Current Electricity

The branch of Physics which deals with the study of motion of electric charges is called current electricity. In an uncharged metallic conductor at rest, some (not all) electrons are continually moving randomly through the conductor because they are very loosely attached to the nuclei. The thermodynamic internal energy of the material is sufficient to liberate the outer electrons from individual atoms, enabling the electrons to travel through the material. But the net flow of charge at any point is zero. Hence, there is zero current. These are termed as free electrons. The external energy necessary to drive the free electrons in a definite direction is called electromotive force (emf). The emf is not a force, but it is the work done in moving a unit charge from one end to the other. The flow of free electrons in a conductor constitutes electric current.

Electric current

The current is defined as the rate of flow of charges across any cross sectional area of a conductor. If a net charge q passes through any cross section of a conductor in time t, then the current $I = q / t$, where q is in coulomb and t is in second. The current I is expressed in ampere. If the rate of flow of charge is not uniform, the current varies with time and the instantaneous value of current i is given by,

$$i = \frac{dq}{dt}$$

Current is a scalar quantity. The direction of conventional current is taken as the direction of flow of positive charges or opposite to the direction of flow of electrons.

1. Drift velocity and mobility

Consider a conductor XY connected to a battery (Fig 2.1). A steady electric field E is established in the conductor in the direction X to Y. In the absence of an electric field, the free electrons in the conductor move randomly in all possible directions.

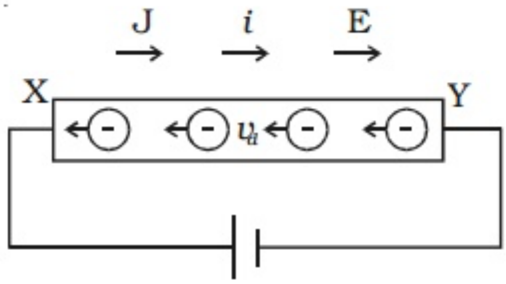

Fig 2.1 Current carrying conductor

They do not produce current. But, as soon as an electric field is applied, the free electrons at the end Y experience a force F = eE in a direction opposite to the electric field. The electrons are accelerated and in the process they collide with each other and with the positive ions in the conductor.

Thus due to collisions, a backward force acts on the electrons and they are slowly drifted with a constant average drift velocity $v_d$in a direction opposite to electric field.

Drift velocity is defined as the velocity with which free electrons get drifted towards the positive terminal, when an electric field is applied.

If τ is the average time between two successive collisions and the acceleration experienced by the electron be *a*, then the drift velocity is given by,

$$v_d = a\tau$$

The force experienced by the electron of mass *m* is

$$F = ma$$

Hence $$a = \frac{eE}{m}$$

$$\therefore v_d = \frac{eE}{m}\tau = \mu E$$

where $$\mu = \frac{e\tau}{m}$$

is the mobility and is defined as the drift velocity acquired per unit electric field. It takes the unit $m^2V^{-1}s^{-1}$. The drift velocity of electrons is proportional to the electric field intensity. It is very small and is of the order of 0.1 cm s^{-1}.

2. Current density

Current density at a point is defined as the quantity of charge passing per unit time through unit area, taken perpendicular to the direction of flow of charge at that point.

The current density J for a current I flowing across a conductor having an area of cross section A is

$$\mathbf{J} = \frac{(q/t)}{A} = \frac{I}{A}$$

Current density is a vector quantity. It is expressed in A m�'2

3. Relation between current and drift velocity

Consider a conductor XY of length *L* and area of cross section A (Fig 2.1). An electric field E is applied between its ends. Let *n*be the number of free electrons per unit volume. The free electrons move towards the left with a constant drift velocity v_d.

The number of conduction electrons in the conductor = *nAL*

The charge of an electron = *e*

The total charge passing through the conductor *q = (nAL) e*

The time in which the charges pass through the conductor, t =L /v_d

The current flowing through the conductor, $I = \frac{q}{t} = \frac{(nAL)e}{(L/v_d)}$

$$I = nAev_d \qquad ...(1)$$

The current flowing through a conductor is directly proportional to the drift velocity.

From equation (1), $\frac{I}{A} = nev_d$

$$\boldsymbol{J} = nev_d \qquad \left[\because \boldsymbol{J} = \frac{I}{A}, \text{current density}\right]$$

4. Ohm's law

George Simon Ohm established the relationship between potential difference and current, which is known as Ohm's law. The current flowing through a conductor is,

$$I = nAev_d$$

But $$v_d = \frac{eE}{m} \cdot \tau$$

$$\therefore \quad I = nAe \frac{eE}{m}\tau$$

$$I = \frac{nAe^2}{mL}\tau V \qquad \left[\because E = \frac{V}{L}\right]$$

where V is the potential difference. The quantity $\frac{mL}{nAe^2\tau}$ is a constant for a given conductor, called electrical resistance (R).

$$\therefore \quad I \propto V$$

The law states that, at a constant temperature, the steady current flowing through a conductor is directly proportional to the potential difference between the two ends of the conductor.

(i.e) $I \propto V$ or $I = \frac{1}{R}V$

$\therefore$ $V = IR$ or $R = \frac{V}{I}$

Resistance of a conductor is defined as the ratio of potential difference across the conductor to the current flowing through it. The unit of resistance is ohm (Ω)

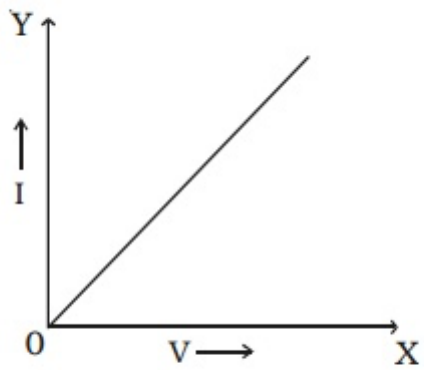

Fig 2.2 V–I graph of an ohmic conductor.

The reciprocal of resistance conductance. Its unit is mho (Ω�'1).

Since, potential difference proportional to the current I, the graph (Fig 2.2) between V and I is a straight line for a conductor. Ohm's law holds good only when a steady current flows through a conductor.

5. Electrical Resistivity and Conductivity

The resistance of a conductor R is directly proportional to the length of the conductor *l* and is inversely proportional to its area of cross section A.

$$R \propto \frac{l}{A} \quad \text{or} \quad R = \frac{\rho l}{A}$$

ρ is called specific resistance or electrical resistivity of the material of the conductor.

If *l* = l m, A = l m2, then ρ = R

The electrical resistivity of a material is defined as the resistance offered to current flow by a conductor of unit length having unit area of cross section. The unit of ρ is ohm�'m (Ω m). It is a constant for a particular material.

The reciprocal of electrical resistivity, is called electrical conductivity,

$\sigma = 1/\rho$

The unit of conductivity is mho m-1 (Ω�'1 m�'1)

6. Classification of materials in terms of resistivity

The resistivity of a material is the characteristic of that particular material. The materials can be broadly classified into conductors and insulators. The metals and alloys which have low resistivity of the order of 10�'6 �' 10�'8 Ω m are good conductors of electricity. They carry current without appreciable loss of energy. Example : silver, aluminium, copper, iron, tungsten, nichrome, manganin, constantan. The resistivity of metals increase with increase in temperature. Insulators are substances which have very high resistivity of the order of 108 �' 1014 Ω m. They offer very high resistance to the flow of current and are termed non�'conductors. Example : glass, mica, amber, quartz, wood, teflon, bakelite. In between these two classes of materials lie the semiconductors (Table 2.1). They are partially conducting. The resistivity of semiconductor is 10�'2 �' 104 Ω m. Example : germanium, silicon.

Table 2.1 Electrical resistivities at room temperature (NOT FOR EXAMINATION)

Classification	Material	ρ (Ω m)
conductors	silver	1.6×10^{-8}
	copper	1.7×10^{-8}
	aluminium	2.7×10^{-8}
	iron	10×10^{-8}
Semiconductors	germanium	0.46
	silicon	2300
Insulators	glass	$10^{10} - 10^{14}$
	wood	$10^{8} - 10^{11}$
	quartz	10^{13}
	rubber	$10^{13} - 10^{16}$

Combination of resistors

In simple circuits with resistors, Ohm's law can be applied to find the effective resistance. The resistors can be connected in series and parallel.

1. Resistors in series

Let us consider the resistors of resistances R_1, R_2, R_3 and R_4 connected in series as shown in Fig 2.6.

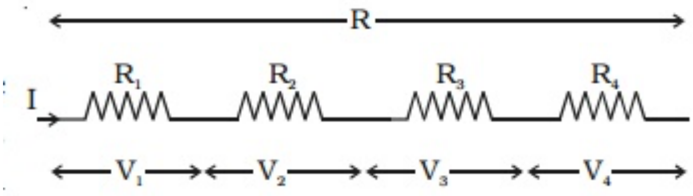

Fig 2.6 Resistors in series

When resistors are connected in series, the current flowing through each resistor is the same. If the potential difference applied between the ends of the combination of resistors is V, then the potential difference across each resistor R_1, R_2, R_3 and R_4 is V_1, V_2, V_3 and V_4 respectively.

The net potential difference $V = V_1 + V_2 + V_3 + V_4$

By Ohm's law

$V_1 = IR_1$, $V_2 = IR_2$, $V_3 = IR_3$, $V_4 = IR_4$ and $V = IR_s$

where R_S is the equivalent or effective resistance of the series combination.

Hence, $IR_S = IR_1 + IR_2 + IR_3 + IR_4$ or $R_S = R_1 + R_2 + R_3 + R_4$ Thus, the equivalent resistance of a number of resistors in series connection is equal to the sum of the resistance of individual resistors.

2. *Resistors in parallel*

Consider four resistors of resistances R_1 , R_2 , R_3 and R_4 are connected in parallel as shown in Fig 2.7. A source of emf V is connected to the parallel combination. When resistors are in parallel, the potential difference (V) across each resistor is the same.

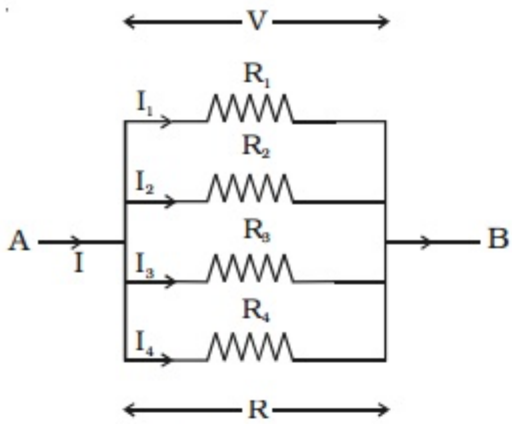

Fig 2.7 Resistors in parallel

A current I entering the combination gets divided into I_1, I_2, I_3 and I_4 through R_1, R_2, R_3 and R_4 respectively,

such that $I = I_1 + I_2 + I_3 + I_4$.

By Ohm's law

$$I_1 = \frac{V}{R_1},\quad I_2 = \frac{V}{R_2},\quad I_3 = \frac{V}{R_3},\quad I_4 = \frac{V}{R_4} \text{ and } I = \frac{V}{R_P}$$

where R_P is the equivalent or effective resistance of the parallel combination.

$$\therefore \frac{V}{R_P} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} + \frac{V}{R_4}$$

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

Thus, when a number of resistors are connected in parallel, the sum of the reciprocal of the resistance of the individual resistors is equal to the reciprocal of the effective resistance of the combination.

Kirchoff's law

Ohm's law is applicable only for simple circuits. For complicated circuits, Kirchoff's laws can be used to find current or voltage. There are two generalised laws : (i) Kirchoff's current law (ii) Kirchoff's voltage law

Kirchoff's first law (current law)

Kirchoff's current law states that the algebraic sum of the currents meeting at any junction in a circuit is zero.

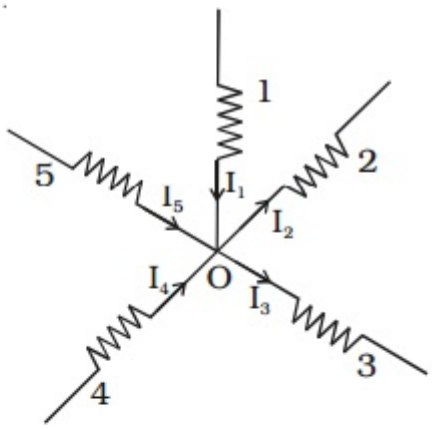

Fig 2.10 Kirchoff's current law

The convention is that, the current flowing towards a junction is positive and the current flowing away from the junction is negative. Let 1,2,3,4 and 5 be the conductors meeting at a junction O in an electrical circuit (Fig 2.10). Let I_1, I_2, I_3, I_4 and I_5 be the currents passing through the conductors respectively. According to Kirchoff's first law.

$$I_1 + (-'I_2) + (-'I_3) + I_4 + I_5 = 0 \text{ or } I_1 + I_4 + I_5 = I_2 + I_3.$$

The sum of the currents entering the junction is equal to the sum of the currents leaving the junction. This law is a consequence of conservation of charges.

Kirchoff's second law (voltage law)

Kirchoff's voltage law states that the algebraic sum of the products of resistance and current in each part of any closed circuit is equal to the algebraic sum of the emf's in that closed circuit. This law is a consequence of conservation of energy.

In applying Kirchoff's laws to electrical networks, the direction of current flow may be assumed either clockwise or anticlockwise. If the assumed direction of current is not the actual direction, then on solving the problems, the current will be found to have negative sign. If the result is positive, then the assumed direction is the same as actual direction.

It should be noted that, once the particular direction has been assumed, the same should be used throughout the problem. However, in the application of Kirchoff's second law, we follow that the current in clockwise direction is taken as positive and the current in anticlockwise direction is taken as negative.

Let us consider the electric circuit given in Fig 2.11a.

Considering the closed loop ABCDEFA,

$$I_1R_2 + I_3R_4 + I_3r_3 + I_3R_5 + I_4R_6 + I_1r_1 + I_1R_1 = E_1 + E_3$$

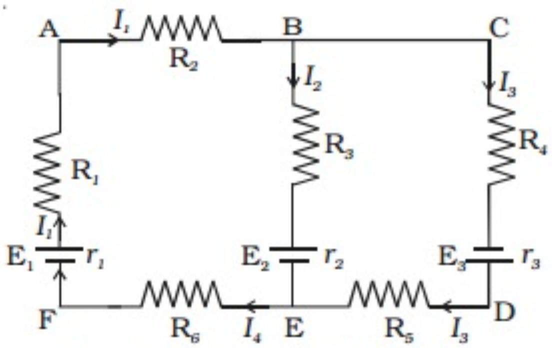

Fig 2.11a Kirchoff's laws

Both cells E_1 and E_3 send currents in clockwise direction.

For the closed loop ABEFA

$$I_1R_2 + I_2R_3 + I_2r_2 + I_4R_6 + I_1r_1 + I_1R_1 = E_1 - E_2$$

Negative sIgn in E_2 indicates that it sends current in the anticlockwise direction.

As an illustration of application of Kirchoff's second law, let us calculate the current in the following networks.

Illustration I

Applying first law to the Junction B, (FIg.2.11b)

$I_1 - I_2 - I_3 = 0$

$\therefore \quad I_3 = I_1 - I_2 \qquad ...(1)$

For the closed loop ABEFA,

$132\ I_3 + 20I_1 = 200 \ ...(2)$

Substituting equation (1) in equation (2)

$132\ (I_1 - I_2) + 20I_1 = 200$

$152I_1 - 132I_2 = 200 \ ...(3)$

For the closed loop BCDEB,

$60I_2 - 132I_3 = 100$

substituting for I_3,

$\therefore \quad 60I_2 - 132\ (I_1 - I_2) = 100$

$-132I_1 + 192I_2 = 100 \ ...(4)$

Solving equations (3) and (4), we obtain

$I_1 = 4.39$ A and $I_2 = 3.54$ A

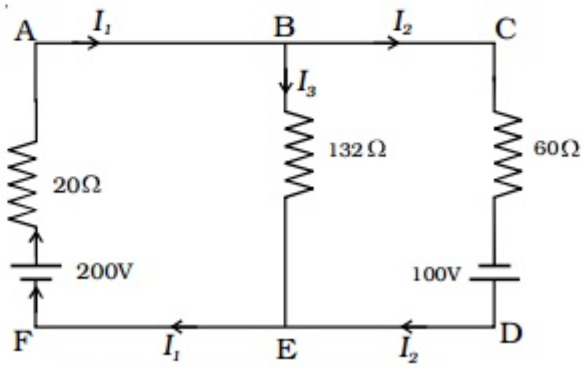

Fig 2.11b Kirchoff's laws

Illustration 2

Taking the current in the clockwise direction along ABCDA as positive (FIg 2.11c)

10 I + 0.5 I + 5 I + 0.5 I + 8 I + 0.5 I + 5 I + 0.5 I + 10 I = 50 - 70 - 30 + 40 I (10 + 0.5 + 5 + 0.5 + 8 + 0.5 + 5 + 0.5 + 10) = -10

40 I = -10

$40\ I = -10$

$I = \frac{-10}{40} = -0.25$ A

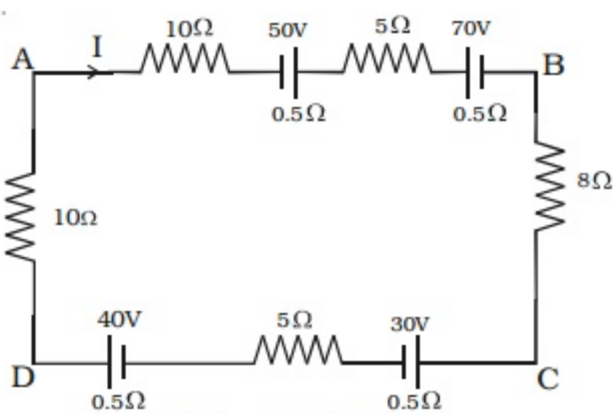

Fig 2.11c Kirchoff's laws

The negative sign indicates that the current flows in the anticlockwise direction.

1. Wheatstone's bridge

An important application of Kirchoff's law is the Wheatstone's bridge (FIg 2.12). Wheatstone's network consists of resistances P, Q, R and S connected to form a closed path. A cell of emf E is connected between points A and C. The current I from the cell is divided into I_1, I_2, I_3 and I_4 across the four branches. The current through the galvanometer is I_g. The resistance of galvanometer is G.

Applying Kirchoff's current law to junction B,

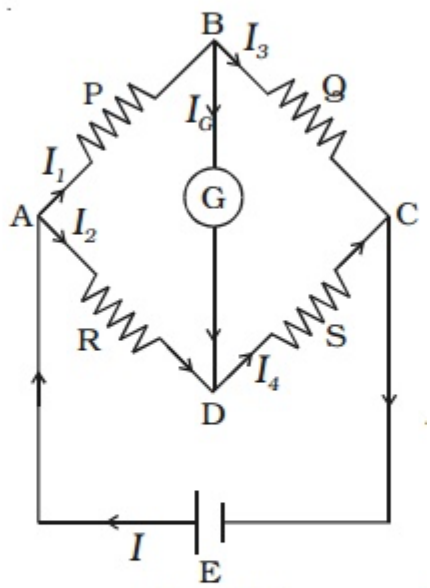

Fig 2.12
Wheatstone's bridge

$$I_1 - I_g - I_3 = 0 \qquad ...(1)$$

Applying Kirchoff's current law to junction D

$$I_2 + I_g - I_4 = 0 \qquad ...(2)$$

Applying Kirchoff's voltage law to closed path ABDA

$$I_1 P + I_g G - I_2 R = 0 \qquad ...(3)$$

Applying Kirchoff's voltage law to closed path ABCDA

$$I_1 P + I_3 Q - I_4 S - I_2 R = 0 \qquad ...(4)$$

When the galvanometer shows zero deflection, the points B and D are at same potential and $I_g = 0$. Substituting $I_g = 0$ in equation (1), (2) and (3)

$$I_1 = I_3 \quad \ldots(5)$$

$$I_2 = I_4 \quad \ldots(6)$$

$$I_1 P = I_2 R \quad \ldots(7)$$

Substituting the values of (5) and (6) in equation (4)

$$I_1 P + I_1 Q - I_2 S - I_2 R = 0$$

$$I_1 (P + Q) = I_2 (R+S) \quad \ldots(8)$$

Dividing (8) by (7)

$$\frac{I_1(P+Q)}{I_1 P} = \frac{I_2(R+S)}{I_2 R}$$

$$\therefore \frac{P+Q}{P} = \frac{R+S}{R}$$

$$1+\frac{Q}{P} = 1+\frac{S}{R}$$

$$\therefore \frac{Q}{P} = \frac{S}{R} \quad \text{or} \quad \frac{P}{Q} = \frac{R}{S}$$

This is the condition for bridge balance. If P, Q and R are known, the resistance S can be calculated.

2. Metre bridge

Metre bridge is one form of Wheatstone's bridge. It consists of thick strips of copper, of negligible resistance, fixed to a wooden board.

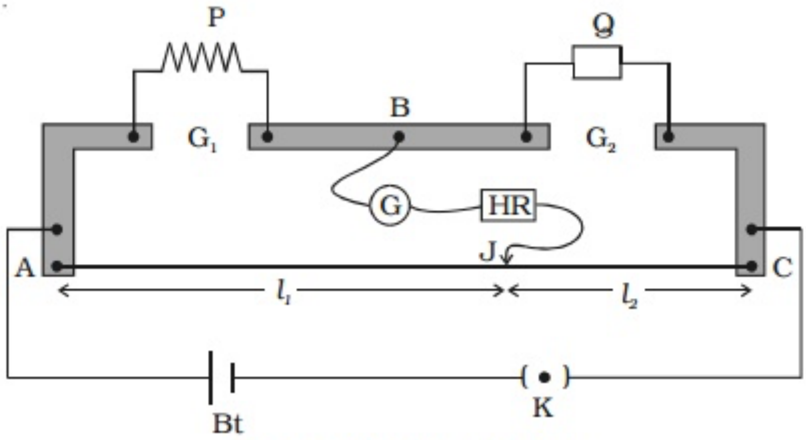

Fig 2.13 Metre bridge

There are two gaps G1 and G2 between these strips. A uniform manganin wire AC of length one metre whose temperature coefficient is low, is stretched along a metre scale and its ends are soldered to two copper strips. An unknown resistance P is connected in the gap G1 and a standard resistance Q is connected in the gap G2 (Fig 2.13). A metal jockey J is connected to B through a galvanometer (G) and a high resistance (HR) and it can make contact at any point on the wire AC. Across the two ends of the wire, a Leclanche cell and a key are connected.

Adjust the position of metal jockey on metre bridge wire so that the galvanometer shows zero deflection. Let the point be J. The portions AJ and JC of the wire now replace the resistances R and S of Wheatstone's bridge. Then

$$\frac{P}{Q}=\frac{R}{S}=\frac{r.AJ}{r.JC}$$

where r is the resistance per unit length of the wire.

$$\therefore \quad \frac{P}{Q}=\frac{AJ}{JC}=\frac{l_1}{l_2}$$

where $AJ = l_1$ and $JC = l_2$

$$\therefore \quad P = Q\frac{l_1}{l_2}$$

Though the connections between the resistances are made by thick copper strips of negligible resistance, and the wire AC is also soldered to such strips a small error will occur in the value of l_1/l_2 to the end resistance. This error can be eliminated, if another set of readings are taken with P and Q interchanged and the average value of P is found, provided the balance point J is near the mid point of the wire AC.

3. Determination of specific resistance

The specific resistance of the material of a wire is determined by knowing the resistance (P), radius (r) and length (L) of the wire using the expression

$$\rho = \frac{P\pi r^2}{L}$$

4. Determination of temperature coefficient of resistance

If R_1 and R_2 are the resistances of a given coil of wire at the temperatures t_1 and t_2, then the temperature coefficient of resistance of the material of the coil is determined using the relation,

$$\alpha = \frac{R_2 - R_1}{R_1 t_2 - R_2 t_1}$$

Potentiometer

The Potentiometer is an instrument used for the measurement of potential difference (Fig 2.14). It consists of a ten metre long uniform wire of B manganin or constantan stretched in ten segments, each of one metre length. The segments are stretched parallel to each other on a horizontal wooden board. The ends of the wire are fixed to copper strips with binding screws. A metre scale is fixed on the board, parallel to the wire. Electrical contact with wires is established by pressing the jockey J.

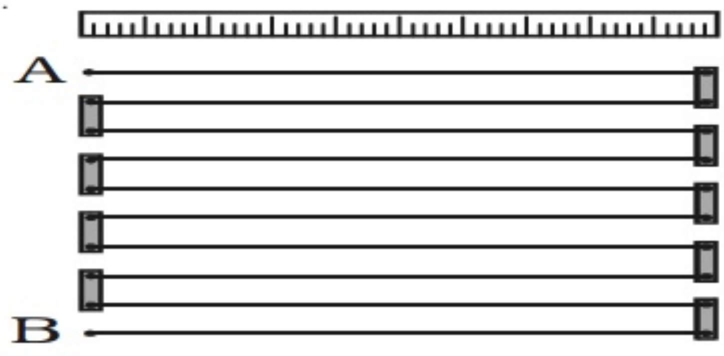

Fig 2.14 Potentiometer

1. Principle of potentiometer

A battery Bt is connected between the ends A and B of a potentio- meter wire through a key K. A steady current I flows through the potentiometer wire (Fig 2.15). This forms the primary circuit. A primary cell is connected in series with the positive terminal A of the potentiometer, a galvanometer, high resistance and jockey. This forms the secondary circuit.

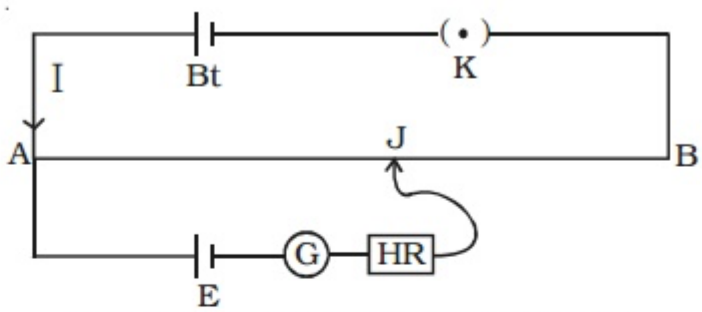

Fig 2.15 Principle of potentiometer

If the potential difference between A and J is equal to the emf of the cell, no current flows through the galvanometer. It shows zero deflection. AJ is called the balancing length. If the balancing length is l, the potential difference across AJ = Irl where r is the resistance per unit length of the potentiometer wire and I the current in the primary circuit.

$\therefore E = Irl$,

since I and r are constants, $E \propto l$

Hence emf of the cell is directly proportional to its balancing length. This is the principle of a potentiometer.

2. *Comparison of emfs of two given cells using potentiometer*

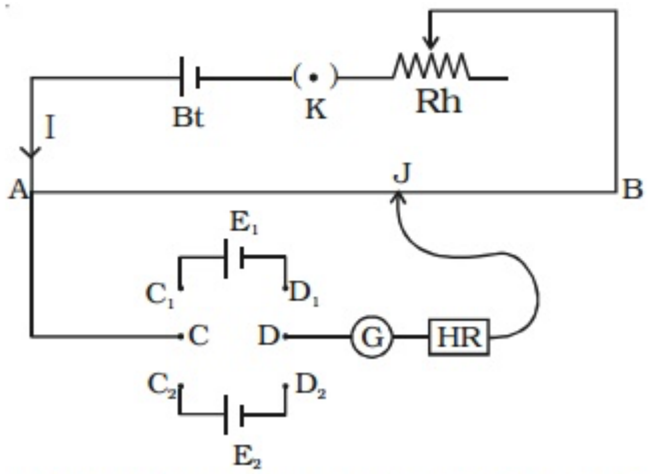

Fig 2.16 comparison of emf of two cells

The potentiometer wire AB is connected in series with a battery (Bt), Key (K), rheostat (Rh) as shown in Fig 2.16. This forms the primary circuit. The end A of potentiometer is connected to the terminal C of a DPDT the terminal C of a DPDT switch (six way key-double terminal D is connected to the jockey (J) through a galvanometer (G) and high resistance (HR). The cell of emf E_1connected between terminals C_1 and D_1 and the cell of emf E_2 connected between C_2 and D_2 of the DPDT switch.

Let I be the current flowing through the primary circuit and *r* be the resistance of the potentiometer wire per metre length.

The DPDT switch is pressed towards C_1, D_1 so that cell E_1 is included in the secondary circuit. The jockey is moved on the wire and adjusted for zero deflection in galvanometer. The balancing length is l_1. The potential difference across the balancing length l_1 = Irl_l. Then, by the principle of potentiometer,

$$E_1 = Irl_1 \qquad \ldots(1)$$

The DPDT switch is pressed towards E_2. The balancing length l_2 for zero deflection in galvanometer is determined. The potential difference across the balancing length is l_2 = Irl_2, then

$$E_2 = Irl_2 \qquad ...(2)$$

Dividing (1) and (2) we get

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

If emf of one cell (E_1) is known, the emf of the other cell (E_2) can be calculated using the relation.

$$E_2 = E_1 \frac{l_2}{l_1}$$

3. Comparison of emf and potential difference

1. The difference of potentials between the two terminals of a cell in an open circuit is called the electromotive force (emf) of a cell. The difference in potentials between any two points in a closed circuit is called potential difference.

2. The emf is independent of external resistance of the circuit, whereas potential difference is proportional to the resistance between any two points.

Superconductivity

Ordinary conductors of electricity become better conductors at lower temperatures. The ability of certain metals, their compounds and alloys to conduct electricity with zero resistance at very low temperatures is called superconductivity. The materials which exhibit this property are called superconductors.

The phenomenon of superconductivity was first observed by Kammerlingh Onnes in 1911. He found that mercury suddenly showed zero resistance at 4.2 K (Fig 2.3). The first theoretical explanation of superconductivity was given by Bardeen, Cooper and Schrieffer in 1957 and it is called the BCS theory.

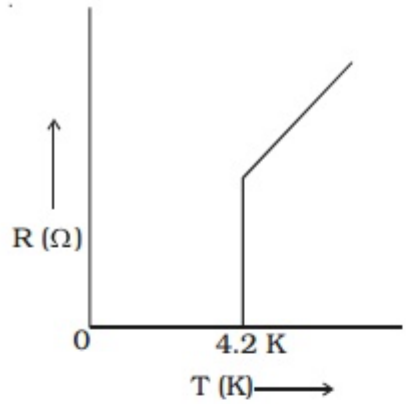

Fig 2.3 Superconductivity of mercury

The temperature at which electrical resistivity of the material suddenly drops to zero and the material changes from normal conductor to a superconductor is called the transition temperature or critical temperature Tc. At the transition temperature the following changes are observed :

1. The electrical resistivity drops to zero.

2. The conductivity becomes infinity

3. The magnetic flux lines are excluded from the material.

Applications of superconductors

1. Superconductors form the basis of energy saving power systems, namely the superconducting generators, which are smaller in size and weight, in comparison with conventional generators.

2. Superconducting magnets have been used to levitate trains above its rails. They can be driven at high speed with minimal expenditure of energy.

3. Superconducting magnetic propulsion systems may be used to launch satellites into orbits directly from the earth without the use of rockets.

4. High efficiency ore�'separating machines may be built using superconducting magnets which can be used to separate tumor cells from healthy cells by high gradient magnetic separation method.

5. Since the current in a superconducting wire can flow without any change in magnitude, it can be used for transmission lines.

6. Superconductors can be used as memory or storage elements in computers.

Carbon resistors

The wire wound resistors are expensive and huge in size. Hence, carbon resistors are used. Carbon resistor consists of a ceramic core, on which a thin layer of crystalline carbon is deposited. These resistors are cheaper, stable and small in size. The resistance of a carbon resistor is indicated by the colour code drawn on it (Table 2.2). A three colour code carbon resistor is discussed here. The silver or gold ring at one end corresponds to the tolerance. It is a tolerable range (-/+) of the resistance. The tolerance of silver, gold, red and brown rings is 10%, 5%, 2% and 1% respectively. If there is no coloured ring at this end, the tolerance is 20%. The first two rings at the other end of tolerance ring are significant figures of resistance in ohm. The third ring indicates the powers of 10 to be multiplied or number of zeroes following the significant figure.

Table Colour code for carbon resistors

Colour	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

Example :

The first yellow ring in Fig 2.4 corresponds to 4. The next violet ring corresponds to 7. The third orange ring corresponds to 10^3. The silver ring represents 10% tolerance. The total resistance is 47 �- 10^3 (-/+) 10% i.e. 47 k Ω, 10%. Fig 2.5 shows 1 k Ω, 5% carbon resistor.

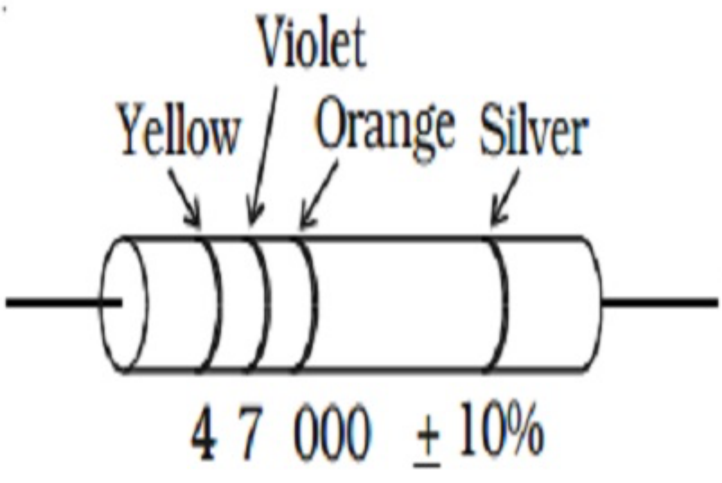

Fig Carbon resistor colour code.

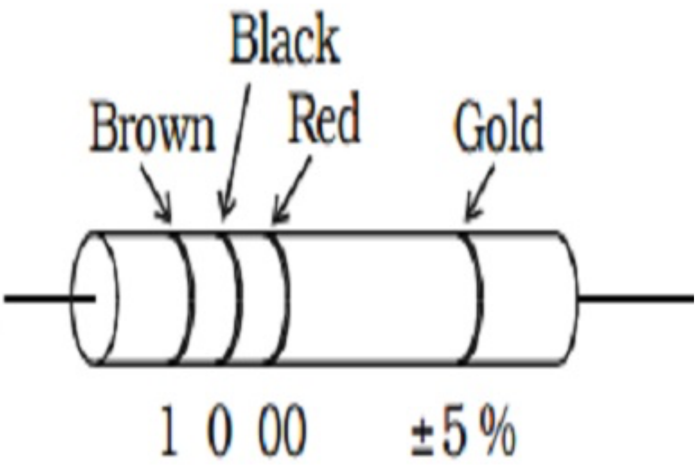

Fig . Carbon resistor

Presently four colour code carbon resistors are also used. For certain critical applications 1% and 2% tolerance resistors are used.

Temperature dependence of resistance

The resistivity of substances varies with temperature. For conductors the resistance increases with increase in temperature. If R_o is the resistance of a conductor at 0_o C and R_t is the resistance of same conductor at t_o C, then

$$R_t = R_o (1 + \alpha t)$$

where α is called the temperature coefficient of resistance.

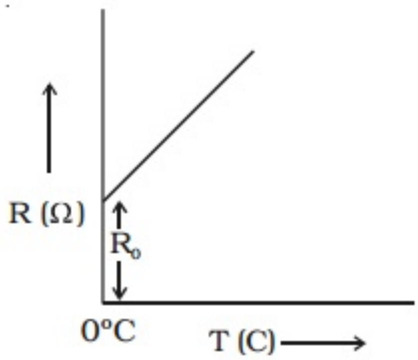

Fig 2.8 Variation of resistance with temperature

$$\alpha = \frac{R_t - R_o}{R_o t}$$

The temperature coefficient of resistance is defined as the ratio of increase in resistance per degree rise in temperature to its resistance at 0_o C. Its unit is per $_o$C.

The variation of resistance with temperature is shown in diagram.

Metals have positive temperature coefficient of resistance, i.e., their resistance increases with increase in temperature. Insulators and semiconductors have negative temperature coefficient of resistance, i.e., their resistance decreases with increase in temperature. A material with a negative temperature coefficient is called a thermistor. The temperature coefficient is low for alloys.

Internal resistance of a cell

The electric current in an external circuit flows from the positive terminal to the negative terminal of the cell, through different circuit elements. In order to maintain continuity, the current has to flow through the electrolyte of the cell, from its negative terminal to positive terminal. During this process of flow of current inside the cell, a resistance is offered to current flow by the electrolyte of the cell. This is termed as the internal resistance of the cell.

A freshly prepared cell has low internal resistance and this increases with ageing.

Determination of internal resistance of a cell using voltmeter

The circuit connections are made as shown in Fig 2.9. With key K open, the emf of cell E is found by connecting a high resistance voltmeter across it. Since the high resistance voltmeter draws only a very feeble current for deflection, the circuit may be considered as an open circuit. Hence the voltmeter reading gives the emf of the cell. A small value of resistance R is included in the external circuit and key K is closed. The potential difference across R is equal to the potential difference across cell (V).

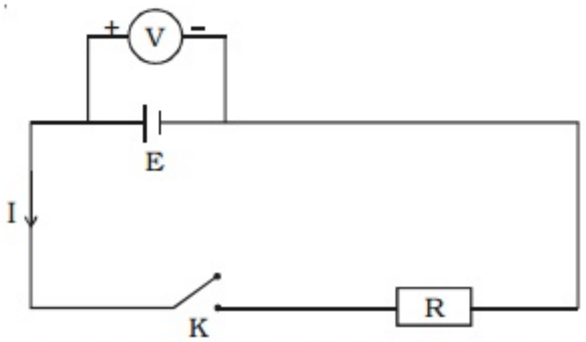

Fig 2.9 Internal resistance of a cell using voltmeter.

The potential drop across R, V = IR .. .. (1)

Due to internal resistance r of the cell, the voltmeter reads a value V, less than the emf of cell.

Then V = E - Ir or Ir = E-V ...(2)

Dividing equation (2) by equation (1)

$$\frac{Ir}{IR} = \frac{E-V}{V} \quad \text{or} \quad r = \left(\frac{E-V}{V}\right)R$$

Since E, V and R are known, the internal resistance *r* of the cell can be determined.

Electric energy and electric power.

If I is the current flowing through a conductor of resistance R in time t, then the quantity of charge flowing is, $q = It$. If the charge q, flows between two points having a potential difference V, then the work done in moving the charge is = $V.\,q = V\,It$.

Then, electric power is defined as the rate of doing electric work.

$$\therefore \quad \text{Power} = \frac{\text{Work done}}{\text{time}} = \frac{VIt}{t} = VI$$

Electric power is the product of potential difference and current strength.

Since V = IR, Power = I^2R

Electric energy is defined as the capacity to do work. Its unit is joule. In practice, the electrical energy is measured by watt hour (Wh) or kilowatt hour (kWh). 1 kWh is known as one unit of electric energy.

(1 kWh = 1000 Wh = 1000 �- 3600 J = 36 �- 10^5 J)

Wattmeter

A wattmeter is an instrument used to measure electrical power consumed i.e energy absorbed in unit time by a circuit. The wattmeter consists of a movable coil arranged between a pair of fixed coils in the form of a solenoid. A pointer is attached to the movable coil. The free end of the pointer moves over a circular scale. When current flows through the coils, the deflection of the pointer is directly proportional to the power.