APPLIED PHYSICS II - MODULE III – Part I

ELECTROMAGNETISM

CO3 : Convert galvanometer into ammeter and voltmeter.

Electromagnetism involves the study of electric and magnetic effects. Both the electric and magnetic effect has its origin in electric charge. An electric charge at rest produces electric effect, where as an electric charge in motion produces magnetic effect in addition to electric effect.

Electric charge:

Electric charge is the property of certain elementary particles due to which it experiences a force when placed near another charge. There are two types of charges found in nature - positive charge and negative charge. The force between a positive charge and a negative charge is attractive and the force between two positive charges or between two negative charges is repulsive. The SI unit of charge is Coulomb (C).

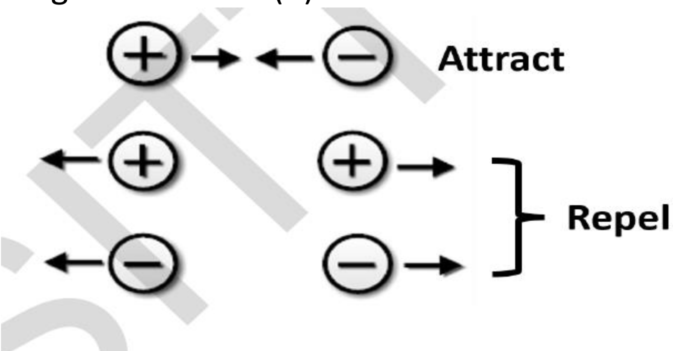

Fig. 3.1 Force of attraction and repulsion between electric charges

The smallest charge is the charge of an electron or a proton. The charge of an electron is negative and the charge of a proton is positive. Its value is 6×10^{-19}C. This charge is also called the elementary charge. All other charges are integral multiples of this elementary charge.

Coulomb's Law:

Coulomb's law states that the force of interaction between two electric charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between the two charges. Let q_1 and q_2 be two charges placed at a distance r between them. According to Coulomb's law, the electrostatic force between the charges q_1 and q_2 is given by

$$F \propto \frac{q_1 q_2}{r^2}$$

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

where k is the proportionality constant depends on the nature of the medium in which the charges are situated. If SI unit system is used, the value of k is given by,

$$k = \frac{1}{4\pi\varepsilon_0}$$

where ε_0 is called the permittivity of the free space. Generally the force between two charges is expressed as,

$$\boldsymbol{F} = \frac{\mathbf{1}}{\mathbf{4}\boldsymbol{\pi\varepsilon_0}}\frac{\boldsymbol{q_1 q_2}}{\boldsymbol{r^2}}$$

The value of ε_0 is 8.854 x 10^{-12} $C^2/N\ m^2$. If the charges are placed in air or vacuum, k has a value 9 x 10^9 Nm^2C^{-2}.

Electric field:

An electric charge placed at a point exerts a force on another charge even if there is no contact between them. This interaction at a distance can be seen as a two step process. The charge produces some kind of field around it and this field exerts a force on any other charge placed in it. *The region of space around a charged particle within which another charge experiences an electric force is called electric field.*

If a charge q experiences a force F when placed at a point in an electric field, then the electric field intensity or the electric field (E) at that point is defined as the force experienced by unit positive charge placed at that point and is given by,

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{\boldsymbol{q}} \quad \textbf{or} \quad \boldsymbol{F} = \boldsymbol{qE}$$

The SI unit of electric field intensity is N/C (newton/coulomb) which can also be expressed as volt/meter.

Electric Potential:

Consider an electric field produced by a positive charge. Another positive charge placed in this electric field experiences a repulsive force. To move the second charge against this repulsive force, work has to be done on it. This amount of work is stored as potential energy of the charge.

The electric potential at a point in an electric field is defined as the work done in moving a unit positive charge from infinity to that point. The unit of electric potential is volt (V). If we consider two points , then the difference in electric potential is called the potential difference or voltage between the two points. The potential difference between two points is one volt if one joule of work is done in moving one coulomb of charge from one point to the other. Thus 1volt=1joule/coulomb. Electric charges always flows from higher potential to lower potential.

Capacitor:

A capacitor is a device used to store electric charge. Capacitor is a system of two conductors placed close to each other with an insulating medium in between them. One of the conductor is given a positive charge (+Q) and the other conductor is given an equal negative charge (-Q).The charge on the positively charged conductor is called the charge of the capacitor.

The potential difference between positively charged conductor and the negatively charged conductor is called potential of the capacitor (V).

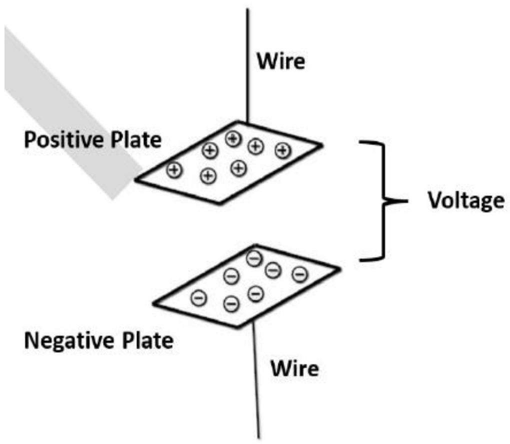

Fig. 3.2 Parallel Plate Capacitor

For a given capacitor, the charge Q on the capacitor is proportional to the potential difference V between the two conductors.

$$Q \propto V$$

$$Q = CV$$

The proportionality constant C is called the capacitance of the capacitor. The capacitance C of a capacitor depends on the shape, size, separation between the conductors and the nature of the insulating medium between the conductors.

The capacitance of a capacitor is the measure of how much charge a capacitor can store.

The SI unit of capacitance is farad(F). Farad is a very large unit, so submultiples of Farad namely microfarad(μF) or picofarad (pF) are generally used for practical purposes.

$$1\, farad = 1\, coulomb/volt$$

$$1\, micro\, farad = 10^{-6}\, farad$$

$$1\, pico\, farad = 10^{-12}\, farad$$

Electric current:

The rate of flow of charges is called electric current. If q quantity of charge flows across an area in t seconds, then electric current is given by

$$\boldsymbol{I = \frac{q}{t}}$$

The SI unit of electric current is Ampere (A).

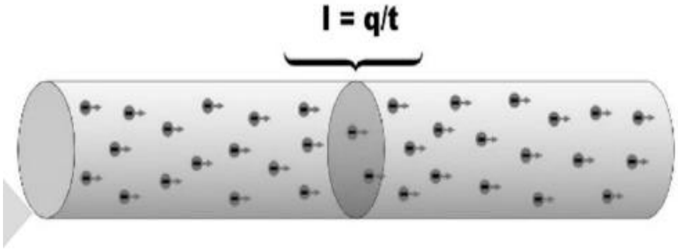

Fig. 3.3 Flow of electric charges

Direct current(DC) and Alternating current(AC):

A cell or a battery connected to a conducting wire produces a current in the wire. The current goes from the positive terminal to the negative terminal of the cell through the wire. The direction and magnitude of the current remains constant. The current whose direction and magnitude remains constant is called direct current or DC.

If the current in a circuit changes its direction alternately, the current is called alternating current or AC. The most common alternating current in use is the sinusoidally varying current which is the electricity powering our homes and industries.

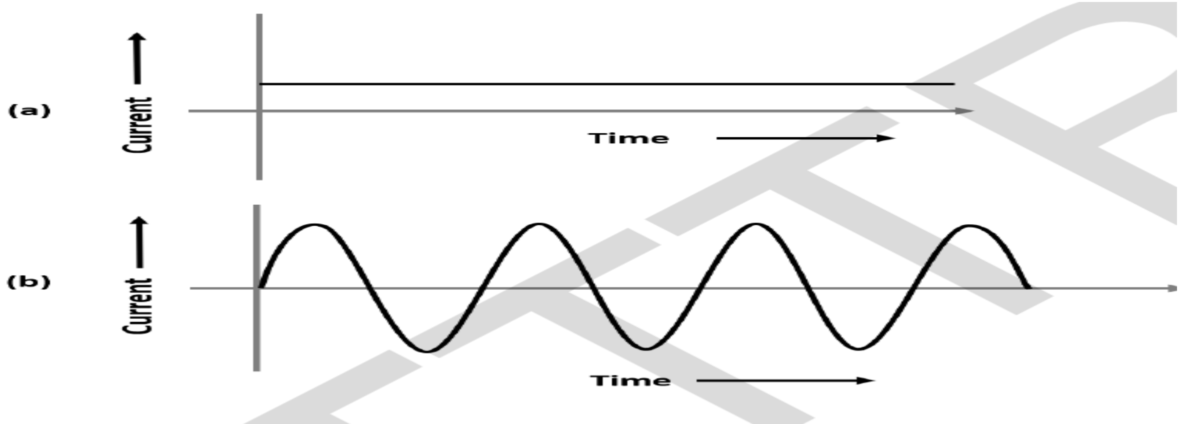

Fig. 3.4 (a) DC current and (b) AC current

Ohm's Law:

Ohm's law states that the current flowing through a conductor is directly proportional to the potential difference across its ends, provided the temperature is constant.

$$V \propto I$$

or $$\frac{V}{I} = R, \text{ a constant}$$

The constant R is called the resistance of the conductor. Its unit is ohm denoted by Ω. The resistance represents the opposition offered by the conductor to the flow of current through it.

For a good conductor, the value of resistance is low. The reciprocal of resistance is called conductance (S). The SI unit of conductance is ohm^{-1} (mho).

$$S = \frac{1}{R} = \frac{I}{V}$$

Conceptual Learning 1:

Find out the following

i) The voltage of our household electricity supply …………….

ii) The voltage required for a TV remote ………………….

iii) The output voltage of a mobile phone charger……………..

iv) The voltage required for an ordinary battery powered wall clock………

v) The output voltage of a car battery………………..

Verification of Ohm's law:

Ohm's law can be verified using the circuit shown below. A conducting wire of resistance R is connected to a cell of emf E through a key K and rheostat Rh. The ammeter A measures the current through the circuit and the voltmeter V measures the potential difference across the resistance R.

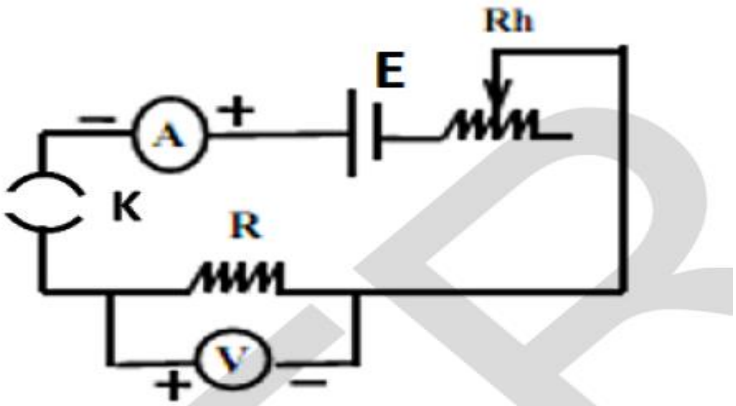

Fig. 3.5 Circuit diagram to verify Ohm's law

When the key K is closed, current flows through the circuit. The rheostat is adjusted to get a particular value of potential difference across the resistance. The corresponding ammeter reading is also noted. The rheostat is adjusted for different value of potential differences and the corresponding value of current through the resistance is obtained from the ammeter. In each case the ratio of V/I is calculated and found to be constant. This constant value gives the resistance R of the conductor.

Specific resistance (Resistivity):

The resistance of a conductor depends on the dimensions and its material. It is found that the resistance of a conductor is directly proportional to the length of the conductor and inversely proportional to the area of cross section of the conductor. If L is the length and A is the area of cross section of a conductor, then its resistance

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

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

The proportionality constant ρ is called the specific resistance or resistivity of the material of the conductor. It the measure of the opposition to the flow of current through a material.

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

The unit of resistivity is ohm m (Ω m).

Specific conductance:

The reciprocal of specific resistance is called the specific conductance (σ) or conductivity of a material.

$$\boldsymbol{\sigma = \frac{1}{\rho}}$$

or $$\boldsymbol{\sigma = \frac{L}{RA}}$$

The unit of specific conductance is ohm^{-1}m^{-1} (Ω^{-1}m^{-1}).

Factors affecting the resistance of a conducting wire:

The resistance of a wire depends on the material of the wire, the length of the wire and the thickness of the wire. In addition to these factors, the resistance of a conducting wire depends on the temperature. The resistance of conducting wires increases with increase in temperature. The factors affecting the resistance of a wire can be summarized as below.

1	Material of the wire	Materials like silver, copper , aluminium has low resistance compared to other materials.
2	Length of the wire	Resistance increases with increase in length
3	Thickness of the wire	Resistance decreases with increase in thickness/cross sectional area
4	Temperature	Resistance increases with increase in temperature

Table 3.2 Resistivity of a few materials

Material	Resistivity (Ω m)
Aluminium	2.65×10^{-8}
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Nichrome	100×10^{-8}
Constantan	49×10^{-8}
Rubber	$10^{13} - 10^{16}$
Germanium	0.6

Carbon resistors:

Resistors have extensive use in electrical and electronic circuits as voltage dividers, voltage droppers and to limit the passage of current through various parts of the circuits. The most commonly used type of resistors are carbon resistors. They are made from a mixture of fine carbon fragments and a non-conducting ceramic powder to bind it all together. Carbon resistors are small in size and are inexpensive.

Carbon resistors are cylindrical in shape with their resistance values are given using colour codes. It has a set of co-axial coloured rings, with each colour assigned a particular value. The first two rings gives the first two significant figures of the resistance value in ohms and the colour of the third ring indicates the decimal multiplier. The last ring represents the variation of the resistor value in percentage.

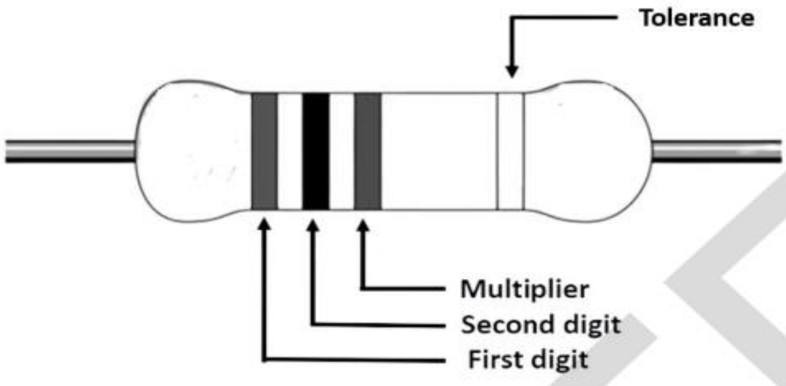

Fig. 3.6 Coloured rings of carbon resistors

Table 3.1 Colour codes of resistors

Colour	Number	Multiplier	Tolerance (%)
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5
Silver		10^{-2}	10
No colour (4^{th} ring absent)			20

Kirchhoff's laws:

Electrical circuits generally contains a number of resistors and cells. The potential difference and the current in different parts of the circuit varies. Kirchhoff's laws are very useful in analysing these complex circuits. It consists of two laws.

1. Kirchhoff's first law or Current law (Junction rule):

Kirchhoff's first law states that the algebraic sum of the currents meeting at a junction is zero. In other words, the sum of all currents directed towards a junction is equal to the sum of all the currents directed away from the junction. The first law follows from the fact that there is no accumulation of charges at any point in a circuit - the total charges flowing in unit time towards a point should be equal to the total charges flowing out in unit time. The current flowing towards the junction is taken as positive and current flowing away from the junction is taken as negative. In the figure, i_1 and i_3 are the currents flowing towards the junction and i_2 and i_4 are the currents flowing away from the junction. Hence according to the first law,

$$i_1 - i_2 + i_3 - i_4 = 0$$

$$i_1 + i_3 = i_2 + i_4$$

Total current coming to the junction = Total current going out of the junction

Or, in general $\sum i = 0$

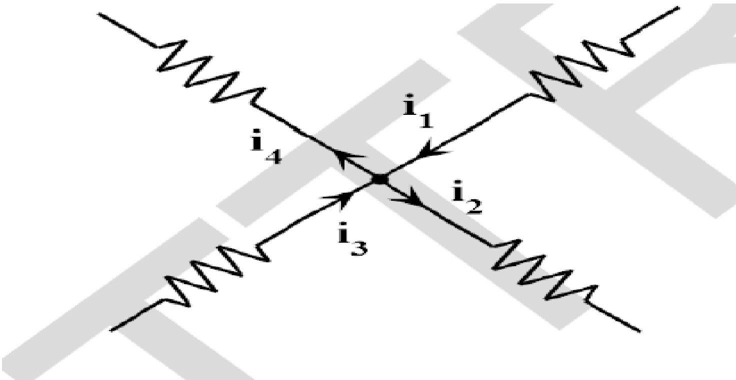

Fig. 3.7 Circuit diagram to illustrate junction rule

2. Kirchhoff's second law or voltage law (loop rule):

Kirchhoff's second law states that the algebraic sum of the potential differences around any closed loop in a circuit is zero.

$$\sum iR + \sum E = 0$$

In applying the rule, one starts from a point on the loop and goes along the loop, either clockwise or anti-clockwise to reach the same point again. The potential difference across a resistance (*iR*) is taken positive when traversed in the direction of the current and potential difference across a cell is taken positive when traversed from the positive terminal to negative terminal inside the cell.

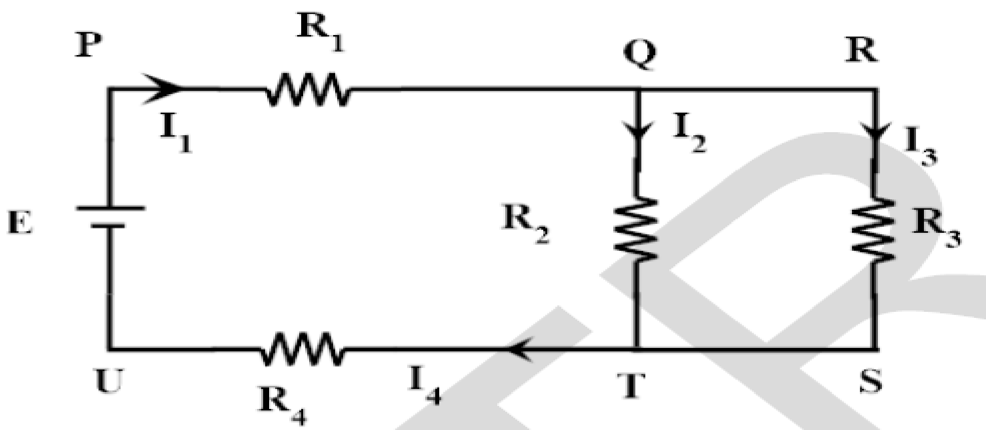

Fig. 3.8 Circuit diagram to illustrate junction rule

Consider the circuit shown in fig 3.8. Applying Kirchhoff 's law,

For the loop PQRSTUP, start from the point P and going in the clockwise direction gives

$$I_1R_1 + I_3R_3 + I_4R_4 - E = 0$$

For the loop PQTUP,

$$I_1R_1 + I_2R_2 + I_4R_4 - E = 0$$

For the loop QRSTQ,

$$I_3R_3 - I_2R_2 = 0$$

Application of Kirchhoff's laws : Wheatstone's Bridge

The Kirchhoff's laws can be used to find the balancing condition of a Wheatstone's bridge. Wheatstone's bridge is a network of four resistances which can be used for the measurement of resistance. To measure a resistance, it is connected as one of the four resistances in the bridge. The resistances are connected as shown in fig 3.9. P , R and S are the known resistances whose value can be varied and X is the unknown resistance. A cell is connected between the opposite points A and C. To detect the flow of current along the path BD a galvanometer of resistance G is connected as shown. The current through various branches is shown in the figure.

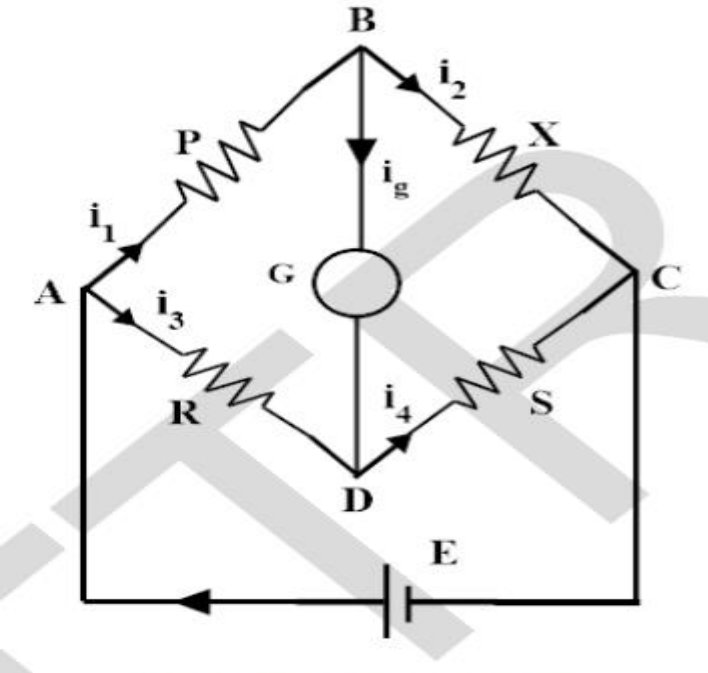

Fig. 3.9 Wheatstone's Bridge

Applying junction rule at the junctions, B and D gives

At junction B: $i_1 - i_2 - i_g = 0$

or $i_1 = i_2 + i_g$ ------------ (1)

At junction D: $i_3 + i_g - i_4 = 0$

or $i_3 + i_g = i_4$ ------------- (2)

Applying Kirchhoff's second law (loop rule) in the closed loop ABDA

$$i_1P + i_gG - i_3R = 0$$

$$i_1P + i_gG = i_3R \text{ ------------ (3)}$$

Similarly in the closed loop BCDB

$$i_2X - i_4S - i_gG = 0$$

$$i_2X = i_4S + i_gG \text{ .... (4)}$$

By varying the values of the resistances of the bridge , the current through the galvanometer can be made zero , $i_g = 0$. This condition is called the balanced condition of the bridge.

Using this condition $i_g = 0$ in equation (1) and (2)

$$i_1 = i_2 \text{ ------------ (5)}$$

$$i_3 = i_4 \text{ ------------ (6)}$$

Similarly putting $i_g = 0$ in equation (3) and (4)

$$i_1P = i_3R \text{ ------------ (7)}$$

$$i_2X = i_4S \text{ ....(8)}$$

Dividing equation (7) by (8) gives,

$$\frac{i_1P}{i_2X} = \frac{i_3R}{i_4S}$$

Using equations (5) and (6) gives, $\boxed{\frac{P}{X} = \frac{R}{S}}$

This is the balancing condition of Wheatstone's bridge. Using the balancing condition, we can calculate the value of the unknown resistance 'X' by knowing the values of P, R and S. This principle is used in the resistance measuring devices like meter bridge.

Meter Bridge:

Meter bridge is a practical arrangement of Wheatstone's bridge used to measure unknown resistance. It consists of a wire AB of length 1m connected between two L-shaped copper strips. The unknown resistance X and the resistance box R are connected between the L-shaped strips and a straight copper strip as shown in fig. 3.10.

A galvanometer is connected between the point C and jockey J. The jockey J can be moved along the wire AB. The whole arrangement is fixed on a wooden base. A cell of emf E is also connected as shown. Current flows through the circuit and the galvanometer shows deflection. The jockey J is moved along the wire and its position is adjusted such that galvanometer shows zero deflection. Now the bridge is balanced. Let l be the balancing length in centimetre as measured from the point A.

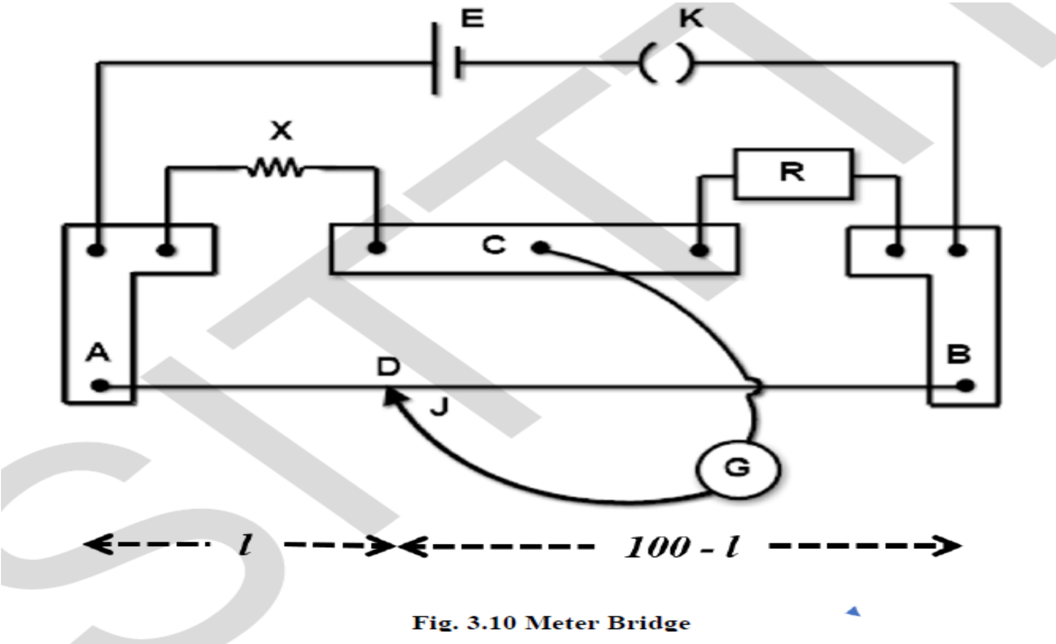

Fig. 3.10 Meter Bridge

The four resistances of the bridge are – (1) resistance X , (2) resistance box R , (3) resistance of length AD of the wire, and (4) resistance of wire DB of the wire.

Using the balancing condition of Wheatstone' s bridge,

$$\frac{X}{R} = \frac{Resistance\ of\ length\ AD\ (l\ cm)}{Resistance\ of\ length\ DB\ (100-l\ cm)}$$

Let r be the resistance per unit length of the wire AB then

$$\frac{X}{R} = \frac{lr}{(100-l)r}$$

The unknown resistance is then,

$$X = \frac{l}{(100-l)} R$$

The experiment is repeated for different values of R and the mean value of X is calculated.

Series and Parallel combination of resistors:

Electrical circuits usually contains network of resistances. These combination of resistances can be replaced by a single effective resistance. The effective resistance or equivalent of a combination of resistors is that single resistance which produces the same effect of the combination of the resistances. The effective resistance draws the same current as drawn by the resistor combination from the power source. The combination of resistors can be classified into two types as (a) Series combination and (b) Parallel combination.

Series combination of resistances:

A combination of resistors is said to be series combination if same current (I) flows through all the resistors. The effective resistance (R_s) of a series combination is that single resistance which draws the same current (I) from the source of potential difference V.

$$R_S = \frac{V}{I} \text{ ------(1)}$$

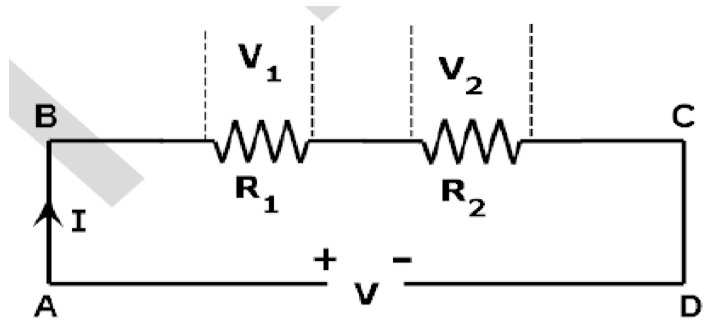

Fig. 3.11 Two resistors connected in series

In the above circuit, the resistances R_1 and R_2 are connected in series. The current through the resistors is I

Applying Kirchhoff's second law (loop rule) in the closed circuit ABCDA

$$IR_1 + IR_2 = V$$

$$V = I(R_1 + R_2)$$

$$\frac{V}{I} = R_1 + R_2 \text{ --------- } (2)$$

From equation (1) and (2) $\boldsymbol{R_S = R_1 + R_2}$

If there are 'n' number of resistors connected in series, then the effective resistance is

$$R_S = R_1 + R_2 + R_3 + \text{----} + R_n$$

Thus the equivalent resistance in series connection is the sum of individual resistances.

Parallel Combination of resistances:

The combination of resistors is said to be a parallel combination if same potential difference exists across all the resistors. The equivalent resistance (R_P) of a parallel combination is that single resistance which draws the same current (I) from the source of emf V.

$$R_P = \frac{V}{I} \text{ ------}(1)$$

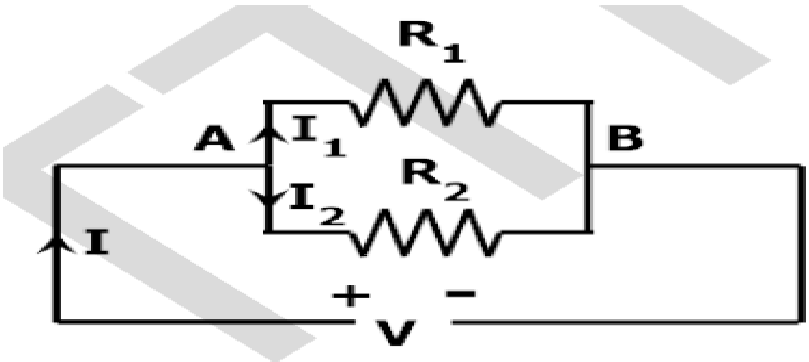

Fig. 3.12 Two resistors connected in parallel

The resistors R_1 and R_2 are connected in parallel. The combination is connected to a power supply of potential difference V.

Applying Kirchhoff's first law (junction rule) at junction A,

we get $I = I_1 + I_2$

Voltage across each resistance is V, therefore using Ohm's law,

$$I = \frac{V}{R_1} + \frac{V}{R_2}$$

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Or $$\frac{I}{V} = \frac{1}{R_1} + \frac{1}{R_2} \text{ ---------------(2)}$$

From equation (1)

$$\frac{I}{V} = \frac{1}{R_P}$$

Then equation (2) becomes

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} \quad \textbf{or} \quad R_P = \frac{R_1 R_2}{R_1 + R_2}$$

If there are 'n' number of resistors in parallel, the effective resistance is given by

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

Thus when a number of resistances are connected in parallel, the reciprocal of the equivalent resistance is equal to the sum of reciprocals of individual resistances. It may be remembered that the equivalent resistance of combination of parallel resistances is always less than that of the least resistance in the group.

……