hp} = 550 \text{ ft·lb/s}$$

This relation can be remembered more easily as 1 hp equals approximately ¾ kilowatt (kW). One kilowatt = 1000 W.

Practical Units of Power and Work

Starting with the watt, we can develop several other important units. The fundamental principle to remember is that power is the time rate of doing work, whereas work is power used during a period of time. The formulas are

$$\text{Power} = \frac{\text{work}}{\text{time}} \tag{3–5}$$

and

$$\text{Work} = \text{power} \times \text{time} \tag{3–6}$$

With the watt unit for power, one watt used during one second equals the work of one joule. Or one watt is one joule per second. Therefore, 1 W = 1 J/s. The **joule** is a basic practical unit of work or energy.

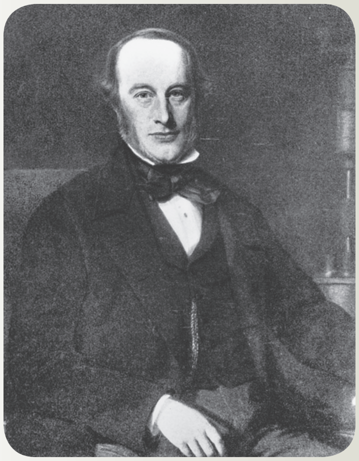
To summarize these practical definitions,

$$1 \text{ joule} = 1 \text{ watt} \cdot \text{second}$$
$$1 \text{ watt} = 1 \text{ joule/second}$$

In terms of charge and current,

$$1 \text{ joule} = 1 \text{ volt} \cdot \text{coulomb}$$
$$1 \text{ watt} = 1 \text{ volt} \cdot \text{ampere}$$

Remember that the ampere unit includes time in the denominator, since the formula is 1 ampere = 1 coulomb/second.



PIONEERS IN ELECTRONICS

The SI unit of measure for electrical energy is the joule. Named for English physicist *James Prescott Joule (1818–1889)*, one joule (J) is equal to one volt-coulomb.

Electron Volt (eV)

This unit of work can be used for an individual electron, rather than the large quantity of electrons in a coulomb. An electron is charge, and the volt is potential difference. Therefore, 1 eV is the amount of work required to move an electron between two points that have a potential difference of one volt.

The number of electrons in one coulomb for the joule unit equals 6.25×10^{18}. Also, the work of one joule is a volt-coulomb. Therefore, the number of electron volts equal to one joule must be 6.25×10^{18}. As a formula,

$$1 \text{ J} = 6.25 \times 10^{18} \text{ eV}$$

Either the electron volt or the joule unit of work is the product of charge times voltage, but the watt unit of power is the product of voltage times current. The division by time to convert work to power corresponds to the division by time that converts charge to current.

Kilowatt-Hours

This is a unit commonly used for large amounts of electrical work or energy. The amount is calculated simply as the product of the power in kilowatts multiplied by the time in hours during which the power is used. As an example, if a lightbulb uses 300 W or 0.3 kW for 4 hours (h), the amount of energy is 0.3 × 4, which equals 1.2 kWh.

We pay for electricity in kilowatt-hours of energy. The power-line voltage is constant at 120 V. However, more appliances and lightbulbs require more current because they all add in the main line to increase the power.

Suppose that the total load current in the main line equals 20 A. Then the power in watts from the 120-V line is

$$P = 120 \text{ V} \times 20 \text{ A}$$
$$P = 2400 \text{ W} \quad \text{or} \quad 2.4 \text{ kW}$$

If this power is used for 5 h, then the energy or work supplied equals 2.4 × 5 = 12 kWh. If the cost of electricity is 6¢/kWh, then 12 kWh of electricity will cost 0.06 × 12 = 0.72 or 72¢. This charge is for a 20-A load current from the 120-V line during the time of 5 h.

Example 3–10

Assuming that the cost of electricity is 6 ¢/kWh, how much will it cost to light a 100-W lightbulb for 30 days?

ANSWER The first step in solving this problem is to express 100 W as 0.1 kW. The next step is to find the total number of hours in 30 days. Since there are 24 hours in a day, the total number of hours for which the light is on is calculated as

$$\text{Total hours} = \frac{24 \text{ h}}{\text{day}} \times 30 \text{ days} = 720 \text{ h}$$

Next, calculate the number of kWh as

$$\begin{aligned} \text{kWh} &= \text{kW} \times \text{h} \\ &= 0.1 \text{ kW} \times 720 \text{ h} \\ &= 72 \text{ kWh} \end{aligned}$$

And finally, determine the cost. (Note that 6¢ = \$0.06.)

$$\begin{aligned} \text{Cost} &= \text{kWh} \times \frac{\text{cost}}{\text{kWh}} \\ &= 72 \text{ kWh} \times \frac{0.06}{\text{kWh}} \\ &= \$4.32 \end{aligned}$$

3–7 Self-Review

Answers at end of chapter.

a. **An electric heater takes 15 A from the 120-V power line. Calculate the amount of power used.**
b. **How much is the load current for a 100-W bulb connected to the 120-V power line?**
c. **How many watts is the power of 200 J/s equal to?**
d. **How much will it cost to operate a 300-W lightbulb for 48 h if the cost of electricity is 7¢/kWh?**

GOOD TO KNOW

The power dissipated by a resistance is proportional to I^2. In other words, if the current, *I*, carried by a resistor is doubled, the power dissipation in the resistance increases by a factor of 4.

GOOD TO KNOW

The power dissipated by a resistance is proportional to V^2. In other words, if the voltage, *V*, across a resistor is doubled, the power dissipation in the resistance increases by a factor of 4.

GOOD TO KNOW

In the distribution of electric power, the power transmission lines often use a very high voltage such as 160 kV or more. With such a high voltage, the current carried by the transmission lines can be kept low to transmit the desired power from one location to another. The reduction in *I* with the much higher *V* considerably reduces the I^2R power losses in the transmission line conductors.

3–8 Power Dissipation in Resistance

When current flows in a resistance, heat is produced because friction between the moving free electrons and the atoms obstructs the path of electron flow. The heat is evidence that power is used in producing current. This is how a fuse opens, as heat resulting from excessive current melts the metal link in the fuse.

The power is generated by the source of applied voltage and consumed in the resistance as heat. As much power as the resistance dissipates in heat must be supplied by the voltage source; otherwise, it cannot maintain the potential difference required to produce the current.

The correspondence between electric power and heat is indicated by the fact that 1W used during 1 s is equivalent to 0.24 calorie of heat energy. The electric energy converted to heat is considered dissipated or used up because the calories of heat cannot be returned to the circuit as electric energy.

Since power is dissipated in the resistance of a circuit, it is convenient to express the power in terms of the resistance R. The formula $P = V \times I$ can be rearranged as follows:

Substituting IR for V,

$$P = V \times I = IR \times I$$

$$P = I^2R \qquad \textbf{(3–7)}$$

This is a common form of the power formula because of the heat produced by current in a resistance.

For another form, substitute V/R for I. Then

$$P = V \times I = V \times \frac{V}{R}$$

$$P = \frac{V^2}{R} \qquad \textbf{(3–8)}$$

In all the formulas, V is the voltage across R in ohms, producing the current I in amperes, for power in watts.

Any one of the three formulas (3–4), (3–7), and (3–8) can be used to calculate the power dissipated in a resistance. The one to be used is a matter of convenience, depending on which factors are known.

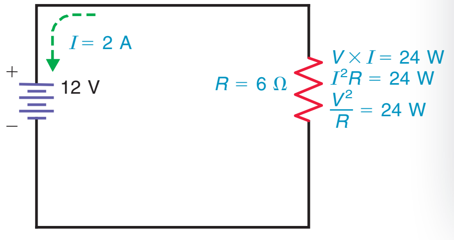
In Fig. 3–6, for example, the power dissipated with 2 A through the resistance and 12 V across it is $2 \times 12 = 24$ W.

Or, calculating in terms of just the current and resistance, the power is the product of 2 squared, or 4, times 6, which equals 24 W.

Using the voltage and resistance, the power can be calculated as 12 squared, or 144, divided by 6, which also equals 24 W.

No matter which formula is used, 24 W of power is dissipated as heat. This amount of power must be generated continuously by the battery to maintain the potential difference of 12 V that produces the 2-A current against the opposition of 6 Ω.

MultiSim **Figure 3–6** Calculating the electric power in a circuit as $P = V \times I$, $P = I^2R$, or $P = V^2/R$.



Example 3–11

MultiSim

Calculate the power in a circuit where the source of 100 V produces 2 A in a 50-Ω R.

ANSWER

$$P = I^2R = 2 \times 2 \times 50 = 4 \times 50$$

$$P = 200 \text{ W}$$

This means that the source delivers 200 W of power to the resistance and the resistance dissipates 200 W as heat.

CALCULATOR

To use the calculator for a problem like Example 3–11, in which I must be squared for $I^2 \times R$, use the following procedure:

- Punch in the value of 2 for I.
- Press the key marked (x^2) for the square of 2 equal to 4 on the display.
- Next, press the multiplication $(\times)$ key.
- Punch in the value of 50 for R.
- Finally, press the $(=)$ key for the answer of 200 on the display.

Be sure to square only the I value before multiplying by the R value.

Example 3–12

MultiSim

Calculate the power in a circuit in which the same source of 100 V produces 4 A in a 25-Ω R.

ANSWER

$$P = I^2R = 4^2 \times 25 = 16 \times 25$$
$$P = 400 \text{ W}$$

Note the higher power in Example 3–12 because of more I, even though R is less than that in Example 3–11.

In some applications, electric power dissipation is desirable because the component must produce heat to do its job. For instance, a 600-W toaster must dissipate this amount of power to produce the necessary amount of heat. Similarly, a 300-W lightbulb must dissipate this power to make the filament white-hot so that it will have the incandescent glow that furnishes the light. In other applications, however, the heat may be just an undesirable by-product of the need to provide current through the resistance in a circuit. In any case, though, whenever there is current I in a resistance R, it dissipates the amount of power P equal to I^2R.

Components that use the power dissipated in their resistance, such as lightbulbs and toasters, are generally rated in terms of power. The power rating is given at normal applied voltage, which is usually the 120 V of the power line. For instance, a 600-W, 120-V toaster has this rating because it dissipates 600 W in the resistance of the heating element when connected across 120 V.

Note this interesting point about the power relations. The lower the source voltage, the higher the current required for the same power. The reason is that $P = V \times I$. For instance, an electric heater rated at 240 W from a 120-V power line takes 240 W/120 V = 2 A of current from the source. However, the same 240 W from a 12-V source, as in a car or boat, requires 240 W/12 V = 20 A. More current must be supplied by a source with lower voltage, to provide a specified amount of power.

3–8 Self-Review

Answers at end of chapter.

a. Current I is 2 A in a 5-Ω R. Calculate P.
b. Voltage V is 10 V across a 5-Ω R. Calculate P.
c. Resistance R has 10 V with 2 A. Calculate the values for P and R.

GOOD TO KNOW

Every home appliance has a power rating and a voltage rating. To calculate the current drawn by an appliance, simply divide the power rating by the voltage rating.

3–9 Power Formulas

To calculate I or R for components rated in terms of power at a specified voltage, it may be convenient to use the power formulas in different forms. There are three basic power formulas, but each can be in three forms for nine combinations.

$$P = VI \qquad P = I^2R \qquad P = \frac{V^2}{R}$$
$$\text{or} \quad I = \frac{P}{V} \qquad \text{or} \quad R = \frac{P}{I^2} \qquad \text{or} \quad R = \frac{V^2}{P}$$
$$\text{or} \quad V = \frac{P}{I} \qquad \text{or} \quad I = \sqrt{\frac{P}{R}} \qquad \text{or} \quad V = \sqrt{PR}$$

CALCULATOR

To use the calculator for a problem like Example 3–14 that involves a square and division for V^2/R, use the following procedure:

- Punch in the *V* value of 120.
- Press the key marked (x^2) for the square of 120, equal to 14,400 on the display.
- Next, press the division (÷) key.
- Punch in the value of 600 for *R*.
- Finally, press the (=) key for the answer of 24 on the display. Be sure to square only the numerator before dividing.

CALCULATOR

For Example 3–15 with a square root and division, be sure to divide first, so that the square root is taken for the quotient, as follows:

- Punch in the *P* of 600.
- Press the division (÷) key.
- Punch in 24 for *R*.
- Press the (=) key for the quotient of 25.

Then press the (√) key for the square root. This key may be a second function of the same key for squares. If so, press the key marked (2nd F) or (SHIFT) before pressing the (√) key. As a result, the square root equal to 5 appears on the display. You do not need the (=) key for this answer. In general, the (=) key is pressed only for the multiplication, division, addition, and subtraction operations.

Example 3–13

How much current is needed for a 600-W, 120-V toaster?

ANSWER

$$I = \frac{P}{V} = \frac{600}{120}$$
$$I = 5 \text{ A}$$

Example 3–14

How much is the resistance of a 600-W, 120-V toaster?

ANSWER

$$R = \frac{V^2}{P} = \frac{(120)^2}{600} = \frac{14{,}400}{600}$$
$$I = 24 \ \Omega$$

Example 3–15

How much current is needed for a 24-Ω *R* that dissipates 600 W?

ANSWER

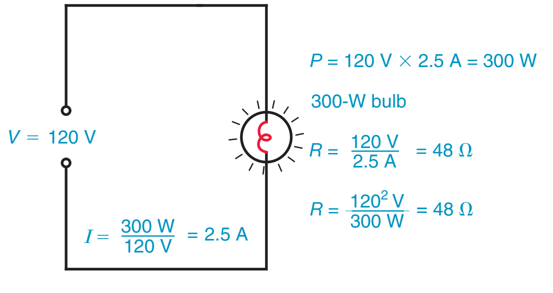
$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{600 \text{ W}}{24 \ \Omega}} = \sqrt{25}$$
$$I = 5 \text{ A}$$

Note that all these formulas are based on Ohm's law $V = IR$ and the power formula $P = VI$. The following example with a 300-W bulb also illustrates this idea. Refer to Fig. 3–7. The bulb is connected across the 120-V line. Its 300-W filament requires a current of 2.5 A, equal to P/V. These calculations are

$$I = \frac{P}{V} = \frac{300 \text{ W}}{120 \text{ V}} = 2.5 \text{ A}$$

The proof is that the *VI* product is 120 × 2.5, which equals 300 W.

Figure 3–7 All formulas are based on Ohm's law.



Furthermore, the resistance of the filament, equal to V/I, is 48 Ω. These calculations are

$$R = \frac{V}{I} = \frac{120\text{ V}}{2.5\text{ A}} = 48\ \Omega$$

If we use the power formula $R = V^2/P$, the answer is the same 48 Ω. These calculations are

$$R = \frac{V^2}{P} = \frac{120^2}{300}$$

$$R = \frac{14{,}400}{300} = 48\ \Omega$$

In any case, when this bulb is connected across 120 V so that it can dissipate its rated power, the bulb draws 2.5 A from the power line and the resistance of the white-hot filament is 48 Ω.

3–9 Self-Review

Answers at end of chapter.

a. How much is the *R* of a 100-W, 120-V lightbulb?
b. How much power is dissipated by a 2-Ω *R* with 10 V across it?
c. Calculate *P* for 2 A of *I* through a 2-Ω resistor.

3–10 Choosing a Resistor for a Circuit

When choosing a resistor for a circuit, first determine the required resistance value as $R = \frac{V}{I}$. Next, calculate the amount of power dissipated by the resistor using any one of the power formulas. Then, select a wattage rating for the resistor that will provide a reasonable amount of cushion between the actual power dissipation and the power rating of the resistor. Ideally, the power dissipation in a resistor should never be more than 50% of its power rating, which is a safety factor of 2. A safety factor of 2 allows the resistor to operate at a cooler temperature and thus last longer without breaking down from excessive heat. In practice, however, as long as the safety factor is reasonably close to 2, the resistor will not overheat.

Example 3–16

Determine the required resistance and appropriate wattage rating of a resistor to meet the following requirements: The resistor must have a 30-V *IR* drop when its current is 20 mA. The resistors available have the following wattage ratings: ⅛, ¼, ½, 1, and 2 W.

ANSWER First, calculate the required resistance.

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

$$= \frac{30\text{ V}}{20\text{ mA}}$$

$$= 1.5\text{ k}\Omega$$

Next, calculate the power dissipated by the resistor using the formula $P = I^2R$.

$$P = I^2R$$

$$= (20\text{ mA})^2 \times 1.5\text{ k}\Omega$$

$$= 0.6\text{ W} \quad \text{or} \quad 600\text{ mW}$$

Now, select a suitable wattage rating for the resistor. In this example, a 1-W rating provides a safety factor that is reasonably close to 2. A resistor with a higher wattage rating could be used if there is space available for it to be mounted. In summary, a 1.5-kΩ, 1-W resistor will safely dissipate 600 mW of power while providing an *IR* voltage of 30 V when the current is 20 mA.

Maximum Working Voltage Rating

The maximum working voltage rating of a resistor is the maximum allowable voltage that the resistor can safely withstand without internal arcing. The higher the wattage rating of the resistor, the higher the maximum working voltage rating. For carbon-film resistors, the following voltage ratings are typical:

⅛ W − 150 V

¼ W − 250 V

½ W − 350 V

1 W − 500 V

It is interesting to note that with very large resistance values, the maximum working voltage rating may actually be exceeded before the power rating is exceeded. For example, a 1 MΩ, ¼ W carbon-film resistor with a maximum working voltage rating of 250 V, does not dissipate ¼ W of power until its voltage equals 500 V. Since 500 V exceeds its 250 V rating, internal arcing will occur within the resistor. Therefore, 250 V rather than 500 V is the maximum voltage that can safely be applied across this resistor. With 250 V across the 1-MΩ resistor, the actual power dissipation is ¹⁄₁₆ W which is only one-fourth its power rating.

For any resistor, the maximum voltage that produces the rated power dissipation is calculated as

$$V_{max} = \sqrt{P_{rating} \times R}$$

Exceeding V_{max} causes the resistor's power dissipation to exceed its power rating. Except for very large resistance values, the maximum working voltage rating is usually much larger than the maximum voltage that produces the rated power dissipation.

Example 3–17

Determine the required resistance and appropriate wattage rating of a carbon-film resistor to meet the following requirements: The resistor must have a 225-V *IR* drop when its current is 150 μA. The resistors available have the following wattage ratings: ⅛, ¼, ½, 1, and 2 W.

ANSWER First, calculate the required resistance.

$$R = \frac{V}{I} = \frac{225\ \text{V}}{150\ \mu\text{A}} = 1.5\ \text{M}\Omega$$

Next, calculate the power dissipated by the resistor using the formula $P = I^2R$.

$$P = I^2R$$
$$= (150\ \mu A)^2 \times 1.5\ M\Omega$$
$$= 33.75\ mW$$

Now, select a suitable wattage rating for the resistor.

In this application a ⅛-W (125 mW) resistor could be considered because it will provide a safety factor of nearly 4. However, a ⅛-W resistor could not be used because its maximum working voltage rating is only 150 V and the resistor must be able to withstand a voltage of 225 V. Therefore, a higher wattage rating must be chosen just because it will have a higher maximum working voltage rating. In this application, a ½-W resistor would be a reasonable choice because it has a 350-V rating. A ¼-W resistor provides a 250-V rating which is only 25 V more than the actual voltage across the resistor. It's a good idea to play it safe and go with the higher voltage rating offered by the ½-W resistor. In summary, a 1.5-MΩ, ½-W resistor will safely dissipate 33.75 mW of power as well as withstand a voltage of 225 V.

3–10 Self-Review

Answers at end of chapter.

a. What is the maximum voltage that a 10-kΩ, ¼-W resistor can safely handle without exceeding its power rating? If the resistor has a 250-V maximum working voltage rating, is this rating being exceeded?

b. Determine the required resistance and appropriate wattage rating of a carbon-film resistor for the following conditions: the *IR* voltage must equal 100 V when the current is 100 μA. The available wattage ratings for the resistor are ⅛, ¼, ½, 1, and 2 W.

3–11 Electric Shock

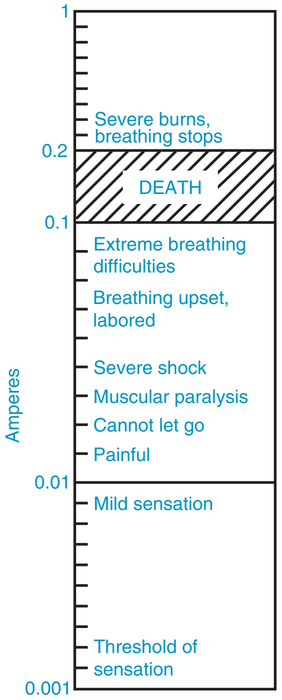
While you are working on electric circuits, there is often the possibility of receiving an electric shock by touching the "live" conductors when the power is on. The shock is a sudden involuntary contraction of the muscles, with a feeling of pain, caused by current through the body. If severe enough, the shock can be fatal. Safety first, therefore, should always be the rule.

The greatest shock hazard is from high-voltage circuits that can supply appreciable amounts of power. The resistance of the human body is also an important factor. If you hold a conducting wire in each hand, the resistance of the body across the conductors is about 10,000 to 50,000 Ω. Holding the conductors tighter lowers the resistance. If you hold only one conductor, your resistance is much higher. It follows that the higher the body resistance, the smaller the current that can flow through you.

A safety tip, therefore, is to work with only one of your hands if the power is on. Place the other hand behind your back or in your pocket. Therefore, if a live circuit is touched with only one hand, the current will normally not flow directly through the heart. Also, keep yourself insulated from earth ground when working on power-line circuits, since one side of the power line is connected to earth ground. The final and best safety rule is to work on circuits with the power disconnected if at all possible and make resistance tests.

Note that it is current through the body, not through the circuit, which causes the electric shock. This is why high-voltage circuits are most important, since sufficient potential difference can produce a dangerous amount of current through the

Figure 3–8 Physiological effects of electric current.



relatively high resistance of the body. For instance, 500 V across a body resistance of 25,000 Ω produces 0.02 A, or 20 mA, which can be fatal. As little as 1 mA through the body can cause an electric shock. The chart shown in Fig. 3–8 is a visual representation of the physiological effects of an electric current on the human body. As the chart shows, the threshold of sensation occurs when the current through the body is only slightly above 0.001 A or 1 mA. Slightly above 10 mA, the sensation of current through the body becomes painful and the person can no longer let go or free him or herself from the circuit. When the current through the body exceeds approximately 100 mA, the result is usually death.

In addition to high voltage, the other important consideration in how dangerous the shock can be is the amount of power the source can supply. A current of 0.02 A through 25,000 Ω means that the body resistance dissipates 10 W. If the source cannot supply 10 W, its output voltage drops with the excessive current load. Then the current is reduced to the amount corresponding to the amount of power the source can produce.

In summary, then, the greatest danger is from a source having an output of more than about 30 V with enough power to maintain the load current through the body when it is connected across the applied voltage. In general, components that can supply high power are physically big because of the need for dissipating heat.

3–11 Self-Review

Answers at end of chapter.

a. The potential difference of 120 V is more dangerous than 12 V for electric shock. (True/False)

b. Resistance in a circuit should be measured with its power off. (True/False)

3–12 Open-Circuit and Short-Circuit Troubles

Ohm's law is useful for calculating *I*, *V*, and *R* in a closed circuit with normal values. However, an open circuit or a short circuit causes trouble that can be summarized as follows: An open circuit (Fig. 3–9) has zero *I* because *R* is infinitely high. It does not matter how much the *V* is. A short circuit has zero *R*, which causes excessively high *I* in the short-circuit path because of no resistance (Fig. 3–10).

In Fig. 3–9*a*, the circuit is normal with *I* of 2 A produced by 10 V applied across *R* of 5 Ω. However, the resistor is shown open in Fig. 3–9*b*. Then the path for current has infinitely high resistance and there is no current in any part of the circuit. The trouble can be caused by an internal open in the resistor or a break in the wire conductors.

In Fig. 3–10*a*, the same normal circuit is shown with *I* of 2 A. In Fig. 3–10*b*, however, there is a short-circuit path across *R* with zero resistance. The result is excessively high current in the short-circuit path, including the wire conductors. It may be surprising, but there is no current in the resistor itself because all the current is in the zero-resistance path around it.

Figure 3–9 Effect of an open circuit. (*a*) Normal circuit with current of 2 A for 10 V across 5 Ω. (*b*) Open circuit with no current and infinitely high resistance.

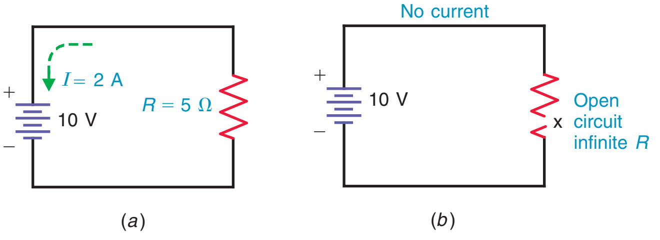
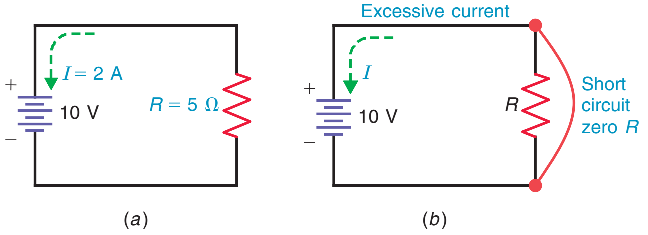


Figure 3–10 Effect of a short circuit. (*a*) Normal circuit with current of 2 A for 10 V across 5 Ω. (*b*) Short circuit with zero resistance and excessively high current.



Theoretically, the amount of current could be infinitely high with no *R*, but the voltage source can supply only a limited amount of *I* before it loses its ability to provide voltage output. The wire conductors may become hot enough to burn open, which would open the circuit. Also, if there is any fuse in the circuit, it will open because of the excessive current produced by the short circuit.

Note that the resistor itself is not likely to develop a short circuit because of the nature of its construction. However, the wire conductors may touch, or some other component in a circuit connected across the resistor may become short-circuited.

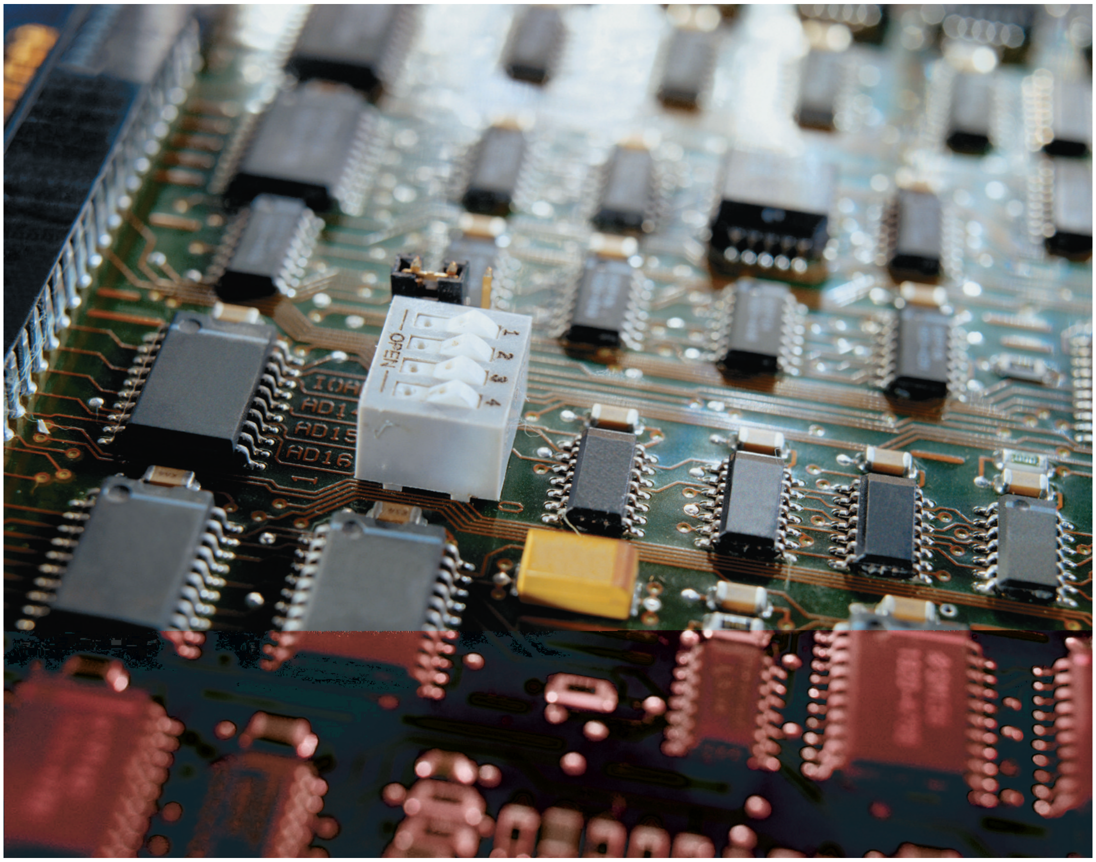
3–12 Self-Review

Answers at end of chapter.

a. An open circuit has zero current. (True/False)

b. A short circuit has excessive current. (True/False)

c. An open circuit and a short circuit have opposite effects on resistance and current. (True/False)



Summary

- The three forms of Ohm's law are $I = V/R$, $V = IR$, and $R = V/I$.
- One ampere is the amount of current produced by one volt of potential difference across one ohm of resistance. This current of 1 A is the same as 1 C/s.
- With R constant, the amount of I increases in direct proportion as V increases. This linear relation between V and I is shown by the graph in Fig. 3–5.
- With V constant, the current I decreases as R increases. This is an inverse relation.
- Power is the time rate of doing work or using energy. The unit is the watt. One watt equals 1 V × 1 A. Also, watts = joules per second.
- The unit of work or energy is the joule. One joule equals 1 W × 1 s.
- The most common multiples and submultiples of the practical units are listed in Table 3–1.
- Voltage applied across your body can produce a dangerous electric shock. Whenever possible, shut off the power and make resistance tests. If the power must be on, use only one hand when making measurements. Place your other hand behind your back or in your pocket.
- Table 3–2 summarizes the practical units of electricity.
- An open circuit has no current and infinitely high R. A short circuit has zero resistance and excessively high current.

Table 3–1 Summary of Conversion Factors

Prefix	Symbol	Relation to Basic Unit	Examples
mega	M	1,000,000 or 1×10^6	5 MΩ (megohms) = 5,000,000 ohms = 5×10^6 ohms
kilo	k	1000 or 1×10^3	18 kV (kilovolts) = 18,000 volts = 18×10^3 volts
milli	m	0.001 or 1×10^{-3}	48 mA (milliamperes) = 48×10^{-3} ampere = 0.048 ampere
micro	μ	0.000 001 or 1×10^{-6}	15 μV (microvolts) = 15×10^{-6} volt = 0.000 015 volt

Table 3–2 Summary of Practical Units of Electricity

Coulomb	Ampere	Volt	Watt	Ohm	Siemens
6.25×10^{18} electrons	$\frac{\text{coulomb}}{\text{second}}$	$\frac{\text{joule}}{\text{coulomb}}$	$\frac{\text{joule}}{\text{second}}$	$\frac{\text{volt}}{\text{ampere}}$	$\frac{\text{ampere}}{\text{volt}}$

Important Terms

Ampere the basic unit of current. $1\ \text{A} = \frac{1\ \text{V}}{1\ \Omega}$.

Electron volt (eV) a small unit of work or energy that represents the amount of work required to move a single electron between two points having a potential difference of 1 volt.

Horsepower (hp) a unit of mechanical power corresponding to 550 ft·lb/s. In terms of electric power, 1 hp = 746 W.

Inverse relation a relation in which the quotient of a fraction decreases as the value in the denominator increases with the numerator constant. In the equation $I = \frac{V}{R}$, I and R are inversely related because I decreases as R increases with V constant.

Joule a practical unit of work or energy. 1 J = 1 W · 1 s.

Kilowatt-hour (kWh) a large unit of electrical energy corresponding to 1 kW · 1 h.

Linear proportion a relation between two quantities which shows how equal changes in one quantity produce equal changes in the other. In the equation $I = \frac{V}{R}$, I and V are directly proportional because equal changes in V produce equal changes in I with R constant.

Linear resistance a resistance with a constant value of ohms.

Maximum working voltage rating the maximum allowable voltage that a resistor can safely withstand without internal arcing.

Nonlinear resistance a resistance whose value changes as a result of current producing power dissipation and heat in the resistance.

Ohm the basic unit of resistance. $1\ \Omega = \frac{1\ \text{V}}{1\ \text{A}}$.

Open circuit a broken or incomplete current path with infinitely high resistance.

Power the time rate of doing work. $\text{Power} = \frac{\text{Work}}{\text{Time}}$.

Short circuit a very low resistance path around or across a component such as a resistor. A short circuit with very low R can have excessively high current.

Volt the basic unit of potential difference or voltage. $1\ \text{V} = 1\ \text{A} \cdot 1\ \Omega$

Volt ampere characteristic a graph showing how much current a resistor allows for different voltages.

Watt the basic unit of electric power. $1\ \text{W} = \frac{1\ \text{J}}{\text{s}}$.

Related Formulas

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

$V = I \times R$

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

$P = V \times I$

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

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

1 hp = 746 W

1 J = 1 W × 1 s

$1\ \text{W} = \frac{1\ \text{J}}{1\ \text{s}}$

1 J = 1 V × 1 C

$1\ \text{J} = 6.25 \times 10^{18}\ \text{eV}$

$P = I^2 R$

$I = \sqrt{\frac{P}{R}}$

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

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

$V = \sqrt{PR}$

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

Self-Test

Answers at back of book.

1. With 24 V across a 1-kΩ resistor, the current, *I*, equals

a. 0.24 A.

b. 2.4 mA.

c. 24 mA.

d. 24 μA.

2. With 30 μA of current in a 120-kΩ resistor, the voltage, *V*, equals

a. 360 mV.

b. 3.6 kV.

c. 0.036 V.

d. 3.6 V.

3. How much is the resistance in a circuit if 15 V of potential difference produces 500 μA of current?

a. 30 kΩ.

b. 3 MΩ.

c. 300 kΩ.

d. 3 kΩ.

4. A current of 1000 μA equals

a. 1 A.

b. 1 mA.

c. 0.01 A.

d. none of the above.

5. One horsepower equals

a. 746 W.

b. 550 ft·lb/s.

c. approximately 3/4 kW.

d. all of the above.

6. With *R* constant

a. *I* and *P* are inversely related.

b. *V* and *I* are directly proportional.

c. *V* and *I* are inversely proportional.

d. none of the above.

7. One watt of power equals

a. 1 V × 1 A.

b. $\frac{1\ J}{s}$

c. $\frac{1\ C}{s}$

d. both a and b.

8. A 10-Ω resistor dissipates 1 W of power when connected to a dc voltage source. If the value of dc voltage is doubled, the resistor will dissipate

a. 1 W.

b. 2 W.

c. 4 W.

d. 10 W.

9. If the voltage across a variable resistance is held constant, the current, *I*, is

a. inversely proportional to resistance.

b. directly proportional to resistance.

c. the same for all values of resistance.

d. both a and b.

10. A resistor must provide a voltage drop of 27 V when the current is 10 mA. Which of the following resistors will provide the required resistance and appropriate wattage rating?

a. 2.7 kΩ, 1/8 W.

b. 270 Ω, 1/2 W.

c. 2.7 kΩ, 1/2 W.

d. 2.7 kΩ, 1/4 W.

11. The resistance of an open circuit is

a. approximately 0 Ω.

b. infinitely high.

c. very low.

d. none of the above.

12. The current in an open circuit is

a. normally very high because the resistance of an open circuit is 0 Ω.

b. usually high enough to blow the circuit fuse.

c. zero.

d. slightly below normal.

13. Which of the following safety rules should be observed while working on a live electric circuit?

a. Keep yourself well insulated from earth ground.

b. When making measurements in a live circuit place one hand behind your back or in your pocket.

c. Make resistance measurements only in a live circuit.

d. Both a and b.

14. How much current does a 75-W lightbulb draw from the 120-V power line?

a. 625 mA.

b. 1.6 A.

c. 160 mA.

d. 62.5 mA.

15. The resistance of a short circuit is

a. infinitely high.

b. very high.

c. usually above 1 kΩ.

d. approximately zero.

16. Which of the following is considered a linear resistance?

a. lightbulb.

b. thermistor.

c. 1-kΩ, 1/2-W carbon-film resistor.

d. both a and b.

17. How much will it cost to operate a 4-kW air-conditioner for 12 hours if the cost of electricity is 7¢/kWh?

a. $3.36.

b. 33¢.

c. $8.24.

d. $4.80.

18. What is the maximum voltage a 150-Ω, 1/8-W resistor can safely handle without exceeding its power rating? (Assume no power rating safety factor.)

a. 18.75 V.

b. 4.33 V.

c. 6.1 V.

d. 150 V.

19. Which of the following voltages provides the greatest danger in terms of electric shock?

a. 12 V.

b. 10,000 mV.

c. 120 V.

d. 9 V.

20. If a short circuit is placed across the leads of a resistor, the current in the resistor itself would be

a. zero.

b. much higher than normal.

c. the same as normal.

d. excessively high.

Essay Questions

1. State the three forms of Ohm's law relating *V*, *I*, and *R*.

2. (**a**) Why does higher applied voltage with the same resistance result in more current? (**b**) Why does more resistance with the same applied voltage result in less current?

3. Calculate the resistance of a 300-W bulb connected across the 120-V power line, using two different methods to arrive at the same answer.

4. State which unit in each of the following pairs is larger: (**a**) volt or kilovolt; (**b**) ampere or milliampere; (**c**) ohm or megohm; (**d**) volt or microvolt; (**e**) siemens or microsiemens; (**f**) electron volt or joule; (**g**) watt or kilowatt; (**h**) kilowatt-hour or joule; (**i**) volt or millivolt; (**j**) megohm or kilohm.

5. State two safety precautions to follow when working on electric circuits.

6. Referring back to the resistor shown in Fig. 1–10 in Chap. 1, suppose that it is not marked. How could you determine its resistance by Ohm's law? Show your calculations that result in the V/I ratio of 10 kΩ. However, do not exceed the power rating of 10 W.

7. Give three formulas for electric power.

8. What is the difference between work and power? Give two units for each.

9. Prove that 1 kWh is equal to 3.6×10^6 J.

10. Give the metric prefixes for 10^{-6}, 10^{-3}, 10^3, and 10^6.

11. Which two units in Table 3–2 are reciprocals of each other?

12. A circuit has a constant R of 5000 Ω, and V is varied from 0 to 50 V in 10-V steps. Make a table listing the values of I for each value of V. Then draw a graph plotting these values of milliamperes vs. volts. (This graph should be like Fig. 3–5c.)

13. Give the voltage and power rating for at least two types of electrical equipment.

14. Which uses more current from the 120-V power line, a 600-W toaster or a 300-W lightbulb?

15. Give a definition for a short circuit and for an open circuit.

16. Compare the R of zero ohms and infinite ohms.

17. Derive the formula $P = I^2R$ from $P = IV$ by using an Ohm's law formula.

18. Explain why a thermistor is a nonlinear resistance.

19. What is meant by the maximum working voltage rating of a resistor?

20. Why do resistors often have a safety factor of 2 in regard to their power rating?

Problems

SECTION 3–1 THE CURRENT $I = V/R$

In Probs. 3–1 to 3–5, solve for the current, I, when V and R are known. As a visual aid, it may be helpful to insert the values of V and R into Fig. 3–11 when solving for I.

3–1 MultiSim a. $V = 10$ V, $R = 5$ Ω, $I = ?$
b. $V = 9$ V, $R = 3$ Ω, $I = ?$
c. $V = 24$ V, $R = 3$ Ω, $I = ?$
d. $V = 36$ V, $R = 9$ Ω, $I = ?$

3–2 MultiSim a. $V = 18$ V, $R = 3$ Ω, $I = ?$
b. $V = 16$ V, $R = 16$ Ω, $I = ?$
c. $V = 90$ V, $R = 450$ Ω, $I = ?$
d. $V = 12$ V, $R = 30$ Ω, $I = ?$

3–3 MultiSim a. $V = 15$ V, $R = 3{,}000$ Ω, $I = ?$
b. $V = 120$ V, $R = 6{,}000$ Ω, $I = ?$
c. $V = 27$ V, $R = 9{,}000$ Ω, $I = ?$
d. $V = 150$ V, $R = 10{,}000$ Ω, $I = ?$

3–4 If a 100-Ω resistor is connected across the terminals of a 12-V battery, how much is the current, I?

3–5 If one branch of a 120-V power line is protected by a 20-A fuse, will the fuse carry an 8-Ω load?

SECTION 3–2 THE VOLTAGE $V = IR$

In Probs. 3–6 to 3–10, solve for the voltage, V, when I and R are known. As a visual aid, it may be helpful to insert the values of I and R into Fig. 3–12 when solving for V.

3–6 MultiSim a. $I = 2$ A, $R = 5$ Ω, $V = ?$
b. $I = 6$ A, $R = 8$ Ω, $V = ?$
c. $I = 9$ A, $R = 20$ Ω, $V = ?$
d. $I = 4$ A, $R = 15$ Ω, $V = ?$

3–7 MultiSim a. $I = 5$ A, $R = 10$ Ω, $V = ?$
b. $I = 10$ A, $R = 3$ Ω, $V = ?$
c. $I = 4$ A, $R = 2.5$ Ω, $V = ?$
d. $I = 1.5$ A, $R = 5$ Ω, $V = ?$

Figure 3–11 Figure for Probs. 3–1 to 3–5.

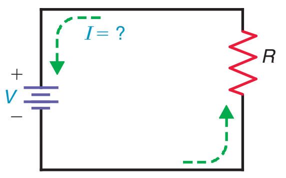


Figure 3–12 Figure for Probs. 3–6 to 3–10.

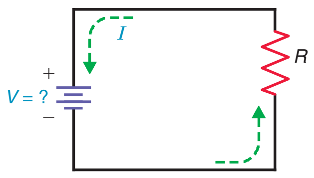


Figure 3–13 Figure for Probs. 3–11 to 3–15.

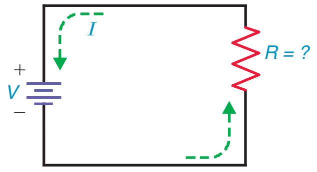
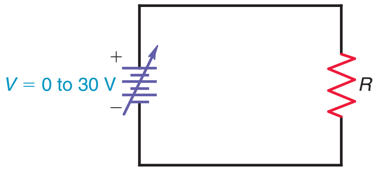


Figure 3–14 Circuit diagram for Prob. 3–21.



3–8 MultiSim a. $I = 0.05$ A, $R = 1200\ \Omega$, $V = ?$
b. $I = 0.2$ A, $R = 470\ \Omega$, $V = ?$
c. $I = 0.01$ A, $R = 15{,}000\ \Omega$, $V = ?$
d. $I = 0.006$ A, $R = 2200\ \Omega$, $V = ?$

3–9 How much voltage is developed across a 1000-Ω resistor if it has a current of 0.01 A?

3–10 A lightbulb drawing 1.25 A of current has a resistance of 96 Ω. How much is the voltage across the lightbulb?

SECTION 3–3 THE RESISTANCE $R = V/I$

In Probs. 3–11 to 3–15, solve for the resistance, *R*, when *V* and *I* are known. As a visual aid, it may be helpful to insert the values of *V* and *I* into Fig. 3–13 when solving for *R*.

3–11 a. $V = 14$ V, $I = 2$ A, $R = ?$
b. $V = 25$ V, $I = 5$ A, $R = ?$
c. $V = 6$ V, $I = 1.5$ A, $R = ?$
d. $V = 24$ V, $I = 4$ A, $R = ?$

3–12 a. $V = 36$ V, $I = 9$ A, $R = ?$
b. $V = 45$ V, $I = 5$ A, $R = ?$
c. $V = 100$ V, $I = 2$ A, $R = ?$
d. $V = 240$ V, $I = 20$ A, $R = ?$

3–13 a. $V = 12$ V, $I = 0.002$ A, $R = ?$
b. $V = 16$ V, $I = 0.08$ A, $R = ?$
c. $V = 50$ V, $I = 0.02$ A, $R = ?$
d. $V = 45$ V, $I = 0.009$ A, $R = ?$

3–14 How much is the resistance of a motor if it draws 2 A of current from the 120-V power line?

3–15 If a CD player draws 1.6 A of current from a 13.6-Vdc source, how much is its resistance?

SECTION 3–5 MULTIPLE AND SUBMULTIPLE UNITS

In Probs. 3–16 to 3–20, solve for the unknowns listed. As a visual aid, it may be helpful to insert the known values of *I*, *V*, or *R* into Figs. 3–11, 3–12, or 3–13 when solving for the unknown quantity.

3–16 a. $V = 10$ V, $R = 100$ kΩ, $I = ?$
b. $V = 15$ V, $R = 2$ kΩ, $I = ?$
c. $I = 200\ \mu$A, $R = 3.3$ MΩ, $V = ?$
d. $V = 5.4$ V, $I = 2$ mA, $R = ?$

3–17 a. $V = 120$ V, $R = 1.5$ kΩ, $I = ?$
b. $I = 50\ \mu$A, $R = 390$ kΩ, $V = ?$
c. $I = 2.5$ mA, $R = 1.2$ kΩ, $V = ?$
d. $V = 99$ V, $I = 3$ mA, $R = ?$

3–18 a. $V = 24$ V, $I = 800\ \mu$A, $R = ?$
b. $V = 160$ mV, $I = 8\ \mu$A, $R = ?$
c. $V = 13.5$ V, $R = 300\ \Omega$, $I = ?$
d. $I = 30$m A, $R = 1.8$ kΩ, $V = ?$

3–19 How much is the current, *I*, in a 470-kΩ resistor if its voltage is 23.5 V?

3–20 How much voltage will be dropped across a 40-kΩ resistance whose current is 250 μA?

SECTION 3–6 THE LINEAR PROPORTION BETWEEN *V* AND *I*

3–21 Refer to Fig. 3–14. Draw a graph of the *I* and *V* values if (*a*) $R = 2.5\ \Omega$; (*b*) $R = 5\ \Omega$; (*c*) $R = 10\ \Omega$. In each case, the voltage source is to be varied in 5-V steps from 0 to 30 V.

3–22 Refer to Fig. 3–15. Draw a graph of the *I* and *R* values when *R* is varied in 2-Ω steps from 2 to 12 Ω. (*V* is constant at 12 V.)

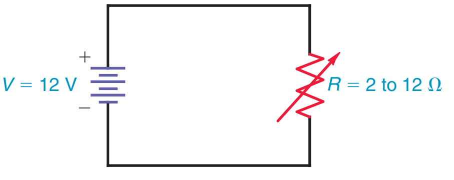
SECTION 3–7 ELECTRIC POWER

In Probs. 3–23 to 3–31, solve for the unknowns listed.

3–23 a. $V = 120$ V, $I = 12.5$ A, $P = ?$
b. $V = 120$ V, $I = 625$ mA, $P = ?$
c. $P = 1.2$ kW, $V = 120$ V, $I = ?$
d. $P = 100$ W, $I = 8.33$ A, $V = ?$

3–24 a. $V = 24$ V, $I = 25$ mA, $P = ?$
b. $P = 6$ W, $V = 12$ V, $I = ?$
c. $P = 10$ W, $I = 100$ mA, $V = ?$
d. $P = 50$ W, $V = 9$ V, $I = ?$

Figure 3–15 Circuit diagram for Prob. 3–22.



3–25 a. $V = 15.81$ V, $P = 500$ mW, $I = ?$
b. $P = 100$ mW, $V = 50$ V, $I = ?$
c. $V = 75$ mV, $I = 2$ mA, $P = ?$
d. $P = 20$ mW, $I = 100$ μA, $V = ?$

3–26 How much current do each of the following lightbulbs draw from the 120-V power line?
a. 60-W bulb
b. 75-W bulb
c. 100-W bulb
d. 300-W bulb

3–27 How much is the output voltage of a power supply if it supplies 75 W of power while delivering a current of 5 A?

3–28 How much power is consumed by a 12-V incandescent lamp if it draws 150 mA of current when lit?

3–29 How much will it cost to operate a 1500-W quartz heater for 48 h if the cost of electricity is 7¢/kWh?

3–30 How much does it cost to light a 300-W lightbulb for 30 days if the cost of electricity is 7¢/kWh?

3–31 How much will it cost to run an electric motor for 10 days if the motor draws 15 A of current from the 240-V power line? The cost of electricity is 7.5¢/kWh.

SECTION 3–8 POWER DISSIPATION IN RESISTANCE

In Probs. 3–32 to 3–38, solve for the power, P, dissipated by the resistance, R.

3–32 a. $I = 1$ A, $R = 100$ Ω, $P = ?$
b. $I = 20$ mA, $R = 1$ kΩ, $P = ?$
c. $V = 5$ V, $R = 150$ Ω, $P = ?$
d. $V = 22.36$ V, $R = 1$ kΩ, $P = ?$

3–33 a. $I = 300$ μA, $R = 22$ kΩ, $P = ?$
b. $I = 50$ mA, $R = 270$ Ω, $P = ?$
c. $V = 70$ V, $R = 200$ kΩ, $P = ?$
d. $V = 8$ V, $R = 50$ Ω, $P = ?$

3–34 a. $I = 40$ mA, $R = 10$ kΩ, $P = ?$
b. $I = 3.33$ A, $R = 20$ Ω, $P = ?$
c. $V = 100$ mV, $R = 10$ Ω, $P = ?$
d. $V = 1$ kV, $R = 10$ MΩ, $P = ?$

3–35 How much power is dissipated by a 5.6-kΩ resistor whose current is 9.45 mA?

3–36 How much power is dissipated by a 50-Ω load if the voltage across the load is 100 V?

3–37 How much power is dissipated by a 600-Ω load if the voltage across the load is 36 V?

3–38 How much power is dissipated by an 8-Ω load if the current in the load is 200 mA?

SECTION 3–9 POWER FORMULAS

In Probs. 3–39 to 3–51, solve for the unknowns listed.

3–39 a. $P = 250$ mW, $R = 10$ kΩ, $I = ?$
b. $P = 100$ W, $V = 120$ V, $R = ?$
c. $P = 125$ mW, $I = 20$ mA, $R = ?$
d. $P = 1$ kW, $R = 50$ Ω, $V = ?$

3–40 a. $P = 500$ μW, $V = 10$ V, $R = ?$
b. $P = 150$ mW, $I = 25$ mA, $R = ?$
c. $P = 300$ W, $R = 100$ Ω, $V = ?$
d. $P = 500$ mW, $R = 3.3$ kΩ, $I = ?$

3–41 a. $P = 50$ W, $R = 40$ Ω, $V = ?$
b. $P = 2$ W, $R = 2$ kΩ, $V = ?$
c. $P = 50$ mW, $V = 500$ V, $I = ?$
d. $P = 50$ mW, $R = 312.5$ kΩ, $I = ?$

3–42 Calculate the maximum current that a 1-kΩ, 1-W carbon resistor can safely handle without exceeding its power rating.

3–43 Calculate the maximum current that a 22-kΩ, $\frac{1}{8}$-W resistor can safely handle without exceeding its power rating.

3–44 What is the hot resistance of a 60-W, 120-V lightbulb?

3–45 A 50-Ω load dissipates 200 W of power. How much voltage is across the load?

3–46 Calculate the maximum voltage that a 390-Ω, $\frac{1}{2}$-W resistor can safely handle without exceeding its power rating.

3–47 What is the resistance of a device that dissipates 1.2 kW of power when its current is 10 A?

3–48 How much current does a 960-W coffeemaker draw from the 120-V power line?

3–49 How much voltage is across a resistor if it dissipates 2 W of power when the current is 40 mA?

3–50 If a 4-Ω speaker dissipates 15 W of power, how much voltage is across the speaker?

3–51 What is the resistance of a 20-W, 12-V halogen lamp?

SECTION 3–10 CHOOSING A RESISTOR FOR A CIRCUIT

In Probs. 3–52 to 3–60, determine the required resistance and appropriate wattage rating of a carbon-film resistor for the specific requirements listed. For all problems, assume that the following wattage ratings are available: $\frac{1}{8}$ W, $\frac{1}{4}$ W, $\frac{1}{2}$ W, 1 W, and 2 W. (Assume the maximum working voltage ratings listed on page 93.)

3–52 Required values of V and I are 54 V and 2 mA.

3–53 Required values of V and I are 12 V and 10 mA.

3–54 Required values of V and I are 390 V and 1 mA.

3–55 Required values of V and I are 36 V and 18 mA.

3–56 Required values of V and I are 340 V and 500 μA.

3–57 Required values of *V* and *I* are 3 V and 20 mA.

3–58 Required values of *V* and *I* are 33 V and 18.33 mA.

3–59 Required values of *V* and *I* are 264 V and 120 μA.

3–60 Required values of *V* and *I* are 9.8 V and 1.75 mA.

Critical Thinking

3–61 The percent efficiency of a motor can be calculated as

$$\% \text{ efficiency} = \frac{\text{power out}}{\text{power in}} \times 100$$

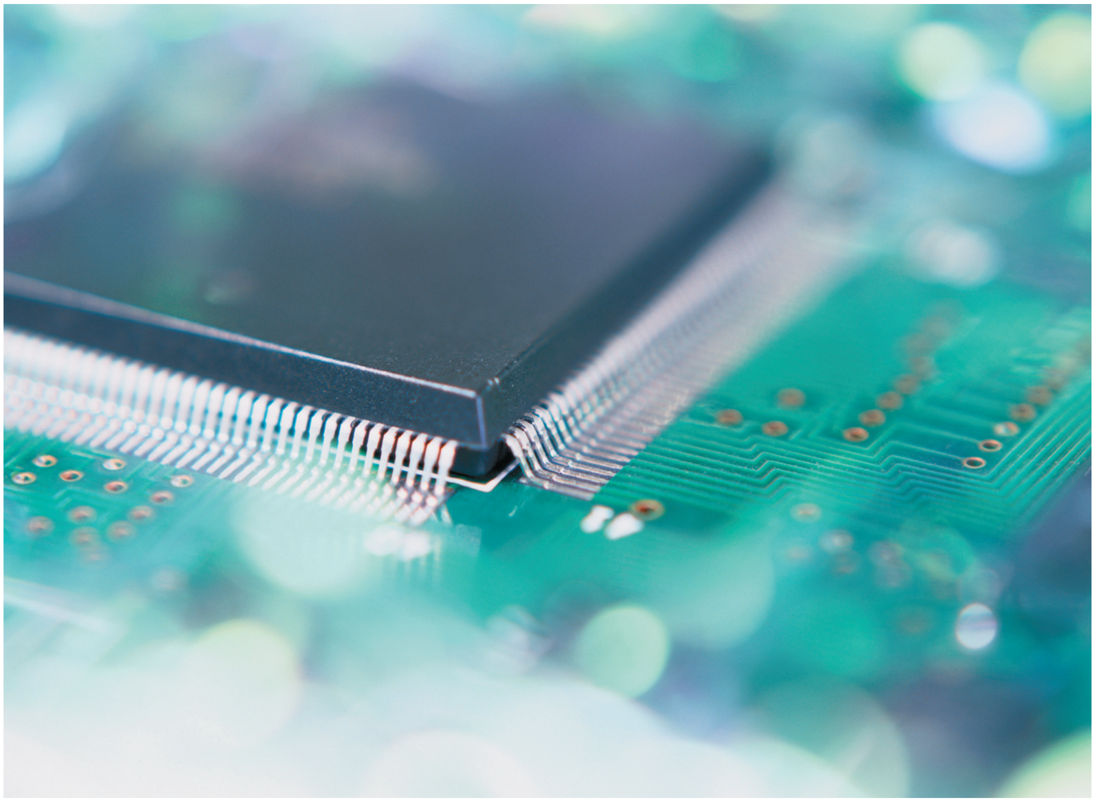
where power out represents horsepower (hp). Calculate the current drawn by a 5-hp, 240-V motor that is 72% efficient.

3–62 A ½-hp, 120-V motor draws 4.67 A when it is running. Calculate the motor's efficiency.

3–63 A ¾-hp motor with an efficiency of 75% runs 20% of the time during a 30-day period. If the cost of electricity is 7¢/kWh, how much will it cost the user?

3–64 An appliance uses 14.4×10^6 J of energy for 1 day. How much will this cost the user if the cost of electricity is 6.5¢/kWh?

3–65 A certain 1-kΩ resistor has a power rating of ½ W for temperatures up to 70°C. Above 70°C, however, the power rating must be reduced by a factor of 6.25 mW/°C Calculate the maximum current that the resistor can allow at 120°C without exceeding its power dissipation rating at this temperature.



Answers to Self-Reviews

3–1 **a.** 3 A
b. 1.5 A
c. 2 A
d. 6 A

3–2 **a.** 2 V
b. 4 V
c. 4 V

3–3 **a.** 4000 Ω
b. 2000 Ω
c. 12,000 Ω

3–4 **a.** 35 V
b. 0.002 A
c. 2000 Ω

3–5 **a.** See Prob. **b**
b. See Prob. **a**
c. 2 mA
d. 125 μA

3–6 **a.** *y* axis
b. linear
c. *I* doubles from 2 A to 4 A
d. *I* is halved from 2 A to 1 A

3–7 **a.** 1.8 kW
b. 0.83 A
c. 200 W
d. $1.01 (approx.)

3–8 **a.** 20 W
b. 20 W
c. 20 W and 5 Ω

3–9 **a.** 144 Ω
b. 50 W
c. 8 W

3–10 **a.** 50 V; no
b. $R = 1\ \text{M}\Omega$, $P_{\text{rating}} = \frac{1}{8}$ W

3–11 **a.** true
b. true

3–12 **a.** true
b. true
c. true

Laboratory Application Assignment

In this lab application assignment you will examine the difference between a linear and nonlinear resistance. Recall from your reading that a linear resistance has a constant value of ohms. Conversely, a nonlinear resistance has an ohmic value that varies with different amounts of voltage and current.

Equipment: Obtain the following items from your instructor.

- Variable dc power supply
- DMM
- 330-Ω, ½-W carbon-film resistor
- 12-V incandescent bulb (½-W rating)

Linear Resistance

Measure and record the value of the 330-Ω carbon-film resistor. *R* = ________

Connect the circuit in Fig. 3–16. Measure and record the current, *I*, with the voltage, *V*, set to 3 V. *I* = ________

Increase the voltage to 6 V and remeasure the current, *I*. *I* = ________

Increase the voltage one more time to 12 V, and remeasure the current, *I*. *I* = ________

For each value of voltage and current, calculate the resistance value as *R* = *V*/*I*. Does *R* remain the same even though *V* and *I* are changing? ________

Nonlinear Resistance

Measure and record the cold resistance of the 12-V incandescent bulb. *R* = ________

In Fig. 3–16 replace the 330-Ω carbon-film resistor with the 12-V incandescent bulb.

Measure and record the current, *I*, with the voltage, *V*, set to 3 V. *I* = ________

Increase the voltage to 6 V, and remeasure the current, *I*. *I* = ________

Increase the voltage one more time to 12 V, and remeasure the current, *I*. *I* = ________

Calculate the resistance of the bulb as *R* = *V*/*I* for each value of applied voltage. When *V* = 3 V, *R* = ________. When *V* = 6 V, *R* = ________. When *V* = 12 V, *R* = ________.

Does *R* remain constant for each value of voltage and current? ________

Does the bulb's resistance increase or decrease as *V* and *I* increase? ________

Calculating Power

(330-Ω resistor)

Calculate the power dissipated by the 330-Ω resistor with V = 3 V. P = _________ W

Calculate the power dissipated by the 330-Ω resistor with V = 6 V. P = _________ W

Calculate the power dissipated by the 330-Ω resistor with V = 12 V. P = _________ W

What happens to the power dissipation each time the voltage, V, is doubled?

____

(12-V incandescent bulb)

Calculate the power dissipated by the incandescent bulb with V = 3 V. P = _________ W

Calculate the power dissipated by the incandescent bulb with V = 6 V. P = _________ W

Calculate the power dissipated by the incandescent bulb with V = 12 V. P = _________ W

What happens to the power dissipation each time the voltage, V, is doubled?

____

How does this compare to the results obtained with the 330-Ω resistor? ____

Volt-Ampere Characteristic Curves

Draw the volt-ampere characteristic curve for the 330-Ω carbon-film resistor. Use the voltage and current values obtained from this experiment. Plot your data on linear graph paper. Repeat this procedure for the 12-V incandescent bulb. Comment on the difference between the two graphs.

Figure 3–16