Chapter 14

ELECTROMAGNETISM

LEARNING OBJECTIVES

At the end of this chapter the students will be able to:

- Appreciate that a force might act on a current carrying conductor placed in a magnetic field.
- Define magnetic flux density and the tesla.
- Derive and use the equation $F = BIL \sin\theta$ with directions.
- Describe and sketch flux patterns due to a long straight wire.
- Define magnetic flux and the weber.
- Derive and use the relation $\Phi = \vec{B} \cdot \vec{A}$.
- Understand and describe Ampere's law.
- Appreciate the use of Ampere's law to find magnetic flux density inside a solenoid.
- Describe the deflection of beams of charged particles moving in a uniform magnetic field.
- Understand and describe method to measure e/m.
- Derive the expression of torque due to couple acting on a coil.
- Know the principle, construction and working of a galvanometer.
- Know how a galvanometer is converted into a voltmeter and an ammeter.
- Describe and appreciate the use of AVO meter/multimeter.

Q.1 Define electromagnetism.

Ans. **ELECTROMAGNETISM**

The branch of physics which deals with the study of magnetic fields due to the motion of charges.

Q.2 Describe the magnetic field due to current in a long straight wire.

Ans. **MAGNETIC FIELD DUE TO CURRENT IN A LONG STRAIGHT WIRE**

Take a straight, thick copper wire and pass it vertically through a hole in a horizontal piece of cardboard. Place small compass needles on cardboard along a circle with the centre at the wire. All the compass needles will point in the direction of N-S. Now pass a heavy current through the wire. It will be seen that the needles will rotate and will set themselves tangential to the circle. On reversing the direction of current, the direction of needles is also reversed. As the current through the wire is stopped, all the needles again point along the N-S direction.

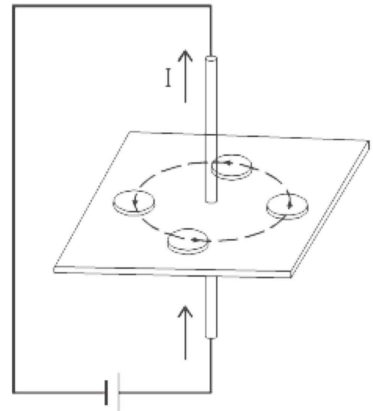


Fig. (a)

Conclusions

(i) A magnetic field is set up in region surrounding current carrying wire.

(ii) Lines of force are circular and their direction depends upon direction of current.

(iii) The magnetic field lasts as long as current is passing through the wire.

(iv) Direction of lines of force can be found by Right Hand Rule.

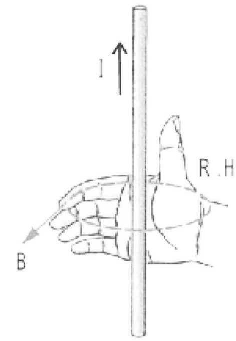


Fig. (b)

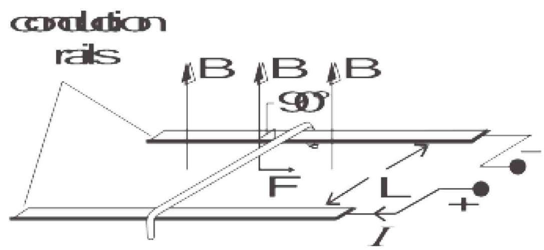
Right Hand Rule

"If the wire is grasped in fist of right hand with the thumb pointing in the direction of current, the curled fingers will circle the wire in the direction of magnetic field".

Q.3 Calculate the force on a current carrying conductor in a uniform magnetic field.

Ans. **FORCE ON A CURRENT CARRYING CONDUCTOR IN A UNIFORM MAGNETIC FIELD**

Consider a rod of copper capable of moving on a pair of copper rails. The whole arrangement is placed between the pole pieces of a horseshoe magnet with magnetic field directed vertically upward as shown in figure.



When a current is passed through a copper rod from a battery, the rod moves on the rails. The force on a conductor is always at right angles to the plane which contains the rod and the direction of magnetic field. The magnitude of the force depends upon the following factors

(i) The force F is directly proportional to sin α. i.e.,

$$F \propto \sin\alpha \qquad \ldots\ldots (i)$$

where α is the angle between conductor and magnetic field.

(ii) The force F is directly proportional to the current I, flowing through the conductor i.e.,

$$F \propto I \quad \text{...... (ii)}$$

(iii) The force F is directly proportional to the length L of the conductor inside the magnetic field i.e.,

$$F \propto L \quad \text{...... (iii)}$$

(iv) The force F is directly proportional to the strength of the applied magnetic field B. i.e.,

$$F \propto B \quad \text{...... (iv)}$$

Combining the above equations

$$F \propto ILB \sin \alpha$$

$$F = KILB \sin \alpha$$

where 'K' is the constant of the proportionality. If we use SI units then

$$K = 1$$

$$\therefore \quad F = ILB \sin \alpha \quad \text{...... (v)}$$

If $I = 1A$

$L = 1m$

$\alpha = 90°$

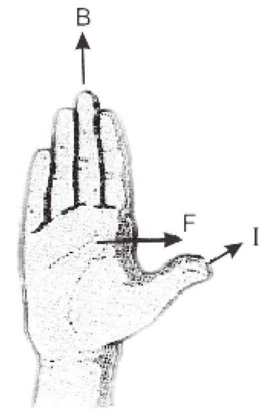
then $F = 1 \times 1 \times B \times \sin 90°$

$F = B$

Thus B, the strength of the magnetic field, which is also known as magnetic field intensity or magnetic induction.

Do You Know?

If the middle finger of the right hand points in th direction of the magnetic field, the thumb in the direction of current, the force on the conductor will be normal to the palm towards the reader.



Magnetic Induction

The force acting on 1m length of the conductor placed at right angle to the magnetic field when 1A current is passing through it.

Unit of B

The SI unit of B is tesla (T).

Other unit of B is G (Gauss)

$$1\ T = 10^4\ G$$

$$1\ G = 10^{-4}\ T$$

Tesla

A magnetic field is said to have a strength of 1 tesla if it exerts a force of 1N on 1m length of the conductor placed at right angles to the field when a current of 1A passes through the conductor.

As $F = ILB$

$$B = \frac{F}{IL}$$

$$= \frac{N}{Am}$$

$$T = Nm^{-1}A^{-1}$$

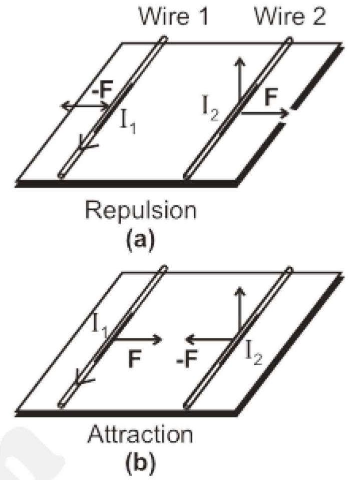
$$\therefore \quad T = \frac{1N}{1m\ 1A}$$

Equation (v) can be written in vector form of

$$\vec{F} = I(\vec{L} \times \vec{B})$$

where $\vec{L}$ vector is in the direction of current flow. Its magnitude is ILB sin α where α is the angle between $\vec{L}$ and $\vec{B}$. The direction of $\vec{F}$ is also given by right hand rule of cross product of $\vec{L}$ and $\vec{B}$, i.e., rotate $\vec{L}$ towards $\vec{B}$ through the smaller angle. Curl the fingers of right hand in the direction of rotation, the thumb points in the direction of force. Direction of $\vec{F}$ can also be determined by right hand palm rule and Fleming's left hand rule.

Do You Know?



(a) Two long parallel wires carrying currents I_1 and I_2 in opposite direction repel each other. (b) The wires attract each other when the currents are in the same direction.

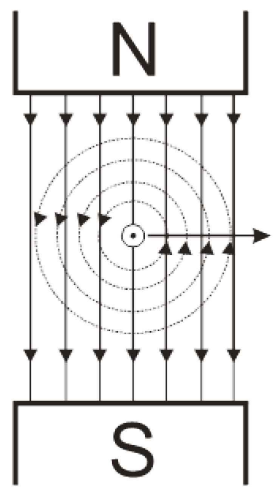
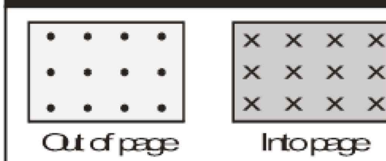


Fig. The magnetic force on the current carrying conductor placed at right angle to a magnetic field.

Direction of Magnetic Field

Consider a straight current carrying conductor held at right angle to a magnetic field such that the current flows out of the plane of paper i.e., towards the reader as shown in plane of paper i.e., towards the reader as shown in figure. It is customary to represent a current flowing towards the reader by a symbol dot (•) and a current flowing away from him by a cross (×).

For Your Information



Convention to represent direction

In order to find the direction of force, consider the lines of force (figure). The two fields tend to reinforce each other on left hand side of the conductor and cancel each other on the right side of it. The conductor tends to move towards the weaker part of the field i.e., the force on the conductor will be directed towards right in a direction at right angles to both the conductor and the magnetic field. This rule is often referred as extension of right hand rule. It can be seen that the direction of the force is the same as given by the direction of the vector **L × B**.

Q.4 Explain magnetic flux and flux density.

Ans. MAGNETIC FLUX AND FLUX DENSITY

Magnetic Flux

The number of magnetic lines passing through a surface placed perpendicular to the magnetic field", is known as magnetic flux. It is denoted by ϕ_B.

(OR)

It is also defined as dot product of $\vec{B}$ and vector area $\vec{A}$.

$$\therefore \quad \phi_B = \vec{B} \cdot \vec{A}$$

$$\phi_B = BA\cos\theta$$

where θ is the angle between $\vec{B}$ and vector area $\vec{A}$.

This formula is only applicable for flat surface.

Case-1 **When surface is placed perpendicular to magnetic field $\vec{B}$ (OR vector area is held parallel to $\vec{B}$)**

i.e., $\theta = 0°$

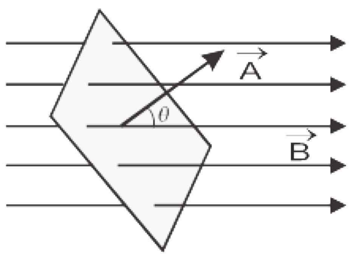
$$\therefore \quad \phi_B = \vec{B} \cdot \vec{A}$$

$$= BA\cos\theta$$

$$= BA\cos 0°$$

$$\phi_B = BA$$

Hence the flux will be maximum.



Case-2 **When surface is placed parallel to $\vec{B}$ (OR vector area $\vec{A}$ is held perpendicular to $\vec{B}$)**

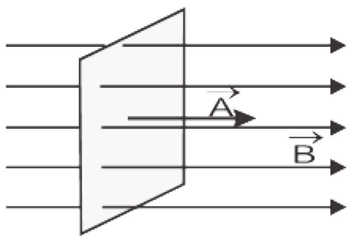
i.e., $\theta = 90°$

$$\therefore \quad \phi_B = \vec{B} \cdot \vec{A}$$

$$= BA\cos 90°$$

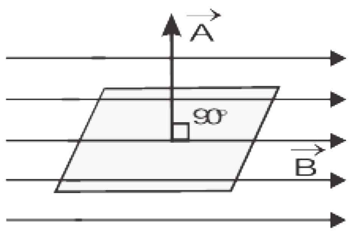
$$\phi_B = 0$$

Hence the flux will be minimum.



Case-3 If the surface makes an angle θ with the magnetic lines of force then the magnetic flux will be

$$\phi_B = BA\cos\theta$$



Unit of Magnetic Flux

The unit of magnetic flux is NmA^{-1}, which is also called weber.

Magnetic Flux Density

"Magnetic flux per unit area of a surface perpendicular to $\vec{B}$ (i.e., $\vec{B}$ and $\vec{A}$ are parallel) is called magnetic flux density".

Mathematically

$$\phi_B = BA\cos\theta$$
$$= BA\cos 0^\circ$$
$$\phi_B = BA$$
$$B = \frac{\phi_B}{A}$$

where B is magnetic flux density. The unit of flux density is $\frac{Wb}{m^2}$ or $Nm^{-1}A^{-1}$.

Q.5 Define Ampere's law and apply it to calculate the magnetic induction inside a long solenoid having steady current I through its each turn.

Ans. AMPERE'S LAW AND DETERMINATION OF FLUX DENSITY (B)

Statement-I

This law states that "the dot product of flux density $\vec{B}$ and $\vec{\Delta L}$ around any closed path is equal to μ_o times the total current enclosed by the path".

Explanation

Consider a close path in the form of a circle of radius r enclosing the current carrying wire as shown in figure. This closed path is referred as amperian path. Divide this path into small elements of length like $\vec{\Delta L}$ vector. Let $\vec{B}$ be the value of flux density at the sight of ΔL. If θ is the angle between $\vec{B}$ and $\vec{\Delta L}$ then

$$\vec{B}\cdot\vec{\Delta L} = B\Delta L\cos\theta$$

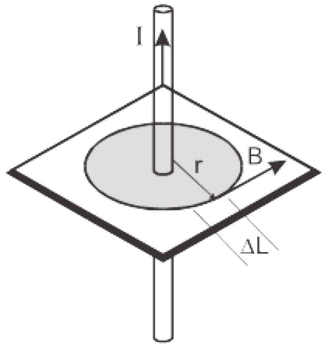


Fig. Ampere's law to find the magnetic field in the vicinity of this long, straight, current-carrying wire.

B cos θ represents the component of $\vec{B}$ parallel to $\vec{\Delta L}$. Thus $\vec{B}\cdot\vec{\Delta L}$ represents the product of length of the element $\vec{\Delta L}$ and the component of $\vec{B}$ parallel to $\vec{\Delta L}$.

Statement-II

Ampere proved that the "sum of the quantities $\vec{B}\cdot\vec{\Delta L}$ for all path elements into which the complete loop has been divided equals μ_o times the total current enclosed by the loop".

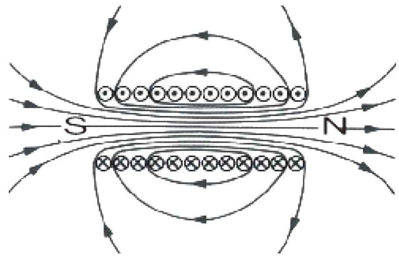
Mathematically

$$(\vec{B}\cdot\vec{\Delta L})_1 + (\vec{B}\cdot\vec{\Delta L})_2 + \ldots + (\vec{B}\cdot\vec{\Delta L})_n = \mu_o \text{ (Current enclosed by loop)}$$

$$\sum_{r=1}^{N} (\vec{B}\cdot\vec{\Delta L})_r = \mu_o \text{ (Current enclosed by loop)}$$

where N is the total number of elements into which the loop has been divided. This is known as Ampere's circuital law.

Field Due to a Current Carrying Solenoid

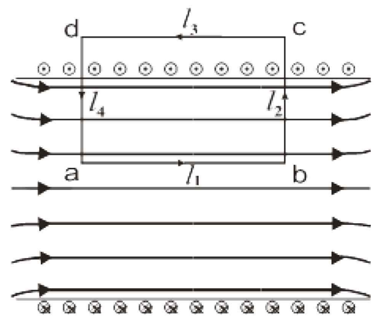


Solenoid

"A **solenoid** is a long, tightly wound, cylindrical coil of wire".

When current passes through such a coil it behaves like a bar magnet as shown in figure. The field inside along solenoid is uniform and much strong whereas weak outside the solenoid.

Calculation of B



Consider a rectangular loop abcda as shown in figure. Divide it into four elements of length i.e.,

$$ab = l_1, \quad bc = l_2, \quad cd = l_3 \text{ and } da = l_4$$

Applying amperes law

$$\sum_{r=1}^{4} (\vec{B} . \Delta\vec{L})_r = \mu_o \quad \text{(current enclosed)}$$

$$(\vec{B} . \Delta\vec{l_1})_1 + (\vec{B} . \Delta\vec{l_2})_2 + (\vec{B} . \Delta\vec{l_3})_3 + (\vec{B} . \Delta\vec{l_4})_4 = \mu_o \times \text{Current enclosed}$$

As field inside the solenoid is uniform and is parallel to $\vec{l_1}$, so

$$(\vec{B} . \Delta\vec{l_1}) = Bl_1 \cos 0°$$

$$= Bl_1 \times 1$$

$$= Bl_1$$

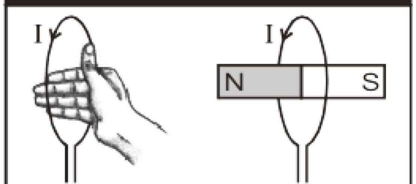
for the element cd = l_3, that lies outside the solenoid, the field B is zero. So

$$(\vec{B} . \Delta\vec{l_3}) = B\Delta l_3 \cos\theta$$

$$= (0)\, l_3 \cos\theta \quad \text{(B is zero)}$$

$$(\vec{B} . \Delta\vec{l})_3 = 0$$

Do You Know?



The current loop can be imagined to be a phantom bar magnet with a north pole and a south pole.

Again $\vec{B}$ is perpendicular to l_2 and l_4 inside the solenoid

$$\therefore \quad (\vec{B} \cdot \vec{\Delta l})_2 = Bl_2 \cos 90^\circ$$

$$= Bl_2 (0)$$

$$(\vec{B} \cdot \vec{\Delta l})_2 = 0$$

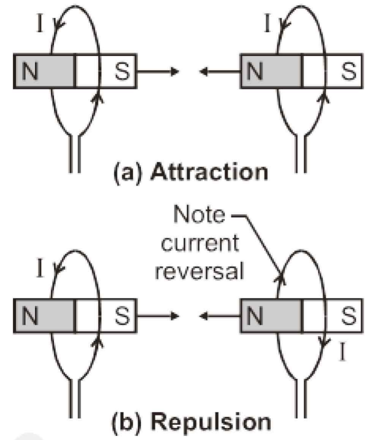
Similarly;

$$(\vec{B} \cdot \vec{\Delta l})_4 = Bl_4 \cos 90^\circ$$

$$= Bl_4 (0)$$

$$(\vec{B} \cdot \vec{\Delta l})_4 = 0$$

For Your Information



The "phantom" magnet included for each loop helps to explain the attraction and repulsion between the loops.

Putting these values in eq. (i), we get

$$Bl_1 + 0 + 0 + 0 = \mu_o \times \text{Current enclosed} \quad \text{...... (ii)}$$

$$Bl_1 = \mu_o \times \text{Current enclosed} \quad \text{...... (iii)}$$

If n is the number of turns per unit length of the solenoid, so the total number of turns in l_1 length is nl_1, each carrying a current I. So the current enclosed by the loop is nl_1I.

$\therefore$ eq. (iii) becomes

$$Bl_1 = \mu_o \times nl_1 I$$

$$B = \mu_o In$$

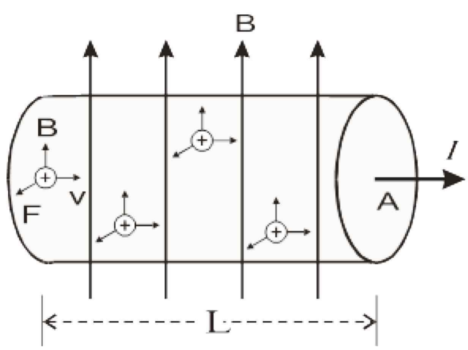
The field B is along the axis of the solenoid and its direction is given by right hand rule, which states "Hold the solenoid in the right hand with finger curling in the direction of current, the thumb will point in the direction of the field.

Q.6 Calculate the force on a moving charge in a magnetic field.

Ans. FORCE ON A MOVING CHARGE IN A MAGNETIC FIELD

We have seen that a current carrying conductor, when placed in a magnetic field, experiences a force. The current through the conductor is because of the motion of charges. Actually the magnetic field exerts force on these moving charges due to which the conductor experiences force. We are interested in calculating the force exerted on the moving charges.

Consider a portion of the wire that is carrying a current I as shown in figure. Let there are n charge carriers per unit volume of the wire and each is moving with velocity $\vec{v}$ as shown in figure.



Volume of the wire segment = AL

Total no. of charge carriers = nAL

If q is the charge on a charge carrier then

Total charge ΔQ = nALq

Now time taken by the charge to cover length L is given by

As $S = v\Delta t$

$\therefore$ $L = v\Delta t$

$$\Delta t = \frac{L}{v}$$

Then from the definition of current, the current I through the conductor is

As $$I = \frac{\Delta Q}{\Delta t}$$

Putting the values of ΔQ and Δt

$$\therefore \quad I = \frac{nALq}{L/v}$$

$$I = nAqv$$

Now the force on the segment $\vec{L}$ of a conductor carrying a current I is given by

$$\vec{F}_L = I(\vec{L} \times \vec{B})$$

Putting the value of I,

$$\therefore \quad \vec{F}_L = nAqv(\vec{L} \times \vec{B})$$

From figure, it can be seen that the direction of $\vec{L}$ is same as the direction of the velocity of charge carriers. If $\hat{L}$ is a unit vector along the direction of the segment $\vec{L}$ and $\hat{v}$ is a unit vector along the velocity vector $\vec{v}$, then

$$\hat{L} = \hat{v}$$

As $$\frac{\vec{L}}{L} = \frac{\vec{v}}{v}$$

$$v\vec{L} = L\vec{v}$$

$$\vec{F}_L = nAqL(\vec{v} \times \vec{B})$$

$$\vec{F}_L = nAqL(\vec{v} \times \vec{B})$$

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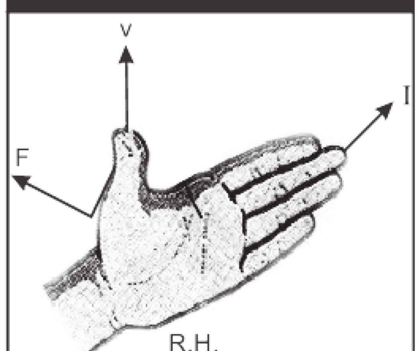


The moving charge experiences a magnetic force F because of the magnetic field B.

This is the force experienced by all the charge while moving through magnetic field $\vec{B}$. Therefore, the force experienced by a single charge carrier is

$$\vec{F} = \frac{\vec{F}_L}{nAL}$$

$$= \frac{nALq(\vec{v} \times \vec{B})}{nAL}$$

$$\boxed{\vec{F} = q(\vec{v} \times \vec{B})}$$

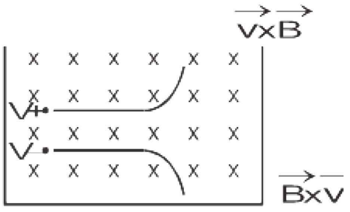
This equation has been derived with reference to the charge carrier moving in a conductor but it does not involve any parameter of the conductor so this equation is general and it holds for any charge carrier moving in a magnetic field.

Note: If an electron is projected in a magnetic field with velocity $\vec{v}$, then

$$\vec{F} = -e(\vec{v} \times \vec{B})$$

In case of proton

$$\vec{F} = e(\vec{v} \times \vec{B})$$



Note that in case of proton or a +ve charge the direction of the force is given by the direction of the vector $\vec{v} \times \vec{B}$. It experiences a force in the upward direction and the proton is deflected upward.

$$-\vec{v} \times \vec{B} = \vec{B} \times \vec{v}$$

The direction of the force on a moving –ve charge will be opposite to that of +ve charge. Due to this force, the electron is deflected in the downward direction as it enter into the magnetic field. Force is given by vector $\vec{B} \times \vec{v}$.

Important Points

- As the magnitude of the force on a moving charge carrier is

  $$F = qvB \sin\theta$$

  where θ is the angle between $\vec{v}$ and $\vec{B}$.

- When a charge particle is projected at right angles to the field.

  i.e., $\theta = 90°$

  $\therefore$ force will be maximum.

- When a charge particle is projected parallel or anti-parallel to the field.

  i.e., $\theta = 0°$ or $\theta = 180°$

  $\therefore$ force will be zero.

- If the charge carrier is at rest i.e., $v = 0$

  As $F = qvB \sin\theta$

  force will be zero.

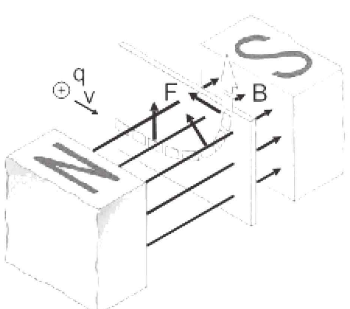
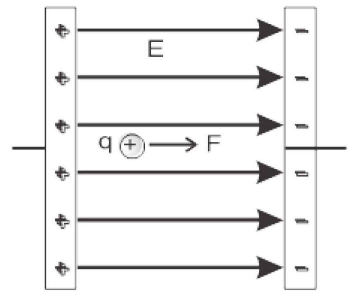


Fig. Magnetic force F is perpendicular to both the magnetic field B and the velocity v and causes the particle's trajectory to bend in a vertical plane.

Q.7 Describe the motion of charged particle in an electric and magnetic field.

Ans. **MOTION OF CHARGED PARTICLE IN AN ELECTRIC AND MAGNETIC FIELD**



When an electric charge q is placed in an electric field $\vec{E}$, it experiences a force $\vec{F}$ parallel to electric field. It is given by

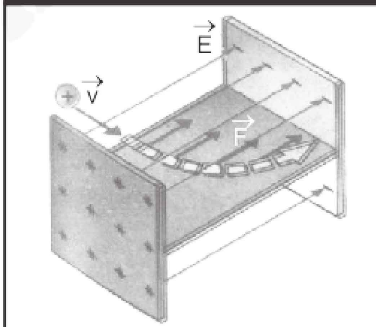
$$\vec{F} = q\vec{E}$$

If the charge is free to move, then it will accelerate according to Newton's second law as

$$\mathbf{a} = \frac{\vec{F}}{m} = \frac{q\vec{E}}{m} \qquad \ldots\ldots \text{(i)}$$

If electric field is uniform, then acceleration is also uniform and hence, the position of the particle at any instant of time can be found by using equations of uniformly accelerated motion.

Do You Know?



The electric force F that acts on a positive charge is parallel to the electric field E and causes the particle's trajectory to bend in a horizontal plane.

When a charge particle q is moving with velocity $\vec{v}$ in a region where there is an electric field $\vec{E}$ and magnetic field $\vec{B}$, the total force $\vec{F}$ is the vector sum of the electric force $q\vec{E}$ and magnetic force $q(\vec{E} \times \vec{B})$ that is,

$$\vec{F} = \vec{F}_e + \vec{F}_b$$

$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B}) \qquad \ldots\ldots \text{(ii)}$$

This force **F** is known as the **Lorentz force**.

Note: *It is to be pointed out that only the electric force does work, while no work is done by the magnetic force which is simply a deflecting force.*

Q.8 Define Lorentz force. Discuss the determination of e/m of an electron.

Ans. **DETERMINATION OF e/m OF AN ELECTRON**

Consider a narrow beam of electrons moving with a constant speed v be projected at right angles to a known uniform magnetic field $\vec{B}$ directed into plane of paper. We have seen that electrons will experience a force.

$$\vec{F} = -e(\vec{v} \times \vec{B})$$

The direction of force will be perpendicular to both $\vec{V}$ and $\vec{B}$. As electron is experiencing a force that acts at right angle to its velocity, so it will change direction of velocity. The magnitude of velocity will remain unchanged.

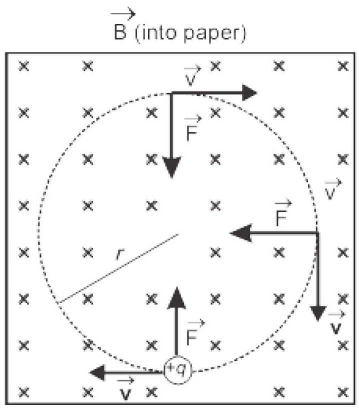


Fig. An electron is moving perpendicular to a constant magnetic field. The magnetic force F causes the particle to move on a circular path.

Magnitude of force is

$$F = evB \sin\theta$$

As $\theta = 90°$

$$\therefore \quad F = evB \sin 90°$$

$$F = evB$$

As V and B do not change, the magnitude of force will remain constant. Under the action of this force, electrons move along circle as shown in figure.

The magnitude of force F = evB provide the necessary centripetal force to electrons of mass m to move along a circular trajectory of radius r.

Thus we have

$$F_m = F_C$$

$$evB = \frac{mv^2}{r}$$

$$\frac{e}{m} = \frac{v}{Br} \qquad \text{...... (i)}$$

If v and r are known, e/m of electron can be determined.

To Find Radius r

The radius r can be measured by making the electronic trajectory visible. This is done by filling a glass tube with a gas such as hydrogen at low pressure. This tube (teltron tube) is placed in a region occupied by a uniform magnetic field of known value. As electrons are shot into this tube, they began to move along the circular trajectory under the action of magnetic force. As the electrons move, they collide with the atoms of the gas. This excites the atoms due to which they emit light and their path becomes visible as a circular ring of light. The diameter (d) of the ring can easily be measured. Hence radius r can be found on dividing d by 2.

To Find Velocity

In order to measure the velocity v of the electrons, we should know the potential difference through which the electrons are accelerated before entering into the magnetic field. If V is this potential difference, the energy gained by electrons during their acceleration is Ve. This appears as the kinetic energy of electrons

$$\frac{1}{2}mv^2 = Ve$$

or
$$v = \sqrt{\frac{2Ve}{m}}$$

Putting value of v in eq. (i)

$$\frac{e}{m} = \frac{\sqrt{\frac{2Ve}{m}}}{Br}$$

Taking square on both sides

$$\frac{e^2}{m^2} = \frac{\frac{2Ve}{m}}{B^2r^2}$$

$$\frac{e}{m} = \frac{2v}{B^2r^2}$$

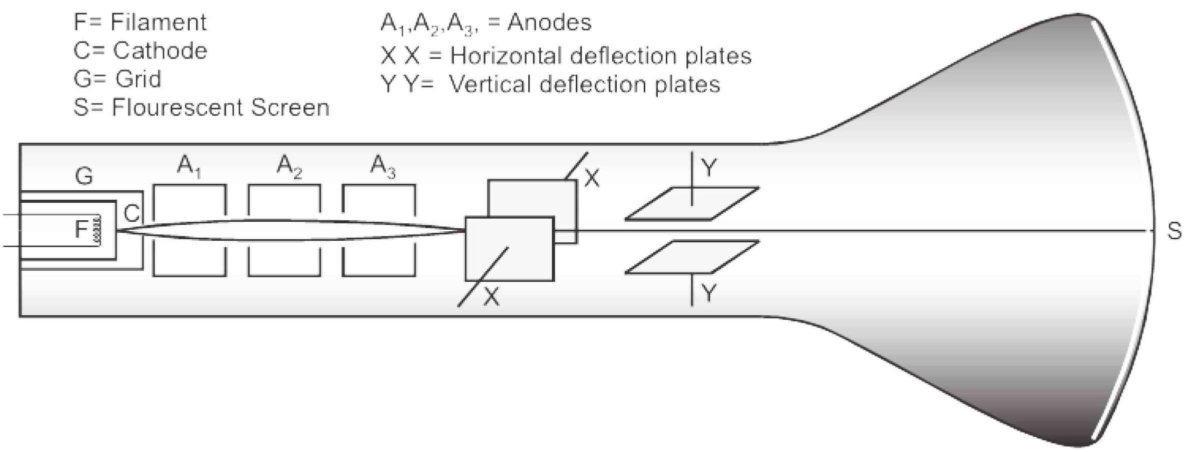
Unit

Unit of $\frac{e}{m}$ is C/kg.

Q.9 Describe cathode ray oscilloscope in detail. What are the uses of CRO?

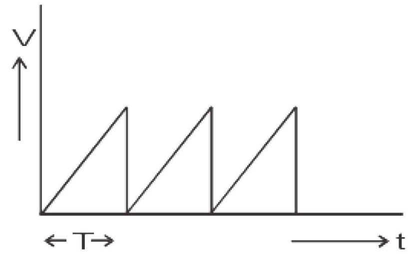
Ans. CATHODE RAY OSCILLOSCOPE

Cathode ray oscilloscope (CRO) is a very versatile electronic instrument which is in fact a high speed graph plotting device. It works by deflecting beam of electrons as they pass through uniform electric field between the two sets of parallel plates as shown in the figure. The deflected beam then falls on a fluorescent screen where it makes a visible spot.



It can display graphs of functions which rapidly vary with time. It is called cathode ray oscilloscope because it traces the desired waveform with a beam of electrons which are also called cathode rays.

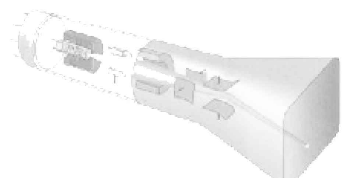
The beam of the electrons is provided by an electron gun which consists of an indirectly heated cathode, a grid and three anodes. The filament F heats the cathode C which emits electrons. The anodes A_1, A_2, A_3 which are at high positive potential with respect to cathode, accelerate as well as focus the electronic beam to fixed spot on the screen S. The grid G is at a negative potential with respect to cathode. It controls the number of electrons which are accelerated by anodes, and thus it controls the brightness of the spot formed on the screen.

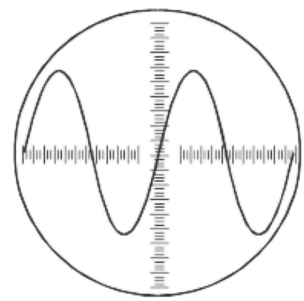


Saw tooth voltage waveform

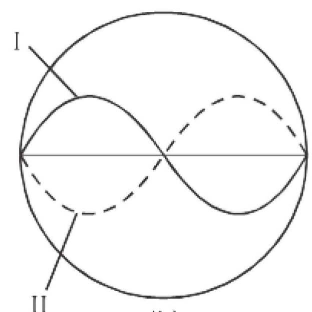
Waveform of Various Voltages in CRO

The two set of deflecting plates, shown in figure (a) are usually referred as x and y deflection plates because a voltage applied between the x-plates deflects the beam horizontally on the screen i.e., parallel to x-axis. A voltage applied across the y-plates deflects the beam vertically on the screen i.e., along the y-axis. The voltage that is applied across the x-plates is usually provided by a circuit that is built in the CRO. It is known as sweep or time base generator. Its output waveform is a saw tooth voltage of period T figure (b). The voltage increases linearly with time for a period T and then drops to zero. As this voltage is impressed across the x plates, the spot is deflected linearly with time along the x-axis for a time T. Then the spot returns to its starting point on the screen very quickly because a saw tooth voltage rapidly falls to its initial value at the end of each period. We can actually see the spot moving on the x-axis. If the time period T is very short, we see just a bright line on the screen.


Three dimensional view of CRO


(a)

If a sinusoidal voltage is applied across the y plates when, simultaneously, the time base voltage is impressed across the x places, the sinusoidal voltage, which itself gives rise to a vertical line, will now spread out and will appear as a sinusoidal trace on the screen. The pattern will appear stationary only if the time T is equal to or is some multiple of the time of one cycle of the voltage on y plates. It is thus necessary to synchronize the frequency of the time base generator with the frequency of the voltage at the y plates. This is possible by adjusting the synchronization controls provided on the front panel of the CRO.



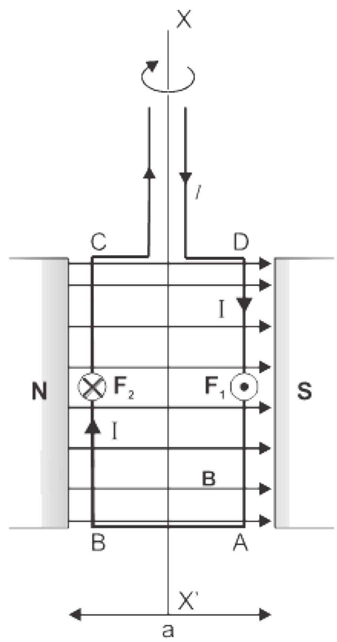
(b)

Uses of CRO

The CRO is used for displaying the waveform of a given voltage. Once the waveform is displayed, we can measure the voltage, its frequency and phase. For example figure (a) shows the waveform of an alternating voltage. As the y-axis is calibrated in volts and the x-axis in time, we can easily find the instantaneous value and peak value of the voltage. The time period can also be determined by using the time calibration of x-axis. Information about the phase difference between two voltages can be obtained by simultaneously displaying their waveforms. For example, the waveforms of two voltages are shown in figure (b). These waveforms show that when the voltage of I is increasing, that of II is decreasing and vice versa. Thus the phase difference between these voltages is 180°.

Q.10 Calculate the torque on a current carrying coil.

Ans. TORQUE ON A CURRENT CARRYING COIL



Consider a rectangular coil carrying a current I. The coil is capable of rotation about an axis. Suppose it is placed in a uniform magnetic field $\vec{B}$ with its plane along the field. Since when a current carrying conductor is placed in a magnetic field it experiences a force i.e., $F = ILB \sin\theta$, where θ is angle between conductor and field.

Now the coil is made of four conducting sides AB, BC, CD and DA. In case of side AB and CD of the coil, the angle is zero or 180°, so force on these sides will be zero ($\because \sin 0° = 0, \sin 180° = 0$).

In case of sides DA and BC the angle is 90°, and force on these sides will be

$$F_1 = ILB \sin\theta$$

As $\theta = 90°$

$$F_1 = ILB$$

Similarly $F_2 = ILB \sin\theta$

As $\theta = 90°$

$$F_2 = ILB$$

So $F_1 = F_2 = ILB$

where L is length of these sides, F_1 is the force on side DA, F_2 is the force on side BC. It can be seen that $\vec{F_1}$ is directed out of the plane of paper and $\vec{F_2}$ is into the plane of paper. Therefore forces $\vec{F_1}$ and $\vec{F_2}$ being opposite and equal form a couple which tends to rotate it about its axis. The torque of this couple is

$$\tau = \text{Force} \times \text{Moment arm of couple}$$

$$= ILB \times a$$

$$= ILBa \quad \text{...... (i)}$$

where a = Moment arm of couple and is equal to length of side AB or CD.

So La is area A of the wire

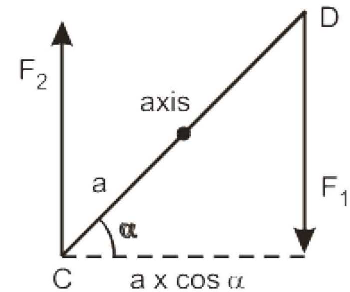
$\therefore$ eq. (i) becomes

$$\tau = IBA \quad \text{...... (ii)}$$

> We can also find τ by moment arm method
>
> $\tau_1 = \text{Force} \times \text{Moment arm}$
>
> $= F_1 \times \frac{a}{2}$
>
> $\tau_2 = \text{Force} \times \text{Moment arm}$
>
> $= F_2 \times \frac{a}{2}$
>
> Combing τ_1 and τ_2
>
> $= F_1 \frac{a}{2} + F_2 \frac{a}{2}$
>
> $= ILB \frac{a}{2} + ILB \frac{a}{2}$
>
> $= \frac{ILBa + ILBa}{2}$
>
> $= \frac{2ILBa}{2}$
>
> $\tau = ILBa$

Eq. (ii) gives the value of torque when filed $\vec{B}$ is parallel to the plane of coil.

However when field makes angle α with the plane of coil the moment arm will become a cos α



Top view of coil

$\therefore \quad \tau = ILB\,(a\cos\alpha)$

$\Rightarrow$ a cos α is perpendicular distance between two points

$$\tau = IBA\cos\alpha$$

Q.11 Define galvanometer. Also describe principle, construction and working of a galvanometer.

Ans. GALVANOMETER

Galvanometer is an electrical instrument used for the detection of electric current.

Principle

When coil is placed in a magnetic field, it experience a force as soon as current passes through it. Due to this force a torque τ acts upon the conductor.

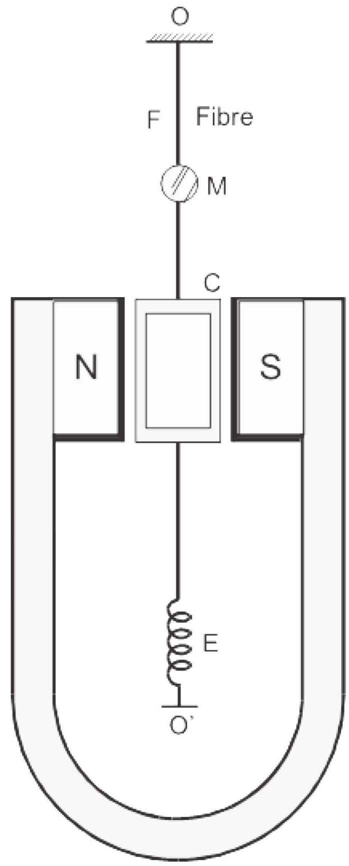
$$\tau = NIBA\cos\alpha$$

Where N = No. of turns, A = Area of coil, I = Current passing through coil, $\vec{B}$ = Magnetic field in which the coil is placed, α = Angle between magnetic field and plane of coil.

Due to action of torque, the coil rotates and hence it detects the current.

Construction

A rectangular coil C is suspended between the concave shaped poles N and S of a U shaped magnet with the help of a fine metallic suspension wire. The rectangular coil is made of enameled copper wire. It is wound on a frame of non-magnetic material. The suspension wire F is also used as one current lead to coil. The other terminal of the coil is connected to a loosely wound spiral E which serves as the second current lead. A soft iron cylinder D is placed inside the coil to make field radial and stronger near the coil.



Working

When current is passed through coil, it is acted upon by a couple which tends to rotate the coil. This couple is known as deflecting couple and is given by NIBA cos α. As the coil is placed in radial magnetic field in which plane of coil is always parallel to field, so α is always zero. This makes cos α = 1 and thus

Deflecting couple = NIBA

As the coil turns under the action of deflecting couple, the suspension wire is twisted which gives rise to torsional couple. It tends to untwist the suspension and restore the coil to its original position. This couple of suspension wire is proportional to angle of deflection θ as long as the suspension wire obeys Hook's law

Restoring torque = $C\theta$

where C = Constant of suspension wire is known as tortional couple and is defined as couple for unit twist

Under the action of these two couples, coil comes to rest when

Deflecting torque = Restoring torque

$$NIBA = C\theta$$

$$I = \frac{C\theta}{BAN}$$

Thus $I \propto \theta$

where $\frac{C}{BAN}$ = Constant

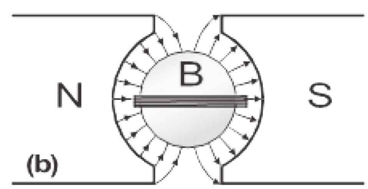


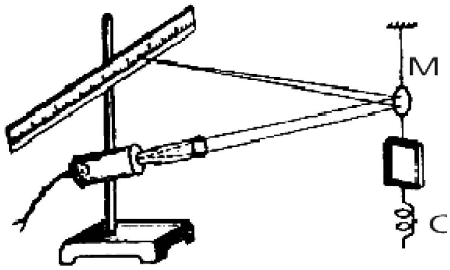
Fig. (a) Moving coil galvanometer (b) Concave pole piece and soft iron cylinder makes the field radial and stronger.

Thus current passing through coil is directly proportional to angle of deflection.

There are two methods commonly used for observing the angle of deflection.

Q.12 What is the lamp and scale arrangement of a galvanometer?

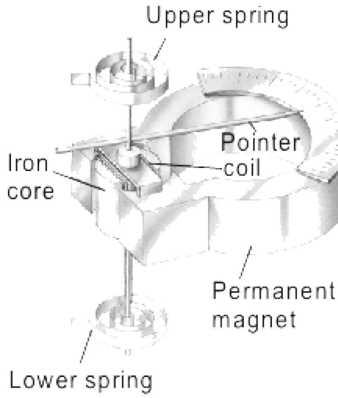
Ans. LAMP AND SCALE ARRANGEMENT



In sensitive galvanometers the angle of deflection is observed by means of small mirror attached to the coil along with a lamp and scale arrangement.

A beam of light from the lamp is directed towards the mirror of galvanometer. After reflection through the mirror it produces a spot on translucent scale placed at a distance of 1m from galvanometer. When coil rotates, the mirror attached to the coil also rotates and spot of light moves along the scale. The displacement of spot of light on scale is proportional to angle of deflection (provided the angle of deflection is small).

Pivoted Type Galvanometer



In this type of galvanometer, the coil is pivoted between two jewelled bearings. The restoring torque is provided by two hair springs which also serves as current lead. A light aluminium pointer is attached to the coil which moves over the scale. It gives angle of deflection of the coil.

Q.13 What is the sensitivity of a galvanometer?

Ans. SENSITIVITY OF GALVANOMETER

We defined current sensitivity of a galvanometer as the current (in microamperes) required to produce 1 mm deflection on a scale placed one meter away from the mirror of galvanometer.

As $$I = \frac{C\theta}{NBA}$$

$$\theta = \frac{I}{C/NBA}$$

Galvanometer can be made more sensitive to give large deflection for a given current if, $\frac{C}{NAB}$ made small. Thus to increase the sensitivity of a galvanometer, C may be decreased. **OR** $\vec{B}$, A and N may be increased. Then couple C for unit twist of the suspension wire can be decreased by increasing its length and by decreasing its diameter. This process cannot be taken too far as the suspension must be strong enough to support coil. To increase the sensitivity of galvanometer increase N. But no. of turns cannot be increased beyond a limit because it will make the coil heavy. If we increase area A of coil, then size of galvanometer increases which is not possible. Hence we increase sensitivity of galvanometer, $\vec{B}$ should be increased.

Stable or Dead Beat Galvanometer

Such a galvanometer in which the coil comes to rest quickly after the current passed through it or the current is stopped flowing through it, it is called dead beat galvanometer.

Q.14 How to convert a galvanometer into an ammeter?

Ans. AMMETER OR CONVERSION OF GALVANOMETER INTO AMMETER

An ammeter is an electrical instrument which is used to measure current in amperes.

The portion of galvanometer causes the needle of the device to move across the scale is known as meter-movement. Suppose we have a galvanometer whose meter movement has a resistance R_g and which gives full scale deflection when current I_g is passed through it.

From Ohm's law

$$V_g = I_g R_g$$

If we want to convert this galvanometer into ammeter, which can measure a maximum current I, we connect a low value by pass resistor called shunt (parallel to galvanometer). The shunt resistance is of such value so that the current I_g for full scale deflection passes, through galvanometer and the remaining current $(I - I_g)$ passes through the shunt.

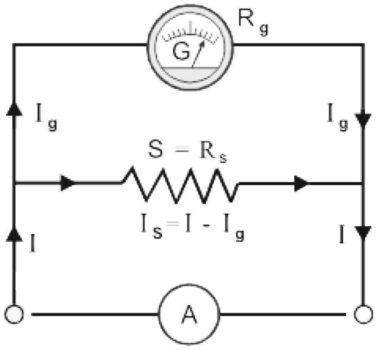


Fig. An ammeter is a galvanometer which is shunted by a proper low resistance.

As the meter-movement (galvanometer) and shunt are connected parallel with each other, therefore

$$V_g = V_s$$

$$I_g R_g = (I - I_g) R_S$$

$$R_S = \frac{I_g R_g}{I - I_g}$$

The shunt resistance is so small that a piece of copper wire serves the purpose. The resistance of the ammeter is usually very small. An ammeter must have a very low resistance so that it does not disturb the circuit in which it is connected in series to measure the current.

- An ammeter is connected in series in circuit to measure the current.
- It is also called low resistance galvanometer.

Q.15 How to convert a galvanometer into a voltmeter?

Ans. VOLTMETER OR CONVERSION OF GALVANOMETER INTO VOLTMETER

A voltmeter is an electrical device which measure potential difference in volts between two points.

Since a voltmeter is always connected in parallel. It must have very high resistance so that it will not short circuit the voltage to be measured. This is done by connecting a very high resistance R_h in series with galvanometer as shown in figure.

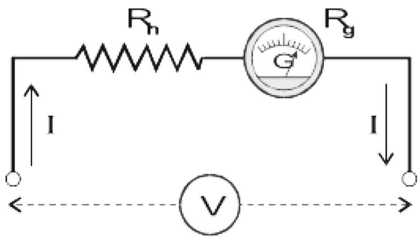


Fig. A galvanometer in series with a high resistance acts as a voltmeter.

Suppose the resistance of galvanometer is R_g which deflects full scale with a current I_g. In order to make a voltmeter of range V volts, the value of high resistance R_h should be such that full scale deflection will be obtained when it is connected across V volts.

Now applying Ohm's law

$$V = I_g(R_g + R_h)$$

$$\frac{V}{I_g} = R_g + R_h$$

$$R_h = \frac{V}{I_g} - R_g$$

This gives the required high resistance. As the voltmeter is connected in parallel, then some current of the circuit flows through voltmeter due to which current in the circuit and hence the potential difference decreases. This error is very small if resistance of the voltmeter is very large as compared to the resistance of the circuit across which voltmeter is connected. It is also called a high resistance galvanometer. It is a high resistance galvanometer.

Q.16 Define ohmmeter. How to find the resistance with ohm meter?

Ans. **OHMMETER**

It is a useful device for rapid measurement of resistance. It consist of a galvanometer and adjustable resistance r_s and a cell connected in series. The series resistance r_s is so adjusted that when terminals c and d are short circuited i.e., when R = 0, the galvanometer gives full scale deflection. So the extreme graduation of usual scale of galvanometer is marked 0 for resistance measurement. When terminals c and d are not joined, no current passes through the galvanometer and its deflection is zero. Thus zero of scale is marked as infinity. Now a known resistance is connected across terminals c and d. The galvanometer deflects to some intermediate point. This point is caliberated as R. In this way the whole scale is caliberated into resistance. The resistance to be measured is connected across the terminals c and d. The deflection on the caliberated scale reads the value of resistance directly.

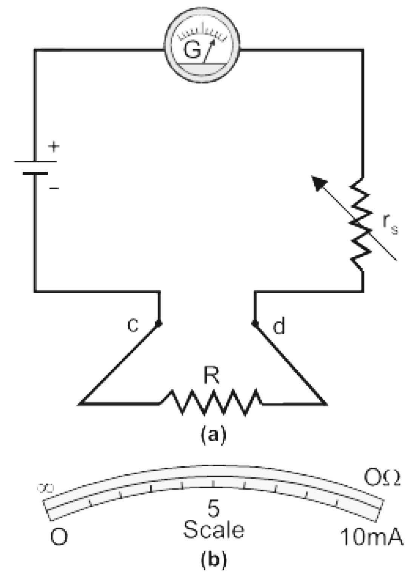
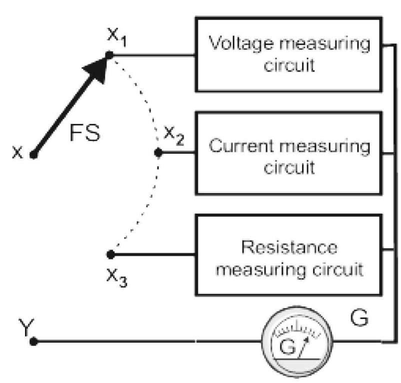


Fig. A moving coil galvanometer is converted into an ohmmeter.

Q.17 Describe AVO meter multimeter.

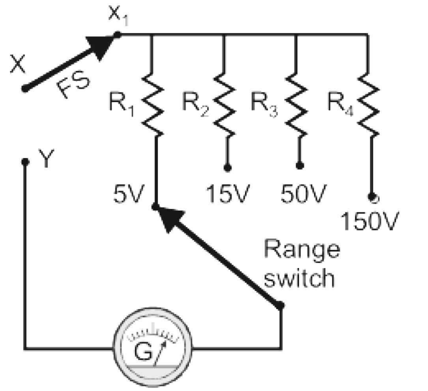
Ans. **AVO METER MULTIMETER**

It is an instrument which can measure current in amperes, potential difference in volts and resistance in ohms. It is basically consists of a sensitive moving coil galvanometer which is converted into a multirange ammeter, voltmeter or ohmmeter accordingly as a current measuring circuit or a voltage measuring circuit or a resistance measuring circuit is connected with the galvanometer with the help of a switch known as function switch (Figure). Here X, Y are the main terminals of the AVO meter which are connected with the circuit in which measurement is required. FS is the function selector switch which connects the galvanometer with relevant measuring circuit.



Voltage Measuring Part of AVO Meter

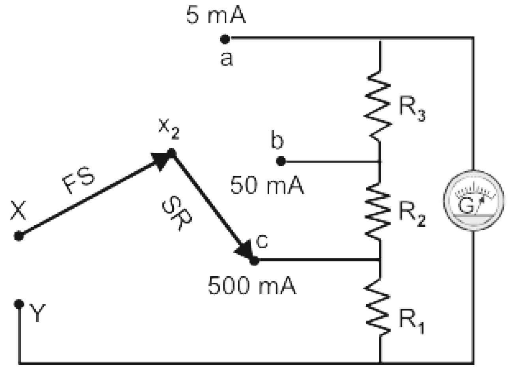
The voltage measuring part of the AVO meter is actually a multirange voltmeter. It consists of a number of resistances each of which can be connected in series with the moving coil galvanometer with the help of a switch called the range switch (Figure). The value of each resistance depends upon the range of the voltmeter which it controls.



Alternating voltages are also measured by AVO meter. AC voltage is first converted into DC voltage by using diode as rectifier and then measured as usual.

Current Measuring Part of AVO Meter

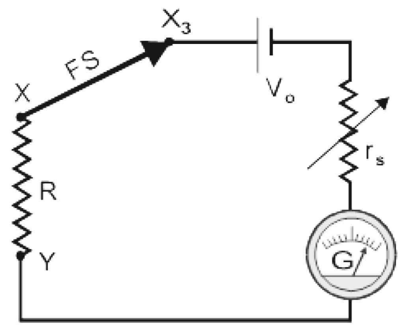
The current measuring part of the AVO meter is actually a multirange ammeter. It consists of a number of low resistances connected in parallel with the galvanometer. The values of these resistances depend upon the range of the ammeter (Figure).



The circuit also has a range selection switch RS which is used to select a particular range of the current.

Resistance Measuring Part of AVO Meter

The resistance measuring part of AVO meter is, in fact, a multirange ohmmeter. Circuit for each range of this meter consists of a battery of emf V_o and a variable resistance r_s connected in series with galvanometer of resistance R_g. When the function switch is switched to position X_a (figure), this circuit is connected with the terminals X, Y of the AVO meter (figure).



Before measuring an unknown resistance by an ohmmeter it is first zeroed which means that we short circuit the terminals X, Y and adjust r_s, to produce full scale deflection.

Digital Multimeter (DMM)

Another useful device to measure resistance, current and voltage is an electronic instrument called digital multimeter.