16

ELECTRICAL ENERGY

All of us have the experience of seeing lightning in the sky during thunderstorm. We also have experience of seeing a spark or hearing a crackle when we take off our synthetic clothes in dry weather. This is Static Electricity. In your toys the source of energy is a battery in which chemical or some other energy is converted into Electrical Energy. This electrical energy also comes from electrical power station to your house through various devices and puts all comforts at our command just with the press of a button. It provides us with heat and light. It powers big machines, appliances and tools at home and in industries e.g. ,radio set, computers, television, vacuum cleaners, washing machines, mixer and grinders, x-ray machines, electric trains etc. Nowadays, it is impossible to think of a world devoid of electrical energy. Life without electricity even for short duration gives a feeling like a fish out of water. Here in this lesson we shall study the nature of electricity and way of its working.

OBJECTIVES

After completing this lesson, you will be able to:

- *cite examples of static electricity from everyday life;*

- *identify two kinds of electric charges and describe the Coulomb's law;*

- *define the terms electrostatic potential, and potential difference;*

- *define electric current;*

- *state ohm's law and define electrical resistance of a conductor;*

- *compute equivalent resistance of a number of series and parallel combination of resistors;*

- *appreciate the heating effect of current by citing examples from everyday life and*

- *define the unit of electric power and electric energy in commercial use and solve problems about these.*

16.1 ELECTROSTATICS

You must have observed that a plastic comb when brought near a piece of paper does not pick up small pieces of a paper. But if you comb your dry hair and bring the comb close to a small piece of paper, you will notice that the bits of paper are attracted towards the comb. Do you know why this happens? This happens because the comb gets charged or electrified when you comb your dry hair . The electricity (or charge) developed on a body on rubbing with another body is called frictional electricity or static electricity. Let us understand more with some simple activities.

? Do you know

An understanding of electric charge and their properties and also of magnetism began in 6th century B.C. i.e. 2500 years ago. One of the founders of Greek science, Thales of Miletus knew that if a piece of amber is rubbed with a woolen cloth, it would then attract light feathers, dust, lint, pieces of leaves etc. Amber is a yellow resinous (gum like) substance found on the shores of the Baltic sea. The Greek name for amber was 'electrum' which is the origin of the familiar words electricity, electric charge, electric force and the electron. However, the systematic study of electricity was done by Dr. William Gilbert, the personal physician of Queen Elizabeth–1 of England. Dr. Gilbert had done the experiments i.e. the rubbing of glass rod with silk, rubber shoes against a wooden carpet etc. which produced electrically charged bodies. Dr. Gilbert named amber like substances Electrica, which became electrically charged by rubbing.

ACTIVITY 16.1

One day Dolly and Jolly were studying, suddenly Dolly spread some bits of paper on the table and asked her sister Jolly to lift the bits of paper with the help of a pen or a balloon. Jolly brought pen near the bits of paper but there was no effect on bits of papers. Then she tried with balloon but could not show the magic. Jolly requested Dolly to show the magic. Dolly took the pen and muttered something meanwhile rubbing it on her sweater, she brought the pen near the pieces of paper and they got attracted towards the pen .This activity thrilled Jolly and she ran to tell this to her mother. Similarly she rubbed an inflated balloon on her dry hair brought near the bits of paper, the pieces of paper got attracted towards the balloon. Now Dolly rolled the pen between the palms of her both hands and then brought it near the bits of paper, the pen could not attract the bits of paper. Jolly was wondering that the trick was indeed some magic or some science was involved! Dolly explained that rubbed pen/inflated balloon attract bits of paper whereas before rubbing it does not attract bits of paper. After rolling between the hands, pen loses the property of attraction. Hence, it is concluded that some bodies acquire electric charge on rubbing but if it is touched to a conducting body in contact with ground, the charge leaks away to the earth.

It was realized that metal can be charged by rubbing but only if it is held in a handle of glass or amber. The metals cannot be charged if it is held directly in the hand. This is because electric charges move along the metal and pass through the human body (conductor) to the earth.

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ACTIVITY 16.2

Take two straws (a hollow tube through which liquid is sucked), a small piece of paper, a piece of silk cloth, two pieces of threads (~50 cm), one small glass bottle a piece of cello-tape, scissors.
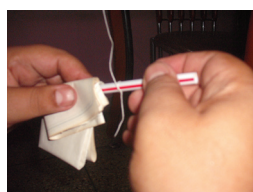
Take one straw and tie one thread at its centre and suspend it from the edge of a table with the help of a piece of cello tape so that it stays horizontally. Let it come to rest. Now bring the other straw nearby the suspended straw and observe the effect. You will notice that there is no effect.

| (i) | (ii) | (iii) | (iv) |

| (v) | (vi) | (vii) | (viii) |

Now rub the suspended straw with a piece of paper and bring the other straw close to one end of the suspended straw. Observe carefully the position of suspended straw. You will observe that the suspended straw moves towards the straw in your hand.

Rub the second straw (which is in your hand) with the piece of a paper and bring it close to one end of the suspended straw. Observe carefully the interaction between the straws. The suspended straw moves away i.e. repelled away.

Now take the glass bottle and rub it with a piece of silk cloth and bring it close to one end of the suspended straw. Observe carefully the interaction between the straw and the glass bottle, the glass bottle attracts the suspended straw.

Attractive force   Repulsive force   Repulsive force
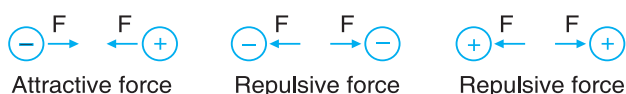
What do you infer? It is inferred that two uncharged straws do not affect each other.

We observed that the charged straws repel each other but a charged straw and a glass bottle attract each other. Therefore it is concluded that:

(i) Two different types of charges (positive and negative) are produced.

(ii) Charge developed on glass bottle on rubbing it with silk cloth has a different nature than the charge developed on straw rubbed with paper. From the basic experiment it is established that glass on rubbing with silk cloth gets positive charge which is opposite in nature to the charge acquired by the straw.

(iii) Like charges repel each other while unlike charges attract each other.

16.1.1 Nature of Charges

Have you ever experienced a shock when you touch a metal door knob after walking across a carpet? Let us try to understand this.

When we walk on a carpet made of insulating material such as rubber, nylon, wool or polyester, friction between soles of our footwear and the material of the carpet cause opposite charges to appear on them. When we touch the metal knob, the free charge on our body(generated due to friction) and free charge on the ground cause a discharge at a high voltage (several thousand volts to as much as 15,000 volts).

In early days a French chemist Charles Dufay observed that the charge acquired by a glass rod rubbed with silk is different from the charge acquired by an ebonite rod rubbed with fur/wool. Dufay termed the charge acquired by glass rod in first case as 'vitreous' and the charge acquired by ebonite rod on rubbing it with wool as 'resinous'. Later on American scientist statesman Benjamin Franklin (1706-1790) introduced the terms positive in place of vitreous and negative in place of resinous, which is followed even today.

On rubbing, two materials acquire positive and negative charges equal in magnitude. Infact the process of rubbing does not create electric charges. It results in only transfer of negative charges from one material to the other. The material, from which the negative charges have been transferred, gets an excess of positive charge and the one which receives the negative charge becomes negatively charged. To answer this we have earlier studied that matter is made up of molecules and atoms. An uncharged body contains a large number of atoms each of which contains an equal number of protons and electrons. In some materials some of the electrons are bound rather loosely with their atoms. On rubbing, if some of the electrons are removed, the material which loses the electrons becomes positively charged and the material which has gained electrons becomes negatively charged. In the process of charging, positive charges in atoms are firmly bound and do not participate in the process of charging. Conservation of charge states that the total amount of electric charge in an isolated system (where no charge can get into or out of the system) does not change with time. Within an isolated system interactions between different bodies of the system

can cause transfer of charge from one body to another but the total amount of charge of the isolated system always remains constant.

The Coulomb's Law governs the force between the charged particles. It was first studied by a French physicist Charles Augustine de Coulomb. Coulomb presented the inference of his experiments in the form of a law which is called Coulomb's law. According to Coulomb's law, **the magnitude of the force of attraction (or repulsion) between two point charges is directly proportional to the product of the quantity of two charges and inversely proportional to the square of the distance between them**.

If a charge, q_1 is placed at a distance, r from a similar charge q_2 the two charges will continue to repel each other with a force

Coulomb (1736-1806)

$$F = \frac{kq_1q_2}{r^2}$$

Where k is a constant of proportionality depending upon the nature of the medium in which the charges are placed. In SI unit $k = 9 \times 10^9$ N m^2 C^{-2} for vacuum (or air). Charge is a scalar quantity. Coulomb is a SI unit of charge represented by C.

q_1 q_2

r

Fig 16.1 *Two charges separated by distance r*

If $q_1 = q_2 = 1C$, $r = 1$m

$$F = \frac{9 \times 10^9 \, \text{Nm}^2\text{C}^{-2} \times 1C \times 1C}{(1\text{m})^2} = 9 \times 10^{-9} \text{ N}$$

Thus, 1C is the charge when placed at a distance of 1m from an equal like charge in vacuum, experiences a repulsive force of 1N. Force is directed along the line joining the centres of the two charges. For like charges force is repulsive (positive in sign), while for unlike charges it is attractive (with negative sign).

16.2 ELECTROSTATIC POTENTIAL AND POTENTIAL DIFFERENCE

Consider an uncharged body like a glass rod which is given a certain charge (say a positive charge), the body acquires that charge. Now if you wish to add more charge of the same nature on it, the charge will experience a force of repulsion due to already existing charge on it. Therefore, some work has to be done by any external

Notes

agent to overcome this force of repulsion. This work will be stored up as electrostatic potential energy in the system of charges. This is analogous to the process of raising a body above the ground against the force of attraction in which work done against gravity is stored in the body as its gravitational potential energy. Let a charge q be moved upto a distance r towards a source charge Q, the electrostatic potential energy possessed by charge q is given by,

$$U = \frac{kQq}{r}$$

The electrostatic potential (or potential) at any point in the vicinity of a charge is defined as the amount of work done in bringing a unit positive charge from infinity to that point. If W is the work done in bringing a positive charge q from infinity to a point in the vicinity of source charge Q, the potential V at the point due to charge Q is

$$V = \frac{W}{q} \quad \text{or} \quad \frac{U}{q} = \frac{kQ}{r}$$

Electrostatic potential is a scalar quantity (It has only magnitude and no direction). Its SI unit is joule/coulomb (JC^{-1}) or volt (V) which is given in the honour of Alessandro Volta (1745-1827) an Italian Physicist.

The potential at a point is 1 V if +1 C charge placed at that point possesses a potential energy of 1 J or the potential at a point is 1 V if 1 J of work is done in bringing 1 C of positive charge from infinity to that point i.e.

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

Consider a charge q is placed at a point as shown in the

Fig. 16.2 *charge q coming from infinity to B or C*

Let B and C be two points where point B is closer to q than C. If a charge q is brought from infinity to C or from infinity to B work done respectively be W_C and W_B. The potential at points B and C respectively be $V_B = \frac{W_B}{q}$ and $V_C = \frac{W_C}{q}$

The potential difference is the difference in potentials V_B and V_C. i.e.

$$V_B - V_C = \frac{W_B - W_C}{q}$$

Where $W_B - W_C$ is the work done in carrying charge from point C to B.

Thus potential difference between two points B and C is equal to the amount of work done in moving a unit charge from point C to point B.

Let us represent $V_B - V_C$ as V; $W_B - W_C$ as W the potential difference

$$V = \frac{\text{Work done}(W)}{\text{Amount of charge transferred}(q)}$$

The potential difference (pd) between two points of a conductor is said to be 1 volt if 1 joule of work is done in moving 1 coulomb of charge from one point to another. Potential difference is a scalar quantity. It is measured using an instrument voltmeter. Voltmeter is always connected in parallel across which we have to measure the potential difference.

Fig. 16.3 *Voltmeter*

Example 16.1: How many electrons make one coulomb?

Solution: Let n electrons make 1C (Since charge is built by the excess or deficiency of electrons only).

Charge on 1 electron is 1.6×10^{-19}C

$$\text{Charge } q = +n|e|$$

$$n = \frac{q}{e} = \frac{1}{1.6 \times 10^{-19}} = 6.25 \times 10^{18} \text{ electrons}$$

Example 16.2: Calculate the work done in moving a charge of 3C across two points having a potential difference of 24V.

Solution: Given $\quad q = 3C, \ V = 24V, \quad W = ?$
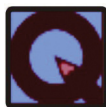
$$W = qV$$
$$= 3C \times 24 \text{ V}$$
$$W = 72 \text{ J}$$

INTEXT QUESTIONS 16.1

1. Define the units of (i) charge (ii) electric potential.

2. When a glass rod is rubbed with a piece of silk it acquires +10 micro coulomb of charge. How many electrons have been transferred from glass to silk?

3. How will the force between two small electrified objects vary if the charge on each of the two particles is doubled and separation is halved?

4. How does the force between two small charged spheres change if their separation is doubled?

5. A particle carrying a charge of 1 micro coulomb (μC) is placed at a distance of 50 cm from a fixed charge where it has a potential energy of 10 J. Calculate

   (i) the electric potential at the position of the particle

   (ii) the value of the fixed charge.

6. Two metallic spheres *A* and *B* mounted on two insulated stands as shown in the Fig. 16.4 are given some positive and negative charges respectively. If both the spheres are connected by a metallic wire, what will happen?
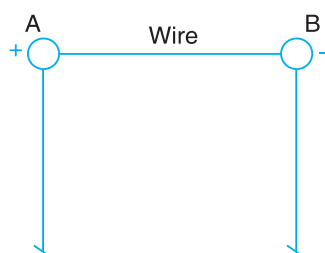
Fig 16.4 *Two metallic spheres mounted on stands*

16.3 ELECTRIC CURRENT

All electrical appliances/gadgets like a bulb or a heater's coil are based on the movement of charges as we know that flowing water constitute water current in rivers, similarly electric charge flowing through a conductor/a metallic wire constitutes electric current i.e., the quantity of charge flowing per unit time. Thus electric current is the charge flowing through any cross section of the conductor in a unit time i.e.,

$$i = \text{charge } (Q)/\text{time}(t)$$

Where Q is the charge in coulomb flowing through the conductor in t seconds. If 1 coulomb (C) of charge flows through any cross section of a conductor in 1 second (s), the current flowing it will be 1 ampere (A) i.e.,

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

Here, ampere is the SI unit of current given in the honour of the French scientist Andre Marie Ampere (1775-1836). However, small currents are more conveniently expressed in milliampere symbolically represented by mA, and microampere symbolically represented by µA. Current is a scalar quantity.

$$1 \text{ mA} = 10^{-3}\text{A}$$

$$1 \text{ µA} = 10^{-6} \text{ A}$$

Andre-Marie Ampere
(1775-1836)

Notes

An ammeter is an instrument which on connecting in series in an electrical circuit indicates how many amperes of current is flowing in the electric circuit.
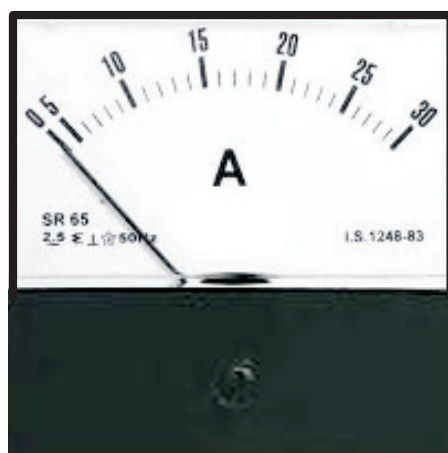
Fig. 16.5 *Ammeter*

? **Do you know**

All metals contain large number of free electrons ($\sim 10^{-29}$ m^{-3}) which act as charge carriers. In a metallic conductor/wire these free electrons move with a sufficiently high velocity of the order of 10^5 m s^{-1} in all possible directions between the atoms of the conductor/wire and even then there is no net flow of electrons. But when battery is connected across the ends of the conductor/wire, the electrons drift in one direction i.e., current flows along the wire in one direction from positive terminal of the battery to the negative terminal of the battery along the wire with a very small velocity $\sim 10^{-4}$m s^{-1} called drift velocity of the electrons.

We have already read that matter is made up of protons, electrons and neutrons. Protons carry positive charge, electrons carry negative charge and neutrons do not carry any charge. An atom is electrically neutral but if a body carries excess of protons

Notes

than the electrons, the body gets positively charge. If the body has excess of electrons than the protons, body gets negatively charged. If a charged body is connected to an uncharged body through a metallic wire, the positive charge flows from higher potential to lower potential while negative charge flows from lower potential to higher potential. The charge flows till both the bodies are at the same potential. To pass the charge continuously from one body to another body through a wire a constant potential difference has to be maintained between the two ends of a wire in a circuit. This is done by an external source of energy which forces the charge carriers (electrons) already present in the wire to move in a definite direction i.e. from lower potential region to higher potential region. The external source of energy is called a cell. **A cell is a device in which chemical energy is converted into electrical energy**. In the cell negatively charged plate repels the electrons which causes the electrons to move along the wire. Hence the electrons flow from the negatively charged plate through the wire to positively charged plate of the cell. This is known as the electron current. Conventionally the direction of the current is taken as opposite to the direction of the flow of electrons i.e., from the positive to the negative terminal.
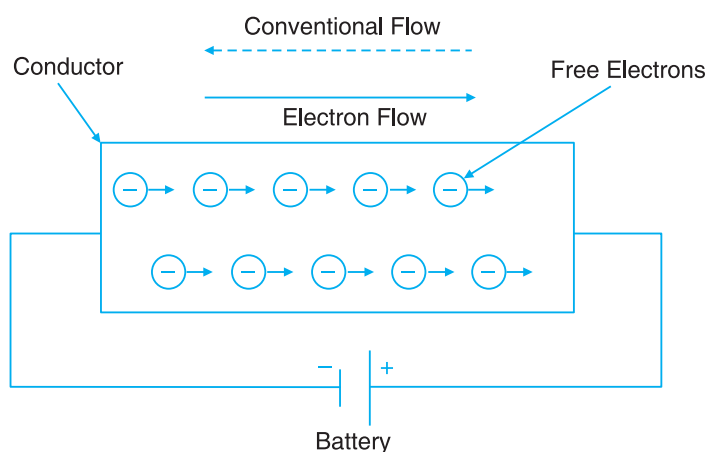
Flow of electron/current

The combination of cells is called a battery. One of the earliest and simplest devices capable of producing steady current was invented by Alessandro Volta (1745-1827) named Voltaic Cell. Batteries are a good source of Direct current. Direct current (DC) means the electric current is flowing in one direction only in a circuit. To measure the current in a circuit, ammeter is used.

Caution: Never connect the two ends of a battery with conducting wire without making the electrons to pass through some load like a light bulb which slows the flow of current. If the electrons flow is increased too much, the conductor may become hot, and the bulb and the battery may be damaged.

16.3.1 Conductors and Insulators

All materials can be divided into two categories on the basis of movement of charges through them viz conductors and insulators.

Conductors are the materials which allow the electric current to flow through them quite freely e.g. metals like silver, copper, aluminum.

Insulators are the materials which do not allow electricity to flow through them freely. e. g. rubber, glass, bakelite etc..

16.3.2 Resistors

The electrical resistance is the tendency to resist the flow of electric current. A wire having a desired resistance for use in an electric circuit is called a resistor. It is represented by the symbol -ᴧᴧᴧ-.

Resistance can be both either desirable or undesirable in a conductor/circuit. In a conductor, to transmit electricity from one place to another place, the resistance is undesirable. Resistance in a conductor causes part of electrical energy to turn into heat, so some electrical energy is lost along the path. On the other hand it is the resistance which allows us to use electricity for light and heat e.g., light that we receive from electric bulb and heat generated through electric heaters.

0.25Ω
0.5Ω
1Ω
2Ω

Resistor
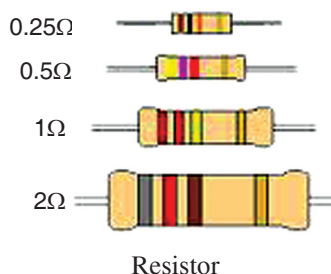
ACTIVITY 16.3

During your laboratory classes at your study centre, you can find the relation between the current flowing through a wire and the potential difference applied across it with the help of your tutor and your friends. Take a dry cell, a voltmeter (range 0-1.5V), an ammeter (range 0-1A), a standard fixed resistance coil (1 ohm), rheostat (0-1 ohm), connecting wires and a plug key.

(i)   Connect the fixed resistor (R), ammeter (A), dry cell (D), plug key (K) and rheostat (Rh) in series (end to end) and voltmeter (V) in parallel to R. as shown in Fig. 16.6 (a).
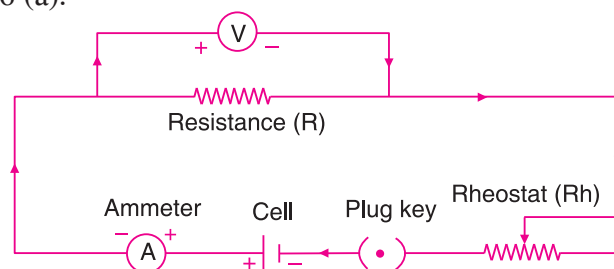
Fig. 16.6 *(a) Circuit diagram to study relationship between voltage and current*

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(ii) When the key K is open, (meaning that the circuit is disconnected), check that the readings in ammeter and voltmeter are zero.

(iii) Insert the plug K in the key and move the sliding contact of the rheostate so that there is some small reading in ammeter and voltmeter. Record these readings.

(iv) Increase the value of current with the help of rheostat. Record ammeter and voltmeter readings again.

(v) After changing the readings 4 to 5 times, record the corresponding values of current and voltage from ammeter and voltmeter.

(vi) Plot a graph between ammeter and voltmeter readings.

What do you observe? You will observe that: (i) On increasing ammeter reading, voltmeter reading increases in the same proportion. (ii) The voltage-current graph is a straight line as shown in Fig. 16.6 (b).
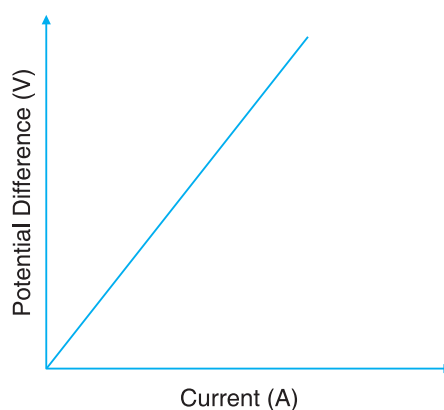

Fig. 16.6 *(b) variation of voltage with current*

What do you conclude? We conclude that the current flowing through a wire is directly proportional to the potential difference applied across its ends.

i. e. $V \propto i$

or $V = Ri$

Here, R is a constant of proportionality and is called the resistance of the given metallic wire. This observation was first made by Georg Simon Ohm and is known as Ohm's Law.

Ohm's Law states that the current flowing through a conductor is directly proportional to the potential difference applied across the ends of the conductor provided temperature of the conductor remains the same.

Now organize a brain storming session with your tutor and other learners on following points. The law can be applied only to conducting wires and that too when its temperature and other physical conditions remain unchanged. If the temperature of the conductor increases its resistance also increases.

'*R*' i.e. resistance of wire, is a constant for a given wire. It can be easily shown that resistance of a wire depends on:

Its length - longer the wire, more the resistance

Its thickness - thicker the wire, lesser the resistance.

Its width – more the width, lesser the resistance.

Therefore, the resistance of the wire is directly proportional to the length and inversely proportional to the cross-sectional area.

The nature of material - copper wire has lesser resistance than iron wire of same length and thickness. The resistance of a wire can never be negative.

Resistance is a scalar quantity and its SI unit is ohm denoted by the symbol Ω (omega). 1 ohm is the resistance of a wire across which when 1V potential difference is applied, 1A current flows through the wire.

i.e. $$1 \text{ ohm} = \frac{1 \text{ volt}}{1 \text{ ampere}}$$

High resistances are measured in kilo ohm (kΩ) and mega ohm (MΩ)

$$1 \text{ k}\Omega = 10^3 \ \Omega$$

$$1 \text{M}\Omega = 10^6 \ \Omega$$

16.4 COMBINATION OF RESISTORS

In an electric circuit, resistors can be connected in two different ways viz.

Series Combination: two or more resistors can be combined end to end consecutively.

Parallel Combination: two or more resistors can be connected between the same two points.

16.4.1 Series Combination

In a circuit (Fig. 16.7), three resistors are connected in series with a cell and an ammeter. You will note that due to one path the same current *i* will flow through all of them.
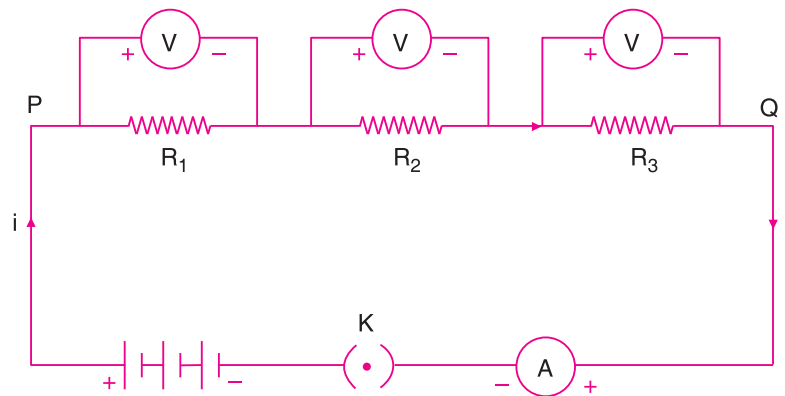
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Fig. 16.7 *Resistors in series*

Let the potential difference between the ends of the resistors R_1, R_2 and R_3 are respectively V_1, V_2 and V_3

By ohm's law potential difference across each resistor

$$V_1 = iR_1$$

$$V_2 = iR_2$$

and $\qquad\qquad\qquad V_3 = iR_3$

Now if the potential difference between P and Q be V

then $\qquad\qquad\qquad V = V_1 + V_2 + V_3$

Substituting the values of the V_1, V_2 and V_3

$$= iR_1 + iR_2 + iR_3$$

$$= i(R_1 + R_2 + R_3) \qquad\qquad (16.1)$$

Let total or equivalent resistance between P and Q is R_s

Then total potential difference $V = iR_s$ $\qquad\qquad (16.2)$

Comparing equations (16.1) and (16.2), we get

$$iR_s = i(R_1 + R_2 + R_3)$$

or $\qquad\qquad\qquad R_s = R_1 + R_2 + R_3$

i.e. The equivalent resistance of three resistors connected in series is equal to the sum of their individual resistances.

16.4.2 Parallel Combination

Figure shows three resistors connected in parallel with a cell and an ammeter. The potential difference between points P and Q will be same across each resistor but

the current flows from P to Q will be equal to the sum of the separate currents passing through each branch of a given resistance. If i_1, i_2 and i_3 respectively represent the current passing through the branches having the resistors R_1, R_2, and R_3 then the total current i in the main circuit will be
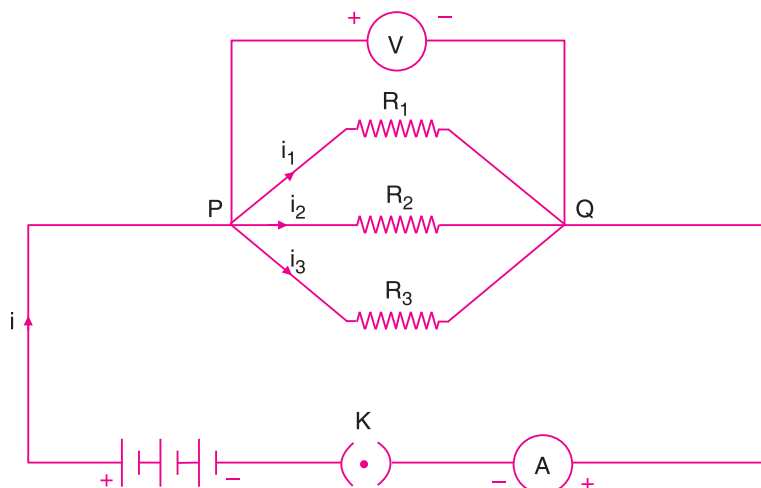
Fig. 16.8 *Resistors in parallel*

$$i = i_1 + i_2 + i_3 \qquad (16.3)$$

if V is the potential difference across each of the resistors, then according to Ohm's law

$$i_1 = \frac{V}{R_1}, \quad i_2 = \frac{V}{R_2} \quad \text{and} \quad i_3 = \frac{V}{R_3} \qquad (16.4)$$

If R_P is the equivalent resistance of the resistors connected in parallel having the same potential difference V then

$$i = \frac{V}{R_p} \qquad (16.5)$$

Using equations (16.4) and (16.5) the equation (16.3) will be

$$\frac{V}{R_P} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

i.e.
$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

i.e. the sum of the reciprocals of the separate resistances is equal to the reciprocal of equivalent or total or resultant resistor R_p.

Remember:

1. Normally all the appliances in our household circuits are connected in parallel. But the chain of small bulbs that we use for decoration on Deepawali has the bulbs connected in series.

2. As we add resistances in series, the circuit resistance increases but when we connect resistances in parallel, the total resistance is smaller than the smallest of the resistances involved.

? **Do you know**

Multimeter is basically an AVO meter i.e., Ammeter, Voltmeter and Ohm meter which is used for measurement of current, voltage and resistance.
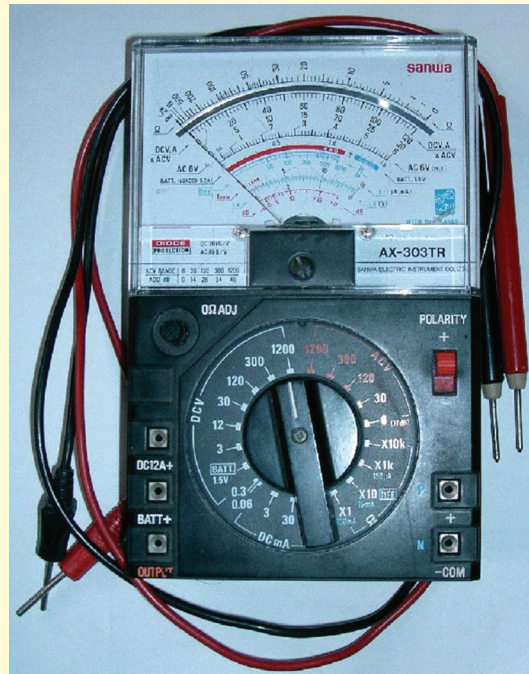
Example 16.3: A current of 0.5 A is drawn by a filament of an electric bulb for 5th part of an hour. Find the amount of electric charge that flows through the circuit.

Solution: Given $i = 0.5A$ $t = \dfrac{1}{5}$ of an hour $= \dfrac{1}{5} \times 60$ min $= 12$ min

$$Q = it = 12 \times 60 \text{ s} = 720 \text{ s}$$

$$= (0.5A) \times 720 \text{ s} = 720 \text{ s}$$

$$= 360 \text{ C}$$

Example 16.4: Find the equivalent resistance of the following combination of resistors.
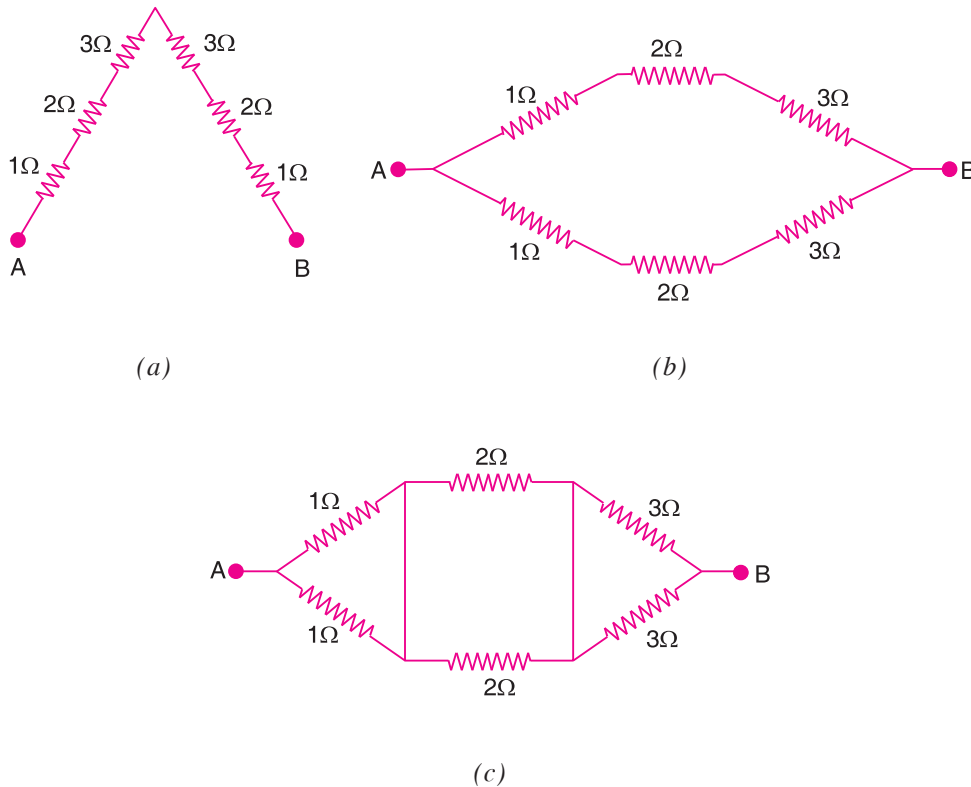

(a)

(b)

Notes

(c)

Fig. 16.9

Solution:

(a) Here all resistors are connected in series.

$$R = r_1 + r_2 + r_3 + r_4 + r_5 + r_6 = 1 + 2 + 3 + 3 + 2 + 1 = 12 \ \Omega$$

(b) Here we have two series combinations of 3 resistors, each connected in parallel.

$$R_1 = 1 + 2 + 3 = 6 \ \Omega$$

$$R_2 = 1 + 2 + 3 = 6 \ \Omega$$

$$R = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{6 \times 6}{6 + 6} = \frac{36}{12} = 3 \ \Omega$$

(c) Here we have 3 parallel combinations of 2 resistors, each connected in series.

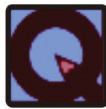$$R = \frac{r_1 \times r_2}{r_1 + r_2} = \frac{1 \times 1}{1 + 1} = \frac{1}{2} \Omega$$

Notes

$$R = \frac{2 \times 1}{2 + 2} = 1\Omega$$

$$R = \frac{3 \times 3}{3 + 3} = \frac{9}{6} = \frac{3}{2} = 1.5\Omega$$

$$R = R_1 + R_2 + R_3 = \frac{1}{2} + 1 + \frac{3}{2} = 3\Omega$$

INTEXT QUESTIONS 16.2

1. Define the SI units of (i) current (ii) resistance.

2. Name the instruments used to measure (i) current (ii) potential difference.

3. Why is a conductor different from an insulator?

4. How is a volt related to an ohm and an ampere?

5. A number of bulbs are connected in a circuit. Decide whether the bulbs are connected in series or in parallel, when (i) the whole circuit goes off when one bulb is fused (ii) only the bulb that get fused goes off.

6. When the potential difference across a wire is doubled, how will the following quantities be affected (i) resistance of the wire (ii) current flowing through the wire?

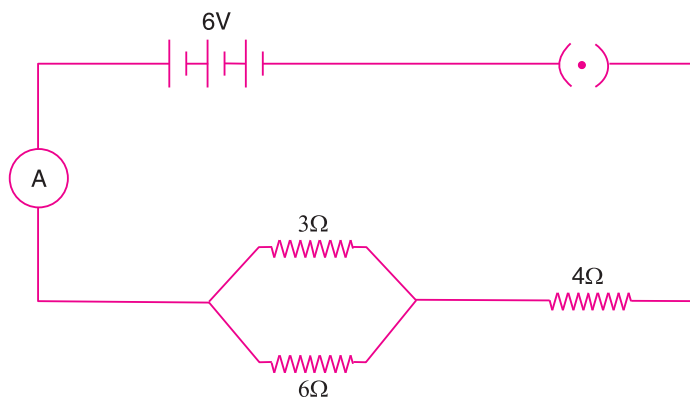7. What is the reading of ammeter in the circuit given below?

Fig. 16.10

8. How can three resistors of resistance 2Ω, 3Ω and 6Ω be connected to give a total resistance of (i) 11Ω (ii) 4.5Ω and (iii) 4Ω?

9. State two advantages of connecting electrical devices in parallel with the battery instead of connecting them in series.

Notes

16.5 HEATING EFFECT OF ELECTRIC CURRENT

It is a matter of common experience that on passing electric current through the filament of an electric bulb, it gets heated and glows brightly. Similarly on passing current through an electric heater, the coil of the heater becomes red hot. Do you know why? It is because in an electric circuit, electrical energy is converted into heat energy. This effect is known as thermal effect of electric current or Joules' heating.

16.5.1 Heat produced in a conductor on passing electric current

Consider a conductor XY of resistance R. Let current 'i' is passed for t seconds through the conductor on applying a potential difference V across the ends X and Y. If the charge Q is to be transferred from point X to Y, the work is done in moving the charge Q across the ends of the conductor. Work done in transferring the charge Q,

$$W = \text{potential difference } (V) \times \text{Charge } (Q)$$

$$= Vit \qquad\qquad (\because Q = it)$$

According to Ohm's law $V = iR$

$$\therefore \qquad\qquad W = (iR)it$$

$$W = i^2Rt.$$

Here the work done in moving the electric charge across a resistance appears in the form of heat. Therefore, the heat produced in the conductor is $H = i^2Rt$.

Hence, the amount of heat produced in a conductor on passing the current i is directly proportional to the square of the current (i^2), the resistance of the conductor (R) and the time (t) for which the current flows through the conductor.

This is known as Joule's law of heating. SI unit of heat is joule (J) (4.18 J = 1 cal)

16.5.2 Electric power

The rate at which electric energy is consumed or dissipated is termed as electric power.

$$\text{Electric power } P = \frac{\text{Work done } (W)}{\text{Time taken } (t)} = \frac{Vit}{t} = Vi$$

$$\therefore \qquad\qquad P = Vi$$

or $\qquad = (iR)i \qquad\qquad\qquad (\because V = iR)$

$\qquad\qquad\qquad = i^2R$

or $\qquad = \left(\dfrac{V}{R}\right)^2 R \qquad\qquad\qquad \left(\because i = \dfrac{V}{R}\right)$

$\qquad\qquad\qquad = \dfrac{V^2}{R}$

SI unit of electric power is joule/second or watt (W) .Thus, from $P = VI$, unit of power is watt i.e 1 watt (W) = 1 volt (V) × 1 ampere (A).

Hence, electric power consumed in a circuit or a device is 1 W if a current of 1A flows through it when a potential difference of one volt is maintained across it.

Since watt is a very small unit of power the bigger units kilowatt (kW) megawatt (MW) are actually used in practice.

$$1 \text{ kilowatt (kW)} = 1000 \ W$$

$$1 \text{ megawatt (MW)} = 10^6 \ W$$

$$1 \text{ gigawatt (GW)} = 10^9 \ W$$

For electric power another bigger unit horse power (hp) is also used.

$$1 \text{ (hp)} = 746 \ W$$

Since electrical energy consumed by an electrical appliance is equal to the product of power and the time for which it is used. The SI unit for the consumption of electric energy is joule but it is very small from practical point of view. Therefore, the electrical energy spent in the electric circuit is generally expressed in watt hour and kilowatt hour.

1 watt hour is the amount of electric energy which is consumed in 1 hour in an electric circuit when the electric power in the circuit is 1 watt.

1 kilowatt hour is the amount of electric energy consumed when 1 kilowatt power is used for 1 hour in an electric circuit.

$$1 \text{ kilowatt hour (kW h)} = 1 \text{ kilowatt} \times 1 \text{ hour}$$

$$= 1000 \text{ watt} \times 3600 \text{ second}$$

$$= 1000 \text{ joule/second} \times 3600 \text{ second}$$

$$= 36 \times 10^5 \text{ joule}$$

$$1 \text{ kW h} = 3.6 \times 10^6 \text{ J}$$

To calculate the cost of electrical energy, special unit kilowatt hour (kW h) is used which is also known as Board of Trade (BOT) unit or simply a unit of electricity. Therefore, the commercial unit of electric energy is kilowatt hour (kW h).

16.5.3 Electrical appliances based on thermal effect of electric current

There is a long list of household appliances based on thermal effect of electric current e.g electric iron, electric kettle, electric immersion rod/heater, electric geyser, cooking range, electric oven, electric toaster, electric stove, room heater, etc.

Beside appliances heating effect of electric current is also used in electric fuse, electric welding and electric arc. In all these appliances potential difference is applied across a conductor, the free electrons inside the conductor get accelerated and during the course of their motion electrons collide with other electrons and atoms/ions of the material of the conductor on their way and transfer their energy to them. The electrons move with constant drift velocity and do not gain kinetic energy. But due to collision with free electrons, the atoms/ions begin to vibrate with increased amplitude .In other words, the average kinetic energy of vibrations of the atoms of conductor increases which results in increase in temperature of the conductor i.e., the heat is produced in the conductor. Thus on applying potential difference, loss in potential energy of the electrons appears in the form of increase of average kinetic energy of the atoms of the conductor which finally appears as heat energy in the conductor

Notes

Electric Tester

It is used to indicate presence of electricity (a.c or d.c) in a circuit. It is like a screw driver. This screwdriver has a handle, which can hold easily. It has a neon indicator bulb. The screw end of the tester is just touched with the chassis of the appliance like electric iron and a finger is kept on the clip of the tester to provide earth. If the neon bulb glows up with reddish light it shows that current is passing through the chassis and it would give a shock, therefore, it is essential to switch off the mains immediately. If the light does not glow, it indicates that there is no leakage of current.

If you put a tester in an electric socket and if the neon bulb does not glow , it indicates that there is no power in the electric socket. It is a must tool for electrical automotive, electronic, appliance repairers.

ACTIVITY 16.4

You can do this simple activity with your friends to study thermal effect of electric current. Take two pieces of the element of electric heater (one of which has 10 turns and the other has 20 turns), two dry cells, connecting wires.

(i)   Attach connecting wires to the free ends of the 10-turn coil permanently.

(ii)   Touch the free ends of the connecting wires to the two terminals of a dry cell, thus passing current through it. Detach the contacts after 10 seconds. Now touch the coil and feel it.

(iii) Repeat the experiment by passing current for 20 seconds.

(iv)   Place two dry cells in contact, making series battery and repeat the second step.

(v)   Repeat steps 2, 3, 4 with 20-turn heater coil and feel it.
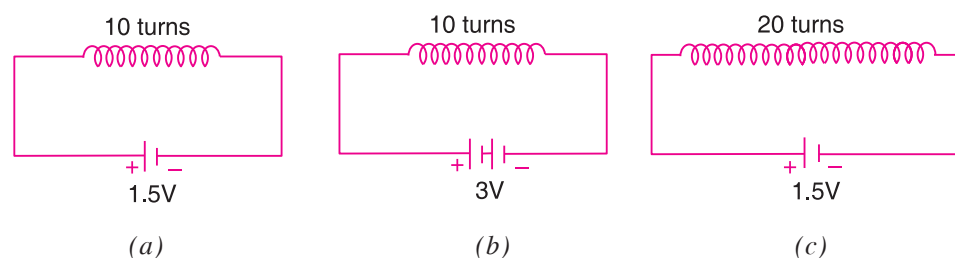
Fig. 16.11 *Study of thermal effect of electric current*

Discuss the observations with your friend, you will observe that on passing current through a conductor it gets heated up. The coil is found to be heated when current is passed for a second. The coil is found to be hotter when greater voltage is applied across it. When same voltage is applied across bigger coil less heat is produced in it. Thus, we conclude that

(i)   Current has a heating effect, i.e. when current is passed through a conductor it gets heated up.

(ii)   More heat is produced in a conductor

       when more potential difference is applied across it.

       current is passed through it for more time (*t*).

       more current is passed through the same conductor.
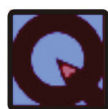
INTEXT QUESTIONS 16.3

1.   Which will produce more heat in 1 second – 1 ohm resistance on 10V or a 10 ohm resistance on the same voltage? Give reason for your answer.

2. How will the heat produced in a conductor change in each of the following cases?

   (i) The current flowing through the conductor is doubled.

   (ii) Voltage across the conductor is doubled.

   (iii) Time for which current passed is doubled.

3. 1 A current flows though a conductor of resistance 10 ohms for 1/2 minute. How much heat is produced in the conductor?

4. Two electric bulbs of 40 W and 60 W are given. Which one of the bulbs will glow brighter if they are connected to the mains in (i) series and (ii) parallel?

5. How is 1 kW h related with SI unit of energy?

6. Name two household electric devices based on thermal effect of electric current.

? Do you know

There are three types of large scale electric power generating plants

(i) Hydroelectric power plants – when potential energy of water stored in a dam is used for generating electricity. e.g. Bhakra- Nangal hydroelectric power plant, Punjab.

(ii) Thermal power plant – where a fossil fuel is burnt to produce steam which runs a turbine to convert mechanical energy into electrical energy. e.g. Namrup thermal power station, Assam.

(iii) Atomic power plant – where nuclear energy is obtained from a fissionable material like uranium is used to run a turbine. e.g. Narora atomic power station, Uttar Pradesh.

In India all the major plants produce A.C. (alternating current) at 50 hertz, 11000 volts or more. This power can be further stepped up to higher voltages using transformers and hence can be transmitted to long distances without much loss of power.

1. Alternating current (AC) means the electric current is alternating directions in a repetitive pattern.

2. AC is created by generators in power plants, and other sources. This AC current is delivered to our homes and businesses by the power lines we see everywhere.

Example 16.5: Find the resistance of the filament of 100 W, 250 V electric bulb.

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

$$= \frac{250 \times 250}{100} = 625\Omega$$

Example 16.6: Calculate the energy consumed in a 2 kW electric heater in 2 hours. Express the result in joules.

Solution:
$$Q = Pt = 2 \text{ kW} \times 2 \text{ h} = 4 \text{ kW h}$$

$$= 4 \times 3.6 \times 10^6 \text{J} = 14.4 \times 10^6 \text{ J}$$

Example 16.7: How much time will take a 2 kW immersion rod to raise the temperature of 1 litre of water from 30°C to 60°C

Solution:
$$Q = Pt$$

$$Q = mc\theta$$

$$mc\theta = Pt \tag{1}$$

Mass of 1 litre of water (m) = 1 kg

Specific heat of water $c = 4.18 \times 10^3 \text{ J kg}^{-1} \text{ }°\text{C}^{-1}$

Rise in temperature of water (θ) = 60 − 30 = 30°C.

$$P = 2 \text{ kW} = 2000\text{W}$$

Substituting in equation (1) we get

$$1 \times 4.18 \times 10^3 \times 30 = 2000 \times t$$

$$t = \frac{125.4 \times 10^3}{2 \times 10^3} = 62.7 \text{ s}$$

Example 16.8: How many kilowatt hour of energy will be consumed by a 2 hp motor in 10 hours?

Solution:
$$P = 2 \text{ hp} = 2 \times 746 \text{ W}$$

$$= 1.492 \text{ kW}$$

$$Q = Pt = 1.492 \text{ kW} \times 10 \text{ h} = 14.92 \text{ kW h}$$

Example 16.9: A potential difference of 250V is applied across a resistance of 1000 ohm. Calculate the heat energy produced in the resistance in 10 s.

Solution: Given $V = 250$ V $R = 1000$ W $t = 10$ s

$$Q = \frac{V^2 t}{R} = \frac{250 \times 250 \times 10}{1000} = 625\,J$$

Notes

Example 16.10: Compute the heat generated while transferring 96 kC of charge in one hour through a potential difference of 50V.
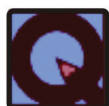
Solution: Given: $V = 50$V $t = 1$ h $q = 96000$ C

$W = qV$

$\qquad = 96000$ C $\times 50$ V

$W = 4800000$ J

$\qquad = 4.8 \times 10^6$ J

$\qquad = 4.8$ MJ.

Example 16.11: An electric iron of resistance 25 Ω takes a current of 5A. Calculate the heat developed in 1 minute.

Solution: Given: $R = 25$ Ω $i = 5$A $t = 1$ min ($= 60$ s)

Heat developed $H = i^2 Rt$

$\qquad = (5\ A)^2 \times 25$ Ω $\times 60$ s

$\qquad = 37500$ J $= 3.75 \times 10^4$ J

INTEXT QUESTIONS 16.4

1. Which has a higher resistance, a 40W-220 V bulb, or a 1 kW-220V electric heater?

2. What is the maximum current that a 100W, 220 V lamp can withstand?

3. How many units of electricity will be consumed by a 60 W lamp in 30 days if the bulb is lighted 4 hours daily?

4. How many joules of electrical energy will a quarter horse power motor consume in one hour?

5. An electric heater is used on 220 V supply and draws a current of 5 A. What is its electric power?

6. Which uses more energy, a television of 250 W in 60 minutes or a toaster of 1.2 kW in (1/6)th of an hour?

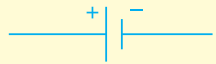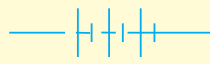**Notes**

? Do you know

Symbols used in Electric Circuit Diagram

Single electric cell

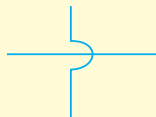Battery

An open plug key or switch

A closed plug key or switch
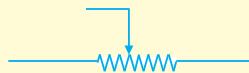
Wires joined

Wires crossed
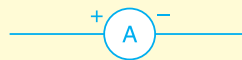
Wires crossing without contact

An electric bulb

A resistor

A Rheostat
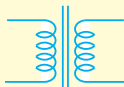
An ammeter

A galvanometer
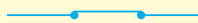
A voltmeter

Electromagnet

Electromagnet with iron core

Transformer

Variable resistance

Open switch

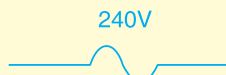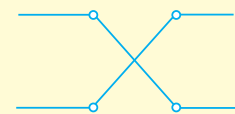Closed switch

Inductor

Tapping key

OR

Electric fuse

Capacitor

240V
a.c. supply

Reversing key

WHAT YOU HAVE LEARNT

- The force of attraction between the electrons and the protons hold an atom together.

- When two bodies are rubbed together in contact, they acquire a peculiar property of attracting small bits of paper. We say the bodies are electrified or charged by friction.

- Charges are of two types. Charge acquired by a glass rod rubbed with silk is positive and that acquired by an ebonite rod rubbed with fur is negative.

- Like charges repel each other and unlike charges attract each other.

- The force between two charges is given by Coulomb's law according to which

  $F = \dfrac{kq_1q_2}{r^2}$. The closer together the charges are, the stronger is the electrostatic force between them.

- Potential is the electrical state of a conductor which determines the direction of flow of charge when the two conductors are either placed in contact or they are connected by a metallic wire.

- Work is done in moving a charge against electric field which is stored up as potential energy of the charge. Hence, when charge is placed at a point in the field it possesses potential energy.

- Potential energy per coulomb of charge at a point is called potential. Positive charge always moves from a higher potential to a lower potential and vice-versa.

- The potential at a point is the amount of work done in bringing a unit positive charge from infinity to that point.

- The potential difference between two points is the amount of work done in moving a unit positive charge from one point to the other.

- Electric current at a place is the charge passing per unit time through that place.

- Electric cell is a device with the help of which we can apply a potential difference between the two ends of a wire due to which current will flow through the wire.

- Circuit diagrams are used to show how all the components connect together to make a circuit.

- Ohm's law states that current flowing through a conductor is directly proportional to the potential difference applied across its ends, provided physical conditions temperature etc.of the conductor remain the same.

- The obstruction offered to the flow of current by the wire is called its resistance. Mathematically ratio of voltage applied across a conductor and the current

Notes

flowing through it is called resistance of the conductor. SI unit of resistance is ohm.

- Resistors may be connected in two different independent ways
  - (i) In series and (ii) in parallel.
- In series, total resistance of the combination is equal to the sum of the individual resistances.
- In parallel, reciprocal of the combined resistance is equal to the sum of the reciprocals of the individual resistances.
- When current is passed through a conductor, it produces two effects.
  - (i) Thermal effect (ii) Magnetic effect.
- Commercial unit of electrical energy is kW h and that of electric power is HP.

For more information:

1. Multimedia CD on Innovative physics experiments developed by Vigyan Prasar, Department of Science & Technology,Govt of India. *www.vigyanprasar.gov.in*

2. Multimedia CD on Fun with Physics developed by Vigyan Prasar, Department of Science & Technology,Govt of India. *www.vigyanprasar.gov.in*

3. Flying circus of Physics by Jearl Walker, John Wiley and sons Publication.

TERMINAL EXERCISE

1. Tick mark the most appropriate answer out of four given options at the end of each of the following statements:

   (a) A charged conductor 'A' having charge Q is touched to an identical uncharged conductor 'B' and removed. Charge left on A after separation will be:

   (i) Q (ii) $Q/2$ (iii) Zero (iv) $2Q$

   (b) J C^{-1} is the unit of

   (i) Current (ii) Charge (iii) Resistance (iv) Potential

   (c) Which of the following materials is an electrical insulator?

   (i) Mica (ii) Copper (iii) Tungsten (iv) Iron

   (d) The device which converts chemical energy into electrical energy is called

   (i) Electric fan (ii) Electric generator

   (iii) Electric cell (iv) Electric heater

(e) The resistance of a conductor does not depend on its

   (i) Temperature   (ii) Length   (iii) Thickness   (iv) Shape

(f) There are four resistors of 12 Ω each. Which of the following values is possible by their combination (series and/or parallel)?

   (i) 9 Ω (ii) 16 Ω (iii) 12 Ω (iv) 30 Ω

(g) In case of the circuit shown below in Fig. 16.12, which of the following statements is/are true:

   (i) R_1, R_2, and R_3 are in series

   (ii) R_2 and R_3 are in series

   (iii) R_2 and R_3 are in parallel

   (iv) The equivalent resistance of the circuit is $[R_1 + (R_2 R_3/R_2 + R_3)]$
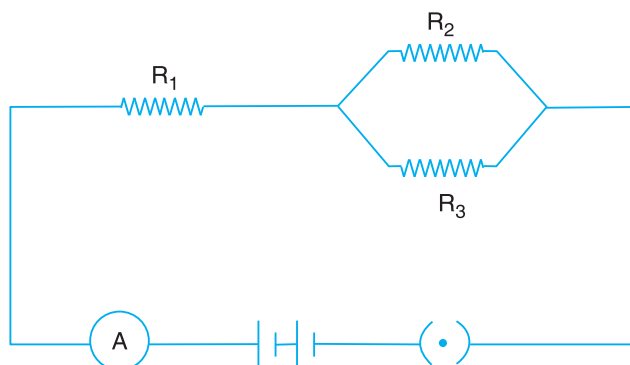

Fig. 16.12

(h) The equivalent resistance of two resistors of equal resistances connected in parallel is —— the value of each resistor.

   (i) Half   (ii) Twice   (iii) Same   (iv) One fourth

2. Fill in the blanks.

   (a) When current is passed through a conductor, its temperature ....

   (b) The amount of .... flowing past a point per unit .... is defined as electric current.

   (c) A current carrying conductor carries an .... field around it.

   (d) One ampere equals one .... per ....

   (e) Unit of electric power is ....

   (f) Of the two wires made of the same material and having same thickness, the longer one has .... resistance.

3. How many types of electric charge exist?

4. In a nucleus there are several protons, all of which have positive charge. Why does the electrostatic repulsion fail to push the nucleus apart?

5. What does it mean to say that charge is conserved?

6. A point charge of +3.0 μC is 10 cm apart from a second point charge of −1.5 μC. Find the magnitude and direction of force on each charge.

7. Name the quantity measured by the unit (a) VC (b) Cs^{-1}

8. Give a one word name for the unit (a) JC^{-1} (b) Cs^{-1}

9. What is the potential difference between the terminals of a battery if 250 J of work is required to transfer 20 C of charge from one terminal of the battery to the other?

10. Give the symbols of (a) cell (b) battery (c) resistor (d) voltmeter.

11. What is the conventional direction of flow of electric current? Do the charge carriers in the conductor flow in the same direction? Explain.

12. Out of ammeter and voltmeter which is connected in series and which is connected in parallel in an electric circuit?

13. You are given two resistors of 3 Ω and 6 Ω, respectively. Combining these two resistors what other resistances can you obtain?

14. What is the current in SI unit if+100 coulombs of charge flows past a point every five seconds?

15. Deduce an expression for the electrical energy spent in flow of current through a conductor.

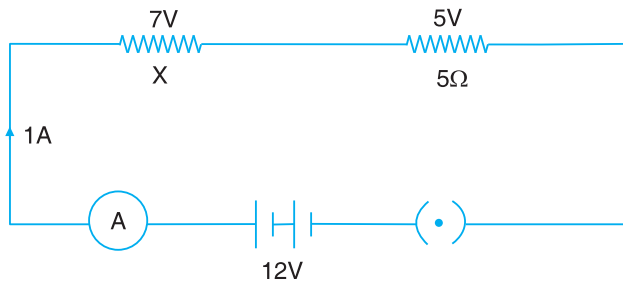16. Find the value of resistor X as shown in Fig. 16.13.

Fig. 16.13

17. In the circuit shown in Fig. 16.14, find (i) Total resistance of the circuit. (ii) Ammeter reading and (iii) Current flowing through 3 Ω resistor.
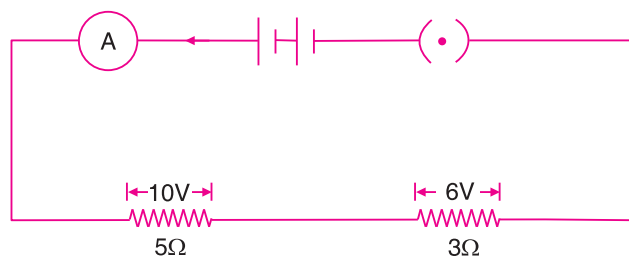

Fig. 16.14

18. For the circuit shown in Fig. 16.15, find the value of:
   (i) Current through 12Ω resistor.
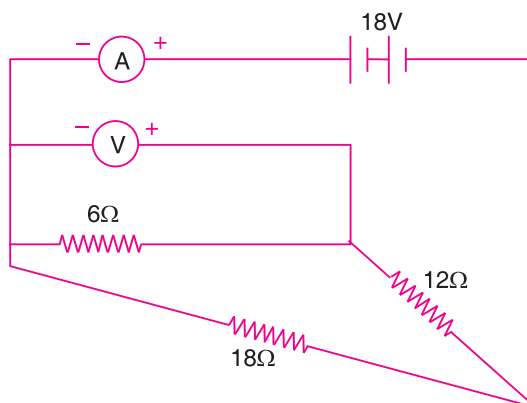   (ii) Potential difference across 6Ω and 18Ω resistor.

Fig. 16.15

19. You are given three resistors of 1 Ω, 2 Ω and 3 Ω. Show by diagrams, how will you connect these resistors to get (a) 6/11 Ω (b) 6 Ω (c) 1.5 Ω?

20. A resistor of 8 Ω is connected in parallel with another resistor of X Ω. The resultant resistance of the combination is 4.8 ohm. What is the value of resistor X?

21. In the circuit Fig. 16.16, find
   (i) Total resistance of the circuit.
   (ii) Total current flowing through the circuit.
   (iii) The potential difference across 4 Ω resistor.
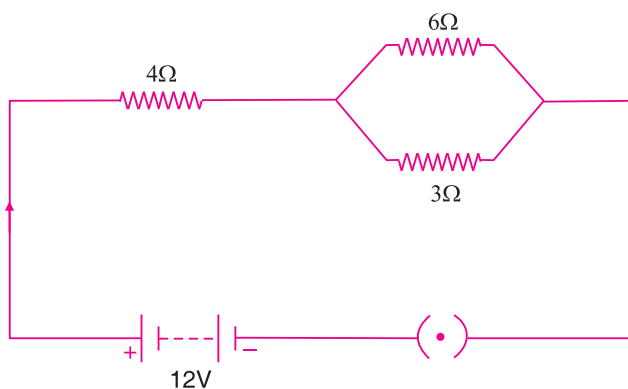

Fig. 16.16

22. How many 132 Ω resistors should be connected in parallel to carry 5 A current in 220 V line?

ANSWERS TO INTEXT QUESTIONS

16.1

1. (i) Unit of charge is Coulomb. 1C charge is the charge which when placed at a distance of 1 m from an equal like charge repels it with a of force of 9×10^9 N.

   (ii) Unit of potential is volt. 1 volt is the potential at a point in an electric field such that if 1C positive charge is brought from outside the field to this point against the field 1 J work is done.

2. $N = \dfrac{Q}{|e|} = \dfrac{10 \times 10^{-6}}{1.6 \times 10^{-19}} = 6.25 \times 10^{13}$ electrons

3. $F = k \dfrac{q_1 q_2}{r^2} \Rightarrow F = k \dfrac{2q_1 \times 2q_2}{(r/2)^2} = 8F$

4. $F' = 1/4 \ F$

5. (i) $V = \dfrac{U}{q} = \dfrac{10}{10^{-6}} = 10^7 \, V$

   (ii) $U = \dfrac{KQq}{r} \quad Q \quad \dfrac{Ur}{Kq} \quad \dfrac{10 \times 0.5}{9 \times 10^9 \times 10^{-6}} \quad \dfrac{5}{9} \quad 10^{-3} C$

6. Electrons will flow from sphere B to sphere A through the wire till the potentials of the two spheres become equal.

16.2

1. (i) Unit of current is ampere. 1A is the current in a wire in which 1C charge flows in 1 second.

   (ii) Unit of resistance is ohm. 1 ohm is the resistance of a wire across which when 1V potential difference is applied, 1A current flows through it.

2. (i) ammeter (ii) voltmeter

3. A conductor has free electrons, whereas an insulator has no free electrons.

4. 1 volt = 1 ohm × 1 ampere

5. (i) If the whole circuit goes off when one bulb is fused, the bulbs are connected in series.

   (ii) If any one bulb goes off and the rest of the circuit remains working, the bulbs are connected in parallel.

6. (i) Resistance of the wire remains unaffected.

   (ii) Current flowing through the wire is doubled.

7. 1A

8. (i) All the three resistors are connected in series.

   (ii) Resistors 2Ω and 6Ω are connected in parallel and 3Ω is connected in series to the combination of 2Ω and 6Ω.

   (iii) Resistors 3Ω and 6Ω are connected in parallel and 2Ω is connected in series to the combination of 3Ω and 6Ω.

9. In a parallel circuit, every electrical gadget operates separately because they take current as per their requirement.

   Total resistance of the circuit is decreased.

   If one component fails, the circuit is not broken and other electrical devices work properly.

16.3

1. $Q/t = V^2/R$. This implies that more the resistance less the power. Therefore, more heat will flow in 1s in 1 ohm resistor.

2. (i) Heat produced becomes four times (ii) heat produced becomes four times(iii) heat produced will be doubled.

3. $Q = i^2Rt = 1 \times 10 \times 30 = 300$ J.

4. $P = V^2/R$ and energy consumed in series $= i^2Rt$ and in parallel $= (V^2/R)t$

   (i) The bulb with lowest wattage (highest resistance) glows with maximum brightness.

   (ii) The bulb with highest wattage (lowest resistance) glows with maximum brightness.

5. 1 kW h $= 3.6 \times 10^6$ J

6. (i) Electric heater (ii) Electric kettle

16.4

1. $R = \dfrac{V^2}{P}$, 40W lamp has higher resistance.

2. $I = \dfrac{P}{V} = \dfrac{100 \text{ W}}{220 \text{ V}} = \dfrac{5}{11}\text{A}.$

3. $Q = Pt = 60\text{W} \times 4\text{h} \times 30 = 7200 \text{ W h} = 7.2 \text{ kW h}$

4. $Q = Pt = \dfrac{746}{4}\text{W} \times 3600\text{s} = 671400\,\text{J}.$

5. $P = VI = 220 \text{ V} \times 5\text{A} = 1100 \text{ W}$

6. Energy used by television = 0.25 kW × 1 h = 0.25 kW h

   Energy used by toaster = 1.2 kW × 1/6 h = 0.2 kW h