2 An introduction to electric circuits

At the end of this chapter you should be able to:

- recognize common electrical circuit diagram symbols
- understand that electric current is the rate of movement of charge and is measured in amperes
- appreciate that the unit of charge is the coulomb
- calculate charge or quantity of electricity Q from $Q = It$
- understand that a potential difference between two points in a circuit is required for current to flow
- appreciate that the unit of p.d. is the volt
- understand that resistance opposes current flow and is measured in ohms
- appreciate what an ammeter, a voltmeter, an ohmmeter, a multimeter and a C.R.O. measure
- distinguish between linear and non-linear devices
- state Ohm's law as $V = IR$ or $I = \dfrac{V}{R}$ or $R = \dfrac{V}{I}$
- use Ohm's law in calculations, including multiples and sub-multiples of units
- describe a conductor and an insulator, giving examples of each
- appreciate that electrical power P is given by

  $$P = VI = I^2R = \frac{V^2}{R} \text{ watts}$$
- calculate electrical power
- define electrical energy and state its unit
- calculate electrical energy
- state the three main effects of an electric current, giving practical examples of each
- explain the importance of fuses in electrical circuits

2.1 Standard symbols for electrical components

Symbols are used for components in electrical circuit diagrams and some of the more common ones are shown in Figure 2.1.

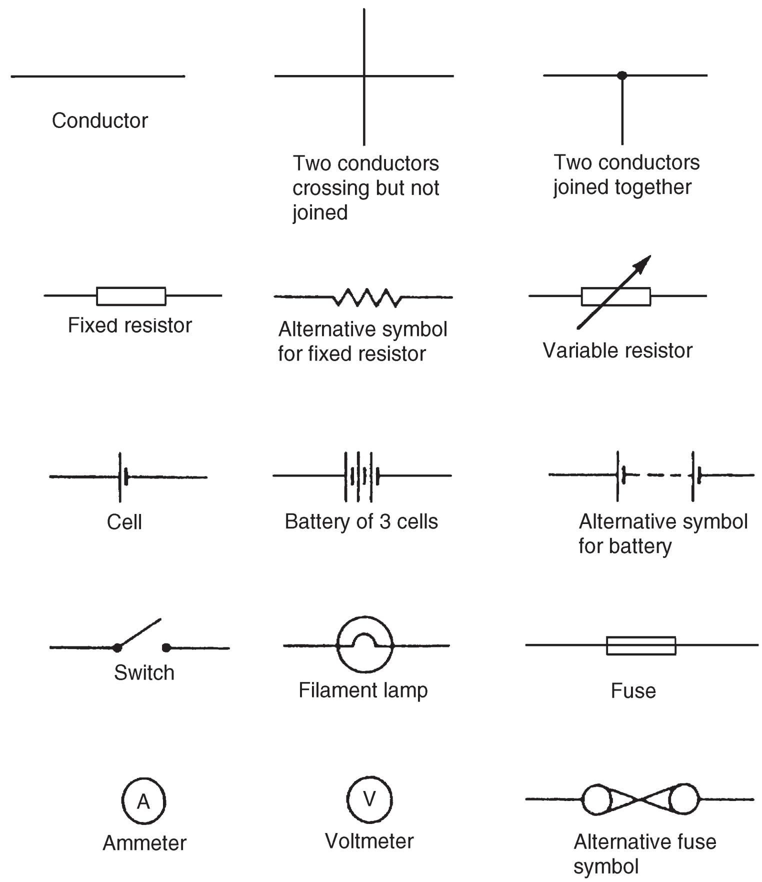

Figure 2.1

2.2 Electric current and quantity of electricity

All **atoms** consist of **protons, neutrons** and **electrons**. The protons, which have positive electrical charges, and the neutrons, which have no electrical charge, are contained within the **nucleus**. Removed from the nucleus are minute negatively charged particles called electrons. Atoms of different materials differ from one another by having different numbers of protons, neutrons and electrons. An equal number of protons and electrons exist within an atom and it is said to be electrically balanced, as the positive and negative charges cancel each other out. When there are more than two electrons in an atom the electrons are arranged into **shells** at various distances from the nucleus.

All atoms are bound together by powerful forces of attraction existing between the nucleus and its electrons. Electrons in the outer shell of an atom, however, are attracted to their nucleus less powerfully than are electrons whose shells are nearer the nucleus.

It is possible for an atom to lose an electron; the atom, which is now called an **ion**, is not now electrically balanced, but is positively charged and is thus able to attract an electron to itself from another atom. Electrons that move from one atom to another are called free electrons and such random motion can continue indefinitely. However, if an electric pressure or **voltage** is applied across any material there is a tendency for electrons to move in a particular direction. This movement of free electrons, known as **drift**, constitutes an electric current flow. **Thus current is the rate of movement of charge**.

Conductors are materials that contain electrons that are loosely connected to the nucleus and can easily move through the material from one atom to another.

Insulators are materials whose electrons are held firmly to their nucleus.

The unit used to measure the **quantity of electrical charge Q** is called the **coulomb C** (where 1 coulomb $= 6.24 \times 10^{18}$ electrons)

If the drift of electrons in a conductor takes place at the rate of one coulomb per second the resulting current is said to be a current of one ampere.

Thus, 1 ampere = 1 coulomb per second or 1 A = 1 C/s

Hence, 1 coulomb = 1 ampere second or 1 C = 1 As

Generally, if I is the current in amperes and t the time in seconds during which the current flows, then $I \times t$ represents the quantity of electrical charge in coulombs, i.e.

quantity of electrical charge transferred, $\boxed{\boldsymbol{Q = I \times t} \textbf{ coulombs}}$

Problem 1. What current must flow if 0.24 coulombs is to be transferred in 15 ms?

Since the quantity of electricity, $Q = It$, then

$$I = \frac{Q}{t} = \frac{0.24}{15 \times 10^{-3}} = \frac{0.24 \times 10^3}{15} = \frac{240}{15} = \mathbf{16\ A}$$

Problem 2. If a current of 10 A flows for four minutes, find the quantity of electricity transferred.

Quantity of electricity, $Q = It$ coulombs

$I = 10$ A; $t = 4 \times 60 = 240$ s

Hence $Q = 10 \times 240 = \mathbf{2400\ C}$

Further problems on $Q = I \times t$ may be found in Section 2.12, problems 1 to 3, page 21.

2.3 Potential difference and resistance

For a continuous current to flow between two points in a circuit a **potential difference (p.d.)** or **voltage**, ***V***, is required between them; a complete conducting path is necessary to and from the source of electrical energy. The unit of p.d. is the **volt**, **V**

Figure 2.2 shows a cell connected across a filament lamp. Current flow, by convention, is considered as flowing from the positive terminal of the cell, around the circuit to the negative terminal.

The flow of electric current is subject to friction. This friction, or opposition, is called **resistance *R*** and is the property of a conductor that limits current. The unit of resistance is the **ohm**; 1 ohm is defined as the resistance which will have a current of 1 ampere flowing through it when 1 volt is connected across it, i.e.

$$\textbf{resistance } \boldsymbol{R} = \frac{\textbf{potential difference}}{\textbf{current}}$$

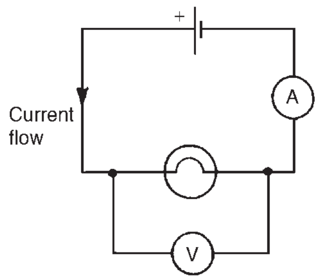

Figure 2.2

2.4 Basic electrical measuring instruments

An **ammeter** is an instrument used to measure current and must be connected **in series** with the circuit. Figure 2.2 shows an ammeter connected in series with the lamp to measure the current flowing through it. Since all the current in the circuit passes through the ammeter it must have a very **low resistance**.

A **voltmeter** is an instrument used to measure p.d. and must be connected **in parallel** with the part of the circuit whose p.d. is required. In Figure 2.2, a voltmeter is connected in parallel with the lamp to measure the p.d. across it. To avoid a significant current flowing through it a voltmeter must have a very **high resistance**.

An **ohmmeter** is an instrument for measuring resistance.

A **multimeter**, or universal instrument, may be used to measure voltage, current and resistance. An 'Avometer' is a typical example.

The **cathode ray oscilloscope (CRO)** may be used to observe waveforms and to measure voltages and currents. The display of a CRO involves a spot of light moving across a screen. The amount by which the spot is deflected from its initial position depends on the p.d. applied to the terminals of the CRO and the range selected. The displacement is calibrated in 'volts per cm'. For example, if the spot is deflected 3 cm and the volts/cm switch is on 10 V/cm then the magnitude of the p.d. is 3 cm × 10 V/cm, i.e. 30 V (See Chapter 10 for more detail about electrical measuring instruments and measurements.)

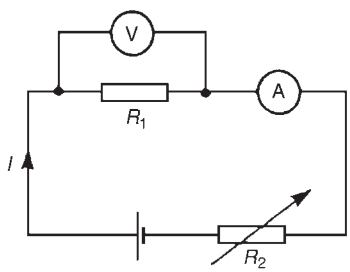

Figure 2.3

2.5 Linear and non-linear devices

Figure 2.3 shows a circuit in which current I can be varied by the variable resistor R_2. For various settings of R_2, the current flowing in resistor R_1, displayed on the ammeter, and the p.d. across R_1, displayed on the voltmeter, are noted and a graph is plotted of p.d. against current. The result is shown in Figure 2.4(a) where the straight line graph passing through the origin indicates that current is directly proportional to the p.d. Since the gradient i.e. (p.d./current) is constant, resistance R_1 is constant. A resistor is thus an example of a **linear device**.

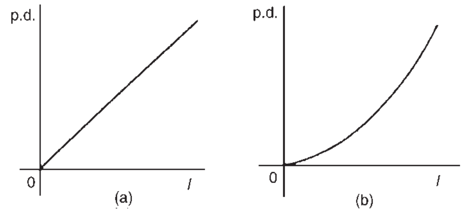

Figure 2.4

If the resistor R_1 in Figure 2.3 is replaced by a component such as a lamp then the graph shown in Figure 2.4(b) results when values of p.d. are noted for various current readings. Since the gradient is changing, the lamp is an example of a **non-linear device**.

2.6 Ohm's law

Ohm's law states that the current I flowing in a circuit is directly proportional to the applied voltage V and inversely proportional to the resistance R, provided the temperature remains constant. Thus,

$$\boxed{\boldsymbol{I = \frac{V}{R}} \text{ or } \boldsymbol{V = IR} \text{ or } \boldsymbol{R = \frac{V}{I}}}$$

> Problem 3. The current flowing through a resistor is 0.8 A when a p.d. of 20 V is applied. Determine the value of the resistance.

From Ohm's law, resistance $R = \dfrac{V}{I} = \dfrac{20}{0.8} = \dfrac{200}{8} = \mathbf{25\ \Omega}$

2.7 Multiples and sub-multiples

Currents, voltages and resistances can often be very large or very small. Thus multiples and sub-multiples of units are often used, as stated in chapter 1. The most common ones, with an example of each, are listed in Table 2.1

TABLE 2.1

Prefix	*Name*	*Meaning*	*Example*
M	mega	multiply by 1 000 000 (i.e., $\times 10^6$)	$2\ \text{M}\Omega = 2\,000\,000$ ohms
k	kilo	multiply by 1000 (i.e., $\times 10^3$)	$10\ \text{kV} = 10\,000$ volts
m	milli	divide by 1000 (i.e., $\times 10^{-3}$)	$25\ \text{mA} = \dfrac{25}{1000}\ \text{A} = 0.025$ amperes
μ	micro	divide by 1 000 000 (i.e., $\times 10^{-6}$)	$50\ \mu\text{V} = \dfrac{50}{1\,000\,000}\ \text{V} = 0.000\,05$ volts

A more extensive list of common prefixes are given on page 972.

Problem 4. Determine the p.d. which must be applied to a 2 kΩ resistor in order that a current of 10 mA may flow.

Resistance $R = 2\ \text{k}\Omega = 2 \times 10^3 = 2000\ \Omega$

Current $I = 10\ \text{mA} = 10 \times 10^{-3}\ \text{A}$ or $\dfrac{10}{10^3}$ or $\dfrac{10}{1000}\ \text{A} = 0.01\ \text{A}$

From Ohm's law, potential difference, $V = IR = (0.01)(2000) = \mathbf{20\ V}$

Problem 5. A coil has a current of 50 mA flowing through it when the applied voltage is 12 V. What is the resistance of the coil?

$$\text{Resistance, } R = \frac{V}{I} = \frac{12}{50 \times 10^{-3}} = \frac{12 \times 10^3}{50} = \frac{12\,000}{50} = \mathbf{240\ \Omega}$$

Problem 6. A 100 V battery is connected across a resistor and causes a current of 5 mA to flow. Determine the resistance of the resistor. If the voltage is now reduced to 25 V, what will be the new value of the current flowing?

$$\text{Resistance } R = \frac{V}{I} = \frac{100}{5 \times 10^{-3}} = \frac{100 \times 10^3}{5} = 20 \times 10^3 = \mathbf{20\ k\Omega}$$

Current when voltage is reduced to 25 V,

$$I = \frac{V}{R} = \frac{25}{20 \times 10^3} = \frac{25}{20} \times 10^{-3} = \mathbf{1.25\ mA}$$

Problem 7. What is the resistance of a coil which draws a current of (a) 50 mA and (b) 200 μA from a 120 V supply?

(a) Resistance $R = \dfrac{V}{I} = \dfrac{120}{50 \times 10^{-3}}$

$$= \frac{120}{0.05} = \frac{12\,000}{5} = \mathbf{2\,400\ \Omega} \text{ or } \mathbf{2.4\ k\Omega}$$

(b) Resistance $R = \dfrac{120}{200 \times 10^{-6}} = \dfrac{120}{0.0002}$

$$= \frac{1200\,000}{2} = \mathbf{600\,000\ \Omega} \text{ or } \mathbf{600\ k\Omega} \text{ or } \mathbf{0.6\ M\Omega}$$

Further problems on Ohm's law may be found in Section 2.12, problems 4 to 7, page 21.

2.8 Conductors and insulators

A **conductor** is a material having a low resistance which allows electric current to flow in it. All metals are conductors and some examples include copper, aluminium, brass, platinum, silver, gold and carbon.

An **insulator** is a material having a high resistance which does not allow electric current to flow in it. Some examples of insulators include plastic, rubber, glass, porcelain, air, paper, cork, mica, ceramics and certain oils.

2.9 Electrical power and energy

Electrical power

Power $\boldsymbol{P}$ in an electrical circuit is given by the product of potential difference V and current I, as stated in Chapter 1. The unit of power is the **watt**, **W**. Hence

$$\boxed{\boldsymbol{P = V \times I} \textbf{ watts}} \tag{2.1}$$

From Ohm's law, $V = IR$
Substituting for V in equation (2.1) gives:

$$P = (IR) \times I$$

i.e. $$\boxed{\boldsymbol{P = I^2 R} \textbf{ watts}}$$

Also, from Ohm's law, $I = \dfrac{V}{R}$
Substituting for I in equation (2.1) gives:

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

i.e. $$\boxed{\boldsymbol{P = \frac{V^2}{R}} \textbf{ watts}}$$

There are thus three possible formulae which may be used for calculating power.

> Problem 8. A 100 W electric light bulb is connected to a 250 V supply. Determine (a) the current flowing in the bulb, and (b) the resistance of the bulb.

Power $P = V \times I$, from which, current $I = \dfrac{P}{V}$

(a) Current $I = \dfrac{100}{250} = \dfrac{10}{25} = \dfrac{2}{5} = \mathbf{0.4\ A}$

(b) Resistance $R = \dfrac{V}{I} = \dfrac{250}{0.4} = \dfrac{2500}{4} = \mathbf{625\ \Omega}$

Problem 9. Calculate the power dissipated when a current of 4 mA flows through a resistance of 5 kΩ

Power $P = I^2R = (4 \times 10^{-3})^2(5 \times 10^3)$

$= 16 \times 10^{-6} \times 5 \times 10^3 = 80 \times 10^{-3}$

$= \mathbf{0.08\ W}$ or $\mathbf{80\ mW}$

Alternatively, since $I = 4 \times 10^{-3}$ and $R = 5 \times 10^3$ then from Ohm's law, voltage $V = IR = 4 \times 10^{-3} \times 5 \times 10^{-3} = 20$ V
Hence, power $P = V \times I = 20 \times 4 \times 10^{-3} = \mathbf{80\ mW}$

Problem 10. An electric kettle has a resistance of 30 Ω. What current will flow when it is connected to a 240 V supply? Find also the power rating of the kettle.

Current, $I = \frac{V}{R} = \frac{240}{30} = \mathbf{8\ A}$

Power, $P = VI = 240 \times 8 = 1920\ \text{W} = \mathbf{1.92\ kW}$

$=$ power rating of kettle

Problem 11. A current of 5 A flows in the winding of an electric motor, the resistance of the winding being 100 Ω. Determine (a) the p.d. across the winding, and (b) the power dissipated by the coil.

(a) Potential difference across winding, $V = IR = 5 \times 100 = \mathbf{500\ V}$

(b) Power dissipated by coil, $P = I^2R = 5^2 \times 100$

$= \mathbf{2500\ W\ or\ 2.5\ kW}$

(Alternatively, $P = V \times I = 500 \times 5 = \mathbf{2500\ W\ or\ 2.5\ kW}$)

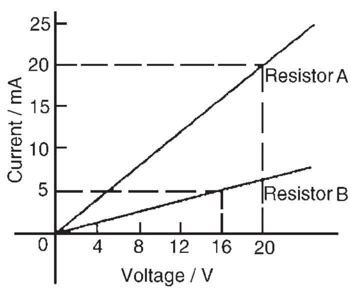

Figure 2.5

Problem 12. The current/voltage relationship for two resistors A and B is as shown in Figure 2.5. Determine the value of the resistance of each resistor.

For resistor A, $R = \frac{V}{I} = \frac{20\ \text{A}}{20\ \text{mA}} = \frac{20}{0.02} = \frac{2\,000}{2} = \mathbf{1\,000\ \Omega\ or\ 1\ k\Omega}$

For resistor B, $R = \frac{V}{I} = \frac{16\ \text{V}}{5\ \text{mA}} = \frac{16}{0.005} = \frac{16\,000}{5} = \mathbf{3\,200\ \Omega\ or\ 3.2\ k\Omega}$

Problem 13. The hot resistance of a 240 V filament lamp is 960 Ω. Find the current taken by the lamp and its power rating.

From Ohm's law, current $I = \frac{V}{R} = \frac{240}{960} = \frac{24}{96} = \mathbf{\frac{1}{4}}$ **A or 0.25 A**

Power rating $P = VI = (240)\left(\frac{1}{4}\right) = \mathbf{60\ W}$

Electrical energy

Electrical energy = power × time

If the power is measured in watts and the time in seconds then the unit of energy is watt-seconds or **joules**. If the power is measured in kilowatts and the time in hours then the unit of energy is **kilowatt-hours**, often called the '**unit of electricity**'. The 'electricity meter' in the home records the number of kilowatt-hours used and is thus an energy meter.

Problem 14. A 12 V battery is connected across a load having a resistance of 40 Ω. Determine the current flowing in the load, the power consumed and the energy dissipated in 2 minutes.

Current $I = \frac{V}{R} = \frac{12}{40} = \mathbf{0.3\ A}$

Power consumed, $P = VI = (12)(0.3) = \mathbf{3.6\ W}$

Energy dissipated = power × time = (3.6 W)(2 × 60 s) = **432 J**

(since 1 J = 1 Ws)

Problem 15. A source of e.m.f. of 15 V supplies a current of 2 A for six minutes. How much energy is provided in this time?

Energy = power × time, and power = voltage × current

Hence energy $= VIt = 15 \times 2 \times (6 \times 60) = 10\,800$ Ws or J = **10.8 kJ**

Problem 16. Electrical equipment in an office takes a current of 13 A from a 240 V supply. Estimate the cost per week of electricity if the equipment is used for 30 hours each week and 1 kWh of energy costs 7p

Power = VI watts = 240 × 13 = 3120 W = 3.12 kW

Energy used per week = power × time = (3.12 kW) × (30 h)

= 93.6 kWh

Cost at 7p per kWh = 93.6 × 7 = 655.2 p

Hence **weekly cost of electricity = £6.55**

> Problem 17. An electric heater consumes 3.6 MJ when connected to a 250 V supply for 40 minutes. Find the power rating of the heater and the current taken from the supply.

$$\text{Power} = \frac{\text{energy}}{\text{time}} = \frac{3.6 \times 10^6}{40 \times 60}\frac{\text{J}}{\text{s}}(\text{or W}) = 1500\ \text{W}$$

i.e. Power rating of heater = **1.5 kW**

$$\text{Power } P = VI, \text{ thus } I = \frac{P}{V} = \frac{1500}{250} = 6\ \text{A}$$

Hence the current taken from the supply is **6 A**

> Problem 18. Determine the power dissipated by the element of an electric fire of resistance 20 Ω when a current of 10 A flows through it. If the fire is on for 6 hours determine the energy used and the cost if 1 unit of electricity costs 7p.

Power $P = I^2R = 10^2 \times 20 = 100 \times 20 =$ **2 000 W or 2 kW**

(Alternatively, from Ohm's law, $V = IR = 10 \times 20 = 200$ V, hence power $P = V \times I = 200 \times 10 = 2000$ W = 2 kW)

Energy used in 6 hours = power × time = 2 kW × 6 h = **12 kWh**

1 unit of electricity = 1 kWh

Hence the number of units used is 12

Cost of energy = 12 × 7 = **84p**

> Problem 19. A business uses two 3 kW fires for an average of 20 hours each per week, and six 150 W lights for 30 hours each per week. If the cost of electricity is 7p per unit, determine the weekly cost of electricity to the business.

Energy = power × time

Energy used by one 3 kW fire in 20 hours = 3 kW × 20 h = 60 kWh

Hence weekly energy used by two 3 kW fires = 2 × 60 = 120 kWh

Energy used by one 150 W light for 30 hours = 150 W × 30 h

= 4500 Wh = 4.5 kWh

Hence weekly energy used by six 150 W lamps = 6 × 4.5 = 27 kWh

Total energy used per week = 120 + 27 = 147 kWh

1 unit of electricity = 1 kWh of energy

Thus weekly cost of energy at 7p per kWh = $7 \times 147 = 1029$p

= **£10.29**

Further problems on power and energy may be found in Section 2.12, problems 8 to 17, page 21.

2.10 Main effects of electric current

The three main effects of an electric current are:

(a) magnetic effect
(b) chemical effect
(c) heating effect

Some practical applications of the effects of an electric current include:

Magnetic effect: bells, relays, motors, generators, transformers, telephones, car-ignition and lifting magnets

Chemical effect: primary and secondary cells and electroplating

Heating effect: cookers, water heaters, electric fires, irons, furnaces, kettles and soldering irons

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2.11 Fuses

A **fuse** is used to prevent overloading of electrical circuits. The fuse, which is made of material having a low melting point, utilizes the heating effect of an electric current. A fuse is placed in an electrical circuit and if the current becomes too large the fuse wire melts and so breaks the circuit. A circuit diagram symbol for a fuse is shown in Figure 2.1, on page 11.

> Problem 20. If 5 A, 10 A and 13 A fuses are available, state which is most appropriate for the following appliances which are both connected to a 240 V supply (a) Electric toaster having a power rating of 1 kW (b) Electric fire having a power rating of 3 kW

Power $P = VI$, from which, current $I = \dfrac{P}{V}$

(a) For the toaster, current $I = \dfrac{P}{V} = \dfrac{1000}{240} = \dfrac{100}{24} = 4\dfrac{1}{6}$ A

Hence a **5 A fuse** is most appropriate

(b) For the fire, current $I = \dfrac{P}{V} = \dfrac{3000}{240} = \dfrac{300}{24} = 12\dfrac{1}{2}$ A

Hence a **13 A fuse** is most appropriate
