ELECTRIC CHARGE AND ITS PROPERTIES

Modern studies have revealed that charge, like mass, is a fundamental property of matter. Charges are of two types:

(a) Positive charge
(b) Negative charge

1. PROPERTIES OF ELECTRIC CHARGE

1.1 The unit of electric charge is coulomb and 1 coulomb is the charge contained in 6×10^{18} electrons. Unlike (opposite) charges attract each and like (similar) charges repel each other.

1.2 COULOMB'S LAW

The force between two charges is directly proportional to the product of two charges $(q_1 \text{ and } q_2)$ and inversely proportional to the square of distance (r) between them

$$F = \frac{K\, q_1 q_2}{r^2}$$

, where K is constant of proportionality.

(a) Electric charge can neither be destroyed nor be created.
(b) Charges are additive i.e. total charge is the algebraic sum of the individual charges.
(b) Charge is quantised.

2. CONDUCTORS AND INSULATORS

2.1 CONDUCTORS

Conductors are the substances through which charges can easily pass through.
e.g. Metals, aqueous solutions of salts and ionized gases etc.

2.2 INSULATORS

Insulators are those substances through which charges cannot pass through e.g. Glass, Wood and Rubber etc.

3. ELECTRIC CURRENT

Electrostatics is the branch of electricity, which deals with the study of charges at rest.
Current Electricity is when charges are in motion.
As air-current means movement of air, electric-current means flow of electric charges through a conductor.

3.1 ELECTRIC CURRENT

Electric Current therefore can be defined as the rate of flow of electric charge.
The quantity of charge flowing per unit time.

$$I = \frac{Q}{t} \quad \text{or } Q = It$$

where, charge (Q) flows through a conductor in time (t) and thus current (I) flows through it.

3.2 UNIT OF ELECTRIC CURRENT

SI unit of current is Ampere (A)

$$1 \text{ Ampere} = \frac{1\,\text{coulomb}}{1\,\text{second}}$$

Therefore, 1 ampere of current is said to be flowing through the conductor if one coulomb of charge flows through it in one second.

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

$$1 \mu\text{A} = 10^{-6} \text{ A}$$

3.3 DIRECTION OF CURRENT

Electric current is the flow of negatively charged electrons, from negative to positive terminal. Conventional current is said to flow from positive to negative, that is, opposite to the flow of electrons.

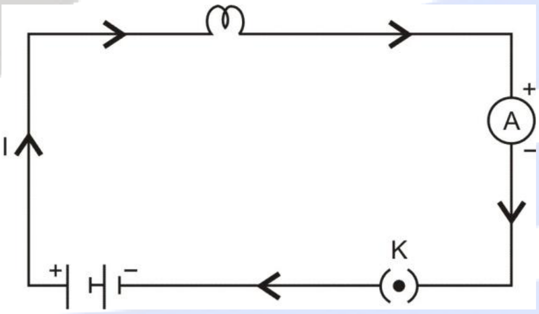


Figure showing direction of flow of electrons

4. ELECTRIC POTENTIAL AND ELECTRIC POTENTIAL DIFFERENCE

An object placed on an inclined plane rolls down. When two containers having different levels of water are joined, water moves from a higher level to a lower level. If two hot bodies are kept in contact, having different temperatures, heat flows from high temperature to low temperature.
Similarly, the work done in charging a body is stored in it as its **electric potential energy.** The electric potential energy per unit charge is called **electric potential.**

$$\text{Electric Potential} = \frac{\text{Electric Potential Energy}}{\text{Charge}}$$

4.1 ELECTRIC POTENTIAL DIFFERENCE

Electric potential difference between two points *P* and *Q* on a conductor through which a current is flowing is defined as the amount of work done to move a unit charge from *P* to *Q*.

$$V = \frac{W}{Q} \quad \text{or} \quad W = QV$$

V = Electric potential difference, Q = charge, W = work done.

4.2 UNIT OF ELECTRIC POTENTIAL DIFFERENCE

The unit of electric potential difference is volt (V)

$$1 \text{ Volt (V)} = \frac{1\,\text{Joule (J)}}{1\,\text{Coulomb (C)}}$$

Electric potential difference or potential difference is said to be one volt if one joule of work is done to move one coulomb of charge from one point to other.

5. ELECTRIC CIRCUIT AND ITS COMPONENTS

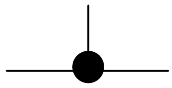
All electrical appliances like lamps, heaters and air-conditioners, which work on electricity, are called **Loads.**

To pass electric current through any 'Load', it has to be connected to a source of electric power through wires called conductors.

A source of electric power (battery), loads and switches connected together through wires form an **Electric Circuit.**

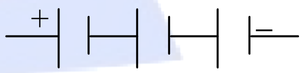
There are many components or elements of an electric circuit:

5.1 Connecting wires: They are also called conductors.

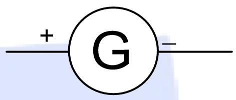


5.2 Resistors, Rheostats: It consists of wires made of Manganin and constantan alloys. Resistors provide fixed resistance whereas rheostats provide variable resistance.

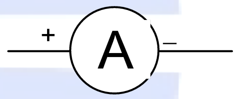
5.3 Battery: It is a combination of two or more cells.



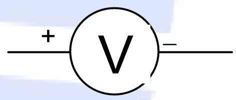
5.4 Galvanometer: It is a device used for detecting flow of current.



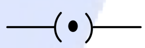
5.5 Ammeter: Also called as ampere-meter, it is used to measure current. It is always placed in series with the circuit.



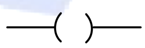
5.6 Voltmeter: Used for measuring potential difference. It is always connected in parallel across the circuit.



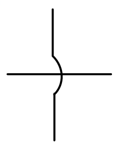
5.7 Closed electric circuit: In this, key is closed and current flows in the circuit continuously.



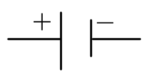
5.8 Open electric circuit: In this, key is open and no current flows in the circuit.



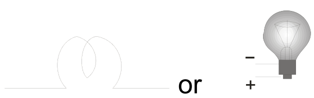
5.9 Wires crossing without joining



5.10 An electric cell



5.11 Electric bulb



6. OHM'S LAW

The flow of electric current through a conductor depends on the potential difference across its ends. At a particular temperature, the strength of current flowing through it is directly proportional to the potential difference across its ends. This is known as **Ohm's Law.**

$I \propto V$

or $V \propto I$ — V = Potential difference

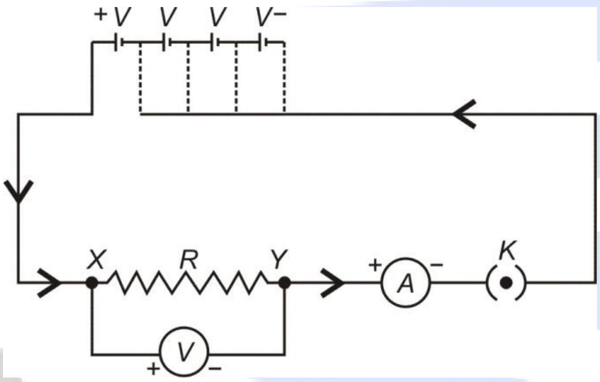
$V = RI$ — R = Resistance

or $R = \frac{V}{I}$ — I = Current

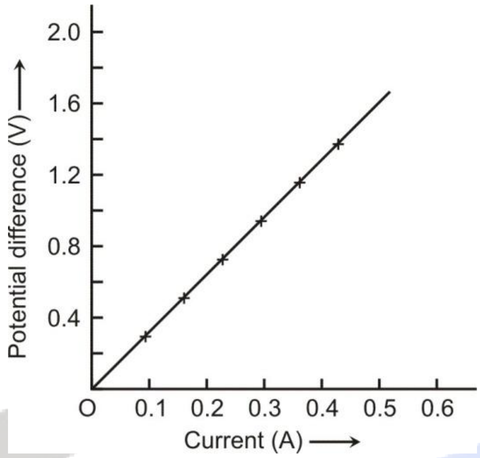
Here, R is the constant of proportionality, which depends on size, nature of material and temperature. R is called the **electrical resistance** or **resistance.**

6.1 EXPERIMENTAL VERIFICATION OF OHM'S LAW

- Set up a circuit as shown in figure consisting of a nichrome wire XY of length, say 0.5 m, an ammeter, a voltmeter and four cells of 1.5 V each. (Nichrome is an alloy of nickel, chromium, manganese, and iron metals.)
- First use only one cell as the source in the circuit. Note the reading in the ammeter I, for the current and reading of the voltmeter V for the potential difference across the nichrome wire XY in the circuit. Tabulate them.
- Next connect two cells in the circuit and note the respective readings of the ammeter and voltmeter for the values of current through the nichrome wire and potential difference across the nichrome wire.



- Repeat the above steps using three cells and then four cells in the circuit separately.
- Calculate the ratio if V to I for each pair of potential difference V and current I.
- Plot a graph between V and I, and observe the nature of the graph.



Thus, V/I is a constant ratio which is called R. It is known as Ohm's Law.

7. RESISTANCE

Resistance of a conductor means the obstruction to the flow of electrons through it.

We know that $V \propto I$

$$V = RI$$

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

R is called the resistance of a conductor through which a current 'I' flows when a potential difference V is applied across its ends.

Resistance of a conductor is therefore the ratio of the potential difference across its ends to the strength of the current flowing through it.

7.1 UNIT OF RESISTANCE

The S.I. unit of resistance is Ohm (Ω)

$$1 \text{ Ohm } (\Omega) = \frac{1\,\text{volt}\,(1\,\text{V})}{1\,\text{Ampere}\,(1\,\text{A})}$$

The resistance of a conductor is said to be one ohm if a current of one ampere flows through it when a potential difference of one volt is applied across its ends.

7.2 DIFFERENCE BETWEEN RESISTOR AND RESISTANCE

A **resistor** is an object of some conducting material having resistance of a desired value.

Resistance is the electrical property of a wire due to which it opposes the flow of electric energy.

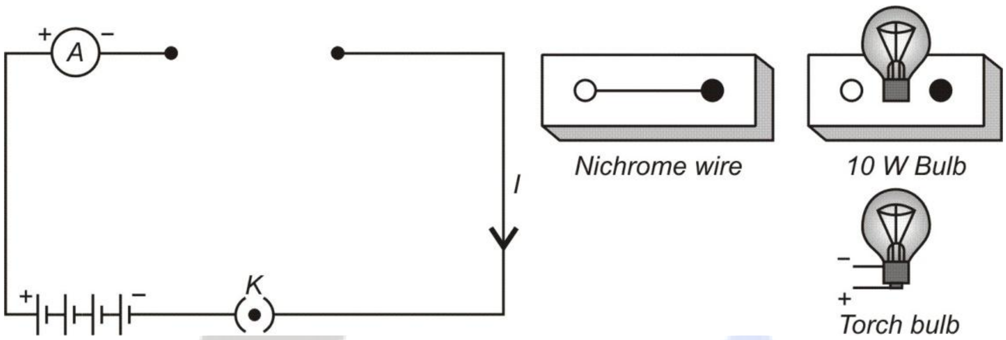
7.3 CONCEPT OF RESISTANCE

There are many free electrons in a conductor. They move randomly when no electric current is passing through it. But when current is passed through it, they being negatively charged, start moving towards positive end of conductor, with a velocity called Drift velocity. During this movement, they collide with atoms, or ions of the conductor and thus their velocity is slowed down. This slow down due to obstruction is called Resistance.

Activity to show that current through an electric component depends upon its resistance:

- Take a nichrome wire, a torch bulb, a 10 W bulb and an ammeter (0-5 A range), a plug key and some connecting wires.

- Set up the circuit by connecting four dry cells of 1.5 V each in series with the ammeter leaving a gap XY in the circuit, as shown in figure.



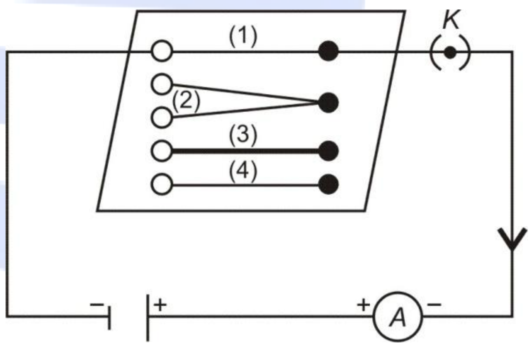
- Complete the circuit by connecting the nichrome wire in the gap XY. Plug the key. Note down the ammeter reading. Take out the key from the plug. [Note: Always take out the key from the plug after measuring the current through the circuit.]
- Replace the nichrome wire with the torch bulb in the circuit and find the current through it by measuring the reading of the ammeter.
- Now repeat the above step with 10 W bulb in the gap XY.
- Are the ammeter readings differ for different components connected in the gap XY? What do the above observations indicate?
- You may repeat this Activity by keeping any material component in the gap. Observe the ammeter readings in each case. Analyse the observations.

  Thus, we come to a conclusion that current through an electric component depends upon its resistance.

7.4 FACTORS AFFECTING RESISTANCE OF A CONDUCTOR

Activity to show that resistance of a conductor depends on its length, cross section area and nature of its material.

- Complete an electric circuit consisting of a cell, an ammeter, a nichrome wire of length□□ [say, marked (1)] and a plug key, as shown in figure.
- Now, plug the key. Note the current in the ammeter.



- Replace the nichrome wire by another nichrome wire of same thickness but twice the length, that is 2□ [marked (2) in the figure].
- Note the ammeter reading.
- Now replace the wire by a thicker nichrome wire, of the same length *l* [marked(3)]. A thicker wire ahs a larger cross-sectional area. Again note down the current through the circuit.
- Instead of taking a nichrome wire, connect a copper wire [marked (4) in figure] in the circuit. Let the wire be of the same length and same area of cross-section as that of the first nichrome wire [marked(1)]. Note the value of the current.
- Notice the difference in the current in all cases.
- Does the current depend on the length of the conductor?
- Does the current depend on the area of cross-section of the wire used?

7.4.1 Length of conductor:

Resistance of a conductor is directly proportional to its length

$$R \propto \ell$$

R = Resistance, l = length of wire.

Longer the conductor, higher the resistance it will have

7.4.2 Cross-section area of conductor.

Resistance of a conductor is inversely proportional to cross-section area (thickness) of the conductor.

$$R \propto \frac{1}{\pi r^2} \quad \text{or} \quad R \propto \frac{1}{A}$$

R = Resistance, r = Radius of wire, A = Cross-section area.

7.4.3 Nature of material of conductor

Different metals offer different resistances to the flow of current. This is also called as the specific resistance or resistivity of a metal.

7.4.4 Temperature

The resistivity and thus the resistance of a conductor changes with temperature.

$$R \propto \ell$$

$$R \propto \frac{1}{A}$$

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

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

R – Resistance

ρ – Resistivity

ℓ – Length of a conductor

A – Cross-sectional area

7.5 RESISTIVITY

If the length of the wire is 1 m and cross-section area is 1 m^2,

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

$$R = \frac{\rho \times 1}{1^2}$$

$$\Rightarrow R = \rho$$

Therefore, resistivity of a material is defined as the resistance offered by a cube of side 1 m of that material.

7.5.1 Unit of resistivity

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

$$\rho = \frac{RA}{l}$$

$$\rho = \frac{\text{Ohm} \times \text{m}^2}{\text{m}}$$

ρ = Ohm × meter = Ohm m (Ωm)

Thus, the S.I. unit of resistivity is Ωm.

7.5.2 Classification of materials based on resistivity

(a) **Conductors:** Metals like copper, aluminium, silver and platinum have large number of free electrons and have small resistivity. It is also true with alloys like nichrome, Manganin and constantan.

(b) **Semi conductors:** They have less free electrons and high resistivity as compared to conductors. Their resistivity decreases with temperature e.g. silicon and germanium.

(c) **Insulators:** They have almost nil free electrons and highest resistivity, which decreases with high temperature.

(d) **Super conductors:** Below a certain temperature, their resistivity becomes zero.

7.6 SPECIFIC USE OF SOME CONDUCTING MATERIALS

7.6.1 Tungsten:

It has high melting point of 3380ºC and emits light at 2400ºK. It is thus used as a filament in bulbs.

7.6.2 Nichrome:

It has high resistivity and melting point. It is used as an element in heating devices.

7.6.3 Constantan and Manganin:

They have modulated resistivity. Thus they are used for making resistances and rheostats.

7.6.4 Tin-lead Alloy:

It has low resistivity and melting point. Thus it is used as fuse wire.

8. COMBINATION OF RESISTORS

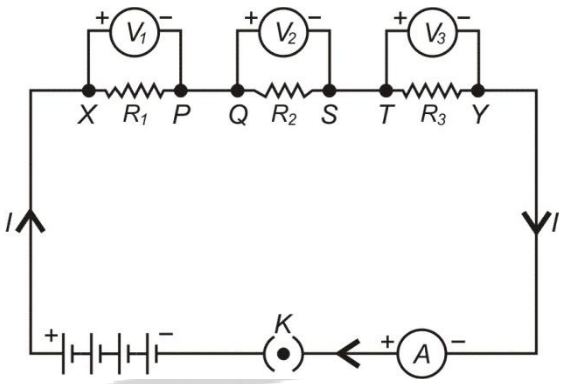
Many times we have to join two or more resistances to get the desirable resistance. There are two ways in which resistances be used:

(a) Resistances in series

(b) Resistances in Parallel

8.1 RESISTANCES IN SERIES

A number of resistances are said to be connected in series if they are joined end to end and the same current flows through each one of them, when a potential difference is applied across the combination.



R_1, R_2, R_3 – Resistances in series.
V – Total potential difference across XY.
V_1, V_2, V_3 – Potential difference across R_1, R_2, R_3 respectively.
I – Current flowing through combination.
So, $V = V_1 + V_2 + V_3$ ... (i)
According to Ohm's Law:

$$V_1 = IR_1 \quad \text{... (ii)}$$
$$V_2 = IR_2 \quad \text{... (iii)}$$
$$V_3 = IR_3 \quad \text{... (iv)}$$

Let R is the resultant or equivalent resistance of the combination. Then

$$V = IR \quad \text{... (v)}$$

From (i), (ii), (iii), (iv) and (v) we get that:

$$IR = IR_1 + IR_2 + IR_3$$
$$IR = I(R_1 + R_2 + R_3)$$
$$\therefore \quad R = R_1 + R_2 + R_3$$

8.1.1 Things to remember in series connection

(a) When a number of resistances are connected in series, the equivalent or resultant resistance is equal to the sum of individual resistances and resultant resistance is greater than any individual resistance.

(b) If n resistances each of value R are connected in series, the equivalent resistance R_e is given by:

$$R_e = R + R + R \text{ .... } n \text{ times}$$
$$R_e = nR$$
$$R_e = \text{Number of resistors} \times \text{resistance of each resistor}$$

(c) Equal current flows through each resistance and it is also equal to the total current in the circuit. This is because there is no other path along which the current can flow.

(d) The potential difference across the ends of the combination is distributed across the ends of each of the resistances. The potential difference across any one of the resistances is directly proportional to its resistance.

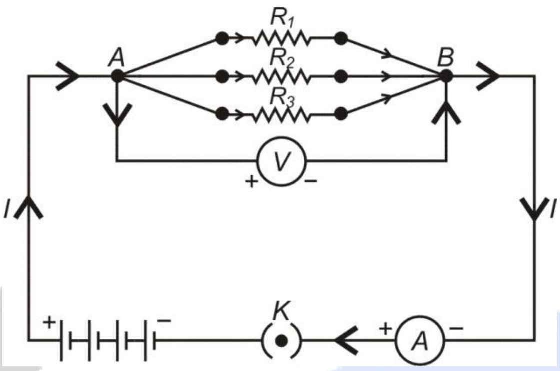
(e) The equivalent resistance when used in place of the combination of resistances produces the same current with the same potential difference applied across its ends.

(f) When two or more resistances are joined in series, the result is the same as increasing the length of the conductor. In both cases the resultant resistance is higher.

(g) In a series combination, the equivalent resistance is greater than the greatest resistance in the combination.

8.2 RESISTANCES IN PARALLEL

A number of resistors are said to be in a parallel connection if one end of each resistance is connected to one point and the other is connected to another point. The potential difference across each resistor is the same and is equal to the applied potential difference between the two points.



R_1, R_2, R_3 – Three resistances in parallel connection.
V – Potential difference across A and B.
I – Total current flowing between A and B.
I_1, I_2, I_3 – Current flowing through R_1, R_2, R_3 respectively.

$$I = I_1 + I_2 + I_3 \quad \text{... (i)}$$

The potential difference across R_1, R_2 and R_3 is same, therefore, according to Ohm's law:

$$\left.\begin{aligned} I_1 &= \frac{V}{R_1} \\ I_2 &= \frac{V}{R_2} \\ I_3 &= \frac{V}{R_3} \end{aligned}\right\} \quad \text{... (ii)}$$

Let R_e be the equivalent resistance. Thus

$$I = \frac{V}{R_e} \quad \text{... (iii)}$$

From equation (i), (ii) and (iii) we get

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

$$\frac{V}{R_e} = V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]$$

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

8.2.1 Things to remember in parallel connection

(a) When a number of resistances are connected in parallel, the reciprocal of the equivalent or resultant resistance is equal to the sum of reciprocals of the individual resistances and is always smaller than the individual resistances. This is because there are a number of paths for the flow of electrons.

(b) If there are n resistances connected in parallel and each resistance has a value of R

$$\frac{1}{R_e} = \frac{1}{R} + \frac{1}{R} + \frac{1}{R} \text{..........} n \text{ times}$$

$$\frac{1}{R_e} = \frac{n}{R}$$

$$\therefore \quad R_e = \frac{R}{n}$$

$$R_e = \frac{\text{Resistance of each resistor}}{\text{number of resistors}}$$

(c) The potential difference across each resistance is the same and is equal to the total potential difference across the combination.

(d) The main current divides itself and a different current flows through each resistor. The maximum current flows through the resistor having minimum resistance and vice versa.

(e) If an equivalent resistance R_e is connected in place of combination, it produces the same current for the same potential difference applied across its ends.

(f) In a parallel combination, the equivalent resistance is lesser than the least of all the resistances.

(g) If two resistances R_1 and R_2 are connected in parallel then

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_1 + R_2}{R_1 R_2}$$

$$R_e = \frac{R_1 R_2}{R_1 + R_2} = \frac{\text{Product of two resistances}}{\text{Sum of two resistances}}$$

(h) If there are n resistors each of resistance R – Let R_S be the resultant resistance of series combination and R_p be the resultant resistance of parallel combination.

Then, $R_S = nR$

$$R_p = \frac{R}{n}$$

$$\therefore \quad \frac{R_S}{R_p} = \frac{nR}{R/n} = n^2 .$$

9. HEATING EFFECT OF CURRENT

It has been a common observation that when an electric current passes through a conductor, the conductor becomes hot. In these cases the electrical energy is converted into heat energy. This property of producing heat is used in case of an electric bulb, electric furnace, electric iron and electric heater.

This property of the conductor to get heated is called Joule Heating or Heating Effect of Current.

Although this effect may be sometimes helpful, but it is not desirable all the time. The heating effect in a electric generator or a transformer causes wastage of electrical energy called "Dissipation of Electric Energy".

9.1 MECHANISM OF PRODUCTION OF HEAT

Metallic wires or appliances have free electrons. When a potential difference is applied, these free electrons start moving from lower potential (Positive terminal) to higher potential (Negative terminal). While drifting these electrons collide with other electrons and also with the ions/atoms of the conductor. The electrons have to do work to overcome this resistance. This work is thus converted into heat.

9.1.1 Factors Affecting Production of Heat

(a) Higher the value of current, more is the number of electrons flowing per second through the conductor. Thus, greater will be the number of collisions and heat produced.

(b) Higher the resistance of the conductor, more is the difficulty faced by electrons to move and higher is the amount of heat produced.

(c) If the current is allowed to pass in the conductor for a longer period of time, more collisions take place and thus higher is the amount of heat produced.

Joule studied the heating effect of electric current and came to the conclusion that the amount of heat produced (H) is given by the following formula:

$$H = I^2Rt$$

Here I represents the electric current, R represents resistance and t represents the time during which current was passed. This is also called as Joule's law of heating.

10. ELECTRIC ENERGY

To maintain an electric current to pass through the conductor, a continuous work has to be done. The total work done by a current in an electric circuit is known as **Electric Energy.**

10.1 DERIVATION OF WORK DONE AND ELECTRIC ENERGY

Now we know that:

$$\text{Current } (I) = \frac{\text{charge (Q)}}{\text{time (t)}} \quad \text{or } Q = IT \qquad \text{... (i)}$$

Also, potential difference is the work done in bringing a charge Q from one end to the other end of the conductor. Thus

$$\text{(Potential Difference)} \quad V = \frac{W}{Q}$$

$$W = VQ \qquad \text{... (ii)}$$

From (i) and (ii), we get that

$$W = V(It)$$

$$W = VIT \qquad \text{... (iii)}$$

But according to Ohm's law

$$V = IR \qquad \text{... (iv)}$$

From equation (iii) and (iv), we get that

$$W = (IR)(IT)$$

$$W = I^2Rt$$

But $I = \frac{V}{R}$ and by putting this value in equation (iii), we get

$$W = V.\left(\frac{V}{R}\right).t$$

$$W = \frac{V^2 t}{R}$$

This work done (*W*) by the current measures the Electric Energy. Thus

$$W \propto I^2$$
$$W \propto R$$
$$W \propto t$$

Thus, $W = H = VIt = I^2Rt = \frac{V^2}{R}t$

11. ELECTRIC POWER (P)

Electric current does work. The rate at which work is done by an electric current is called **Electric Power.**

Electric power can also be defined as the rate at which electric energy is consumed or dissipated.

$$W = VIt$$

Where, *W* is the work done when a current **I** flows for time t in a conductor against a potential difference, *V*.

As, power is the rate at which work is done,

$$P = \frac{W}{t}$$

$$P = \frac{VIt}{t} = VI$$

$$P = VI \qquad \text{... (i)}$$

The S.I unit of electric power is watt (*W*).

1 watt (*W*) = 1 volt (*V*) × 1 ampere (*A*)

Thus, the power of an electric circuit is said to be one watt if one ampere of current flows in it against a potential difference of one volt.

1 kilowatt (*kW*) = 1000 watt

But according to Ohm's law

$$V = IR \qquad \text{... (ii)}$$

From (1) and (2), we get that

$$P = (IR)I$$

$$P = I^2R$$

Also, as $I = \frac{V}{R}$

$$P = V\left[\frac{V}{R}\right] = \frac{V^2}{R}$$

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

12. COMMERCIAL UNIT OF ELECTRIC ENERGY

The commercial unit of electric energy is called kilowatt hour (kWh) or unit.
Kilowatt hour is the electric current consumed when an electric appliance of power one kilowatt works for one hour.

∴ $1kWh$ = 1 kW × 1h
= (1000 W) × (60 × 60 s)

$$\left[1\,\text{W} = \frac{1\text{J}}{1\text{s}}\right]$$

= 1000 J/s × 3600 s
= 3.6×10^6 J

As, W = VIt
1 Wh = 1 volt × 1 ampere × 1 hour

Thus, electric energy,

$$W(kWh) = \frac{V\,(\text{volt}) \times I\,(\text{ampere}) \times t\,(\text{hour})}{1000}$$

When current flows through an electric circuit and an appliance works, the electrons flowing are not consumed. Whatever electric energy we provide sets these electrons in motion. Whatever electricity bill we pay is to keep these electrons moving through various electric gadgets like an air-conditioner, fan and refrigerator.

13. RATING OF ELECTRIC APPLIANCES

Normally we see ratings like 60W – 220V. This means that the appliance consumes 60W of electric energy when connected to 220V supply. In other words, it also means that an electrical energy of 60 J will be converted to heat and light in this appliance every second.
If we want, we can calculate the resistance of this appliance.

We know that, $$R = \frac{V^2}{P}$$

$$R = \frac{(220)^2}{60} = \frac{48400}{60} = 806.67\ \Omega$$

When this bulb is not glowing, its actual resistance will be much lesser than this. This is because resistance increases with temperature.
Current through the filament of bulb can be calculated as:

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

$$= \frac{60}{220} = 0.27 \text{ A}$$

This is the maximum value of current that can flow through the filament.

14. APPLICATION OF HEATING EFFECT OF CURRENT

14.1 The following electrical appliances are based on heating effect:
Electric iron, geyser, toaster, oven, kettle etc

14.2 An electric bulb has tungsten filament, which gets heated up and then emits light.

14.3 Another important application of heating effect of current is **Electrical Fuse.** If the electrical current flowing through the circuit increases above a specified value, more heat is produced, the fuse melts, breaks the circuit and therefore saves the valuable electrical appliances and gadgets. We have different ratings of fuses like 1A, 2A, 3A, 5A and 10A for domestic uses.
For example an electric geyser consumes 1 kW of electric power when operated at 220V.
This will draw a current of 1000 W / 220 V = 4.54 A. Therefore a fuse of 5A is required for this appliance.