Introduction

Electric circuit theory and electromagnetic theory are the two fundamental theories upon which all branches of electrical engineering are built. In electrical engineering, we are often interested in communicating or transferring energy from one point to another. To do this requires an interconnection of electrical devices. Such interconnection is referred to as an electric circuit, and each component of the circuit is known as an element. ***An electric circuit is an interconnection of electrical elements***. A simple electric circuit is shown in Fig. 1.1. It consists of three basic elements: a battery, a lamp, and connecting wires. Such a simple circuit can exist by itself; it has several applications, such as a flashlight, a search light, and so forth.

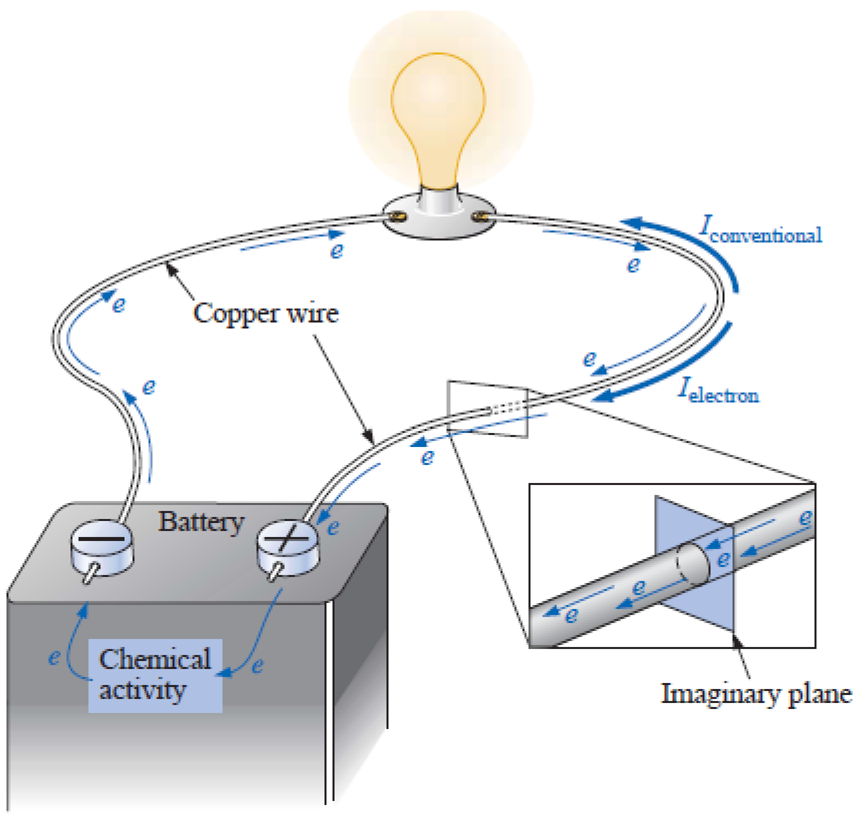

Fig. 1.1 *A simple electric circuit.*

1.1 Systems of Units

As electrical engineers, we deal with measurable quantities. Our measurement, however, must be communicated in a standard language that virtually all professionals can understand, irrespective of the country where the measurement is conducted. Such an international measurement language is the International System of Units (SI), adopted by the General Conference on Weights and Measures in 1960. In this system, the units of all other physical quantities can be derived from seven principal units. Table 1.1 shows the six units and one derived unit that are relevant to this text. The SI units are used throughout this text.

One great advantage of the SI unit is that it uses prefixes based on the power of 10 to relate larger and smaller units to the basic unit. Table 1.2 shows the SI prefixes and their symbols. For example, the following are expressions of the same distance in meters (m):

600,000,000 mm 600,000 m 600 km

TABLE 1.1

Six basic SI units and one derived unit relevant to this text.

Quantity	Basic unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Charge	coulomb	C

TABLE 1.2

The SI prefixes.

Multiplier	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

1.2 Charge and Current

The concept of electric charge is the underlying principle for explaining all electrical phenomena. Also, the most basic quantity in an electric circuit is the electric charge. We all experience the effect of electric charge when we try to remove our wool sweater and have it stick to our body or walk across a carpet and receive a shock.

Charge is an electrical property of the atomic particles of which matter consists, measured in coulombs (C).

Electric current is the time rate of change of charge, measured in amperes (A).

If $6.242 * 10^{18}$ *electrons* drift at uniform velocity through the imaginary circular cross section of Fig. 1.1 in 1 *second*, the flow of charge, or *current*, is said to be 1 **ampere** (A)

$$\text{Charge/electron} = Q_e = \frac{1\ \text{C}}{6.242 \times 10^{18}} = 1.6 \times 10^{-19}\ \text{C}$$

The current in amperes can now be calculated using the following equation:

$$\boxed{I = \frac{Q}{t}} \qquad \begin{aligned} I &= \text{amperes (A)} \\ Q &= \text{coulombs (C)} \\ t &= \text{seconds (s)} \end{aligned} \qquad (1.1)$$

$$\boxed{Q = It} \qquad \text{(coulombs, C)} \qquad 1.2$$

and

$$\boxed{t = \frac{Q}{I}} \qquad \text{(seconds, s)} \qquad 1.3$$

Example 1.1 The charge flowing through the imaginary surface of Fig. 1.1 is 0.16 C every 64 ms. Determine the current in amperes.

Solution :

$$I = \frac{Q}{t} = \frac{0.16\text{ C}}{64 \times 10^{-3}\text{ s}} = \frac{160 \times 10^{-3}\text{ C}}{64 \times 10^{-3}\text{ s}} = \mathbf{2.50\ A}$$

Example 1.2 Determine the time required for (4 * 10^{16}) electrons to pass through the imaginary surface of Fig. 1.1 if the current is 5 mA.

Solution :

$$4 \times 10^{16}\ \cancel{\text{electrons}} \left(\frac{1\text{ C}}{6.242 \times 10^{18}\ \cancel{\text{electrons}}} \right) = 0.641 \times 10^{-2}\text{ C}$$

$$= 0.00641\text{ C} = 6.41\text{ mC}$$

Calculate *t* [Eq. (1.3)]:

$$t = \frac{Q}{I} = \frac{6.41 \times 10^{-3}\text{ C}}{5 \times 10^{-3}\text{ A}} = \mathbf{1.282\ s}$$

1.3 VOLTAGE

Charge can be raised to a higher potential level through the expenditure of energy from an external source, or it can lose potential energy as it travels through an electrical system. In any case, by definition:

A potential difference of 1 volt (V) exists between two points if 1 joule (J) of energy is exchanged in moving 1 coulomb (C) of charge between the two points.

The unit of measurement **volt** was chosen to honor ***Alessandro Volta***.

a potential difference or voltage is always measured between two points in the system. Changing either point may change the potential difference between the two points under investigation.

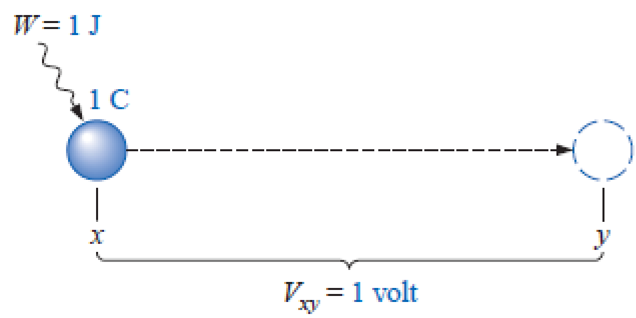

Fig. 1.2 *Defining the unit of measurement for voltage.*

In general, the potential difference between two points is determined by :

$$\boxed{V = \frac{W}{Q}} \quad \text{(volts)} \qquad (1.4)$$

Through algebraic manipulations, we have

$$\boxed{W = QV} \quad \text{(joules)} \qquad (1.5)$$

and

$$\boxed{Q = \frac{W}{V}} \quad \text{(coulombs)} \qquad (1.6)$$

Example 1.3 Find the potential difference between two points in an electrical system if 60 J of energy are expended by a charge of 20 C between these two points.

Solution: equ. 1.4

$$V = \frac{W}{Q} = \frac{60\ \text{J}}{20\ \text{C}} = \mathbf{3\ V}$$

Example 1.4 Determine the energy expended moving a charge of 50 μC through a potential difference of 6 V.

Solution : equ. 1.5

$$W = QV = (50 \times 10^{-6}\ \text{C})(6\ \text{V}) = 300 \times 10^{-6}\ \text{J} = \mathbf{300\ \mu J}$$

1.4 Resistance

The flow of charge through any material encounters an opposing force similar in many respects to mechanical friction. This opposition, due to the collisions between electrons and between electrons and other atoms in the material, *which converts electrical energy into another form of energy such as heat*, is called the **resistance** of the material. The unit of measurement of resistance is the **ohm,** for which the symbol is **Ω**, the capital Greek letter omega. The circuit symbol for resistance appears in .The resistance of any material with a uniform cross-sectional area is determined by the following four factors:

1. Material
2. Length
3. Cross-sectional area
4. Temperature

At a fixed temperature of 20°C (room temperature), the resistance is related to the other three factors by

$$\boxed{R = \rho \frac{l}{A}} \qquad \text{(ohms, } \Omega) \qquad \textbf{(1.7)}$$

Example 1.5 Determine the resistance of 100 ft of #28 copper telephone wire if the diameter is 0.0126 in.

solution:

$$l = 100\ \cancel{\text{ft}}\left(\frac{12\ \cancel{\text{in.}}}{1\ \cancel{\text{ft}}}\right)\left(\frac{2.54\ \text{cm}}{1\ \cancel{\text{in.}}}\right) = 3048\ \text{cm}$$

$$d = 0.0126\ \text{in.}\left(\frac{2.54\ \text{cm}}{1\ \text{in.}}\right) = 0.032\ \text{cm}$$

Therefore,

$$A = \frac{\pi d^2}{4} = \frac{(3.1416)(0.032\ \text{cm})^2}{4} = 8.04 \times 10^{-4}\ \text{cm}^2$$

$$R = \rho\frac{l}{A} = \frac{(1.723 \times 10^{-6}\ \Omega\cdot\text{cm})(3048\ \text{cm})}{8.04 \times 10^{-4}\ \text{cm}^2} \cong \mathbf{6.5\ \Omega}$$

Using the units for circular wires and Table 3.2 for the area of a # wire, we find

$$R = \rho\frac{l}{A} = \frac{(10.37\ \text{CM}\cdot\Omega/\text{ft})(100\ \text{ft})}{159.79\ \text{CM}} \cong \mathbf{6.5\ \Omega}$$

Temperature Effects

for good conductors, an increase in temperature will result in an increase in the resistance level. Consequently, conductors have a positive temperature coefficient.

for semiconductor materials, an increase in temperature will result in a decrease in the resistance level. Consequently, semiconductors have negative temperature coefficients.

Inferred Absolute Temperature

Figure 1.3 reveals that for copper (and most other metallic conductors), the resistance increases almost linearly (in a straight-line relationship) with an increase in temperature. Since temperature can have such a pronounced effect on the resistance of a conductor, it is important that we have some method of determining the resistance at any temperature within operating limits. An equation for this purpose can be obtained by approximating the curve of Fig. 1.3 by the straight dashed line that intersects the temperature scale at -234.5°C. Although the actual curve extends to **absolute zero** (_273.15°C, or 0 K), the straight-line approximation is quite accurate for the normal operating temperature range. At two different temperatures, $T1$ and $T2$, the resistance of copper is $R1$ and $R2$, as indicated on the curve. Using a property of similar triangles, we may develop a mathematical relationship between these values of resistances at different temperatures. Let x equal the distance from -234.5°C to $T1$ and y the distance from -234.5°C to $T2$, as shown in Fig. 1.3. From similar triangles,

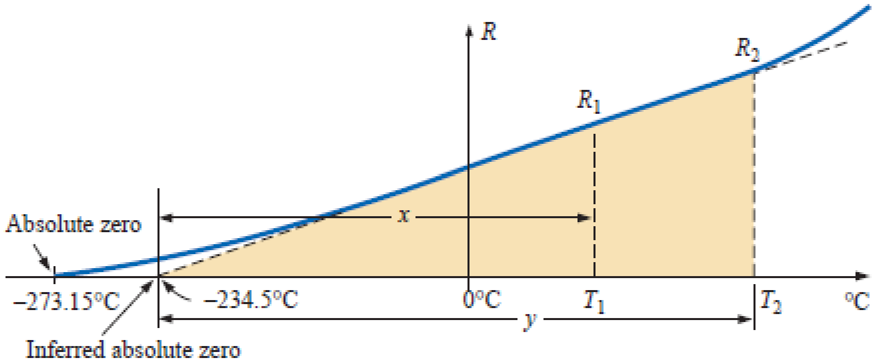

FIG. 1.3
Effect of temperature on the resistance of copper.

$$\frac{x}{R_1} = \frac{y}{R_2}$$

$$\boxed{\frac{234.5 + T_1}{R_1} = \frac{234.5 + T_2}{R_2}} \qquad (1.8)$$

or

$$\boxed{\frac{|T_1| + T_1}{R_1} = \frac{|T_1| + T_2}{R_2}} \qquad (1.9)$$

where $|T1|$ indicates that the inferred absolute temperature of the material involved is inserted as a positive value in the equation. In general, therefore, associate the sign only with $T1$ and $T2$.

Example 1.6 If the resistance of a copper wire is 50 Ω at 20°C, what is its resistance at 100°C (boiling point of water)?

Solution:

$$\frac{234.5°\text{C} + 20°\text{C}}{50\ \Omega} = \frac{234.5°\text{C} + 100°\text{C}}{R_2}$$

$$R_2 = \frac{(50\ \Omega)(334.5°\text{C})}{254.5°\text{C}} = \mathbf{65.72\ \Omega}$$

Table 1.3

Inferred absolute temperatures (T_i).

Material	°C
Silver	−243
Copper	−234.5
Gold	−274
Aluminum	−236
Tungsten	−204
Nickel	−147
Iron	−162
Nichrome	−2,250
Constantan	−125,000

Example 1.7 If the resistance of an aluminum wire at room temperature (20°C) is 100 mΩ(measured by a milliohmmeter), at what temperature will its resistance increase to 120 mΩ?

Solution:

$$\frac{236°\text{C} + 20°\text{C}}{100\ \text{m}\Omega} = \frac{236°\text{C} + T_2}{120\ \text{m}\Omega}$$

and

$$T_2 = 120\ \text{m}\Omega\left(\frac{256°\text{C}}{100\ \text{m}\Omega}\right) - 236°\text{C}$$

$$T_2 = \mathbf{71.2°C}$$