UNIT II
MACHINES AND MEASURING INSTRUMENTS

Machines: Construction, principle and operation of (i) DC Motor, (ii) DC Generator, (iii) Single Phase Transformer, (iv) Three Phase Induction Motor and (v) Alternator, Applications of electrical machines.

Measuring Instruments: Construction and working principle of Permanent Magnet Moving Coil (PMMC), Moving Iron (MI) Instruments and Wheat Stone bridge.

ELECTRICAL MACHINES

Principle of Operation of a DC Generator

An electric generator is a machine that converts mechanical energy into electrical energy.

All the generators work on a principle of dynamically induced e.m.f. This principle is nothing but the Faraday's law of electromagnetic induction. It states that, 'whenever the number of magnetic lines of force i.e. flux linking with a conductor or a coil changes, an electromotive force is set up in that conductor or coil.' The change in flux associated with the conductor can exist only when there exists a relative motion between a conductor and the flux. The relative motion can be achieved by rotating conductor with respect to flux or by rotating flux with respect to a conductor. So a voltage gets generated in a conductor, as long as there exists a relative motion between conductor and the flux.

Such an induced e.m.f. which is due to physical movement of coil or conductor with respect to flux or movement of flux with respect to coil or conductor is called dynamically induced e.m.f.

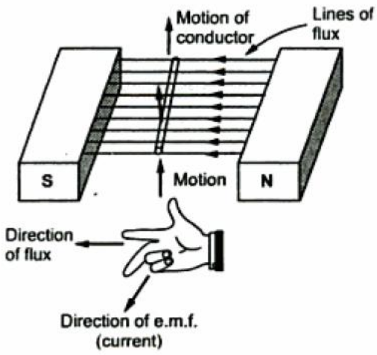
So a generating action requires following basic components to exist, i) The conductor or a coil ii) The flux iii) The relative motion between conductor and flux.

In a practical generator, the conductors are rotated to cut the magnetic flux, keeping flux stationary. To have a large voltage as the output, the numbers of conductors are connected together in a specific manner, to form a winding. This winding is called armature winding of a DC machine.

The part on which this winding is kept is called armature of a DC machine. To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prime mover. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc. The necessary magnetic flux is produced by current carrying winding which is called field winding. The direction of the induced e.m.f. can be obtained by using Fleming's right hand rule.

Fleming's Right Hand Rule :

If three fingers of a right hand, namely thumb, index finger and middle finger are outstretched so that everyone of them is at right angles with the remaining two, and if in this position index finger is made to point in the direction of lines of flux, thumb in the direction of the relative motion of the conductor with respect to flux then the Outstretched middle finger gives the direction of the e.m.f. induced in the conductor. Visually the rule can be represented as shown in the following Fig.

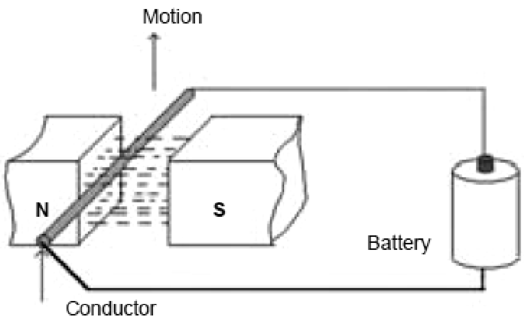


This rule mainly gives direction of current which induced e.m.f. in conductor will set up when closed path is provided to it.

Principle of operation of DC Motor:

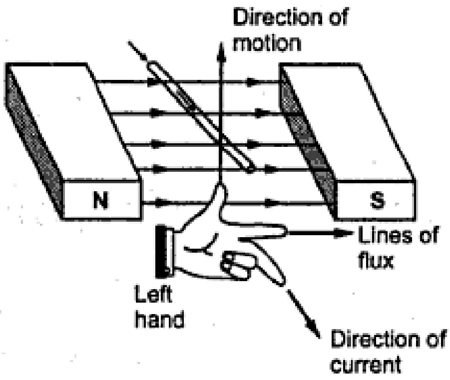
A machine that converts Electrical power into mechanical power is known as a DC motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force and it is shown in the fig. The direction of this force is given by Fleming's left hand rule and magnitude is given by;

$$F = BIl \text{ newtons}$$



Fleming's Left Hand Rule:

The rule states that, 'Outstretch the three fingers of the left hand namely the first finger, middle finger and thumb such that they are mutually perpendicular to each other. Now point the first finger in the direction of magnetic field and the middle finger in the direction of the current, then the thumb gives the direction of the force experienced by the conductor'. The Fleming's left hand rule can be diagrammatically shown as in the Fig.



Basically, there is no constructional difference between a DC motor and a DC generator. The same DC machine can be run as a generator or motor.

Construction of DC machines

The d.c. generators and d.c. motors have the same general construction. Any d.c. generator can be run as a d.c. motor and vice-versa.

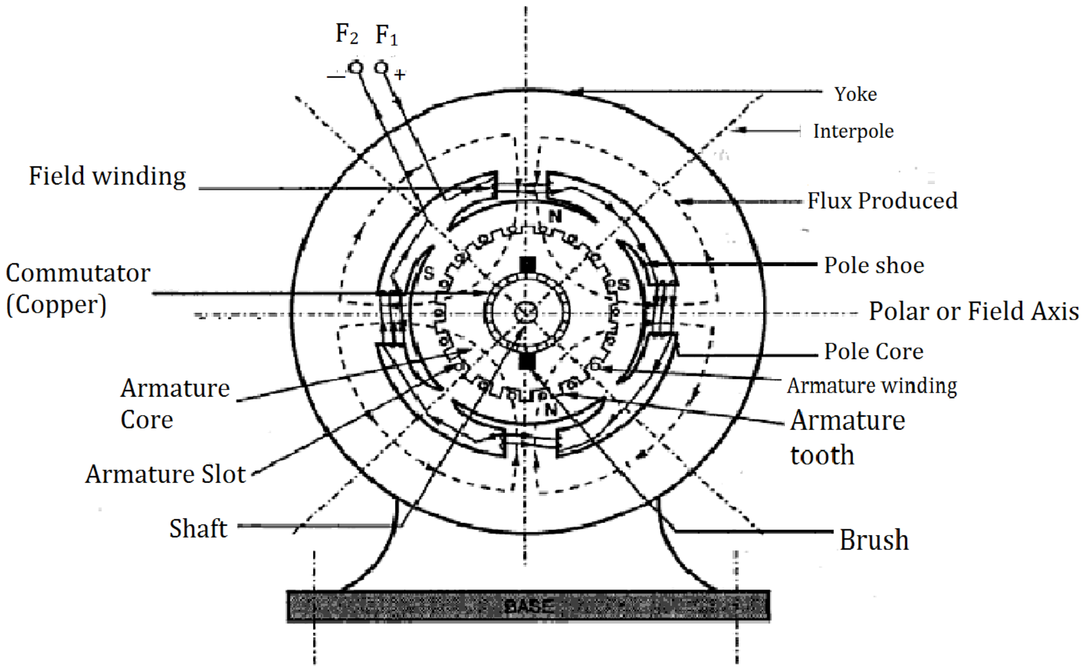
A D.C. machine consists of two main parts :

(i) Stationary part : It is designed mainly for producing a magnetic flux.

(ii) Rotating part : It is called the armature, where mechanical energy is converted into electrical (electrical generator), or conversely, electrical energy into mechanical (electric motor).

The stationary and rotating parts are separated from each other by an air gap. The stationary part of a D.C. machine consists of main poles, designed to create the magnetic flux, commutating poles interposed between the main poles and designed to ensure sparkles operation of the brushes at the commutator (in very small machines with a lack of space commutating poles are not used) ; and a frame/yoke.

The construction details and main parts of a DC machine are shown in the following fig.



The essential parts of the DC machine are

1.Magnetic Frame or Yoke **2.** Pole-Cores and Pole-Shoes

3.Pole Coils or Field Coils **4.** Armature **5.**Armature Windings or Conductors

6. Commutator **7.** Brushes and Bearings

1) YOKE :

The outer frame or yoke serves two main purposes. They are

(*i*) It provides mechanical support for the poles and acts as a protecting cover for the whole machine.

(*ii*)It carries the magnetic flux produced by the poles.

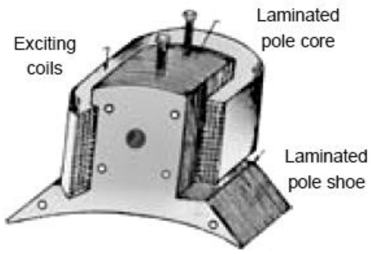
In small generators, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is employed. The modern process of forming the yoke consists of rolling a steel slab round a cylindrical mandrel and ten welding it at the bottom. The feet and the terminal box etc. are welded to the frame afterwards. Such yokes possess sufficient mechanical strength and have high permeability.

2) POLE-CORES AND POLE-SHOES :

The field magnets consist of pole cores and pole shoes. The pole shoes serve two purposes (*i*) they spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path
(*ii*) they support the exciting coils (or field coils).

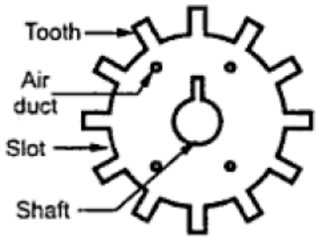
3) Pole Coils :

The field coils or pole coils, which consist of copper wire or strip, are former-wound for the correct dimension. Then, the former is removed and wound coil is put into place over the core as shown in the fig. When current is passed through these coils, they electro-magnetize the poles which produce the necessary flux that is cut by revolving armature conductors.



4) Armature :

It is further divided into two parts namely, i) Armature core ii) Armature winding
i) **Armature core** : Armature core is cylindrical in shape mounted on the shaft. It consists of slots on its periphery and the air ducts to permit the air flow through armature which serves cooling purpose.
a) Functions :
1. Armature core provides house for armature winding i.e. armature conductors.
2. To provide a path of low reluctance to the magnetic flux produced by the field winding.
b) Choice of material :
As it has to provide a low reluctance path to the flux, it is made up of magnetic material like cast iron or cast steel. It is made up of laminated construction to keep eddy current loss as low as possible. A single circular lamination used for the construction of the armature core is shown in the Fig.



5) Armature Winding :

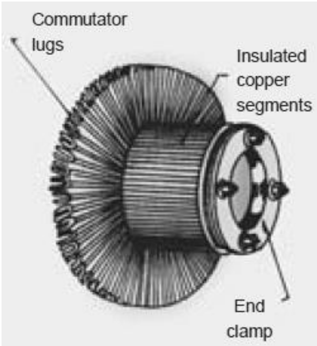
Armature winding is nothing but the interconnection of the armature conductors, placed in the slots provided on the armature core periphery. When the armature is rotated, in case of generator, magnetic flux gets cut by armature conductors and e.m.f. gets induced in them.
a) Functions :
1. Generation of e.m.f. takes place in the armature winding in case of generators.
2. To carry the current supplied in case of DC motors.
3 To do the useful work in the external circuit.

b) Choice of material :

As armature winding carries entire current which depends on external load, it has to be made up of conducting material, which is copper. Armature winding is generally former wound. The conductors are placed in the armature slots which are lined with tough insulating material.

6) Commutator :

The function of the commutator is to facilitate collection of current from the armature conductors. It converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high-conductivity hard-drawn or drop forged copper. These segments are insulated from each other by thin layers of mica. The number of segments is equal to the number of armature coils. Each commutator segment is connected to the armature conductor by means of a copper lug or strip (or riser). To prevent them from flying out under the action of centrifugal forces, the segments have *V*-grooves, these grooves being insulated by conical micanite rings. A general appearance of the commutator is shown in the Fig.



7)Brushes and Bearings :

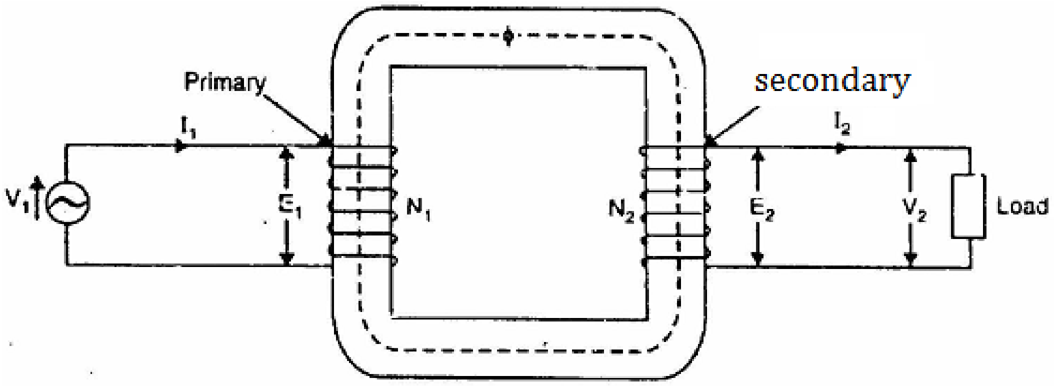
Brushes are stationary and resting on the surface of the commutator.

a) Function : To collect current from commutator and make it available to the stationary external circuit.

b) Choice of material : Brushes are normally made up of soft material like carbon.
Brushes are rectangular in shape. They are housed in brush holders, which are usually of box type. The brushes are made to press on the commutator surface by means of a spring, whose tension can be adjusted with the help of lever. A flexible copper conductor called pig tail is used to connect the brush to the external circuit. To avoid wear and tear of commutator, the brushes are made up of soft material like carbon.

Principle of operation of Transformer

A transformer is a static piece of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary).



The alternating voltage V_1 whose magnitude is to be changed is applied to the primary. Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating e.m.f. E_2 is induced in the secondary. This induced e.m.f. E_2 in the secondary causes a secondary current I_2. Consequently, terminal voltage V_2 will appear across the load. If $V_2 > V_1$, it is called a step up-transformer. On the other hand, if $V_2 < V_1$, it is called a step-down transformer.

Working:

When an alternating voltage V_1 is applied to the primary, an alternating flux f is set up in the core. This alternating flux links both the windings and induces e.m.f.s E_1 and E_2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E_1 is termed as primary e.m.f. and e.m.f. E_2 is termed as secondary e.m.f.

$$\text{Clearly,} \qquad E_1 = -N_1 \frac{d\phi}{dt}$$

$$\text{and} \qquad E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \qquad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Thus the magnitudes of E_2 and E_1 depend upon the number of turns on the secondary and primary respectively. If $N_2 > N_1$, then $E_2 > E_1$ (or $V_2 > V_1$) and we get a step-up transformer. On the other hand, if $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E_2 will cause a current I_2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

The following points may be noted carefully:

(i) The transformer action is based on the laws of electromagnetic induction.

(ii) There is no electrical connection between the primary and secondary. The a.c. power is transferred from primary to secondary through magnetic flux.

(iii) There is no change in frequency i.e., output power has the same frequency as the input power.
(iv) The losses that occur in a transformer are:
(a) core losses—eddy current and hysteresis losses
(b) copper losses—in the resistance of the windings

Construction and types of Transformers

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and the steel core. Other necessary parts are : some suitable container for assembled core and windings ; a suitable medium for insulating the core and its windings from its container : suitable bushings (either of porcelain, oil-filled or capacitor-type) for insulating and bringing out the terminals of windings from the tank.

In all types of transformers, the core is constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-Rap included. The steel used is of high silicon content. Sometimes heat treated to produce a high permeability and a low hysteresis loss at the usual operating flux densities. The eddy current loss is minimized by laminating the core. The laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface.

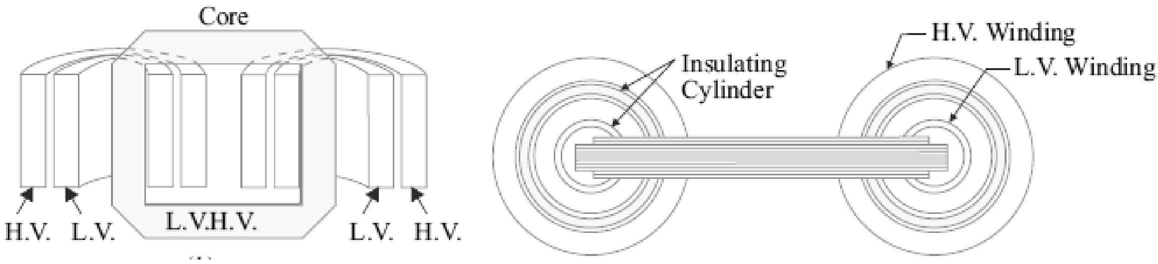
Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core. The two types are known as **(i) core-type and (ii) shell type.**

Core-type Transformers

The coils used are form-wound and are of the cylindrical type. The general form of these coils may be circular or oval or rectangular. In small size core-type transformers, a simple rectangular core is used with cylindrical coils which are either circular or rectangular in form. But for large-size core-type transformers, round or circular cylindrical coils are used which are so wound as to fit over a cruciform core section as shown in Fig.

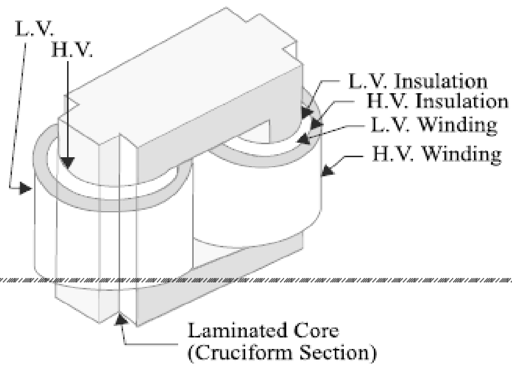
The circular cylindrical coils are used in most of the core-type transformers because of their mechanical strength. Such cylindrical coils are wound in helical layers with the different layers insulated from each other by paper, cloth micarta board or cooling ducts.

The following Fig. shows the general arrangement of these coils with respect to the core. Insulating cylinders of filler board are used to separate the cylindrical windings from the core and from each other. Since the low voltage (LV) winding is easiest to insulate, it is placed nearest to the core.



Shell-type Transformers

In these case also, the coils are form-would but are multi-layer disc type usually wound in the form of pancakes. The different layers of such multi-layer discs are insulated from each other by paper. The complete winding consists of stacked



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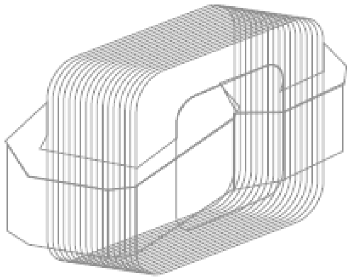
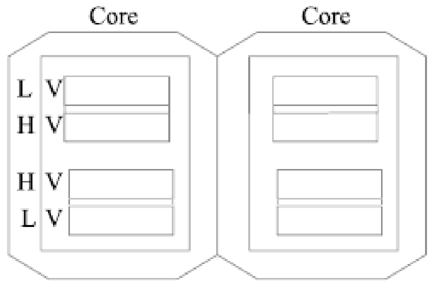
discs with insulation space between the coils-the spaces forming horizontal cooling and insulating ducts. A shell-type transformer may have a simple rectangular form as shown in Fig.(a) or it may have distributed form as shown in Fig. (b).



(a)



(b)

Differences between core type and shell type transformers

CORE TYPE TRANSFORMER	SHELL TYPE TRANSFORMER
➢ The winding is surrounded considerable part of core. ➢ It has single magnetic circuit. ➢ Core has two limbs. ➢ Concentric cylindrical windings are used. ➢ Natural cooling is provided. ➢ Repairing and maintenance is easy. ➢ Used for low voltage transformers.	➢ Core is surrounded considerable part of winding of transformer. ➢ It has double magnetic circuit. ➢ Core has three limbs. ➢ Sandwiched windings are used. ➢ Natural cooling cannot provide ➢ Maintenance and repairing is not easy. ➢ Used for high voltage transformer.

Principle of operation of 3-Φ Induction motors :

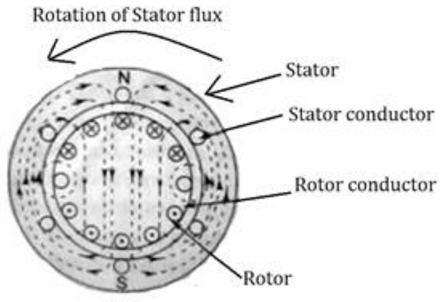
When the stator of an induction motor is connected across a balanced three phase AC supply, it draws a balanced three-phase current and these current sets up a rotating magnetic field of constant magnitude. The magnetic flux rotating, at the synchronous speed, sweeps past the rotor conductors which are stationary at the start and induces emfs in them. The frequency of the induced emfs in the rotor conductors is same as the supply frequency.

As the rotor conductors are short circuited, the induced emfs produce three phase rotor currents which in turn produce a magnetic field that revolves at the same speed as the stator field. A starting torque is produced due to the interaction of these two fields and tends to turn the rotor in the direction of rotation of the stator field.

According to Lenz's law, the developed torque must oppose the cutting of flux lined by rotor conductors. Hence, the developed torque makes the rotor move in the direction of flux waves so as to reduce the relative speed between the stator flux wave and the rotor conductors and thereby reducing the cutting of flux lines by the rotor conductors.

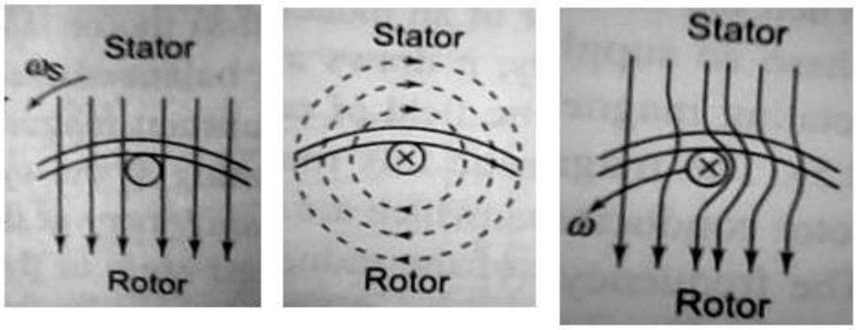
If the starting torque is sufficient to overcome the load torque on the motor shaft, the motor will start rotating and reach its operating speed. The operating speed can never be equal to the synchronous speed N_S i.e. the rotor speed N of an induction motor is always slightly less than the synchronous speed N_S.

The distribution of flux of an induction motor is shown in the fig-(a).



(a)

If the stator winding flux rotates in anti-clockwise at an angular velocity $\omega_s = 2\pi f$, the direction of the induced emf generated in the stationary rotor conductors can be determined by Fleming's right hand rule.
The emf generated in one rotor conductor is shown in fig-(b).



(b)

In the fig-(b), the first part shows the stator flux rotating at an angular ω_s and links the rotor conductor. The second part shows that the induced current circulating in the rotor conductor produces a flux around it in the clockwise direction which is determined by Maxwell's corkscrew rule. The third part shows the effect of the flux which strengthens the flux density on the right hand side and weakens that on the left hand side of the conductor.

Thus causes the conductor to be pushed towards the left. Thus the rotor also begins to rotate in the anti-clockwise direction i.e. in the direction of rotating magnetic field. Thus, **the induction motors are self-starting**.

<u>Construction Features Of Three-Phase Induction Motors</u> :

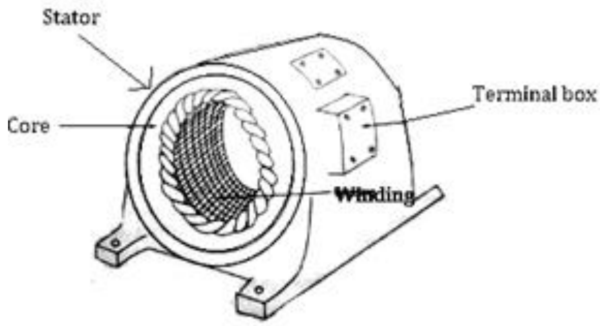
A 3-phase induction motor has two main parts (i) stator (outer part) and (ii) rotor (inner part). The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor.

1) Stator:

The stator of the three phase induction motor consists of three main parts :
i) Stator frame ii) Stator core iii) Stator winding or field winding.

Stator Frame

It is the outer most part of the three phase induction motor. Its main function is to support the stator core and the field winding. It acts as a covering and it provide protection and mechanical strength to all the inner parts of the induction motor. The frame is either made up of die cast or fabricated steel. The frame of three phase induction motor should be very strong and rigid as the air gap length of three phase induction motor is very small, otherwise rotor will not remain concentric with stator, which will give rise to unbalanced magnetic pull.



Stator Core

The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current loss, the stator core is laminated. These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick. All the stamping are stamped together to form stator core, which is then housed in stator frame. The stamping is generally made up of silicon steel, which helps to reduce the hysteresis loss occurring in motor.

Stator Winding or Field Winding

The slots on the periphery of stator core of the three phase induction motor carries three phase windings. This three phase winding is supplied by three phase ac supply. The three phases of the winding are connected either in star or delta depending upon which type of starting method is used. The squirrel cage motor is mostly started by star – delta stater and hence the stator of squirrel cage motor is delta connected. The slip ring three phase induction motor are started by inserting resistances so, the stator winding of slip ring induction motor can be connected either in star or delta. The winding wound on the stator of three phase induction motor is also called field winding and when this winding is excited by three phase ac supply it produces a rotating magnetic field.

A perspective view of the stator of a three-phase induction motor is shown in the fig.

2) Rotor:

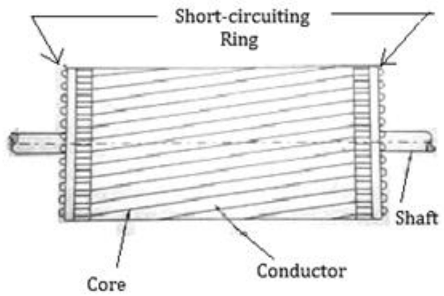
The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

(i) Squirrel cage type (ii) Wound type

(i) Squirrel cage rotor : [Squirrel cage induction motor]

It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminium bar is placed in each slot. All these bars are joined at each end by metal rings called end rings. This forms a permanently short-circuited winding which is indestructible. The entire construction (bars and end rings) resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator.

Those induction motors which employ squirrel cage rotor are called squirrel cage induction motors. Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances. However, it suffers from the disadvantage of a low starting torque. It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque. A squirrel cage rotor is shown in the fig.



`In this type of rotor, it may be noted that slots are not made parallel to the shaft but they are 'skewed' to serve the following purposes:
(i) To make the motor run quietly by reducing the magnetic hum.
(ii) To reduce the locking tendency of the rotor.

Advantages of squirrel cage induction motor:

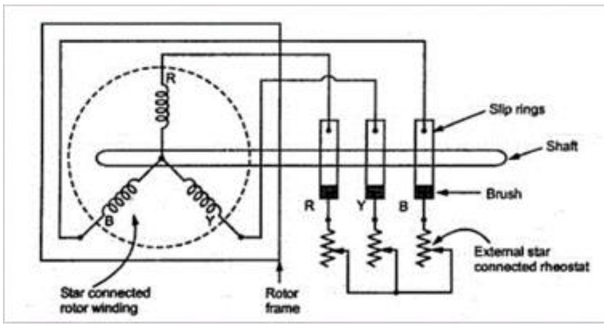
i)Its construction is very simple and rugged.
ii)As there are no brushes and slip ring, these motors requires less maintenance.

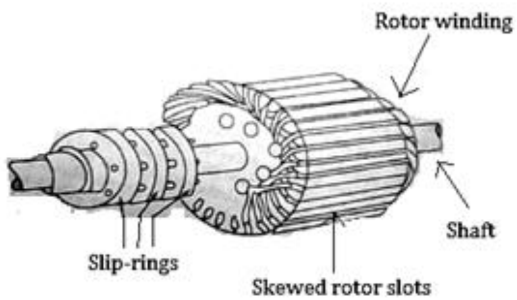
Applications:

Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

(ii) Slip-ring or Wound rotor : [Slip-ring induction motor]

It consists of a laminated cylindrical core and carries a 3- phase winding, similar to the one on the stator. The rotor winding is uniformly distributed in the slots and is usually star-connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. At starting, the external resistances are included in the rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed.





The external resistances are used during starting period only. When the motor attains normal speed, the three brushes are short-circuited so that the wound rotor runs like a squirrel cage rotor.

When running under normal conditions, the slip-rings are automatically short-circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together.

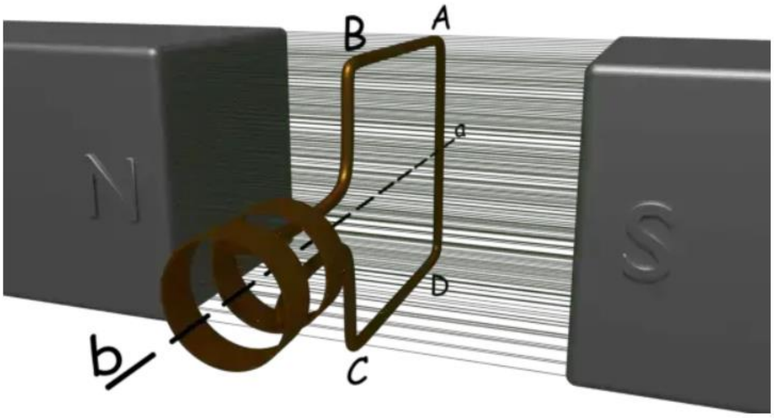
Next, the brushes are automatically lifted from the slip-rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel-case rotor. A slip-ring or wound rotor of an induction motor is shown in fig.

Advantages of slip ring induction motor :
i)It has high starting torque and low starting current.
ii)Possibility of adding additional resistance to control speed.

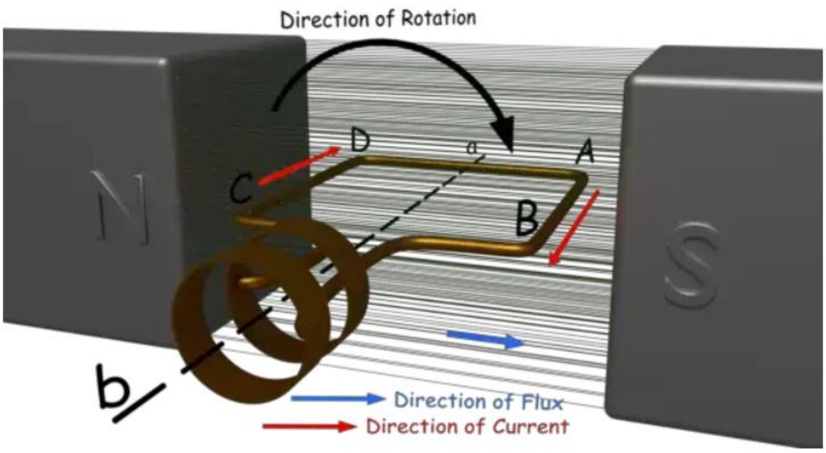
Application:
Slip ring induction motors is used where high starting torque is required i.e in hoists, cranes, elevator etc.

Principle of Operation of Alternator

The working principle of an alternator is very simple. It is just like the basic principle of DC generator. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field.



For understanding working of alternator let us think about a single rectangular turn placed in between two opposite magnetic poles as shown above.



Let this single turn loop ABCD can rotate against axis a-b. Suppose this loop starts rotating clockwise. After 90o rotation the side AB or conductor AB of the loop comes in front of S-pole and conductor CD comes in front of N-pole. At this position the tangential motion of the conductor AB is just perpendicular to the magnetic flux lines from N to S pole. Hence, the rate of flux cutting by the conductor AB is maximum here and for that flux cutting there will be an induced current in the

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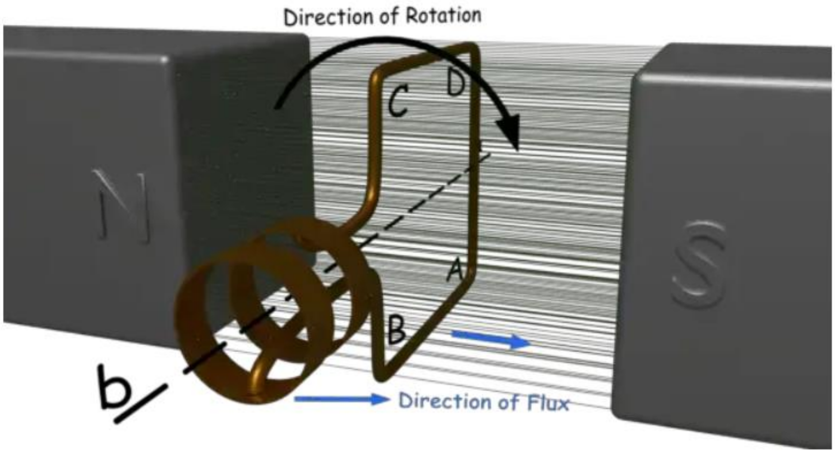
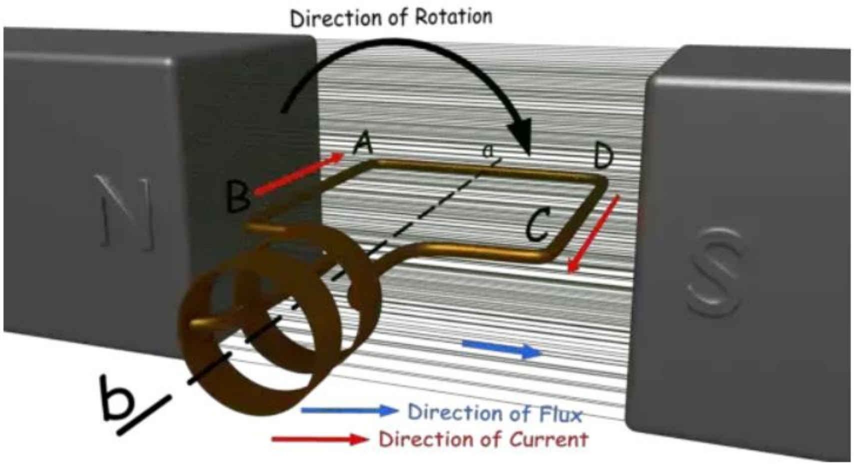
conductor AB and the direction of the induced current can be determined by Fleming's right-hand rule. As per this rule the direction of this current will be from A to B. At the same time conductor CD comes under N pole and here also if we apply Fleming right-hand rule we will get the direction of induced current and it will be from C to D.

Now after clockwise rotation of another 90o the turn ABCD comes at the vertical position as shown below. At this position tangential motion of conductor AB and CD is just parallel to the magnetic flux lines, hence there will be no flux cutting that is no current in the conductor.

While the turn ABCD comes from a horizontal position to a vertical position, the angle between flux lines and direction of motion of conductor, reduces from 90o to 0o and consequently the induced current in the turn is reduced to zero from its maximum value.



After another clockwise rotation of 90o the turn again comes to horizontal position, and here conductor AB comes under N-pole and CD comes under S-pole, and here if we again apply Fleming right-hand rule, we will see that induced current in conductor AB, is from point B to A and induced current in the conductor CD is from D to C.



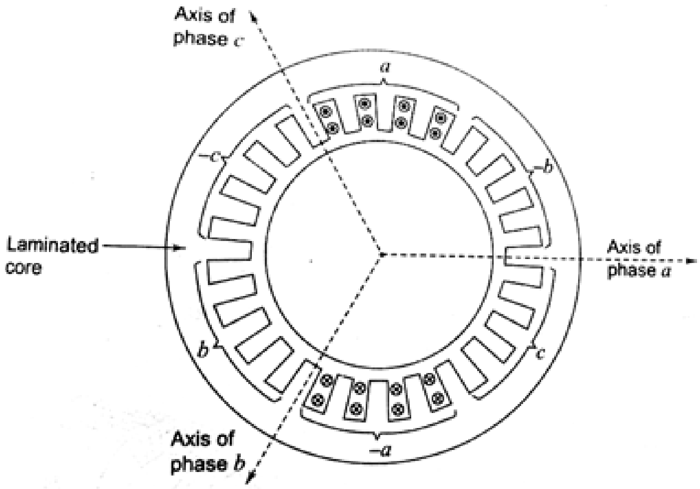
As at this position the turn comes at a horizontal position from its vertical position, the current in the conductors comes to its maximum value from zero. That means current is circulating in the close turn from point B to A, from A to D, from D to C and from C to B, provided the loop is closed although it is not shown here. That means the current is in reverse of that of the previous horizontal position when the current was circulating as A → B → C → D → A.

While the turn further proceeds to its vertical position the current is again reduced to zero. So if the turn continues to rotate the current in turn continually alternate its direction. During every full revolution of the turn, the current in turn gradually reaches to its maximum value then reduces to zero and then again it comes to its maximum value but in opposite direction and again it comes to zero. In this way, the current completes one full sine wave cycle during each 360o revolution of the turn. So, we have seen how alternating current is produced in a turn is rotated inside a magnetic field.

Construction of Alternator

Construction of Stator :

The stator consists of an armature made of laminations of silicon steel having slots on its inner periphery to accommodate armature windings. The Figure shows a cross-sectional view of the stator of a three-phase two-pole synchronous machine. Double layer armature windings of three phase a, b, and c are placed in the slots. Since an alternating flux is produced in the stator due to the flow of alternating current in the armature winding, the stator is made of high permeability laminated steel stampings in order to reduce hysteresis and eddy-current losses. The provision of radial and axial ventilating spaces in the stampings assists in cooling the machine.



The laminations are stamped out in complete rings for smaller machines and stamped in segments for large machines and are insulated from each other with varnish. The whole structure is held in a frame made of cast steel or welded-steel plates.

Slots provided on the stator core are mainly of two types: open slots and semi-closed slots. Open slots are commonly used for commercial generators because the coils can be form-wound and insulated prior to placing them in the slots and the removal and replacement of defective coils can he easily carried out. However, non-uniform air gaps due to open slots may produce ripples in the emf waveform. The use of semi-closed type slots can minimize ripples by distributing the flux as uniformly as possible.

Coils of armature winding are made from insulated copper conductors. For machines of small ratings, double-cotton-covered copper wires are used. For large machines, conductor with rectangular cross section is used and each conductor has impregnated cotton tape insulation.

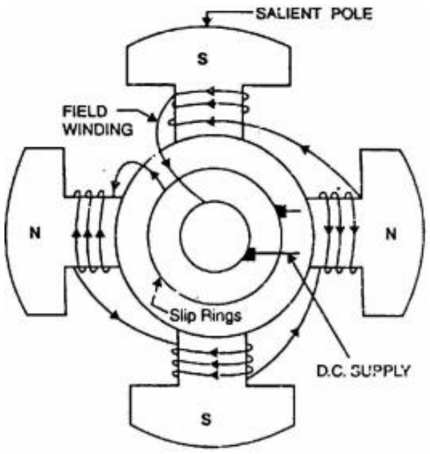
Construction of Rotor :

The rotor carries a field winding which is supplied with direct current through two slip rings by a separate d.c. source. This d.c. source (called exciter) is generally a small d.c. shunt or compound generator mounted on the shaft of the alternator. Rotor construction is of two types, namely;

(i) Salient (or projecting) pole type
(ii) Non-salient (or cylindrical) pole type

(i) Salient pole type :

In this type, salient or projecting poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator as shown in the Fig. The individual field pole windings are connected in series in such a way that when the field winding is energized by the d.c. exciter, adjacent poles have opposite polarities.



Low and medium-speed alternators (120-400 r.p.m.) such as those driven by diesel engines or water turbines have salient pole type rotors due to the following reasons:

(a) The salient field poles would cause .an excessive windage loss if driven at high speed and would tend to produce noise.

(b) Salient-pole construction cannot be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speeds.

Since a frequency of 50 Hz is required, we must use a large number of poles on the rotor of slow-speed alternators. Low-speed rotors always possess a large diameter to provide the necessary spate for the poles. Consequently, salient-pole type rotors have large diameters and short axial lengths.

(ii) Non-salient pole type :

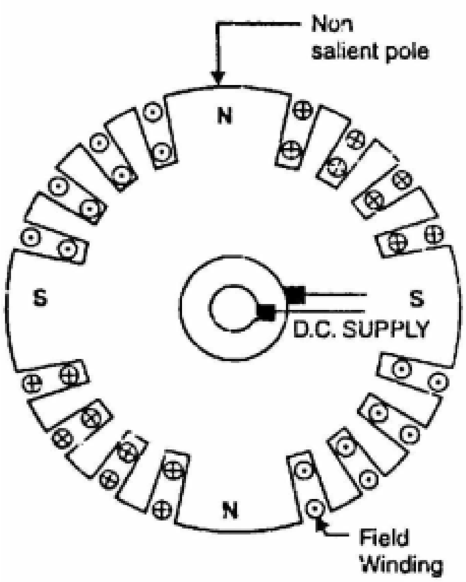
In this type, the rotor is made of smooth solid forged-steel radial cylinder having a number of slots along the outer periphery. The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c. exciter. The regions forming the poles are usually left un-slotted as shown in the Fig. It is clear that the poles formed are non-salient i.e., they do not project out from the rotor surface.

High-speed alternators (1500 or 3000 r.p.m.) are driven by steam turbines and use non-salient type rotors due to the following reasons:

(a) This type of construction has mechanical robustness and gives noiseless operation at high speeds.

(b) The flux distribution around the periphery is nearly a sine wave and hence a better e.m.f. waveform is obtained than in the case of salient-pole type.

Since steam turbines run at high speed and a frequency of 50Hz is required, we need a small number of poles on the rotor of high-speed alternators (also called turbo alternators). We can use not less than 2 poles and this fixes the highest possible speed. For a frequency of 50 Hz, it is 3000 r.p.m. The next lower speed is 1500 r.p.m. for a 4-pole machine. Consequently, turbo alternators possess 2 or 4 poles and have small diameters and very long axial lengths.



APPLICATIONS OF ELECTRICAL MACHINES

Applications of DC Motors:

Type of Motor	Characteristics	Applications
Shunt	Speed is fairly constant and medium starting torque.	1. Blowers and fans 2. Centrifugal and reciprocating pumps 3. Lathe machines 4. Machine tools 5. Milling machines 6. Drilling machines
Series	High starting torque. No load condition is dangerous. Variable speed.	1. Cranes 2. Hoists, Elevators 3. Trolleys 4. Conveyors 5. Electric locomotives
Cumulative compound	High starting torque. No load condition is allowed.	1. Rolling mills 2. Punches 3. Shears 4. Heavy planers 5. Elevators
Differential compound	Speed increases as load increases.	Not suitable for any practical applications

Applications of DC Generators:

Types of DC generator	Application of DC generator
Separately excited generator	It is used for electroplating and booster. It can be used for lighting and power purpose with field regulator.
Self-excited generator (Shunt)	It is used for ordinary lighting and power purpose with the regulator. Used for lighting battery
Self-excited generator (Series)	Used for lighting arc lamps. It can be used as a constant current generator. It can be used as a booster.
Compounds generator	It is used for compensator of the line drops in traction For energy transmission over a long distance.

Applications of Transformers:

(1) To step up or step down voltage and current (useful for power transmission and distribution)

(2) To isolate one portion of a circuit from another

(3) As an impedance matching device for maximum power transfer

(4) Frequency-selective circuits

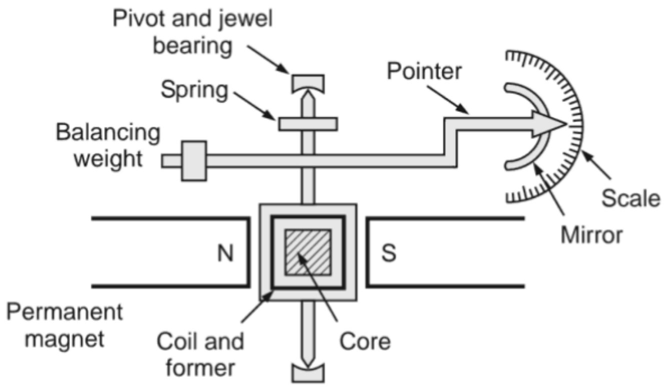
Applications of 3-phase induction motor

1) Lifts
2) Cranes
3) Hoists
4) Large capacity exhaust fans
5) Driving lathe machines
6) Crushers
7) Oil extracting mills
8) Textile and etc.

MEASURING INSTRUMENTS

PERMANENT MAGNET MOVING COIL (PMMC) INSTRUMENTS

The permanent magnet moving coil instruments are most accurate type for d.c. measurements.The action of these instruments is based on the motoring principle. When a current carrying coil is placed in the magnetic field produced by permanent magnet, the coil experiences a force and moves. As the coil is moving and the magnet is permanent, the instrument is called permanent magnet moving coil instrument. This basic principle is called **D'Arsonval principle.** The amount of force experienced by the coil is proportional to the current passing through the coil.



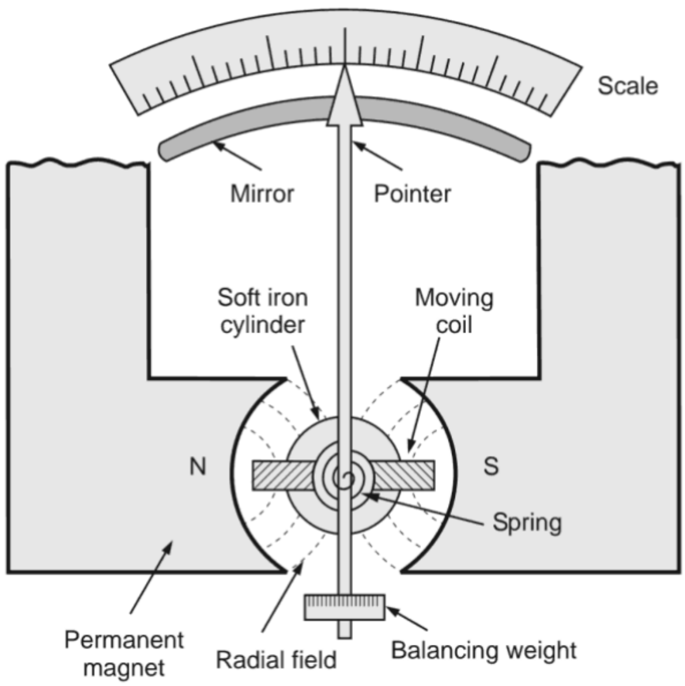
The PMMC instrument is shown in the Fig.

The moving coil is either rectangular or circular in shape. It has number of turns of fine wire. The coil is suspended so that it is free to turn about its vertical axis. The coil is placed in uniform, horizontal and radial magnetic field of a permanent magnet in the shape of a horse-shoe. The iron core is spherical if coil is circular and is cylindrical if the coil is rectangular. Due to iron core, the deflecting torque increases, increasing the sensitivity of the instrument.

The controlling torque is provided by two phosphor bronze hair springs.

The damping torque is provided by eddy current damping. It is obtained by movement of the aluminium former, moving in the magnetic field of the permanent magnet.

The pointer is carried by the spindle and it moves over a graduated scale. The pointer has light weight so that it can deflect rapidly. The mirror is placed below the pointer to get the accurate reading by removing the parallax. The weight of the instrument is normally counter balanced by the weights situated diametrically opposite and rigidly connected to it. The scale markings of the basic d.c. PMMC instruments are usually linearly spaced as the deflecting torque and hence the pointer deflection are directly proportional to the current passing through the coil.



The top view of PMMC instrument is shown in the Fig.

In a practical PMMC instrument, a Y shaped member is attached to the fixed end of the front control spring. An eccentric pin through the instrument case engages the Y shaped member so that the zero position of the pointer can be adjusted from outside.

Torque Equation

The equation for the developed torque can be obtained from the basic law of the electromagnetic torque. The deflecting toque is given by,

$$\boxed{T_d = NBAI}$$

where T_d = Deflecting torque in N-m

B = Flux density in air gap, Wb/m^2

N = Number of turns of the coil

A = Effective coil area m^2

I = Current in the moving coil, amperes

$\therefore \quad T_d = GI$

where $G = NBA$ = Constant

The controlling torque is provided by the springs and is proportional to the angular deflection of the pointer.

AVRK

$$T_c = K\theta$$

where T_c = Controlling torque

K = Spring constant, Nm/rad or Nm/deg

θ = Angular deflection

For the final steady state position,

$$T_d = T_c$$

$$\therefore \quad GI = K\theta$$

$$\therefore \quad \theta = \left(\frac{G}{K}\right)I$$

or $$\boxed{I = \left(\frac{K}{G}\right)\theta}$$

Thus the deflection is directly proportional to the current passing through the coil.

The pointer deflection can therefore be used to measure current.

As the direction of the current through to the coil changes, the direction of the deflection of the pointer also changes. Hence such instruments are well suited for the d.c. measurements.

Advantages

The various advantages of PMMC instruments are,

1) It has uniform scale.
2) With a powerful magnet, its torque to weight ratio is very high. So operating current is small.
3) The sensitivity is high.
4) The eddy currents induced in the metallic former over which coil is wound, provide effective damping.
5) It consumes low power, of the order of 25 W to 200 μW.
6) It has high accuracy.
7) Instrument is free from hysteresis error.
8) Extension of instrument range is possible.
9) Not affected by external magnetic fields called stray magnetic fields.

Disadvantages

The various disadvantages of PMMC instruments are,

1) Suitable for d.c. measurements only.
2) Ageing of permanent magnet and the control springs introduces the errors.
3) The cost is high due to delicate construction and accurate machining.
4) The friction due to jewel-pivot suspension.

MOVING IRON (MI) INSTRUMENTS

The moving iron instruments are classified as :

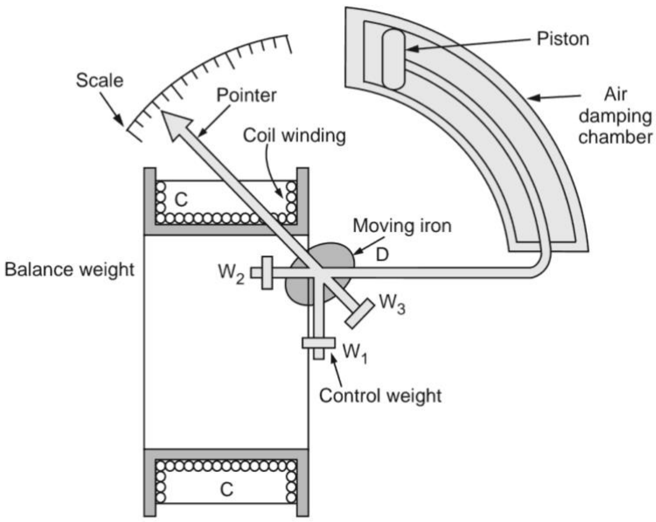
i) Moving iron attraction type instruments and

ii) Moving iron repulsion type instruments

Moving Iron Attraction Type Instruments

The basic working principle of these instruments is very simple that a soft iron piece if brought near the magnet gets attracted by the magnet.

The construction of the attraction type instrument is shown in the Fig.



It consists of a fixed coil C and moving iron piece D. The coil is flat and has a narrow slot like opening. The moving iron is a flat disc which is eccentrically mounted on the spindle. The spindle is supported between the jewel bearings. The spindle carries a pointer which moves over a graduated scale. The number of turns of the fixed coil are dependent on the range of the instrument.For passing large current through the coil only few turns are required.

The controlling torque is provided by the springs but gravity control may also be used for vertically mounted panel type instruments.

The damping torque is provided by the air friction. A light aluminium piston is attached to the moving system. It moves in a fixed chamber. The chamber is closed at one end. It can also be provided with the help of vane attached to the moving system.

The operating magnetic field in moving iron instruments is very weak. Hence eddy current damping is not used since it requires a permanent magnet which would affect or distort the operating field.

Moving Iron Repulsion Type Instrument

These instruments have two vanes inside the coil, the one is fixed and other is movable. When the current flows in the coil, both the vanes are magnetised with like polarities induced on the same side. Hence due to the repulsion of like polarities, there is a force of repulsion between the two vanes causing the movement of the moving vane. The repulsion type instruments are the most commonly used instruments.

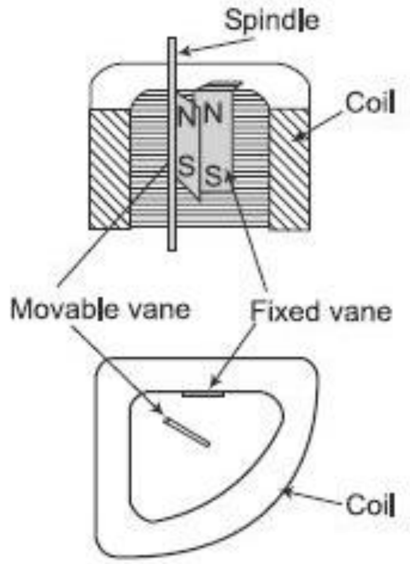
The two different designs of repulsion type instruments are :

i) Radial vane type and

ii) Co-axial vane type

Radial Vane Repulsion Type Instrument

The Fig. shows the radial vane repulsion type instrument. Out of the other moving iron mechanisms, this is the most sensitive and has most linear scale.



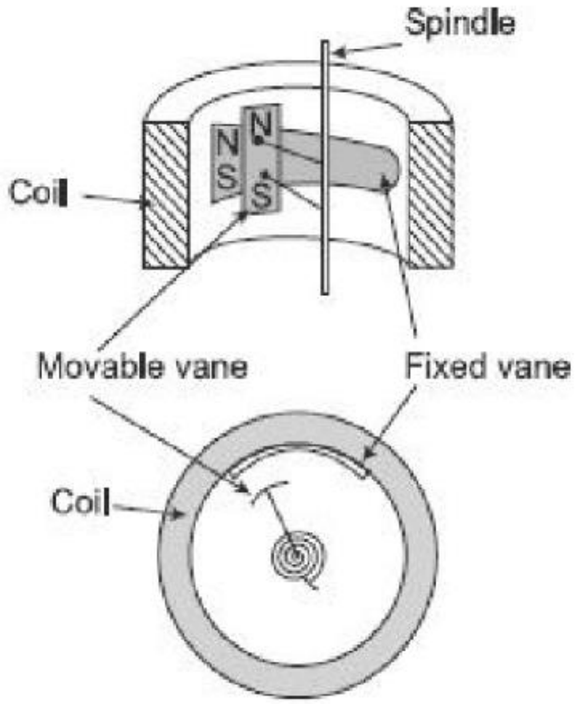
The two vanes are radial strips of iron. The fixed vane is attached to the coil. The movable vane is attached to the spindle and suspended in the induction field of the coil. The needle of the instrument is attached to this vane.

Eventhough the current through the coil is alternating, there is always repulsion between the like poles of the fixed and the movable vane. Hence the deflection of the pointer is always in the same direction.The deflection is effectively proportional to the actual current and hence the scale is calibrated directly to read amperes or volts. The calibration is accurate only for the frequency for which it is designed because the impedance is different for different frequencies.

Concentric Vane Repulsion Type Instrument

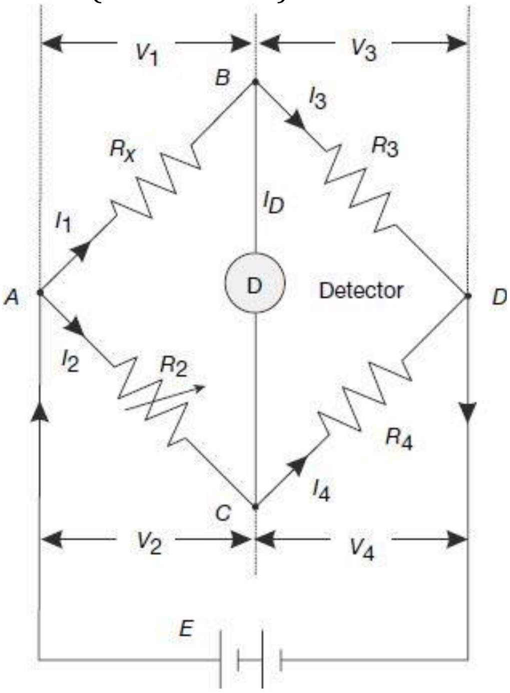
The Fig. shows the concentric vane repulsion type instrument. The instrument has two concentric vanes. One is attached to the coil frame rigidly while the other can rotate coaxially inside the stationary vane.

Both the vanes are magnetised to the same polarity due to the current in the coil. Thus the movable vane rotates under the repulsive force. As the movable vane is attached to the pivoted shaft, the repulsion results in a rotation of the shaft. The pointer deflection is proportional to the current in the coil. The concentric vane type instrument is moderately sensitive and the deflection is proportional to the square of the current through coil. Thus the instrument is said to have square law response. Thus the scale of the instrument is non-uniform in nature. Thus whatever may be the direction of the current in the coil, the deflection in the moving iron instruments is in the same direction. Hence moving iron instruments can be used for both a.c. and d.c. measurements. Due to square law response, the scale of the moving iron instrument is non-uniform.



WHEATSTONE BRIDGE FOR MEASURING RESISTANCE

The Wheatstone bridge is the most commonly used circuit for measurement of medium range resistances. The Wheatstone bridge consists of four resistance arms, together with a battery (voltage source) and a galvanometer (null detector). The circuit is shown in Figure.



In the bridge circuit, R_3 and R_4 are two fixed known resistances, R_2 is a known variable resistance and R_X is the unknown resistance to be measured. Under operating conditions, current I_D through the galvanometer will depend on the difference in potential between nodes B and C. A bridge balance condition is achieved by varying the resistance R_2 and checking whether the galvanometer pointer is resting at its zero position. At balance, no current flows through the galvanometer. This means that at balance, potentials at nodes B and C are equal. In other words, at balance the following conditions are satisfied:

1. The detector current is zero, i.e., $I_D = 0$ and thus $I_1 = I_3$ and $I_2 = I_4$
2. Potentials at node B and C are same, i.e., $V_B = V_C$, or in other words, voltage drop in the arm AB equals the voltage drop across the arm AC, i.e., $V_{AB} = V_{AC}$ and voltage drop in the arm BD equals the voltage drop across the arm CD, i.e., $V_{BD} = V_{CD}$.

From the relation $V_{AB} = V_{AC}$ we have $I_1 \times Rx = I_2 \times R_2$

At balanced ‘null’ position, since the galvanometer carries no current, it as if acts as if open circuited, thus

$$I_1 = I_3 = \frac{E}{R_X + R_3} \text{ and } I_2 = I_4 = \frac{E}{R_2 + R_4}$$

$$\frac{E}{R_X + R_3} \times R_X = \frac{E}{R_2 + R_4} \times R_2$$

$$\frac{R_X + R_3}{R_X} = \frac{R_2 + R_4}{R_2}$$

$$\frac{R_X + R_3}{R_X} - 1 = \frac{R_2 + R_4}{R_2} - 1$$

$$\frac{R_X + R_3 - R_X}{R_X} = \frac{R_2 + R_4 - R_2}{R_2}$$

$$\frac{R_3}{R_X} = \frac{R_4}{R_2}$$

$$\frac{R_X}{R_2} = \frac{R_3}{R_4}$$

$$R_X = R_2 \times \frac{R_3}{R_4}$$

Thus, measurement of the unknown resistance is made in terms of three known resistances. The arms BD and CD containing the fixed resistances R_3 and R_4 are called the ratio arms. The arm AC containing the known variable resistance R_2 is called the standard arm. The range of the resistance value that can be measured by the bridge can be increased simply by increasing the ratio R_3/R_4.