



ELECTRICITY

Electricity is the most important, convenient and controllable form of energy in the modern times. It can be easily converted to light, heat and mechanical energies for using in our homes for-lighting ; operating fans, washing machine etc. It is also used in schools, hospitals, industries and so on. In this chapter we shall study to answer some basic questions viz. what is the basis of electricity ? How does electric current flow in electrical circuits ? What are the factors that affect the flow or regulate the current in electrical circuits ? We shall also discuss the application of heating effect of electric current in household electric appliances. In fact, it is now difficult to imagine a world without electricity.

8.1 Electric Charge: Current and Circuit

The word electricity means the energy associated with electric charges such as electrons either stationary or in motion. We also know that in air current and water current in rivers – air particles and water particles are flowing respectively. Likewise, electric current is said to flow in a wire or conductor, if the electric charges flow continuously through it. Let us take up an example. In a torch, you have seen that there are cells(or a battery when placed in proper order) to provide the flow of electric charges i.e. to constitute an electric current through the bulb. Such a current makes the bulb to glow. We have also observed that the bulb glows giving out light only when the switch of the torch is on. What is the function of the switch? Now, you know that a switch provides a conducting link for the electric current between the cell and the bulb. **Such a continuous and closed path of an electric current is called an electric circuit.** When the switch of the torch is turned off the bulb does not glow because the circuit is broken.

The electric current is expressed by the quantity of charge flowing through a particular area in unit time i.e. it is the rate of flow of electric charges through the conductor. Thus, larger the rate of flow of charge the greater is the current.

8.1.1 Direction of Electric Current

When electricity was invented, a long time back, two types of charges : positive and negative charges were known. But electron was not discovered at that time. So, electric current was considered to be the flow of positive charges and this direction was taken to be the direction of electric current. **Thus the conventional direction of electric current is from positive terminal of a cell or battery to the negative terminal through the outer circuit.** So in circuit diagrams you will see an arrowhead on the connecting wire pointing from the positive terminal of the cell or battery towards the negative terminal. In circuits using metallic wires, electrons constitute the flow of charges and actual direction of electron flow is from negative terminal to the positive terminal of the cell or battery which is opposite to the direction of conventional current.

8.1.2 Expression of Electric Current

Amount of charge flowing through a given cross-section of a conductor per unit time constitutes electric current. If a net charge ‘Q’ flows across any cross-section of a conductor, perpendicular to the direction of current flow, in time ‘t’ then the current ‘I’ through the cross-section is

$$I = \frac{Q}{t} \quad \dots \quad 8.1$$

The SI unit of electric charge is coulomb (C) while that for electric current is ampere(A), named after the French scientist, Andre-Marie Ampere (1775–1836). Thus one ampere of electric current is constituted by the flow of one coulomb of charge per second, that is given by

$$1 \text{ A} = \frac{1 \text{ C}}{1 \text{ s}}$$

(Since an electron possesses negative charge of $1.6 \times 10^{-19} \text{ C}$, 1C of charge is equivalent to the charge contained in nearly 6×10^{18} electrons)

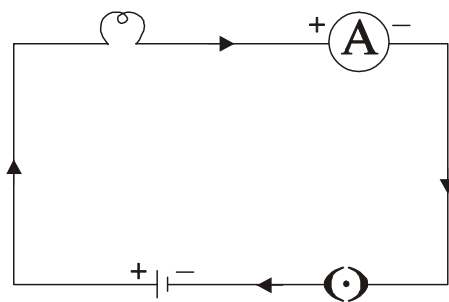


Figure 8.1 A schematic diagram of an electric circuit

The electric current in a circuit is measured by an instrument called **ammeter**. It is always connected in series in a circuit. Figure 8.1 shows the schematic diagram of typical electric circuit comprising a cell, a torch light bulb, an ammeter and a switch in the form of a plug key. It may be noted that the electric current flows in the circuit from the positive terminal of the cell through the bulb and ammeter.

Smaller quantities of current are expressed in milliampere ($1\text{mA}=10^{-3}\text{ A}$) or in microampere ($1\text{ }\mu\text{ A}=10^{-6}\text{ A}$), or in nanoampere ($1\text{nA}=10^{-9}\text{ A}$).

Example 8.1 A current of 0.4 A is made to pass through an electric circuit for 15 minutes. Find the amount of electric charge that flows through the circuit.

Solution We are given, $I = 0.4\text{ A}$; $t = 15\text{ min} = 15 \times 60\text{s}$.

From Eq (8.1), we have

$$\begin{aligned} Q &= I t \\ &= 0.4\text{ A} \times (15 \times 60)\text{s} \\ &= 4 \times 15 \times 6\text{ As} = 360\text{ C}. \end{aligned}$$

Try to Answer

1. What do you mean by an electric circuit ?
2. Define one ampere of current.
3. Calculate the number of electrons in 4.8 C of electric charge.

8.2 Electric Potential and Potential Difference

The charges do not flow in a metallic wire by themselves just as water in a perfectly horizontal pipe or tube does not flow by itself. Then we can put a question – What makes the electric charges to flow ? In order to answer let us consider the analogy of flow of water in a pipe. When one end of the pipe is connected to a tank of water which is kept at a higher level than the other end of the pipe then water flows out. This flow is due to the pressure difference between the two ends of the tube, caused by gravity. For flow of charges in a conducting wire, say copper wire, gravity has no role to play but the electrons move only if there exists a difference of electric pressure along the conductor or conducting wire. This difference of electric pressure is called the **potential difference**. This difference of potential is generated by a battery, consisting of one or more cells. The chemical action within such cells generates the electric potential difference between its terminals, even when no current is drawn from it i.e. when no electric circuit is connected to the cell. When the cell is connected to an electric circuit, the potential difference sets the charges (electrons) in motion within the conductor and produces an electric current. In order to maintain the current in a given circuit, the cell has to expend its stored chemical energy.

Note that in metals each atom allows some of its outermost electrons to detach from it and to move quite freely in the whole of the metal. When an electron is detached from the atom, the atom becomes positively charged. Such a charged atom is called a **positive ion**. So the metal can be visualised as collection of positive ions fixed in their respective positions and a large number of free electrons moving here and there. These free electrons are not bound to any specific atom or location but wander throughout the body of the metal with random speeds and directions, as shown in figure 8.2.

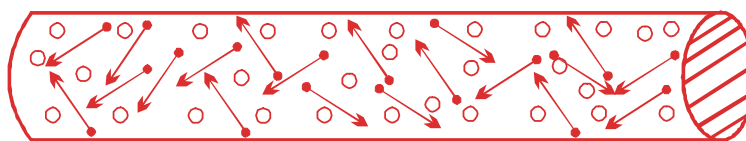


Figure 8.2

A schematic diagram of random motion of electrons

o —————> positive ion
• —————> electron.

When a potential difference is maintained across the metal, the electrons move in a more systematic way and in a specific direction towards the positive terminal of the cell or battery in the circuit. The schematic diagram is shown in figure 8.3.

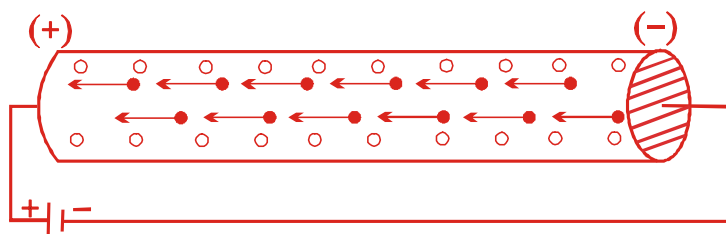


Figure 8.3 *Schematic diagram of motion of electrons under applied potential difference.*

o —————> positive ion
• —————> electron.

The electric potential difference between two points in an electric circuit carrying current is defined as the amount of work done to move a unit charge from one point to the other.

Thus, potential difference (V) between two points = $\frac{\text{Work done (W)}}{\text{Charge (Q)}}$

$$V = \frac{W}{Q} = \frac{W}{I t} \quad \dots\dots\dots 8.2$$

The SI unit of potential difference is one volt (V), named after Alessandro Volta (1745–1827), an Italian physicist. One volt is the potential difference between two points in a current carrying conductor when one joule of work is to be done in order to move a charge of one coulomb from one point to the other.

$$\text{Thus, } 1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

$$\text{OR, } 1 \text{ V} = \frac{1 \text{ J}}{1 \text{ C}} = 1 \text{ J/C} = 1 \text{ J C}^{-1} \quad \dots\dots\dots 8.3$$

The potential difference is measured by means of an instrument called **voltmeter**. This instrument is always connected in parallel across the points whose potential difference is to be measured.

Example 8.2 How much work will be done in moving a charge of 2.5C across two points having a potential difference of 6V ?

Solution Amount of charge Q flowing between the two points = 2.5 C
Potential difference between the points, V = 6 volt.

Thus, the amount of work done in moving the charge is

$$\begin{aligned} W &= VQ \\ &= 6 \text{ volt} \times 2.5 \text{ C} \\ &= 15.0 \text{ J} \end{aligned}$$

Example 8.3 Calculate the amount of work done by a battery in a circuit where a current of 2 A flows for 1 min between two points of potential difference 2V.

Solution Quantity of charge flowing in 1 min is $Q = 2 \text{ A} \times (1 \times 60) \text{ s}$
 $= 120 \text{ C}$

Potential difference = 2V

Thus, the amount of work done,

$$W = VQ = 2 \text{ V} \times 120 \text{ C} = 240 \text{ J.}$$

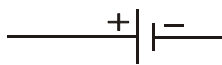
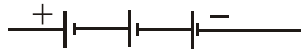
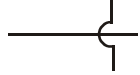
Try to Answer

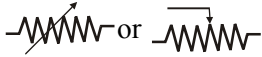
1. What is the device that can maintain a potential difference across a conductor?
2. What is meant by saying that the potential difference between two points is 1 volt ?
3. How much energy is given to 2 coulomb of charge passing through a cell of 1.5 volt?

8.3 Electrical Symbols

It is convenient to draw a schematic diagram for electrical circuits in which different components used in the circuit are represented by symbols. Conventional symbols for commonly used electrical components are given in Table 8.1.

Table 8.1 *Symbols of some commonly used components in electrical circuit diagrams*

Sl. No	Components	Symbol
1.	An electric cell	
2.	A battery (a combination of cells)	
3.	Connecting wire	
4.	An open switch	
5.	An open plug key	
6.	A closed switch	
7.	A closed plug key	
8.	A wire joint	
9.	Wires crossing without contact	
10.	Electric bulb	

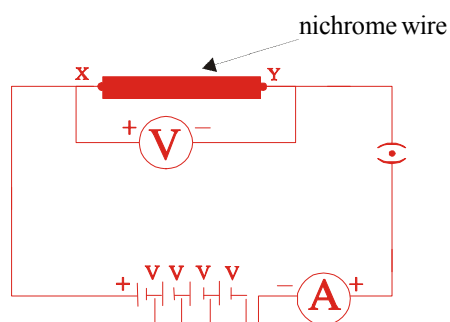
11.	A resistor of fixed resistance	
12.	Variable resistance or rheostat	
13.	Ammeter	
14.	Voltmeter	
15.	Galvanometer	
16.	Electric fuse	

8.4 Ohm's Law

So far, we have studied potential difference as the cause of current flow along a conductor. Let us explore the relationship between potential difference across a conductor and current flowing through it, with the help of an Activity.

Activity 8.1

Take a nichrome wire of suitable length say 0.5 m, an ammeter, a voltmeter, a plug key and four torch cells of 1.5 volt each. Set up a circuit as shown in figure 8.4



First use one cell only as the source in the circuit. Note the reading in

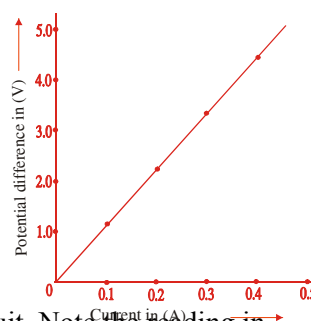


Figure 8.4 Electric circuit for the Activity 8.1

Figure 8.5 V-I Graph for a wire of metal

the ammeter for the current I and the reading in the voltmeter for the potential difference V across the nichrome wire in the circuit. Enter or tabulate the readings in the Table 8.2 given below.

In the next step, connect two cells in the circuit and note the respective readings of the ammeter and voltmeter and enter the readings in the Table 8.2.

Repeat the above steps using three cells and then four cells in the circuit in turn. Calculate the ratio of voltage (V) across the nichrome wire to current (I) flowing through the wire for each step of observation.

Table 8.2

Step No.	Number of cells in the circuit	Current through the nichrome, I in ampere	Potential difference across the nichrome wire, V in volt	$\frac{V \text{ volt}}{I \text{ ampere}}$
1	1			
2	2			
3	3			
4	4			

In this Activity you will see that the ratio of V to I almost remains the same for each step of observation. Now plot a graph of the potential difference (V) against current (I). The graph will be a straight line passing through the origin as shown in Fig. 8.5 Thus the value of $\frac{V}{I}$ is a constant ratio. This is Ohm's law.

Since the unit of potential difference is one volt (V) and that of the current is ampere (A), the ratio $\frac{V}{I}$ is in $\frac{\text{volt}}{\text{ampere}}$.

In 1827, a German physicist George Simon Ohm (1787 – 1854) found out the relationship between the current flowing through a metallic conductor (wire) and the potential difference across its ends. **He stated that at a constant temperature the current flowing through a conductor is directly proportional to the potential difference across its ends. The above statement is called Ohm's law.**

If 'I' is the current flowing through a conductor and 'V' is the potential difference (or voltage) across its ends then according to the above law :

$$V \propto I$$

$$\text{OR } \frac{V}{I} = \text{a constant (R)} \quad \dots\dots\dots 8.4$$

$$\text{OR } V = I R \quad \dots\dots\dots 8.5$$

In equation (8.4), R is a constant called 'resistance' of the conductor. The value of this constant depends on the nature of the material of the conductor, length, area of cross-section and temperature of the conductor. It is the property of a conductor to resist the flow of charges through it. In other words, every conductor (metal) offers some resistance to the flow of current and to increase the amount of current through it proportionally, more energy per coulomb of charge is required. The SI unit for resistance of a conductor is ohm, represented by the Greek letter Ω . The above equation can also be written as :

$$R = \frac{V}{I} \quad \dots\dots\dots 8.6$$

If potential difference across the ends of a conductor is 1 volt and the current through it is 1 ampere, then its resistance R, at that temperature is 1 ohm.

$$\text{Thus, } 1 \Omega = \frac{1V}{1A}$$

$$\text{From equation 8.5, we get, } I = \frac{V}{R} \quad \dots\dots\dots 8.7$$

From equation 8.7, it is obvious that the current through a conductor is inversely proportional to its resistance. If the resistance is doubled the current gets halved and vice-versa. In practice it is necessary to vary the current in an electric circuit. A component or a device is generally used to regulate the quantity of current in the circuit without changing the voltage of the source. This device is called **rheostat**. Thus a rheostat is used to change the resistance in the circuit.

8.4.1 Resistance of conductors

Activity 8.2

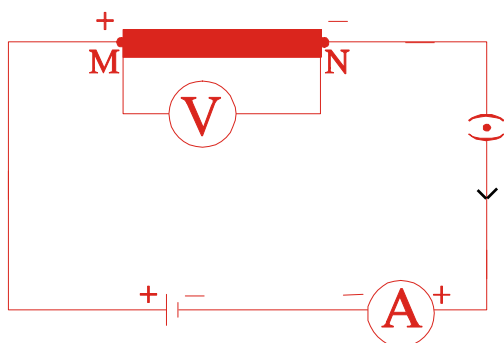


Figure 8.6

Make the connection as shown in Fig. 8.6. Then place wires each of 50cm in length and having the same area of cross-sections but of different metals e.g. iron, copper, nichrome, silver, aluminium etc. in turn across MN. Bulbs of different wattages may also be used in the gap MN.

Complete the circuit by connecting the iron wire in gap MN. Plug the key and note down the readings of ammeter and voltmeter.

Take out the key from the plug as soon as the readings are noted.

Replace the iron wire by copper wire in the gap MN and note the readings of the ammeter and voltmeter as in the above step.

Now, repeat the above step with torch bulb in the gap MN of the circuit.

Are the ammeter and voltmeter readings different for different wires and for different bulbs connected in the gap MN?

What do the above observations indicate?

Repeat this Activity by keeping any other wires in the gap and note down the readings of the ammeter in each case. Analyse the observations.

In the above Activity you will notice that the current is different for different components. This indicates that the conductors having identical dimensions and temperature but of different materials offer resistance to the flow of current to different degrees. This means that certain components offer an easy path for the flow of current while the others resist the flow. In other words, certain material components offer more resistance to the flow of electric current than others. This property of a material component due to which it opposes the flow of electric current through it is called electrical resistance or simply **resistance** of the conductor.

In the above we have learnt that the motion of electrons in the body of the conductor in an electric circuit constitutes an electric current. However, the motion of electrons in a conductor are not completely free. Their motions

are restrained as they collide with other electrons and with the atoms and ions present in the body of the conductor. Thus, the motion of electrons through a conductor is retarded by its resistance and plays an important role in electric circuits. Any component of a given size in the circuit which offers low or negligible resistance is a good conductor. Sometimes, components of a circuit are designed to offer high or appreciable resistance to the flow of current. They are called the **resistors**. A component of identical size that offers a higher resistance is a poor conductor. An insulator of the same size offers even higher or infinite resistance to the flow of current.

8.5 Factors on which the Resistance of a Conductor Depends

There are a number of factors on which the resistance of a conductor at a constant temperature depends. To study those factors, let us take up the following Activity.

Activity 8.3

Connect a cell, an ammeter, a nichrome wire of fixed length, a plug key as shown in a circuit given in Fig. 8.7. Let the nichrome wire be of length ' l ' cm and marked 'X'.

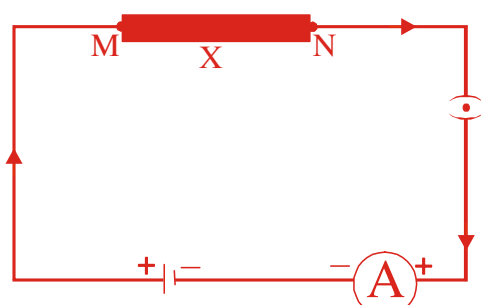


Figure 8.7(a) Electric circuit to study the factors affecting resistance of conducting wire.

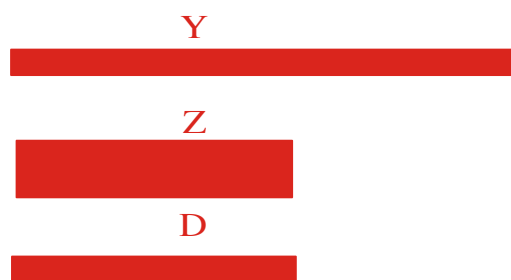


Figure 8.7(b) Different wires

Connecting the gap MN by the sample wire 'X', plug the key and note the current, I_1 A (say) indicated by the ammeter reading.

Replace the nichrome wire 'X' by another wire of nichrome of same thickness but twice the length i.e. $2l$ cm which is marked as 'Y' shown in Fig. 8.7 (b). Record the current I_2 A (say) from the ammeter reading.

Now, replace the wire 'Y' by a thicker nichrome wire marked 'Z' having

the same length ' l ' cm as that of the sample marked 'X'. A thicker wire has a larger cross-sectional area. Again record the current I_3 A (say) from the ammeter reading.

In the next step, connect a copper wire marked 'D' in Fig. 8.7 (b) in the gap MN of the circuit. The wire 'D' has the same length and same cross-sectional area as that of the first nichrome wire marked 'X'. Record the current I_4 A (say) from the ammeter reading.

After examining the currents in each of the steps, you will notice the difference in the current. This result shows that the current depends on (i) the length of the wire (conductor) (ii) the area of cross-section of the wire (iii) the nature of the material of the respective wires though they have the identical geometrical dimensions.

It is observed that the ammeter reading i.e. the quantity of current decreases to one-half when the length of the nichrome wire is doubled though they have the same cross-sectional areas. The ammeter reading is increased when a thicker wire of the same material and of the same length is used in the circuit. A change in the ammeter reading is observed when a wire of different material but of the same length and of the same area of cross-section is used in the circuit.

Using Ohm's law given in (Eqs. 8.5 to 8.7), we can understand that the resistance of a metallic conductor of a given material at constant temperature is directly proportional to its length (l) and inversely proportional to its area of cross-section (A). That is

$$R \propto l \quad \dots\dots\dots 8.8$$

$$\text{and } R \propto \frac{1}{A} \quad \dots\dots\dots 8.9$$

Combining Eqs. 8.8 and 8.9 we have,

$$R \propto \frac{l}{A}$$

$$\text{OR, } R = \frac{\rho l}{A} \quad \dots\dots\dots 8.10$$

$$\text{Thus, } \rho = \frac{RA}{l} \quad \dots\dots\dots 8.11$$

Here ρ (rho) is a constant of proportionality and is called the electrical

resistivity of the material of the conductor. The SI unit of ' ρ ' is $\Omega \text{ m}$ (ohm-metre) and it is a characteristic property of the material. In general, the metals and their alloys have low resistivity in the range of $10^{-8} \Omega \text{ m}$ to $10^{-6} \Omega \text{ m}$. They are treated as good conductors of electricity. The substances like rubber and glass which are well known insulators have resistivity of the order of 10^{12} to $10^{17} \Omega \text{ m}$. Both the resistance and resistivity of a material vary with temperature.

Note : Ohm's law does not hold for the flow of currents through electrolytic cells, vacuum tubes, semi-conductor devices and electric discharge tubes. They are called non-ohmic substances.

The electrical resistivity of some substances at 20°C are given in Table 8.3 (Need not to memorise but values can be used for solving problems whenever required.)

Table 8.3 : Electrical resistivity of some materials at 20°C .

Substance	Material	Resistivity ($\Omega \text{ m}$)
Metals	Silver	1.60×10^{-8}
	Copper	1.62×10^{-8}
	Aluminium	2.63×10^{-8}
	Tungsten	5.20×10^{-8}
	Nickel	6.84×10^{-8}
	Iron	10.00×10^{-8}
	Chromium	12.9×10^{-8}
	Mercury	94.0×10^{-8}
	Manganese	1.84×10^{-6}
Alloys	Constantan (alloy of copper and nickel)	49×10^{-6}
	Manganin (alloy of copper, manganese, nickel)	44×10^{-6}
	Nichrome (alloy of nickel, chromium, manganese and iron)	100×10^{-6}

Insulators	Glass	$10^{10} - 10^{14}$
	Hard rubber	$10^{13} - 10^{16}$
	Ebonite	$10^{15} - 10^{17}$
	Diamond	$10^{12} - 10^{13}$
	Paper (dry)	10^{12}

Example 8.4 A 4.5 V battery is connected to a bulb of resistance $9\ \Omega$. Calculate the current through the bulb.

Solution We have given $V = 4.5\text{ V}$; $R = 9\ \Omega$

From the Eq. 8.7, we get the current through the bulb,

$$I = \frac{4.5\text{V}}{9\Omega} = 0.5\text{A}$$

Example 8.5 When a heater draws a current 4A from a battery, the terminal potential difference across it is 24V. What current will the heater draw when it is connected across a battery of 60 V ?

Solution We are given the potential difference, $V = 24\text{V}$; current, $I = 4\text{A}$

From Ohm's law, the resistance of the heater, $R = \frac{V}{I} = \frac{24}{4} = 6\ \Omega$

When the potential difference applied is 60V, the current I' passing through the heater will be

$$I' = \frac{V}{R} = \frac{60\text{V}}{6\Omega} = 10\text{ A}$$

Thus, the current through the heater becomes 10 A.

Example 8.6 The resistance of a wire is $50\ \Omega$ at 20°C . If the length and diameter of the wire are 1m and $5 \times 10^{-4}\text{ m}$ respectively, calculate the resistivity of the material of the wire.

Solution We are given the resistance R of the wire = $50\ \Omega$; the diameter ' d ' = $5 \times 10^{-4}\text{ m}$ and the length ' l ' = 1m.

Thus, from Eq. 8.11, the resistivity of the material of the wire is

$$\rho = \frac{RA}{l} = \frac{R \cdot \pi d^2}{4l} \quad [\because \text{the area of cross-section, } A = \frac{\pi d^2}{4}]$$

Substituting the values in the above, we get

$$\rho = \frac{50 \times 22 \times (5 \times 10^{-4})^2}{7 \times 4 \times 1} = 9.82 \times 10^{-6} \Omega \text{m}$$

Thus, the resistivity of the metal at 20°C is $9.82 \times 10^{-6} \Omega \text{m}$.

Example 8.7 A wire of certain length has a resistance of 4Ω . The wire is elongated or stretched to double its length. Calculate the new resistance of the wire.

Solution

We are given, $R = 4 \Omega$

When the wire is stretched to double its length, the area of cross-section would be half. Thus a wire of length ' l ' and area of cross-section ' A ' becomes of length $2l$ and area of cross-

section $\frac{A}{2}$ respectively.

Thus, from Eqn. 8.11, we get

$$R = \frac{\rho l}{A}$$

And $R_1 = \frac{\rho \times 2l}{\frac{A}{2}}$ Where R_1 is the new resistance.

$$\therefore \frac{R_1}{R} = \frac{4\rho l}{A} \times \frac{A}{\rho l} = 4$$

Hence, $R_1 = 4R = 4 \times 4 = 16 \Omega$

The new resistance of the wire is 16Ω .

Try to Answer

1. Name the factors on which the resistance of a conductor depends.
2. Through which of the wires – a thick one and a thin one of the same material will current flow easily, when connected to the same battery or cell? Why?
3. Suppose the potential difference across an electrical component of fixed resistance decreases to half of its former value. What change will occur in the current passing through it?

8.6 Combination of Resistances (or Resistors)

In the preceding sections, we have learnt about potential difference, current and resistances in simple electric circuits. We have also noticed how the current through a conductor depends upon its resistance and potential difference applied across its ends. In electrical circuits of radio, television and electrical gadgets, we often use resistors in various combinations in order to get the required current in the circuit. There are two methods of joining two or

more resistors in a circuit. The methods are (i) series combination and (ii) parallel combination.

Figure 8.8 shows an electric circuit in which three resistors of resistances R_1 , R_2 , R_3 are joined end to end.

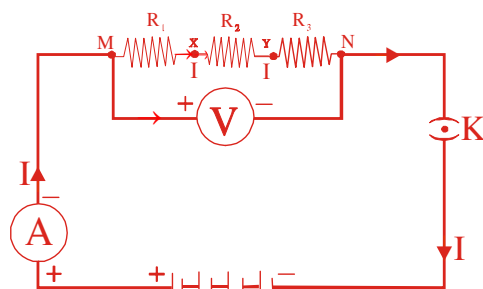


Figure 8.8 Resistors in series

The resistors are connected end to end between the points M and N. Here, the resistors are said to be in series.

Figure 8.9 shows another combination of resistors in which the resistors R_1 , R_2 , R_3 are connected together between the points M and N of the circuit. Here, the resistors are said to be combined in parallel.

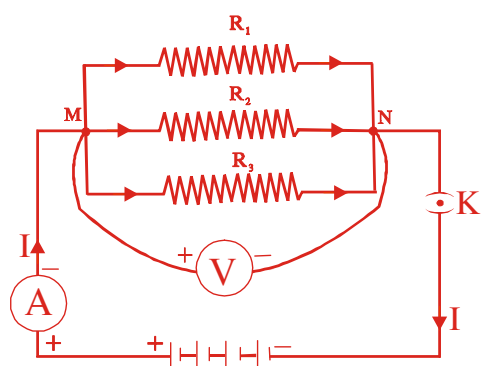


Figure 8.9 Resistors in parallel

8.6.1 Resistors in Series

In order to know the value of the current flowing through the circuit when a number of resistors are connected in series and value of equivalent resistance, let us perform the following Activity.

Activity 8.4

Take three resistors having values like 2Ω , 4Ω , 6Ω and a battery 12V for performing this activity. Connect them as shown in Fig. 8.8.

Plug the key and note the ammeter reading.

Change the position of ammeter to anywhere in between the resistors. Record the ammeter reading for each of the positions of it.

Try to observe for any change in the value of current through the ammeter.

You will observe that the value of current in the ammeter will remain the same independent of its position in the circuit. This result shows that in a series combination of resistors the current is the same through each of the resistors irrespective of resistance and is equal to the total current of the circuit. Now, note down the reading V volt (say) of the voltmeter.

In the next step, take out the plug key and disconnect the voltmeter. Now insert the same voltmeter across the ends M and X of the resistor R_1 as shown in figure 8.10.

Now, plug the key and record the potential difference V_1 across the resistor R_1 .

In the same manner, measure the potential difference V_2 , V_3 across the resistors R_2 , R_3 respectively. Try to observe the relation between V_1 , V_2 , V_3 and V .

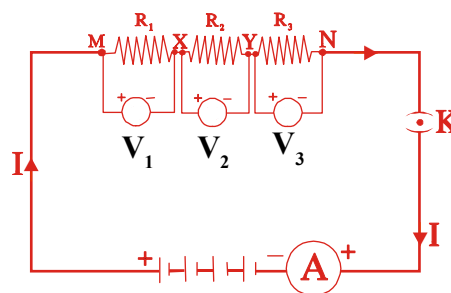


Figure 8.10

From the record, you will find that the potential difference V is equal to the sum of potential differences V_1 , V_2 and V_3 . This shows that the total potential difference across a combination of resistors in series is always equal to the sum of potential differences across the individual resistors.

$$\text{Thus, } V = V_1 + V_2 + V_3 \dots\dots\dots 8.12$$

Referring to the circuit in Fig. 8.10, let I be the current through the circuit. The current through each of the resistors is also I (from the above Activity). It is now possible to replace the three resistors joined in series by an equivalent single resistor having a resistance R_s such that the potential difference across it is ' V ' when the current ' I ' through the circuit remains the same.

Applying Ohm's law to the entire circuit, we get

$$V = I R_s \dots\dots\dots 8.13$$

Again, applying Ohm's law to the individual resistors, we have,

$$V_1 = I R_1 \quad \dots\dots\dots 8.14$$

$$V_2 = I R_2 \quad \dots\dots\dots 8.15$$

$$V_3 = I R_3 \quad \dots\dots\dots 8.16$$

From Eq. 8.12, $I R_s = I R_1 + I R_2 + I R_3$

$$\text{OR} \quad R_s = R_1 + R_2 + R_3 \quad \dots\dots\dots 8.17$$

Hence, we can conclude that when two or more resistors are combined in series, the equivalent or resultant resistance R_s equals to the sum of their individual resistances and R_s is greater than the greatest of the individuals.

8.6.2 Resistors in Parallel

Referring to the circuit given in figure 8.9, let us try to understand the current flowing through each of the resistors and potential difference across each with the help of the following Activity.

Activity 8.5

Make a parallel combination MN of three resistors R_1, R_2, R_3 and complete the circuit connections as shown in the Figure 8.9.

Plug the key and note the ammeter reading as well as the voltmeter reading. The ammeter reading 'I' ampere (say) and voltmeter reading 'V' volt (say) give the total current in the circuit and total potential difference across the parallel combination MN respectively.

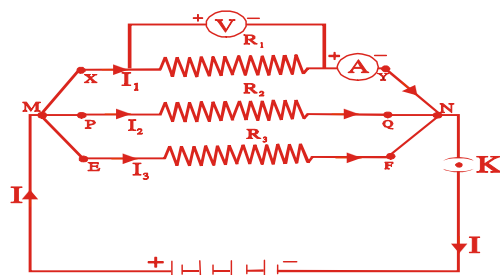


Figure 8.11

Remove the plug from the key, ammeter and voltmeter from the circuit. Then complete the circuit connection as shown in the figure 8.11. Here, voltmeter is connected across R_1 while the ammeter is connected in series to R_1 .

Insert the plug in the key and note the ammeter reading, say, I_1 and voltmeter reading V_1 , and then remove the plug. Now connect voltmeter across R_2 and ammeter in series to it. Insert the plug and note the reading I_2 of the ammeter and voltmeter reading V_2 . Then remove the plug. Repeat the observation for the branch EF and let I_3 and V_3 be the ammeter reading and

voltmeter reading respectively. Analyse the relationship between (a) I_1 , I_2 , I_3 and I (b) V_1 , V_2 , V_3 and V .

From the Activity, it is observed that the total current I is equal to the sum of the separate currents flowing through each branch of combination.

$$\text{Thus, } I = I_1 + I_2 + I_3 \quad \dots\dots\dots 8.18$$

$$\text{and } V = V_1 = V_2 = V_3$$

It is now possible to replace the three resistors joined in parallel by an equivalent resistor having a resistance R_p (say) such that the total current ' I ', from Ohm's law, is given by

$$I = \frac{V}{R_p} \quad \dots\dots\dots 8.19$$

Again, applying Ohm's law to each branch resistor, we have,

$$I_1 = \frac{V}{R_1} ; I_2 = \frac{V}{R_2} ; I_3 = \frac{V}{R_3} \quad \dots\dots\dots 8.20$$

Combining the Eqs. 8.18, 8.19 and 8.20, we have,

$$\begin{aligned} \frac{V}{R_p} &= \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \\ \text{OR } \frac{1}{R_p} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad \dots\dots\dots 8.21 \end{aligned}$$

Thus, we may conclude that the reciprocal of the equivalent resistance of a group of two or more resistors connected in parallel is always equal to the sum of the reciprocals of the individual resistances. This means that R_p is less than the least of the resistances in the grouping.

8.6.3 Laws of Combination of Resistances

(i) Series combination :—

- (a) The combined resistance of any number of resistors connected in series is equal to the sum of individual resistances.
- (b) The same current flows through all resistors irrespective of the value of resistance.
- (c) The potential difference across each individual resistor is directly proportional to the resistance.

(ii) **Parallel combination :-**

- (a) The reciprocal of the combined resistance of any number of resistors connected in parallel is equal to the sum of the reciprocal of all the resistances.
- (b) The potential difference across each individual resistor remains same, irrespective of the values of the resistance.
- (c) The current flowing through each of the resistors is inversely proportional to the value of resistance.

8.6.4 How are the Household Electric Appliances/Components connected to the Mains Supply ?

You have seen different electrical components used in a house. For example, electric bulb, fan, toaster, heater, iron, television, radio receivers etc. They need electric currents of widely different values to operate properly. Thus it becomes obviously impracticable to connect those different components in series, since each of them needs different current to operate properly. Moreover, the total resistance will increase with the increasing number of components and the smaller will be the current flowing through the series arrangement. Thus none of the components may operate, if the arrangement were in series. This is the disadvantage of series combination. Another major disadvantage of series combination is that when one of the components gets fused, the circuit is broken and none of the components will work. Series connection is generally used in 'fairy light' to decorate buildings, temples on festivals and marriage celebrations etc. If the system does not work, it is very difficult and time consuming task for the electricians to locate and replace the dead bulb.

On the other hand, if the above cited components were combined in parallel, the circuit divides the total current to the components accordingly. Since, the total resistance in a parallel circuit is decreased with the increasing number of resistors or components (Eq. 8.21), more and more current will be drawn from the source i.e. mains supply. This is helpful particularly when each component has different resistance and requires different current to operate properly. Another major advantage for parallel connection of electric components is that when one of the components gets fused or fails, the other components are not affected. That is why in the household, the electric wiring is done in parallel circuits.

Example 8.7 A resistor of 10Ω is connected in series to an electric bulb of 20Ω . The combination is connected to a battery of $6V$ comprising four cells, (Fig 8.12). Calculate (i) total resistance of the circuit (ii) total current in the circuit (iii) potential difference across the bulb and the resistor.

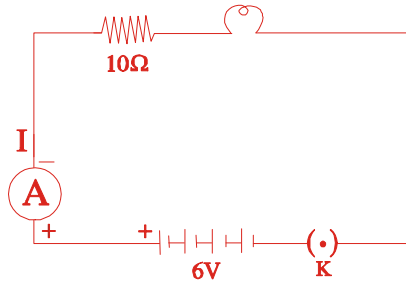


Figure 8.12 An electric bulb and a resistor connected in series to a battery

Solution

The resistance R_1 of the bulb $= 20\Omega$ and that of the conductor,
 $R_2 = 10\Omega$

Then the total resistance of the circuit,

$$R_s = R_1 + R_2 = 20 + 10 = 30\Omega$$

The total potential difference, $V = 6V$

Applying Ohm's law, the current flowing through the circuit,

$$I = \frac{V}{R_s} = \frac{6V}{30\Omega} = 0.2\text{ A}$$

Again, potential difference across the bulb,

$$V_1 = I \times R_1 = 0.2 \times 20 = 4\text{ V}$$

And, potential difference across the resistor,

$$V_2 = I \times R_2 = 0.2 \times 10 = 2V$$

Here, $V_1 + V_2 = 4V + 2V = 6V =$ the total potential difference across the battery terminal.

Example 8.8 Consider the circuit shown in (Fig. 8.13). Calculate the potential difference across each resistor.

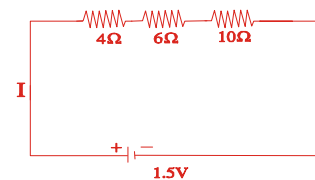


Figure 8.13

Solution

The three resistors are in series and the equivalent resistance,

$$R_s = 4\Omega + 6\Omega + 10\Omega = 20\Omega$$

$$\text{Current through the circuit, } I = \frac{1.5V}{20\Omega} = 0.075A$$

The same current of 0.075 A passes through all the resistors.

Applying Ohm's law, the potential difference

across the 4Ω resistor $= 0.075 \times 4 = 0.3\text{V}$
 across the 10Ω resistor $= 0.075 \times 10 = 0.75\text{V}$
 across the 6Ω resistor $= 0.075 \times 6 = 0.45\text{V}$

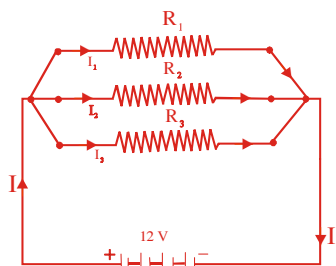


Figure 8.14

Example 8.9 Three resistors $R_1 = 4\Omega$; $R_2 = 10\Omega$; $R_3 = 20\Omega$ are arranged in parallel across a 12V battery as shown in Figure 8.14. Calculate the (i) total circuit resistance (ii) current in the circuit (iii) current through each resistor.

Solution Total circuit resistance, R_p is given by [Eq. 8.21],

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{4} + \frac{1}{10} + \frac{1}{20}$$

$$\text{OR } \frac{1}{R_p} = \frac{5+2+1}{20} = \frac{8}{20} = \frac{2}{5}$$

$$\therefore R_p = \frac{5}{2} = 2.5\Omega$$

$$\text{Current through the circuit, } I = \frac{V}{R_p} = \frac{12}{2.5} = 4.8\text{ A}$$

Applying Ohm's law, the current

$$\text{through } R_1, I_1 = \frac{V}{R_1} = \frac{12}{4} = 3.0\text{ A}$$

$$\text{through } R_2, I_2 = \frac{V}{R_2} = \frac{12}{10} = 1.2\text{ A}$$

$$\text{through } R_3, I_3 = \frac{V}{R_3} = \frac{12}{20} = 0.6\text{ A}$$

Since the resistors are in parallel, the total current is $I_1 + I_2 + I_3$
 $= (3.0 + 1.2 + 0.6) = 4.8\text{ A}$

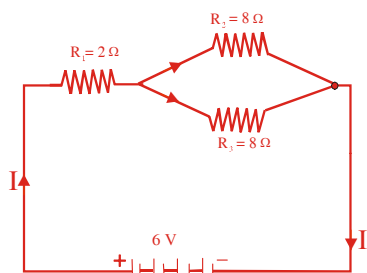


Figure 8.15

Example 8.10 Find the current supplied by the battery in the circuit shown in Fig. 8.15 .

Solution

Suppose we replace the parallel combination of R_2 and R_3 by R_p , which is the equivalent resistance.

Then from Eq. 8.21 we have,

$$\frac{1}{R_p} = \frac{1}{8} + \frac{1}{8} = \frac{2}{8} = \frac{1}{4}$$

$$\therefore R_p = 4\Omega$$

Thus, the total resistance,

$$R = R_1 + R_p = 2\Omega + 4\Omega = 6\Omega$$

To calculate total current supplied by the battery, we use Ohm's law and get

$$I = \frac{V}{R} = \frac{6}{6} = 1\text{A}$$

8.7 Heating Effect of Electric Current

In section 8.2 we have learnt that the potential difference between the terminals of the cell is generated with the help of chemical reaction in it. This potential difference sets the electrons in motion along a definite direction. As a result, current flows through conductor and resistor or a system of resistors connected to the battery. At the same time the cell which is the source of electrical energy has to keep expending its stored energy. Where does the energy go ? Out of the total energy expended, a part may be consumed in maintaining the current for useful work such as in rotating the blades of an electric fan while the remaining part may be expended in the form of heat energy resulting to raise of temperature of electric gadgets viz. television, fan etc. As an example, you must have observed the rise in temperature of table fan or television when used continuously for longer time. On the other hand, if the electric circuit comprises purely resistive components i.e. resistors only, the source energy of the battery gets dissipated in the form of heat energy. This is called the heating effect of electric current. Because of this effect, when an electric current is passed through nichrome wire which have high resistance, it becomes very hot and produces heat. In other words, the heating effect of electric current is obtained by the transformation of electrical energy into heat energy. This effect is utilised in devices like electric heater, electric kettle and cooker, electric iron etc.

Imagine a resistor R connected across the terminals of a battery. Let I be the current flowing through it when the potential difference across it is V , shown in the Fig. 8.16. The amount of electrical work done in moving the charge Q through a potential difference V is VQ . If 't' is the time during which

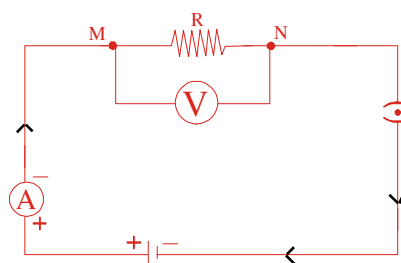


Figure 8.16

the amount of charge Q flows through, as explained above, the source must supply an energy equal to VQ . Hence the energy input to the circuit by the source (i.e. battery) per unit time is

$$\frac{VQ}{t} = VI \quad \dots\dots\dots 8.22$$

$$\text{Here, } I = \frac{Q}{t}$$

In other words the energy supplied to the resistive circuit by the battery in time t is $VI t$. Thus, the energy supplied gets dissipated as heat in the resistor. That is, the amount of heat ' H ' produced in time ' t ' is

$$\begin{aligned} H &= VIt \\ &= I^2 Rt \quad \dots\dots\dots 8.23 \end{aligned}$$

[From Ohm's law, (Eq 8.5), $V = IR$]

When V is in volt, I is in ampere, t is in second and H is in joule.

The above relation is known as Joule's law of heating effect.

The law states that heat produced in a resistor is directly proportional to

- (i) the square of the current for a given resistance
i.e. $H \propto I^2$ when R is constant.
- (ii) the resistance for a given current
i.e. $H \propto R$ when I is constant.
- (iii) the time for which the steady current flows through the given resistance i.e. $H \propto t$ when R and I remain constant.

For using the Eq. 8.23, the current through the resistor is

$$\text{calculated from the relation } I = \frac{V}{R}$$

8.7.1 Applications of Heating Effect of Electric Current

Since electrical conductors have resistance, whether large or small, the generation of heat in a conductor is an inevitable consequence. In electrical circuits, the inevitable heating can increase the overall or ambient temperature of the components and may lead to alter their properties. In most of the circuits, radiating devices are used to reduce the excessive heating.

On the other hand heating effect of electric current has many useful household applications. The appliances such as electric toaster, electric iron, electric oven, electric cooker, electric kettle, electric immersion heater are some of the familiar devices based on law of heating effect.

The heating effect of electric current is utilised in electric bulbs for producing light. When electric current passes through a thin, high resistance tungsten wire called the filament of the bulb, the filament becomes white hot since it retains as much of the heat generated as is possible and emits light. Since the melting point of tungsten is about 3380°C , it does not melt inside the bulb. The filament is also thermally isolated by using insulating supports. The bulbs are usually filled with chemically inactive nitrogen and argon gases at low pressure. This prolongs the life of the filament. A larger part of the power consumed by the filament appears as heat while a smaller part of it is in the form of light radiated. It must be noted that the same amount of electric current flowing through the filament of tungsten produces enormous heat but negligible heat is produced in the connecting copper wires. This is because of the fact that tungsten filament has very high resistance whereas connecting copper wires have very low resistance.

Another important and common application of heating effect of electric current is **electric fuse** in electric circuits. When the current in electric circuits and appliances rises too much, the fuse wire gets heated to such an extent that it melts and breaks the circuit. Thus, a fuse wire protects the circuit components. The fuse wire is placed in series with the device. The fuse wire is made of a metal or alloy of **low melting point** and of **high resistivity**. A cheaper variety of fuse wire is made of an alloy of tin and copper. The thickness and length of fuse wire depends on the maximum current permissible through the circuit. The fuse wire is generally encased in a cartridge of porcelain or similar material with metal ends and with a marking of rated current as 0.3A, 0.5 A, 1A, 2A, 3A, 5A, etc. As an example, if an electric appliance is of maximum current 4.5A then a 5 A fuse must be used.

8.8 Electric Power

In class IX, you have studied that the rate of doing work is power. In one sense, it is also the rate of consumption of energy. Equation (8.22) gives the rate at which electrical energy is dissipated or consumed in an electric circuit. Thus the electric power P is given by

$$P = VI$$

$$\text{OR, } P = IR \times I = I^2 R = \frac{V^2}{R} \dots\dots\dots 8.24$$

The SI unit of power is watt (W). 1 watt is the power consumed by a device that carries 1A of current when operated at a potential difference of 1V.

$$\begin{aligned} \text{Thus, 1 watt(W)} &= 1 \text{ volt (V)} \times 1 \text{ ampere (A)} \\ &= 1 \text{ VA} \end{aligned}$$

The unit ‘watt’ is very small. In actual practice a much larger unit called kilowatt (kW) is used. 1 kW = 1000W. Since the electrical energy is the product of power and time, the unit of electrical energy is watt hour (Wh) which is the energy consumed when 1W of power is used for 1 hour. The commercial unit of electrical energy is ‘kilowatt hour’ (kWh) and is commonly known as one unit of energy.

$$\begin{aligned} 1 \text{ kWh} &= 1000 \text{ watt} \times (60 \times 60) \text{ second} \\ &= 3.6 \times 10^6 \text{ watt second} \\ &= 3.6 \times 10^6 \text{ joule (J)} = 3.6 \text{ MJ} \end{aligned}$$

Note : We pay the electricity department for providing electrical energy to move electrons through the household electric gadgets like bulb, fan, motor for water pump, television etc. In fact electrons are not consumed in an electric circuit. We pay for energy that we use.

Try to Answer

1. Why does the connecting wires i.e. the cord of an electric iron or an electric heater not glow while the heating element glows ?

Example 8.11 A potential difference of 250 V is applied across a resistance of 500Ω in an electric iron. Calculate (i) the current through the resistor (heating element) (ii) power of the electric iron (iii) heat energy produced in joule in 30 seconds.

Solution

- (i) The current through the resistor can be calculated by using Ohm’s law :

$$\text{Thus, the current } I = \frac{V}{R} = \frac{250\text{V}}{500\Omega} = 0.5\text{A}$$

(ii) The power $P = VI$
 $= 250 \times 0.5 \text{ VA or J/s or Watt}$
 $= 125 \text{ W}$

(iii) The heat energy produced can be calculated by using the formula

$$\begin{aligned} H &= I^2 \times R \times t \\ &= (0.5)^2 \times 500 \times 30 \\ &= 0.25 \times 500 \times 30 \\ &= 25 \times 5 \times 30 \\ &= 3750 \text{ J} \end{aligned}$$

Example 8.12 An electric motor marked (or rated) 750 W operates 8 hours/day in a workshop. What will be the cost of energy to operate it for one month (i.e. 30 days) at Rs 3.00 per unit of energy ?

Solution Total energy consumed in 30 days would be
 $750 \text{ W} \times 8 \text{ hours/day} \times 30 \text{ days}$
 $= 750 \times 8 \times 30 \text{ Wh}$
 $= 180000 \text{ Wh}$
 $= 180 \text{ kWh}$

Thus, the cost of energy for 30 days is $180 \text{ kWh} \times \text{Rs } 3.00/\text{kWh} = \text{Rs } 540.00$

POINTS TO REMEMBER

- i. The motion of electrons through a conductor constitutes the (flow of) electric current.
- ii. The direction of current is taken opposite to the direction of flow of electrons.
- iii. The SI unit of charge is coulomb (C).
- iv. The SI unit of current is ampere (A).
- v. To set the electrons in motion through an electric circuit, a cell or a battery is required. A cell or a battery generates a potential difference across its terminals.
- vi. The SI unit of potential difference is volt (V).

- vii. The resistance is an inherent property that resists the flow of electrons in a conductor. Resistance controls the magnitude of current.
- viii. The SI unit of resistance is Ohm (Ω).
- ix. Ohm's law – The potential difference across the ends of a metallic wire is directly proportional to the current flowing through it, provided its temperature remains constant.
- x. The resistance of a conductor is directly proportional to its length ;inversely proportional to its area of cross- section and depends on the nature of the material of the conductor.
- xi. The resistivity of a conductor or an alloy of metals is independent of the geometrical dimensions but depends on the nature of material and temperature of it.
- xii. When two or more resistors are combined in series, the equivalent resistance is equal to the sum of their individual resistances. The equivalent resistance, R_s is greater than the greatest of the individuals.
- xiii. When two or more resistors are combined in parallel, the equivalent resistance, R_p is given by $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \dots\dots$ and R_p is less than the least among the individuals.
- xiv. The electrical energy dissipated in a resistor is given by
$$W = V \times I \times t = I^2 R t = \frac{V^2}{R} \cdot t = \text{power} \times \text{time of current flow.}$$
- xv. The SI unit of power is watt (W).
- xvi. The commercial unit of electrical energy is kilowatt hour (kWh) ;
 $1\text{kWh} = 3.6 \times 10^6 \text{ J.}$

EXERCISES

1. 3×10^{17} electrons cross in 30 seconds through an area. What is the electric current ? (1.6×10^{-3} A)
2. The potential at a point is 20V. Calculate the amount of work done to bring a charge of 0.5 C from infinity to this point. (10 J)
3. A potential difference of 20V appears across the ends of a resistor when 2.5 A of current is passed through it. What is the resistance of the resistor? (8Ω)
4. How much charge flows through a wire carrying 2.5 A of current in 20 minutes? (3×10^3 C)
5. A nichrome wire has diameter 1.0mm and resistivity of $1.0 \times 10^{-4} \Omega \text{ m}$. Calculate the required length of this wire to make a resistance of 14Ω . (11cm)
6. A copper wire of certain length has a resistance of 10Ω . What will be its resistance after stretching to double its length ? (40Ω)
7. Two resistors of resistances 10Ω and 20Ω are connected in parallel. A battery supplies a current of 6A to the combination shown in the circuit in Fig. 8.17. Calculate the current in each resistor.

$$(i_1 = 4\text{A} ; i_2 = 2\text{A})$$

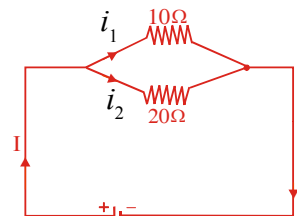


Figure 8.17

8. You are given three resistors of resistance 1,2,3 ohms. Show by diagrams, how with the help of these resistors you can get resistance of
 (i) 6Ω (ii) 1.5Ω (iii) 2.2Ω (iv) $\frac{6}{11} \Omega$ (v) $\frac{11}{3} \Omega$
9. A resistor of 10Ω is combined in parallel with another resistor of 'X' Ω . The resultant resistance of the combination is found to be 3.75Ω . What is the value of 'X'? (6Ω)
10. How many resistors of 200Ω each are required in parallel combination, so as to carry 5A on a 200V line supply ? (5)

11. Suppose there are a number of bulbs rated at 220V – 100W each. How many bulbs can be connected in parallel across a 220V supply line, if the maximum permissible current is 5A only ? (11)
12. Calculate the energy transferred in kWh by a 5A current flowing through a resistance of $2\ \Omega$ for 40 minutes. (0.033)
13. An electric bulb is rated at 220V – 200W. What is the resistance of the filament ? ($242\ \Omega$)
14. Two resistors of $10\ \Omega$ and $20\ \Omega$ are connected in series across a 12V battery. Calculate the power consumed by each of them respectively. (1.6W; 3.2W)
15. If the potential difference between the ends of a fixed resistor is doubled, to how much does the electric power change ? (4 times)
16. Which one will consume more energy – (i) a 300W Television set in 1 hr. (ii) 1000W electric heater in 10 minutes ? (Television set)
17. State whether an electric heater will consume more or less electrical energy per second when the length of its heating element is reduced. Give an explanation for your answer. (More electrical energy)
18. Is it possible to have a particle with charge $2.0 \times 10^{-19}\text{C}$. (No)
19. A bulb is rated as 250V ; 0.4A. Find its (i) resistance (ii) power . ($625\ \Omega$; 100W)
20. An electric kettle rated at 220V, 2.2 kW, works for 3 hours. Find the energy consumed and current drawn. (6.6 kWh ; 10A)
21. **A piece of nichrome wire of resistance R is cut into four equal parts. These parts are then combined in parallel. If R' is the equivalent resistance of the parallel combination then the ratio $\frac{R}{R'}$ will be**
 (A) 16 (B) 4 (C) $\frac{1}{4}$ (D) $\frac{1}{16}$ (A)
22. **The term that does not represent the electrical power of a circuit is**
 (A) $I^2 R$ (B) $I R^2$ (C) $\frac{V^2}{R}$ (D) $V I$ (B)

23. An electric bulb is rated 220V – 100W. The same is operated at 110V due to load shedding. The actual power consumed will be
(A) 100 W (B) 75 W (C) 50 W (D) 25 W (D)
24. Two identical heating coils are first connected in series and then in parallel across the same potential difference. The ratio of heat generated in series to that of parallel would be
(A) 1:1 (B) 1:2 (C) 1:4 (D) 4:1 (C)
25. A positive charge free to move is released from rest. It will move towards the regions of
(A) lower potential (B) higher potential
(C) equal potential (D) any of the above (A)
26. Joule/coulomb is the same as
(A) watt. (B) volt. (C) ohm. (D) ampere. (B)
27. An ammeter is always connected in and a voltmeter in The proper words for the empty places are respectively.
(A) series ; series (B) parallel ;parallel
(C) series ; parallel (D) parallel ; series (C)
28. Three equal resistances, when combined in series have equivalent resistance of 90Ω . Their equivalent resistance when combined in parallel will be
(A) 60Ω (B) 30Ω (C) 20Ω (D) 10Ω (D)
29. Why is the series arrangement of components not used for domestic circuits ? Explain.
30. Why are copper and aluminium wires usually used for transmission of electricity ? Explain.

★★★★★