8

Induction Machines

8.1 Introduction

For general lighting purpose in shops, offices, houses, schools etc. single phase supply is commonly used. There are numerous domestic applications like mixer, automatic washing machine etc. which work on single phase supply, consisting of single phase motors. The power rating of such motors is very small. Some of them are even fractional horse power motors, hence also called fractional kW motors. Hence study of working principle, construction and applications of such motors is discussed in this chapter.

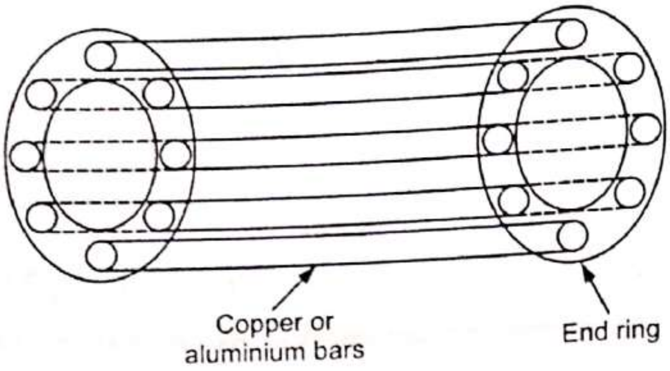
8.2 Construction of Single Phase Induction Motors

Similar to a d.c. motor, single phase induction motor has basically two main parts, one rotating and other stationary. The stationary part in single phase induction motors is called stator while the rotating part is called **rotor**.

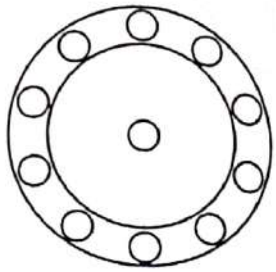
The stator has laminated construction, made up of stampings. The stampings are slotted on its periphery to carry the winding called **stator winding** or **main winding**. This is excited by a single phase a.c. supply. The laminated construction keeps iron losses to minimum. The stampings are made up of material like silicon steel which minimises the hysteresis loss. The stator winding is wound for certain definite number of poles means when excited by single phase a.c. supply, stator produces the magnetic field which creates the effect of certain definite number of poles. The number of poles for which stator winding is wound, decides the synchronous speed of the motor. The synchronous speed is denoted as N_s and it has a fixed relation with supply frequency f and number of poles P. The relation is given by,

$$\boxed{N_s = \frac{120\,f}{P} \text{ r.p.m.}}$$

The **induction motor never rotates with the synchronous speed** but rotates at a speed which is slightly less than the synchronous speed. The rotor construction is of **squirrel cage type**. In this type, rotor consists of uninsulated copper or aluminium bars, placed in the slots. The bars are permanently shorted at both the ends with the help of conducting rings called end rings. The entire structure looks like cage hence called **squirrel cage rotor.** The construction and symbol is shown in the Fig. 8.1.



(a) Cage type structure



(b) Symbolic representation

Fig. 8.1 Rotor construction

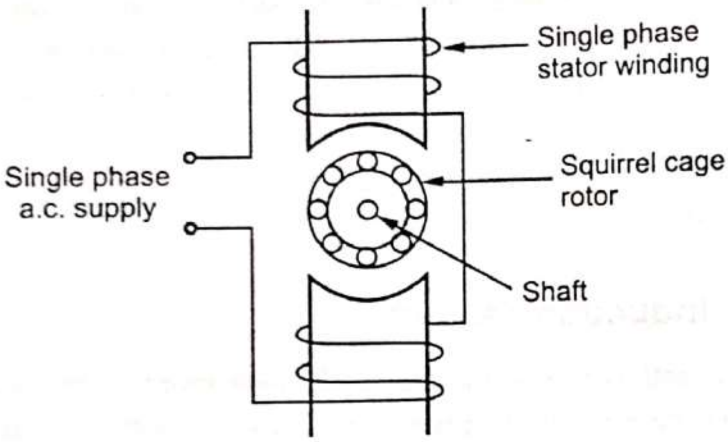


Fig. 8.2

As the bars are permanently shorted to each other, the resistance of the entire rotor is very very small. The air gap between stator and rotor is kept uniform and as small as possible. The main feature of this rotor is that it automatically adjusts itself for same number of poles as that of the stator winding.

The schematic representation of two pole single phase induction motor is shown in the Fig. 8.2.

8.3 Working Principle of Single Phase Motors

For the motoring action, there must exist two fluxes which interact with each other to produce the torque. In d.c. motors, field winding produces the main flux while d.c. supply given to armature is responsible to produce armature flux. The main flux and armature flux interact to produce the torque.

In the single phase induction motor, single phase a.c. supply is given to the stator winding. The stator winding carries an alternating current which produces the flux which is also alternating in nature. This flux is called **main flux**. This flux links with the rotor conductors and due to transformer action e.m.f. gets induced in the rotor. The induced e.m.f. drives current through the rotor as rotor circuit is closed circuit. This rotor current produces another flux called **rotor flux** required for the motoring action. Thus second flux is produced according to induction principle due to induced e.m.f. hence the motor is called **induction motor**. As against this in d.c. motor a separate supply is required to armature to produce armature flux. This is an important difference between d.c. motor and an induction motor.

Another important difference between the two is that the d.c. motors are self starting while **single phase induction motors** are **not self starting**. Let us see why single phase induction motors are not self starting with the help of a theory called double revolving field theory.

At start these two torq... ...nced by the torque tries to rotate the rotor in its own dire... ... rotor is **zero at start**. And hence the single phase induction motors are not self starting.

8.4.1 Torque-Speed Characteristics

The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics. It is shown in the Fig. 8.4.

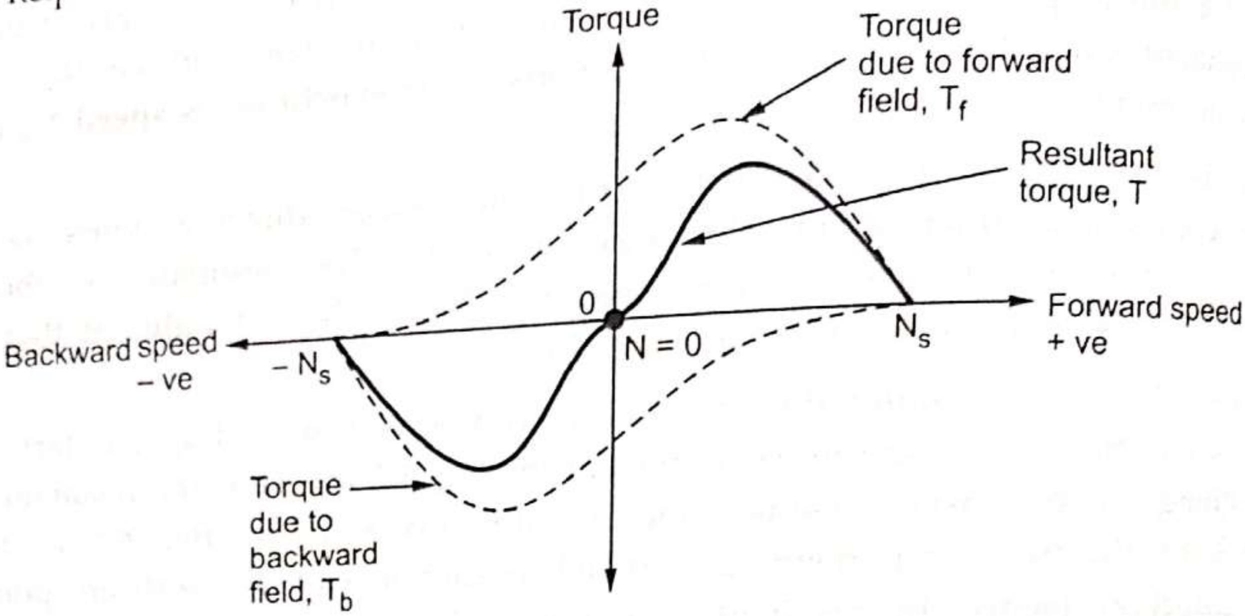


Fig. 8.4 Torque-speed characteristics

It can be seen that at start N = 0 and at that point resultant torque is zero. So single phase motors are not self starting.

However if the rotor is given an initial rotation in any direction, the resultant average torque increases in the direction in which rotor is initially rotated. And motor starts rotating in that direction. But in practice it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.

8.5 Types of Single Phase Induction Motors

In practice some arrangement is provided in the single phase induction motors so that the stator flux produced becomes **rotating type** rather than the alternating type, which rotates in one particular direction only. So torque produced due to such rotating magnetic field is unidirectional as there is no oppositely directed torque present. Hence under the influence of rotating magnetic field in one direction, the induction motor becomes self starting. It rotates in same direction as that of rotating magnetic field. Thus depending upon the methods of producing **rotating** stator magnetic flux, the single phase induction motors are classified as,

1. Split phase induction motor
2. Capacitor start induction motor

3. Capacitor start capacitor run induction motor
4. Shaded pole induction motor.

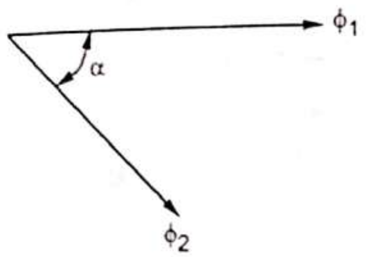


Fig. 8.5

To produce rotating magnetic field, it is necessary to have minimum two alternating fluxes having a phase difference between the two. The interaction of such two fluxes produce a resultant flux which is rotating magnetic flux, rotating in space in one particular direction. So an attempt is made in all the single phase induction motors to produce an additional flux other than stator flux, which has a certain phase difference with respect to stator flux. Such two fluxes are shown in the Fig. 8.5 having phase difference of α between them.

More the phase difference angle α, more is the starting torque produced. Thus **production of rotating magnetic field** at start is important to make the single phase induction motors self starting. Once the motor starts, then another flux ϕ_2 may be removed and motor can continue to rotate under the influence of stator flux or main flux alone.

Let us see how the rotating magnetic field is produced in various types of single phase induction motors.

8.6 Split Phase Induction Motor

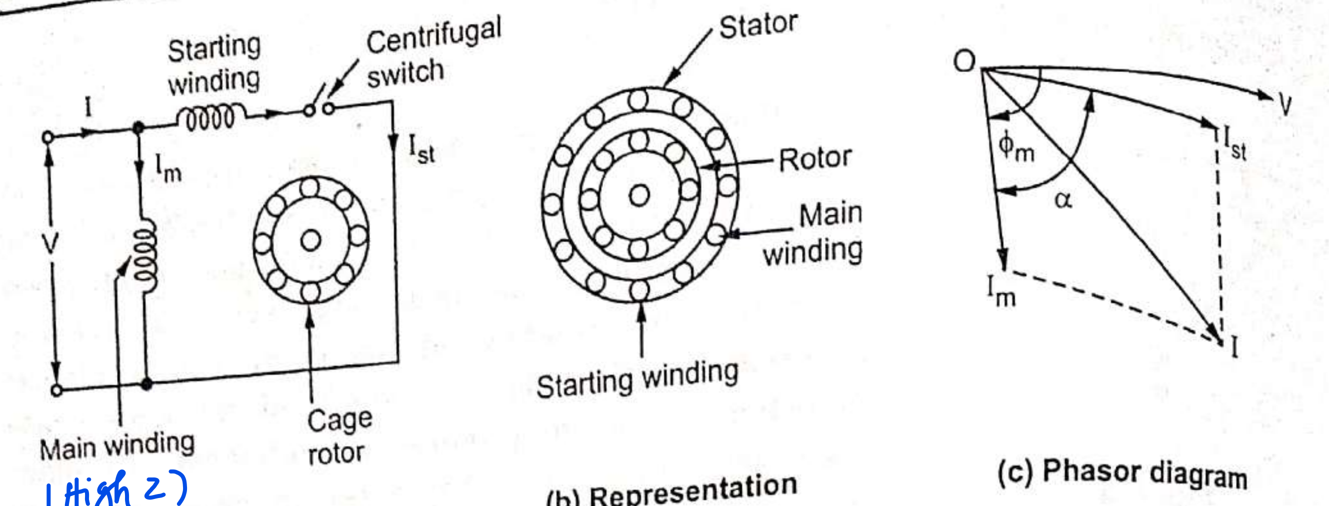
This type of motor has single phase stator winding called **main winding**. In addition to this, stator carries one more winding called **auxiliary winding** or **starting winding**. The auxiliary winding carries a series resistance such that its impedance is highly resistive in nature. The main winding is inductive in nature.

Let $\qquad I_m$ = Current through main winding

and $\qquad I_{st}$ = Current through auxiliary winding

As main winding is inductive, current I_m lags voltage V by a large angle ϕ_m while I_{st} is almost in phase in V as auxiliary winding is highly resistive. Thus there exists a phase difference of α between the two currents and hence between the two fluxes produced by the two currents. This is shown in the Fig. 8.6 (c). The resultant of these two fluxes is a rotating magnetic field. Due to this, the starting torque, which acts only in one direction is produced.

The auxiliary winding has a centrifugal switch in series with it. When motor gathers a speed upto 75 to 80% of the synchronous speed, centrifugal switch gets opened mechanically and in running condition auxiliary winding remains out of the circuit. So motor runs only on stator winding. So auxiliary winding is designed for short time use while the main winding is designed for continuous use. As the current I_m and I_{st} are splitted from each other by angle 'α' at start, the motor is commonly called **split phase motor**.



(a) Circuit diagram (b) Representation (c) Phasor diagram

Fig. 8.6 Split phase induction motor

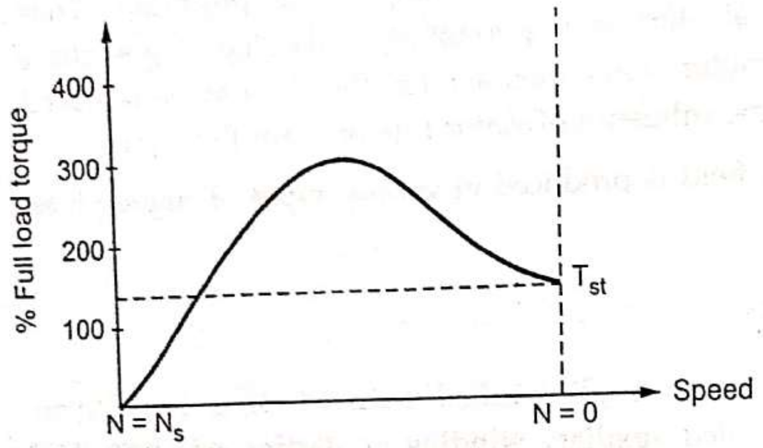


Fig. 8.7

The torque-speed characteristics of split phase motors is shown in the Fig. 8.7.

The starting torque T_{st} is proportional to the split angle 'α'. but split phase motors give poor starting torque which is 125 to 150% of the full load torque.

The direction of rotation of this motor can be reversed by reversing the terminals of either main winding or auxiliary winding. This changes the direction of rotating magnetic field which in turn changes the direction of rotation of the motor.

8.6.1 Applications

These motors have low starting current and moderate starting torque. These are used for easily started loads like fans, blowers, grinders, centrifugal pumps, washing machines, oil burners, office equipments etc. These are available in the range of 1/20 to 1/2 kW.

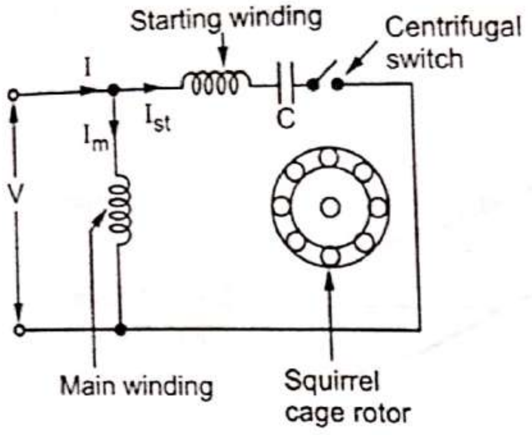
8.7 Capacitor Start Induction Motors

The construction of this type of motor is similar to the resistance split phase type. The difference is that in series with the auxiliary winding the capacitor is connected. The capacitive circuit draws a leading current, this feature is used in this type to increase the split phase angle α between the two currents I_m and I_{st}.

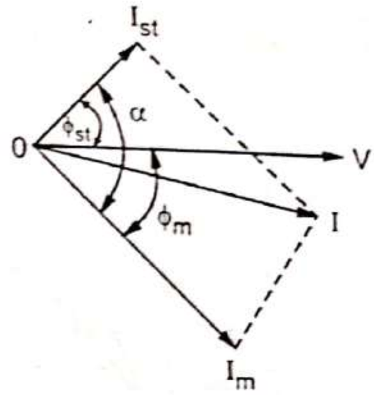
Depending upon whether capacitor remains in the circuit permanently or is disconnected from the circuit using centrifugal switch, these motors are classified as,

1. Capacitor start motors and 2. Capacitor start capacitor run motors

The construction of capacitor start motor is shown in the Fig. 8.8 (a). The current I_m lags the voltage by angle ϕ_m while due to capacitor the current I_{st} leads the voltage by angle ϕ_{st}. Hence there exists a large phase difference between the two currents which is almost 90°, which is an ideal case. The phasor diagram is shown in the Fig. 8.8 (b).



(a) Schematic representation



(b) Phasor diagram

Fig. 8.8 Capacitor start motor

The starting torque is proportional to 'α' and hence such motors produce very high starting torque.

When speed approaches to 75 to 80% of the synchronous speed, the starting winding gets disconnected due to operation of the centrifugal switch. The capacitor remains in the circuit only at start hence it is called capacitor start motors.

In case of capacitor start capacitor run motor, there is no centrifugal switch and capacitor remain permanently in the circuit. This improves the power factor. The schematic representation of such motor is shown in the Fig. 8.9.

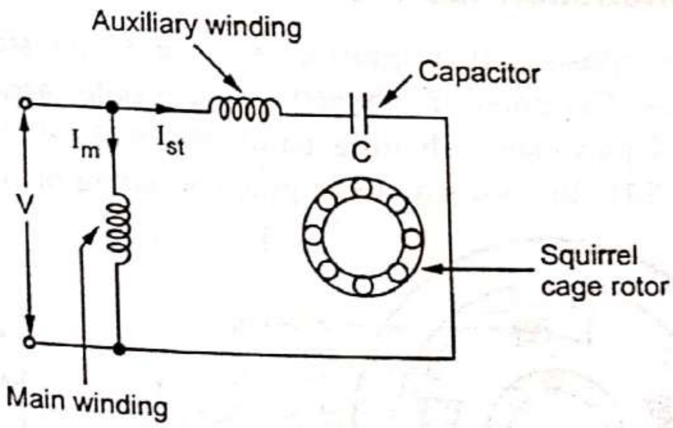


Fig. 8.9 Capacitor start capacitor run motor

The phasor diagram remains same as shown in the Fig. 8.8 (b). The performance not only at start but in running condition also depends on the capacitor C hence its value is to be designed so as to compromise between best starting and best running condition. Hence the starting torque available in such type of motor is about 50 to 100% of full load torque.

The direction of rotation, in both the types can be changed by interchanging connections of main winding or auxiliary winding. The capacitor permanently in the circuit improves the power factor. These motors are more costly than split phase type motors.

The capacitor value can be selected as per the requirement of starting torque. The starting torque can be as high as 350 to 400% of full load torque. The torque-speed characteristics is as shown in the Fig. 8.10.

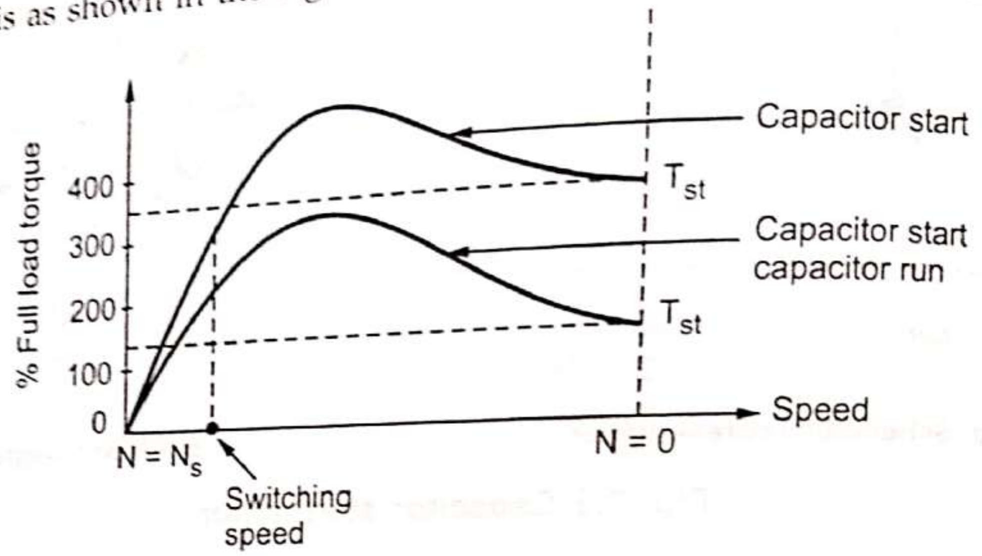


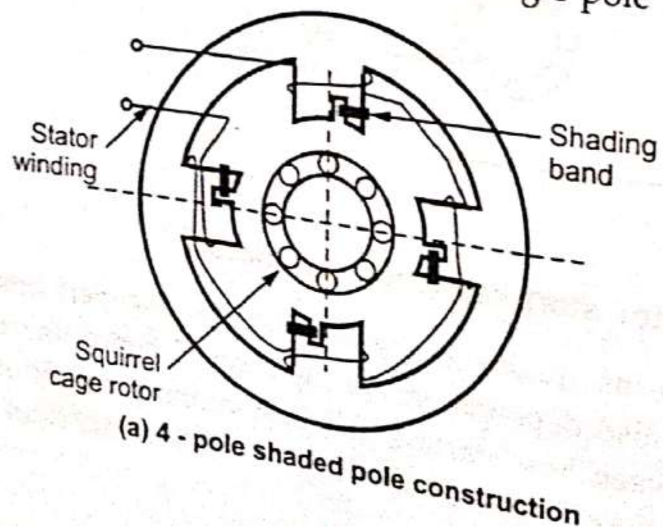
Fig. 8.10 Torque-speed characteristics of capacitor split phase motor

8.7.1 Applications

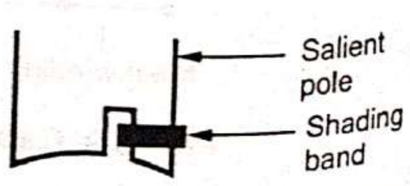
These motors have high starting torque and hence are used for hard starting loads. These are used for compressors, conveyors, grinders, fans, blowers, refrigerators, air conditioners etc. These are most commonly used motors. The capacitor start capacitor run motors are used in ceiling fans, blowers and air-circulators. These motors are available upto 6 kW.

8.8 Shaded Pole Induction Motors

This type of motor consists of a squirrel cage rotor and stator consisting of salient poles i.e. projected poles. The poles are shaded i.e. each pole carries a copper band on one of its unequally divided part called **shading band**. Fig. 8.11 (a) shows 4 pole shaded pole construction while Fig. 8.11 (b) shows a single pole consisting of copper shading band.



(a) 4 - pole shaded pole construction



(Stepper motor)

Variable - Reluctance stepper motor

When the stator phases are excited with dc current in proper sequence, the resultant air gap field steps around and the rotor follows the axis of the air gap field by virtue of reluctance torque.

This reluctance torque is generated because of the tendency of the ferromagnetic rotor to align itself along the direction of the resultant magnetic field.

Fig shows the mode of operation for a 45° step in the clockwise direction. The windings are energized in the sequence A, A+B, B, B+C. and so forth, and this sequence is repeated. When winding A is excited, the rotor aligns with the axis of phase A. Next, both windings A and B are excited, which makes the resultant mmf axis move 45° in the clockwise direction. The rotor aligns with this resultant mmf axis.

Thus, at each transition the rotor moves through 45° as the resultant field is switched around. The direction of rotation can be reversed by reversing the sequence of switching the windings, that is, A, A+B, D, D+C, etc.

Stepper motor

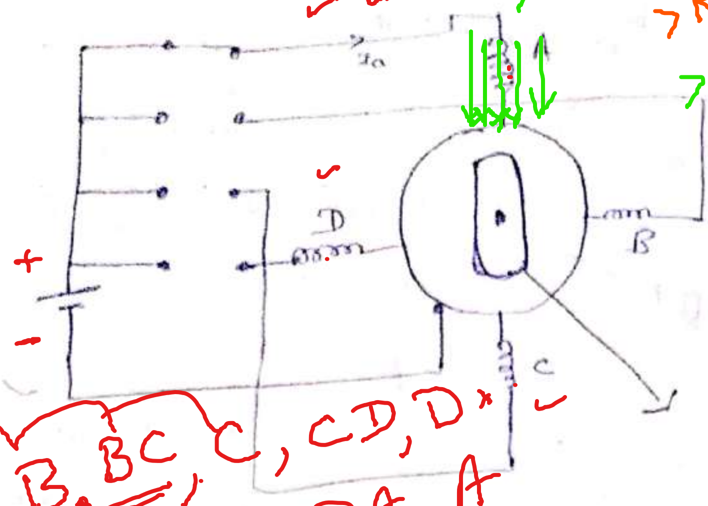
Rotation depends on the proper sequence of firing

Each step will 45° movement/ jump.

→ flux direction [Resultant magnetic field]

→ Rotor

→ low reluctance path



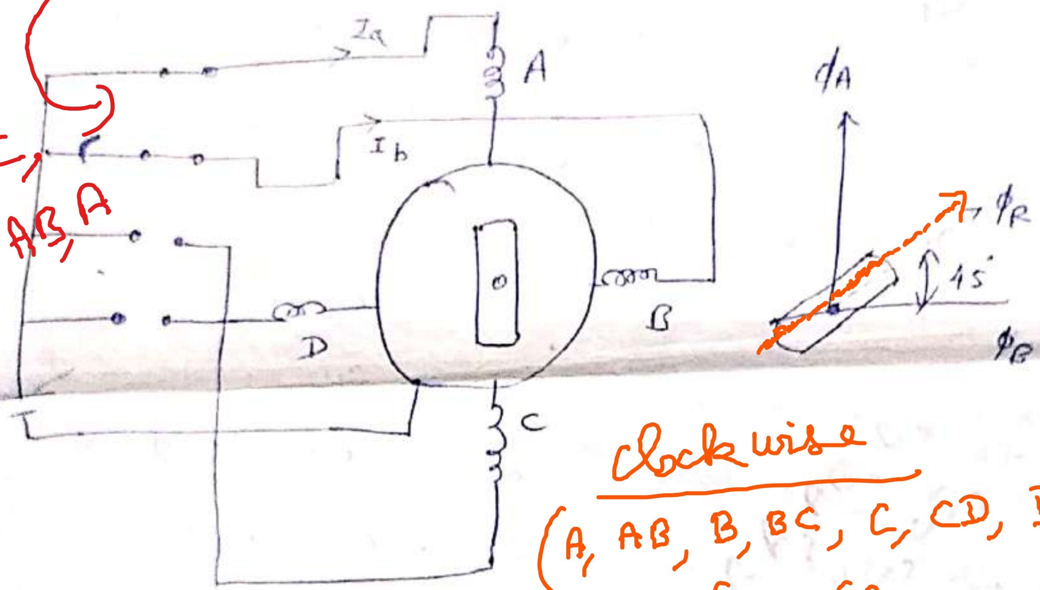
ferromagnetic Rotor

Align

clockwise rot

A, AB, B, BC, C, CD, D, DA, A

A, AD, D, DC, C, CB, B, AB, A



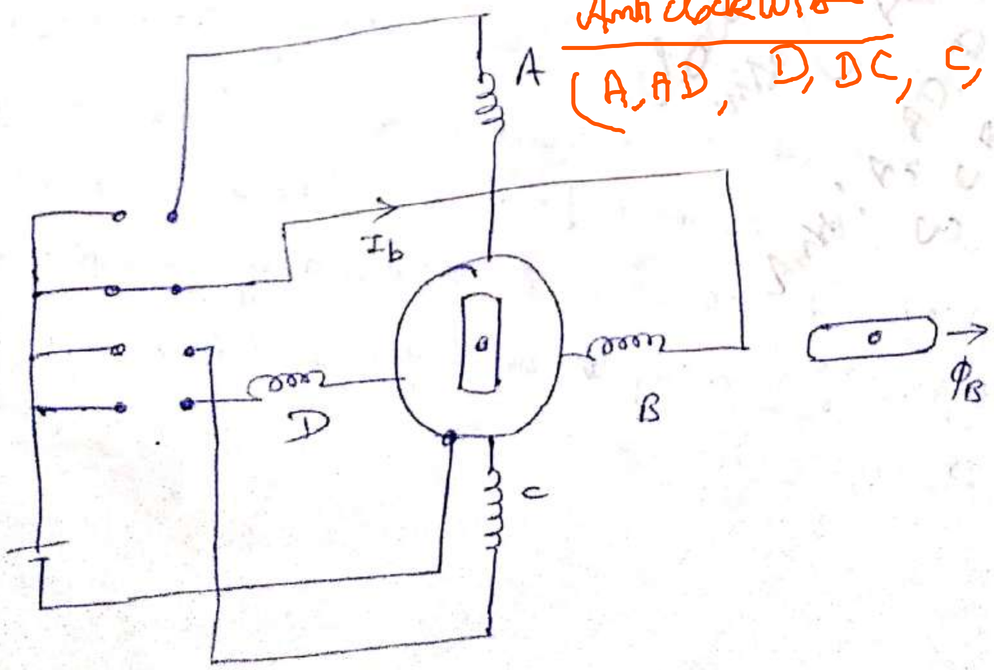
Clockwise

(A, AB, B, BC, C, CD, D, DA, A)

Sequence

Anticlockwise

(A, AD, D, DC, C, CB, B, BA)



operating modes of stepper motor for 45° step.

6

Transformers

1. GENERAL ASPECTS

Although the transformer is not classified as an electric machine, the principles of its operation are fundamental for the induction motor and synchronous machines. Since A.C. electric machines are normally built for low frequencies only the low-frequency power transformer will be considered in this text.

Function. *The function of a transformer, as the name implies, is to transform alternating current energy from one voltage into another voltage*. The transformer has *no rotating parts*, hence it is often called a *static transformer*.

When energy is transformed into a higher voltage the transformer is called a *step-up transformer* but when the case is otherwise it is called a *step-down transformer*. Most power transformers operate at constant voltage, *i.e.*, if the power varies the current varies while the voltage remains fairly constant.

Applications. A transformer performs many important functions in prominent areas of electrical engineering.

- In *electrical power engineering* the transformer makes it possible to convert electric power from a generated voltage of about 11 kV (as determined by generator design limitations) to higher values of 132 kV, 220 kV, 400 kV, 500 kV and 765 kV thus permitting transmission of huge amounts of power along long distances to appropriate distribution points at tremendous savings in the cost of transmission lines as well as in power losses.
- At *distribution points* transformers are used to reduce these high voltages to a safe level of 400/230 volts for use in homes, offices etc.
- In *electric communication circuits* transformers are used for a variety of purposes *e.g.*, as an impedance transformation device to allow maximum transfer of power from the input circuit to the output device.
- In *radio and television circuits* input transformers, interstage transformers and output transformers are widely used.

- Transformers are also used in *telephone circuits, instrumentation circuits* and *control circuits.*

2. BASIC DEFINITIONS

- A *transformer* is a *static electromagnetic device designed for the transformation of the (primary) alternating current system into another (secondary) one of the same frequency with other characteristics, in particulars, other voltage and current.*
- As a rule a transformer consists of a core assembled of sheet transformer steel and two or several windings coupled *electromagnetically*, and in the case of *autotransformer, also electrically.*
- A transformer with two windings is called *double-wound transformer* ; a transformer with three or more windings is termed a *triple wound* or *multi-winding* one.
- According to the kind of current, transformers are distinguished as single-phase, three-phase and poly-phase ones. A *poly-phase transformer winding is a group of all phase windings of the same voltage*, connected to each other in a definite way.
- **Primary and secondary windings.** The transformer winding to which the energy of the alternating current is delivered is called the *primary winding* ; the other winding from which energy is received is called the *secondary winding.*
- In accordance with the names of the windings, all quantities pertaining to the primary winding as, for example, power, current, resistance etc., are also primary, and those pertaining to the secondary winding secondary.
- **h.v. and l.v. windings.** The winding connected to the circuit with the higher voltage is called the *high-voltage winding* (h.v.), the winding connected to the circuit with the lower voltage is called the *low-voltage winding.* (l.v.). If the secondary voltage is *less* than the primary one, the transformer is called a *step-down transformer* and if *more-a step-up transformer.*
- *A tapped transformer* is one whose windings are fitted with special taps for changing its voltage or current ratio.
- **Oil and dry transformers.** To avoid the deterimental effect of the air on the winding insulation and improve the cooling conditions of the transformer its core together with the windings assembled on it is immersed in a tank filled with transformer oil. Such transformers are called **oil transformers**. Transformers not immersed in oil are called **dry transformers.**

3. WORKING PRINCIPLE OF A TRANSFORMER

A transformer operates on the principle of *mutual inductance,* between two (and sometimes more) inductively coupled coils. It consists of two windings in close proximity as shown in Fig. 1. *The two windings are coupled by magnetic induction.* (There is no conductive connection between the windings). One of the windings called *primary* is energised by a sinusoidal voltage. The second winding, called *secondary* feeds the load. The alternating current in the primary winding sets up an alternating flux (ϕ) in the core. The secondary winding is linked by most of this flux and e.m.fs are induced in the two windings. The e.m.f. induced in the secondary winding drives a current through the load connected to the winding. Energy is transferred from the primary circuit to the secondary circuit through the medium of the magnetic field.

In brief, a transformer is a *device* that :

(*i*) *transfers electric power from one circuit to another ;*

(*ii*) *it does so without change of frequency ; and*

(*iii*) *it accomplishes this by electromagnetic induction (or mutual inductance).*

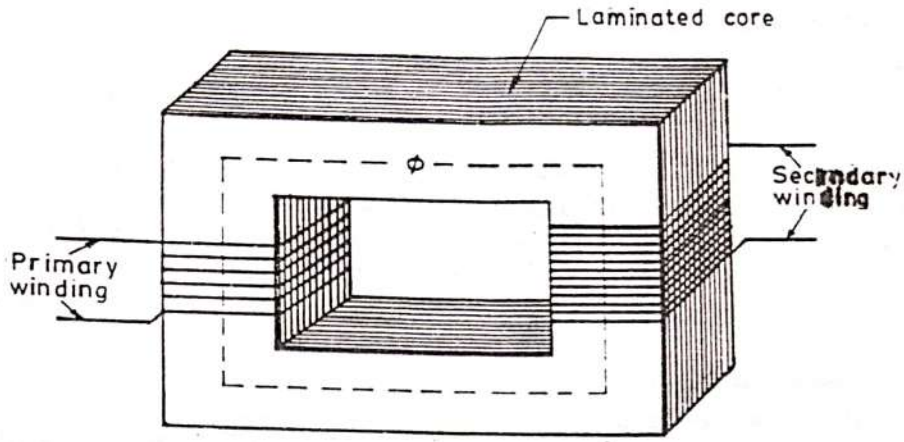


Fig. 1. Two-winding transformer.

4. TRANSFORMER RATINGS

The rated quantities of a transformer, its power, voltage, frequency, etc. are given in Manufacturer's name plate, which should always be arranged so as to be accessible. But the term 'rated' can also be applied to quantities not indicated on the name plate, but relating to the rated duty, as for example, the rated efficiency, rated temperature conditions of the cooling medium, etc. :

- *The rated duty* of a transformer is determined by the quantities given in the name plate.
- The *rated power* of the transformer is the power at the secondary terminals, indicated in the name plate and expressed in kVA.
- *The rated primary voltage* is the voltage indicated in the transformer name plate ; if the primary is provided with taps, the rated tapped voltage is specially noted.
- *The rated secondary voltage* is the voltage across the transformer *secondary terminals at no-load* and with the rated voltage across the primary terminals ; if the secondary winding has taps, then their rated voltage is specially indicated.
- *The rated currents of the transformer*, primary and secondary, are the currents indicated in the name plate of the transformer and calculated by using the corresponding rated values of power and voltage.

5. KINDS OF TRANSFORMERS

The following kinds of transformers are the most important ones :

1. **Power transformers.** *For the transmission and distribution of electric power.*

2. **Auto-transformers.** *For converting voltages within relatively small limits to connect power systems of different voltages, to start A.C. motors etc.*

3. **Transformer for feed installations with static convertors.** (Mercury arc rectifiers, ignitrons, semi-conductor valves, etc.) *When converting A.C. into D.C.* (rectifying) *and converting D.C. into A.C. (inverting).*

4. **Testing transformers.** *For conducting tests at high and ultra-high voltages.*

5. **Power transformers for special applications.** Furnace, welding etc.

6. **Radio-transformers.** *It is used in radio engineering etc.*

Note. *Distribution transformers* should be designed to have maximum efficiency at a load much *lower than full-load (about 50 per cent).*

Power transformers should be designed to have maximum efficiency *at or near full-load.*

6. TRANSFORMER CONSTRUCTION

All transformers have the following essential elements :

1. Two or more **electrical windings** insulated from each other and from the core (except in auto-transformers).

2. A **core,** which in case of a single-phase distribution transformers usually comprises *cold-rolled silicon-steel strip* instead of an assembly of punched silicon-steel laminations such as are used in the larger power-transformer cores. The *flux path in the assembled core is parallel to the directions of steel's grain or 'orientation'.* This results in a *reduction in core losses* for a given flux density and frequency, or *it permits the use of higher core densities* and *reduced size of transformers for given core losses.*

Other necessary parts are :

- A *suitable container* for the assembled core and windings.
- A *suitable medium* for insulating the core and its windings from each other and from the container.
- Suitable *bushings* for insulating and bringing the terminals of the windings out of the case.

The two basic types of transformer construction are :

1. *The core type.*
2. *The shell type.*

The above two types differ in their relative arrangements of copper conductors and the iron cores. In the *'core type'*, the *copper virtually surrounds the iron core*, while *in the 'shell type'*, *the iron surrounds the copper winding*.

6.1. Core Type Transformer. The completed magnetic circuit of the core-type transformer is in the shape of the hollow rectangle, exactly as shown in Fig. 2 in which I_0 is the no-load current and ϕ is the flux produced by it. N_1 and N_2 are the number of turns on the primary and secondary sides respectively.

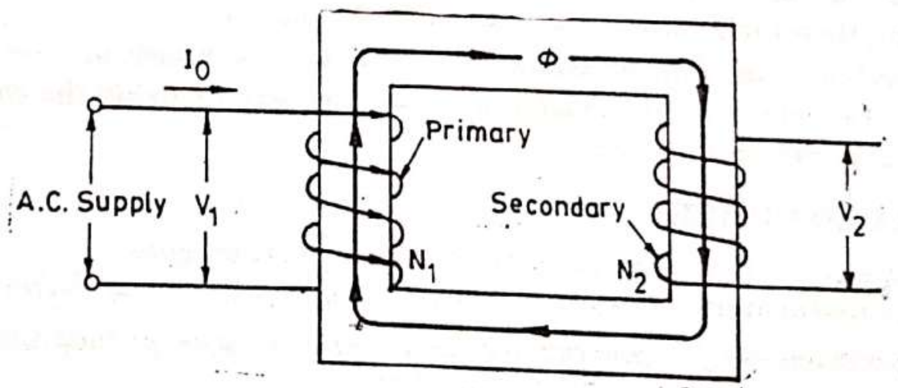


Fig. 2. Magnetic circuit of a core-type transformer.

The core is made up of *silicon-steel laminations* which are, either rectangular or L-shaped. With the coils wound on two legs the appearance is that of Fig. 3. If the two coils shown were the respective high and low-side coils as in Fig. 3, the *leakage reactance would be much too great.* In order to provide maximum *linkage* between windings, the group on *each leg is made up of both high-tension and low-tension coils.* This may be seen in Fig. 4, where a cross-sectional cut is taken across the legs of the core. By placing the high-voltage winding around the low-voltage winding, only one layer of high-voltage insulation is required, that between the two coils. ***If the high-voltage coils were adjacent to the core, an additional high-voltage insulation layer would be necessary between the coils and the iron core.***

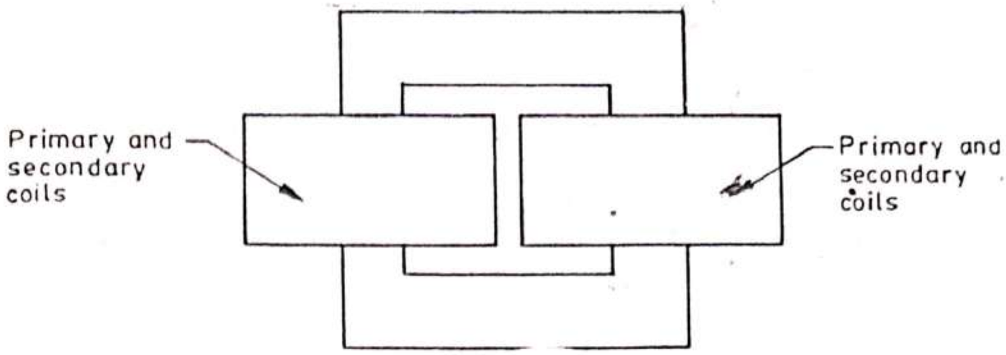


Fig. 3. Core-type transformer.

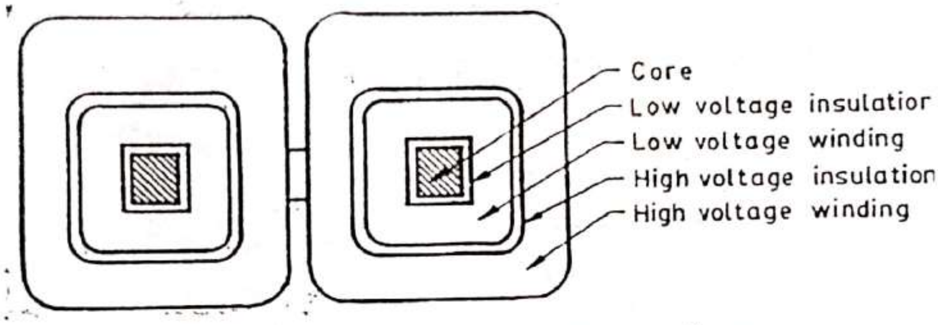


Fig. 4. Cross-section of a core-type transformer.

Fig. 5 shows the coils and laminations of a core-type transformer with a cruciform core and circular coils.

- Fig. 6 shows *the different types of cores used in core type transformers.*

Rectangular cores [Fig. 6 (*a*)] with rectangular cylindrical coils can be used for small size core-type transformers. For large size transformers it becomes wasteful to use rectangular cylindrical coils and so circular cylindrical coils are preferred. For such purposes, '*square cores*' may be used as shown in Fig. 6 (*b*) where circles represent the tubular former carrying the coils. Evidently a considerable amount of useful space is still wasted. A common improvement on the square core is to employ a '*cruciform core*' [Fig. 6 (*c*)] which demands, atleast, two sizes of core strips. For *very large transformers*, further core stepping is done as in Fig. 6 (*d*) where atleast three sizes of core plates are necessary. *Core stepping not only gives high space factor but also results in reduced length of the mean turn and the consequent I^2R loss. Three stepped core is the most commonly* used although more steps may be used for very large transformers as shown in Fig. [6 (*e*)].

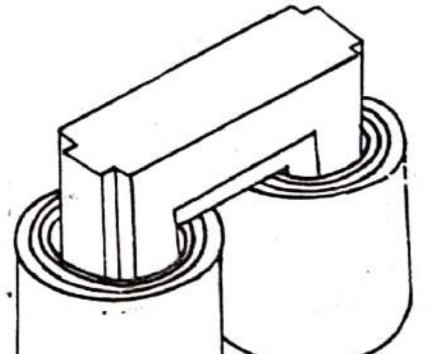


Fig. 5. Coils and laminations of a core-type transformer.

6.2. Shell-Type Transformer. In the shell-type construction the iron almost entirely surrounds the copper (Fig. 7). The core is made up of E-shaped or F-shaped laminations which are stacked to give a rectangular figure eight. All the windings are placed on the centre leg, and in order to reduce leakage, each high-side coil is adjacent to a low-side coil. The coils actually occupy the entire space of both windows, are flat or pencake in shape, and are usually constructed of strip copper. Again, *to reduce the amount the high-voltage insulation required, the low-voltage coils are placed adjacent to the iron core.*

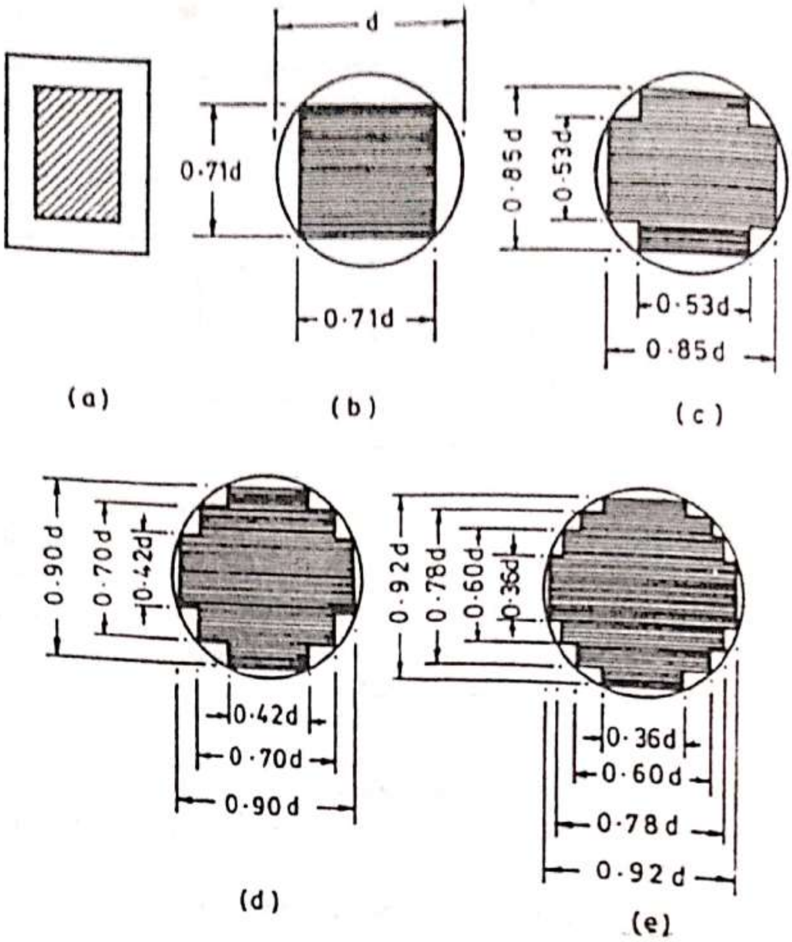


Fig. 6. Various types of cores.

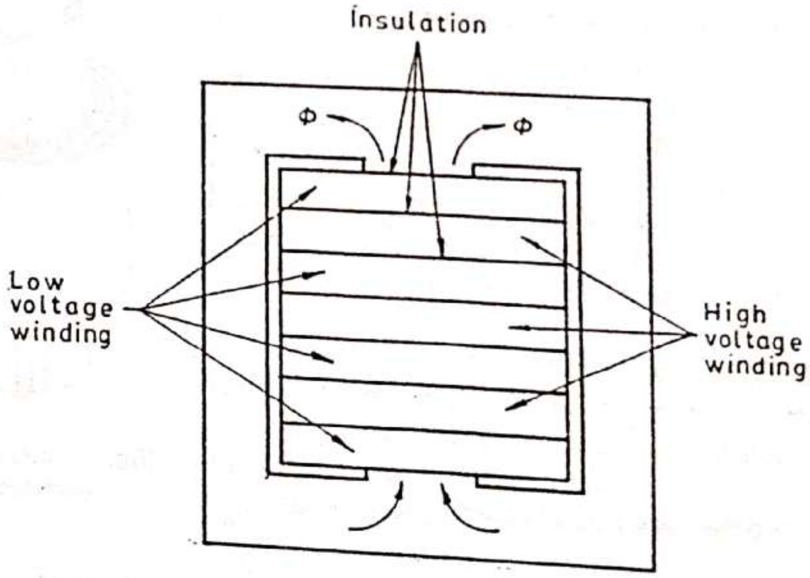


Fig. 7. Shell-type transformer.

Fig. 8 shows the coils and laminations of a typical shell-type transformer.

Choice of Core- or Shell-Type Construction. In general, the core-type has a longer mean length of core and a shorter mean length of coil turn. The core type also has a smaller cross-section of iron and so will need a greater number of turns of wire, since, in general, not as high a flux may be reached in the core. However, *core type is better adopted for some high-voltage service since there is more room for insulation*. The *shell-type has better provision for mechanically supporting and*

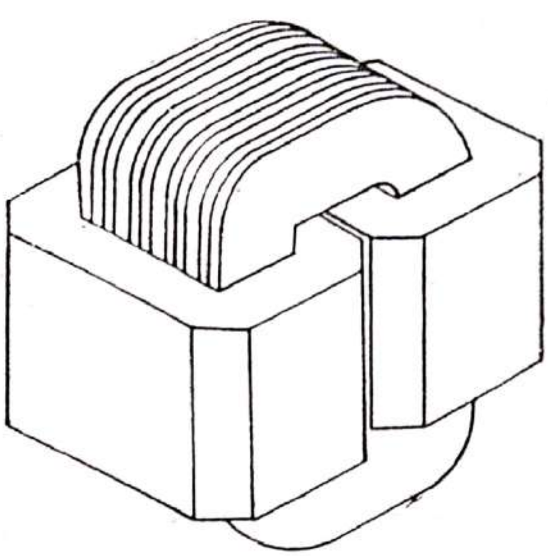


Fig. 8. Coils and laminations of a shell-type transformer.

bracing the coils. This allows better resistance to the very high mechanical forces that develop during a high-current short circuit.

The choice of core- or shell-type construction is usually one of *cost*, for similar characteristics can be obtained with both types.

Both core and shell forms are used, and selection is based upon many factors such as voltage rating, kVA rating, weight, insulation stress, mechanical stress, and heat distribution.

6.3. Spiral Core Transformer. The typical spiral core is shown in Fig. 9. The core is assembled either of a *continuous* strip of transformer steel wound in the form of a circular or elliptical cylinder or of a group of short strips assembled to produce the same elliptical-shaped core. By using this construction the core flux always follows along the grain of the iron. Cold-rolled steel of high silicon content enables the designer to use higher operating flux densities with lower loss per kg. *The higher flux density reduces the weight per kVA.*

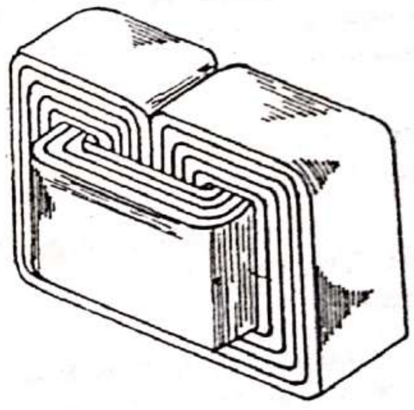


Fig. 9. Spiral-core transformer.

7. TRANSFORMER WINDINGS—TERMINALS, TAPPINGS AND BUSHINGS

7.1. Transformer Windings. The most important requirements of transformer windings are :

1. The winding should be *economical both as regards initial cost*, with a view to the market availability of copper, and the efficiency of the transformer in service.

2. The heating conditions of the windings should *meet standard requirements*, since departure from these requirements towards allowing higher temperature will drastically shorten the service life of the transformer.

3. The winding should be *mechanically stable* in respect to the forces appearing when sudden short circuit of the transformer occur.

4. The winding should ha ve the *necessary electrical strength in respect to over voltages.*

The different *types of windings* are *classified* and briefly discussed below :

1. Concentric windings :

(*i*) Cross-over (*ii*) Helical

(*iii*) Disc.

2. Sandwich windings

1. Concentric windings. Refer Fig. 10. These windings are *used for core type transformers.* Each limb is wound with a group of coils consisting of both primary and secondary turns which may be concentric cylinders. The l.v. winding is placed next to the core and h.v. winding on the outside. But the two windings can be sub-divided, *and interlaced with high tension and low tension section alternately to reduce leakage reactance.* These windings can be further divided as follows :

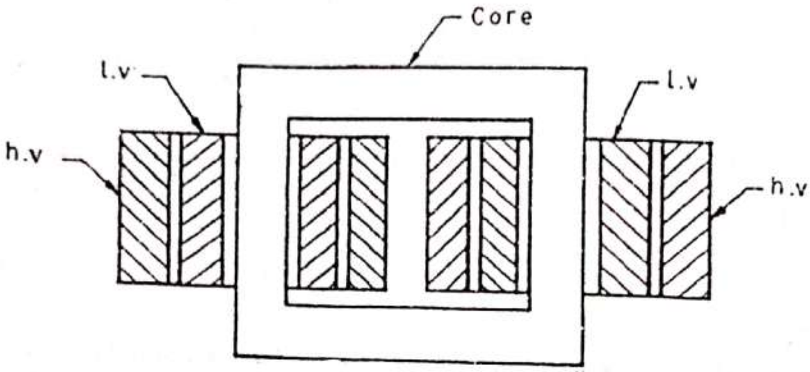


Fig. 10. Concentric coils.

(*i*) **Cross-over windings.** Cross-over windings are used for currents up to 20 A and so they are suitable for h.v. winding of small transformers. The conductors are either cotton covered round wires or strips insulated with paper. Cross-over coils are wound over formers and each coil consists of a number of layers with a number of turns per layer. The complete winding consists of a number of coils connected in series. Two ends of each coil are brought out, one from inside and one from outside. The inside end of a coil is connected to the outside end of the adjacent coil.

(*ii*) **Helical winding.** A helical winding consists of rectangular strips wound in the form of a helix. The strips are wound in parallel radially and each turn occupies the total radial depth of winding.

Helical coils are well suited for *l.v. windings of large transformers*. They can also be used for h.v. windings by putting extra insulation between layers in addition to insulation of conductors.

(*iii*) **Continuous disc winding.** This type of winding consists of a number of flat strips wound spirally from inside (radially) outwards. The conductor is used in such lengths as are sufficient for complete winding or section of winding between tappings. The conductor can either be a single strip or a number of strips in parallel, wound on the flat. This gives a robust construction for each disc. The discs are wound on insulating cylinders spaced from it by strips along the length of cylinder. The discs are separated from each other with press board sectors attached to the vertical strips. The vertical and horizontal spacers provide ducts for free circulation of oil which is in contact with every turn.

2. Sandwich coils. Sandwich coils (Fig. 11) are employed in transformers of *shell-type.* Both high and low voltage windings are split into a number of sections. Each high voltage section lies between the low voltage sections.

The *advantage of sandwich coils is that their leakage can be easily controlled and so any desired value of leakage reactance can be had by the division of windings.*

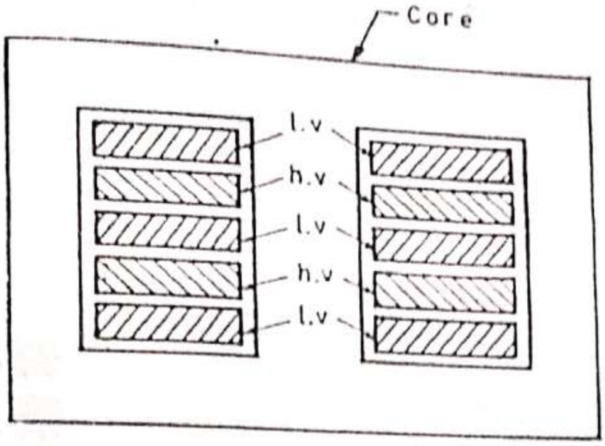


Fig. 11. Sandwich coils.

7.2. Terminals and Leads. The connection to the windings are of insulated copper rods or bars. The shape and size of leads is important in high voltage transformers owing to dielectric stress and corona which are caused at bends and corners. Connections from windings are directly taken to the busbars in the case of air-cooled transformers while they are taken to insulated bushings in the case of oil-cooled transformers.

7.3. Tappings. In a supply network the voltage can be controlled by changing the transformation ratio. This can be done by tapping the winding in order to alter the number of turns. The change in number of turns may be effected when the transformer is out of circuit (known as off load tap changing) or when on load (known as on load tap changing). *The tappings are provided on the high voltage winding because a fine voltage variation is obtained owing to large number of turns. It is difficult to obtain voltage variation within close percentage limits in low voltage winding as there are few turns and voltage per turn is a large percentage of the total voltage.*

In transformers, the tappings can be provided at :

(*i*) phase ends ; and

(*ii*) neutral point or in the middle of the windings.

- The advantage of providing tappings at *phase ends* is that the number of bushing insulators is reduced, this is important where the cover space is limited. Some transformers have reinforced insulation at the phase ends. It is essential that in such cases either the tapping should not be provided at end turns or the reinforcement should be carried beyond the lower tap.
- When the tappings are made at the *neutral point* the insulation between various parts is small. *This arrangement is economical especially in the case of high voltage transformers.*

7.4. Bushings. The bushings are *employed for insulating and bringing out terminals of the winding from the container to the external circuit.* For low-voltage transformers this is accomplished by employing *bushings of porcelain around the conductor at the point of entry.* For high voltages it is necessary to employ bushings of larger sizes. In modern transformers the problem is met by using *large porcelain or composition bushings for voltages as high as 33 kV, above that oil filled* or *condenser type bushings are used.*

8. TRANSFORMER COOLING

8.1. Cooling Methods. The transformers get heated due to iron and copper losses occurring in them. It is necessary to dissipate this heat so that the temperature of the windings is kept below the value at which the insulation begins to deteriorate. *The cooling of transformers is more difficult than that of rotating machines because the rotating machines create a turbulent air flow which assists in removing the heat generated due to losses.* Luckily the losses in transformers are comparatively small. Nevertheless the elaborate cooling arrangements have been devised to deal with the whole range of sizes.

As far as cooling methods are concerned, the transformers are of following two types :

1. Dry type.
2. Oil immersed type.

Dry Type Transformers. Small transformers upto *25 kVA size* are of the *dry type* and have the following cooling arrangements :

(*i*) **Air natural.** In this method the natural circulation of surrounding air is utilized to carry away the heat generated by losses. A sheet metal enclosure protects the winding from mechanical injury.

(*ii*) **Air blast.** Here the transformer is cooled by a continuous blast of cool air forced through the core and windings (Fig. 12). The blast is produced by a fan. The air supply must be filtered to prevent accumulation of dust in ventilating ducts.

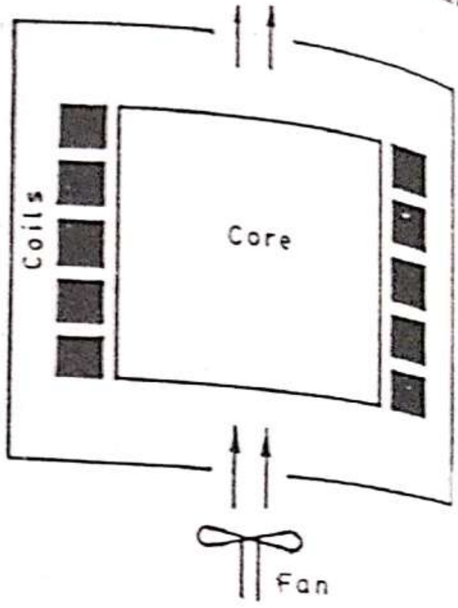


Fig. 12

Oil Immersed Transformers. In general most transformers are of oil immersed types. The *oil provides better insulation than air and it is a better conductor of heat than air*. Mineral oil is used for this purpose.

Oil immersed transformers are classified as follows :

(*i*) **Oil immersed self-cooled transformers.** The transformer is immersed in oil and heat generated in cores and windings is passed to oil by conduction. Oil in contact with heated parts rises and its place is taken by cool oil from the bottom. The natural oil transfers its heat to the tank walls from where heat is taken away by the ambient air. The oil gets cooler and falls to the bottom from where it is dissiptated into the surroundings. The tank surface is the best dissipator of heat but a plain tank will have to be excessively large, if used without any auxiliary means for high rating transformers. As both space and oil are costly, these auxiliary means should not increase the cubic capacity of the tank. The heat dissipating capacity can be increased by providing (*i*) corrugations, (*ii*) fins, (*iii*) tubes (Fig. 13) and (*iv*) radiator tanks.

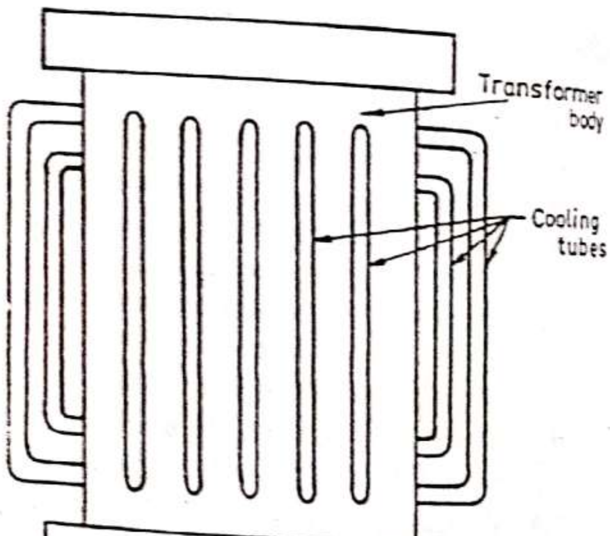


Fig. 13. Transformer with cooling tubes.

The *advantages of 'oil natural' cooling is that it does not clog the ducts and the windings are free from effects of moisture.*

(*ii*) **Oil immersed forced air-cooled transformers.** In this type of cooling, air is directed over the outer surfaces of the tank of the transformer immersed in oil.

(*iii*) **Oil immersed water-cooled transformers.** Heat is extracted from the oil by means of a stream of water pumped through a metallic coil immersed in the oil just below the top of the tank. The heated water is in turn cooled in a spray pond or a cooling tower.

(*iv*) **Oil immersed forced oil cooled transformers.** In such transformers heat is extracted from the oil by pumping the oil itself upward through the winding and then back by way of external radiators which may themselves be cooled by fans. The *extra cost of oil pumping equipment must of* *course be economically justified but it has incidentally the advantage of reducing the temperature difference between the top and bottom of enclosing tank.*

Fig. 14 shows the cooling of transformers having capacities from 10000 kVA and higher. In such cases air blast cooling of radiator is used.

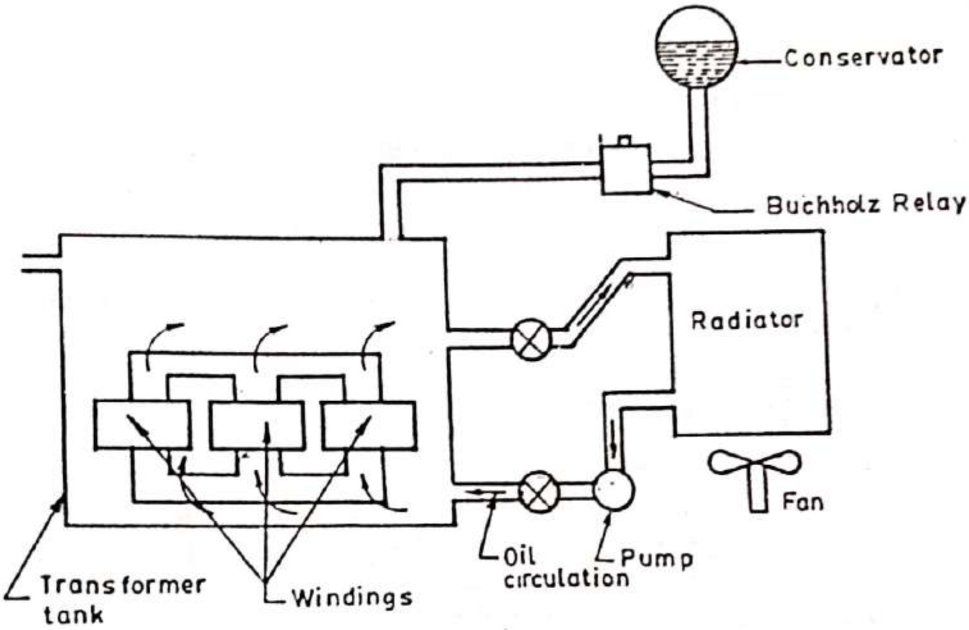


Fig. 14. Air blast cooling of radiator.

8.2. Transformer Oil. It is a *mineral oil obtained by refining crude petroleum*. It serves the following *purposes* :

(*i*) Provides additional insulation.

(*ii*) Carries away the heat generated in the core and coils.

(*iii*) Protects the paper from dirt and moisture.

The transformer oil should possess the following *properties* :

1. High dielectric strength.
2. Low viscosity to provide good heat transfer.
3. Good resistance to emulsion.
4. Free from inorganic acid, alkali and corrosive sulphur.
5. Free from sludging under normal operating conditions.
6. High flash/fire point.

8.3. Conservator and Breather

Conservator. The oil should not be allowed to come in contact with atmospheric air as it may take up moisture which may spoil its insulating properties. Also air may cause acidity and sludging of oil. To prevent this, many transformers are provided with conservators. The *function of a conservator (Fig. 14) is to take up contraction and expansion of oil without allowing it to come in contact with outside air*. The conservator consists of an air tight metal-drum fixed above the level of the top of the tank and connected with it by a pipe. The main tank is completely filled with oil when cold. The *conservator is partially filled with oil*. So the oil surface in contact with air is greatly reduced. The sludge thus formed remains in the conservator itself and does not go to the main tank.

Breather. When the temperature changes, the oil expands or contracts and there is a displacement of air. When the transformer cools, the oil level goes down, and air is drawn in. This is known as *breathing*. The air, coming in, is passed through an apparatus called *breather* for the purpose of extracting moisture. The *breather consists of a small vessel which contains a drying agent like silica get crystal impregnated with cobalt crystal.*

Note. *Sludging* means the slow formation of solid hydrocarbons due to heating and oxidation. The sludge deposit itself on the windings and cooling ducts producing overheating. This makes transformer still hotter producing more sludge. This process may continue till the transformer becomes unusable due to overheating. So the contact of oil with air should be avoided as the air contains oxygen.

9. SINGLE PHASE TRANSFORMER

9.1. Elementary Theory of an Ideal Transformer. The basic theory of a transformer is not difficult to understand. To simplify matters as much as possible, let us first consider an *ideal transformer*, that is, *one in which the resistance of the windings is negligible and the core has no losses*.

Let the secondary be open (Fig. 15), and let a sine wave of potential difference v_1 (Fig. 16) be impressed upon the primary. The impressed potential difference causes an alternating current to

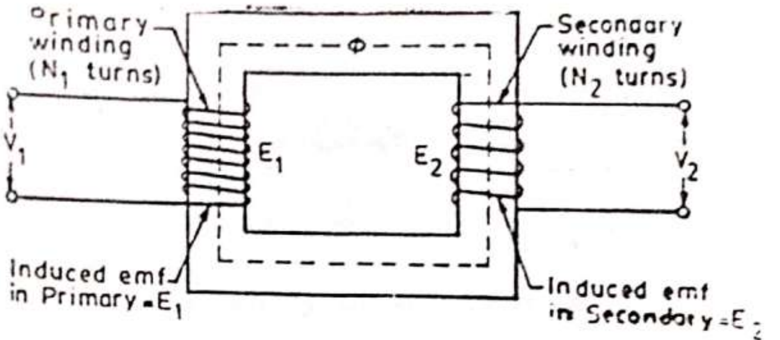


Fig. 15. Elementary diagram of an ideal transformer with an open secondary winding.

flow in the primary winding. Since the primary resistance is negligible and there are no losses in the core, the effective resistance is zero and the circuit is purely reactive. Hence the current wave i_m lags the impressed voltage wave v_1 by 90 time degrees, as shown in Fig. 17. The reactance of circuit is very high and the magnetizing current is very small. This current in the N_1 turns of the primary magnetizes the core and produces a flux ϕ that is at all times proportional to the current (if the permeability of the circuit is assumed to be constant), and therefore in time phase with the current. The flux, by its rate of change, induces in the primary winding E_1 which at every instant of time is equal in value and opposite in direction to V_1. It is called *counter e.m.f.* of the primary. The value which the primary current attains must be such that the flux which it produces in the core is of sufficient value to induce in the primary the required counter e.m.f.

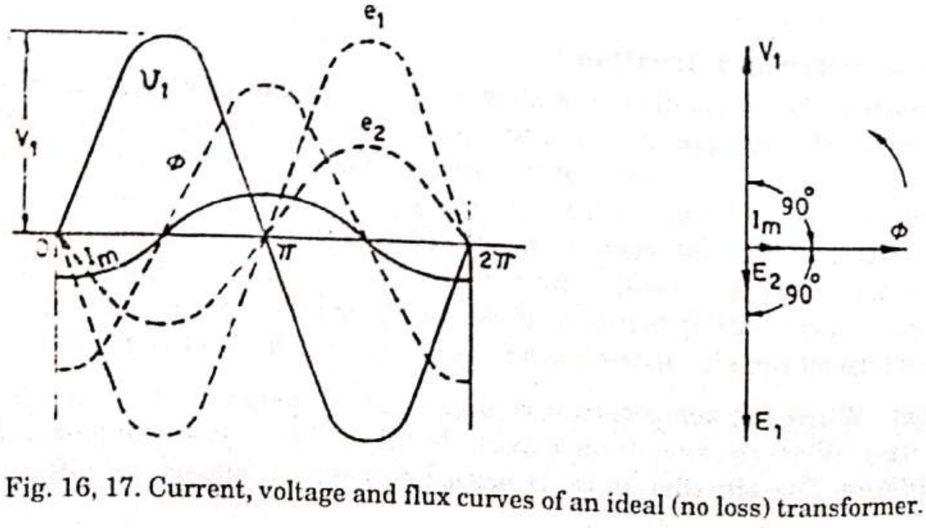


Fig. 16, 17. Current, voltage and flux curves of an ideal (no loss) transformer.

Since the flux also threads (or links) the secondary winding a voltage e_2 is induced in the secondary. This voltage is likewise proportional to the rate of change of flux and so is in time phase with e_1, but it may have any value depending upon the number of turns N_2 in the secondary.

9.2. E.M.F. Equation of a Transformer

Let N_1 = number of turns in primary,

N_2 = number of turns in secondary,

ϕ_m = maximum flux in the core, Wb.

$= B_m \times A$, [where B_m is the maximum flux density in the core and A is the core area], and

f = frequency of a.c. input, Hz.

Refer Fig. 18. Since the flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle *i.e.*, in $\frac{T}{4}$ or $\frac{1}{4f}$ second (T being time-period of the cycle),

$\therefore$ Average rate of change of flux

$$= \frac{\phi_m}{\frac{1}{4f}} = 4f\phi_{max} \text{ Wb/s or volt}$$

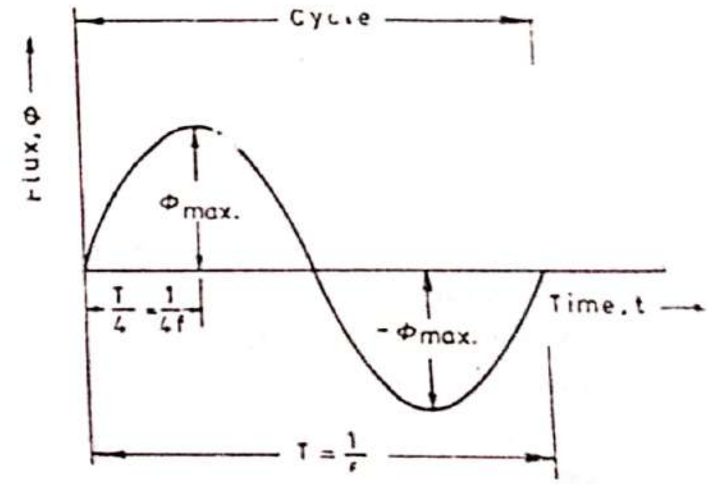


Fig. 18

If flux ϕ varies *sinusoidally*, then r.m.s. (root mean square) value of inducted e.m.f. is obtained by multiplying the average value with form factor.

But, form factor $= \frac{\text{r.m.s. value}}{\text{average value}} = 1.11$

$\therefore$ r.m.s. value of e.m.f./turn

$$= 1.11 \times 4f\phi_{max} = 4.44f\phi_{max} \text{ volt}$$

Now, r.m.s. value of induced e.m.f. in the whole of primary winding,

$$E_1 = 4.44f\phi_{max} N_1 \qquad ...(1)$$

Similarly r.m.s. value of induced e.m.f. in secondary is,

$$E_2 = 4.44f\phi_{max} N_2 \qquad ...(2)$$

In an ideal transformer on no-load $V_1 = E_1$ and $V_2 = E_2$ (Fig. 15).

9.3. Voltage Transformation Ratio (K). The *transformation ratio is defined as the ratio of the secondary voltage to primary voltage*. It is denoted by the letter K.

From eqns. (1) and (2), $$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \qquad ...(3)$$

- If $N_2 > N_1$ *i.e.*, $K > 1$, then transformer is called *step-up transformer*.
- If $N_2 < N_1$ *i.e.*, $K < 1$, then transformer is called *step-down transformer*.

Again for an *ideal transformer*

$$\text{Input } (VA) = \text{Output } (VA)$$

$$V_1 I_1 = V_2 I_2 \text{ or } E_1 I_1 = E_2 I_2$$

or $$\frac{I_2}{I_1} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{1}{K} \qquad ...(4)$$

i.e., Primary and secondary currents are inversely proportional to their respective turns.

Example 1. *A 40 kVA, single phase transformer has 400 turns on the primary and 100 turns on the secondary. The primary is connected to 2000 V, 50 Hz supply. Determine :*

(*i*) *The secondary voltage on open circuit.*

(*ii*) *The current flowing through the two windings on full-load.*

(*iii*) *The maximum value of flux.*

Solution. Rating $= 40$ kVA

Primary turns, $N_1 = 400$

Secondary turns, $N_2 = 100$

Primary induced voltage, $E_1 = V_1 = 2000$ V

(*i*) **Secondary voltage on open, circuit $\mathbf{V_2}$:**

Using the relation, $$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$$E_2 = E_1 \times \frac{N_2}{N_1}$$

$\therefore$ $$E_2 = V_2 = 2000 \times \frac{100}{400} = 500 \text{ V}$$

Hence, $\mathbf{V_2 = 500\ V.}$ **(Ans.)**

(*ii*) **Primary current, $\mathbf{I_1}$:**

Secondary current, $\mathbf{I_2}$:

Primary full-load current, $$I_1 = \frac{\text{kVA} \times 100}{V_1} = \frac{40 \times 1000}{2000} = \mathbf{20\ A.}\ \textbf{(Ans.)}$$

Secondary full-current, $$I_2 = \frac{\text{kVA} \times 1000}{V_2} = \frac{40 \times 1000}{500} = \mathbf{80\ A}\ \textbf{(Ans.)}$$

(*iii*) **Maximum value of flux, ϕ_{max} :**

Using e.m.f. equation, $$E_1 = 4.44 f \phi_{max} N_1$$

$\therefore$ $$2000 = 4.44 \times 50 \times \phi_{max} \times 400$$

$\therefore$ $$\phi_{max} = \frac{2000}{4.44 \times 50 \times 400} = 0.0225 \text{ Wb.}$$

Hence, $\phi_{max} = \mathbf{0.0225\ Wb.}$ **(Ans.)**

Example 2. *The no-load ratio required in a single-phase 50 Hz transformer is 6600/600 V. If the maximum value of flux in the core is to be about 0.08 Wb, find the number of turns in each winding.*

Solution. Primary, $E_1 = V_1 = 6600$ V

Secondary, $E_2 = V_2 = 600$ V

Maximum value of flux $\phi_{max} = 0.08$ Wb.

Primary turns, $\mathbf{N_1}$:

Secondary turns, $\mathbf{N_2}$:

Using the relation, $$E_1 = 4.44 f \phi_{max} N_1$$

$$6600 = 4.44 \times 50 \times 0.08 \times N_1$$

$\therefore$ $$N_1 = \frac{6600}{4.44 \times 50 \times 0.08} \simeq 372$$

Hence, $\mathbf{N_1 = 372.}$ **(Ans.)**

Also $$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$\therefore$ $$N_2 = \frac{E_2 N_1}{E_1} = \frac{600 \times 372}{6600} = 34$$

Hence, $\mathbf{N_2 = 34.}$ **(Ans.)**

Example 3. *A single-phase transformer is connected to a 230 V, 50 Hz supply. The net cross-sectional area of the core is 60 cm². The number of turns in the primary is 500 and in the secondary 100. Determine :*

(i) Transformation ratio. *(ii) E.m.f. induced in secondary winding.*

(iii) Maximum value of flux density in the core.

Solution. Primary turns, $N_1 = 500$

Secondary turns, $N_2 = 100$

Primary, $E_1 = V_1 = 230$ V

Core area, $a = 60 \text{ cm}^2 = 60 \times 10^{-4} \text{ m}^2$

(i) **Transformation ratio, K :**

$$K = \frac{N_2}{N_1} = \frac{100}{500} = 0.2$$

Hence, $\mathbf{K = 0.2.}$ **(Ans.)**

(ii) **Maximum value of flux density, $\mathbf{B_{max}}$:**

Using the e.m.f. equation, $$E_1 = 4.44 f \phi_{max} N_1$$

$\therefore$ $$230 = 4.44 \times 50 \times \phi_{max} \times 500$$

$$\phi_{max} = \frac{230}{4.44 \times 50 \times 500} = 0.00207 \text{ Wb}$$

Now, $$B_{max} = \frac{\phi_{max}}{A} = \frac{0.00207}{60 \times 10^{-4}} = 0.345 \text{ T}$$

[where T stands for tesla (Wb/m²)]

Hence, $\mathbf{B_{max} = 0.345}$ **T. (Ans.)**

(iii) **E.m.f. induced in the secondary winding, $\mathbf{E_2}$:**

Using the relation, $$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$$\frac{E_2}{230} = \frac{100}{500}$$

$\therefore$ $\mathbf{E_2 = 46}$ **V. (Ans.)**

Example 4. *3300/300 V single-phase 300 kVA transformer has 1100 primary turns. Find :*

(i) Transformation ratio. *(ii) Secondary turns.*

(iii) Voltage/turn.

(iv) Secondary current when it supplies a load of 200 kW at 0.8 power factor lagging.

Solution. Primary, $E_1 = 3300$ V

$N_1 = 1100$

Secondary, $E_2 = 300$ V

Rating of the transformer $= 300$ kVA

Output $= 200$ kW

4

Direct Current (D.C.) Machines

1. CONSTRUCTION OF D.C. MACHINES

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*

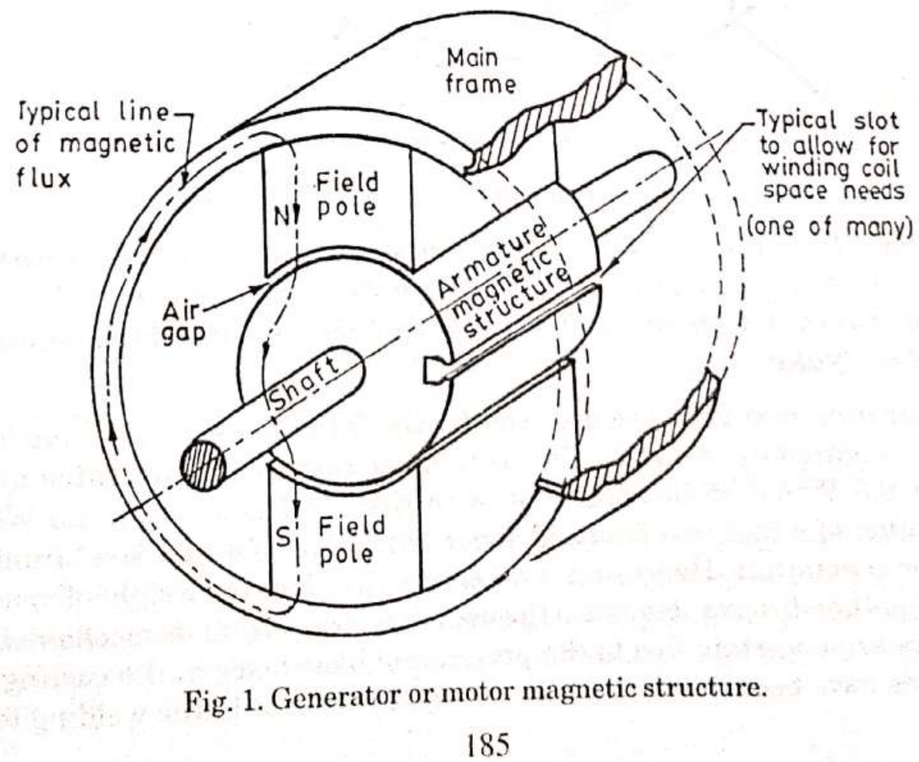


Fig. 1. Generator or motor magnetic structure.

ensure sparkless 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 *armature* is a cylindrical body rotating in the space between the poles and comprising a *slotted armature core*, a *winding* inserted in the armature core slots, a *commutator*, and *brush gear*.

Fig. 1 shows generator or motor magnetic structure.

Description of Parts of D.C. Machines :

1.1. Frame. Fig. 2 shows the sectional view of four pole D.C. machine.

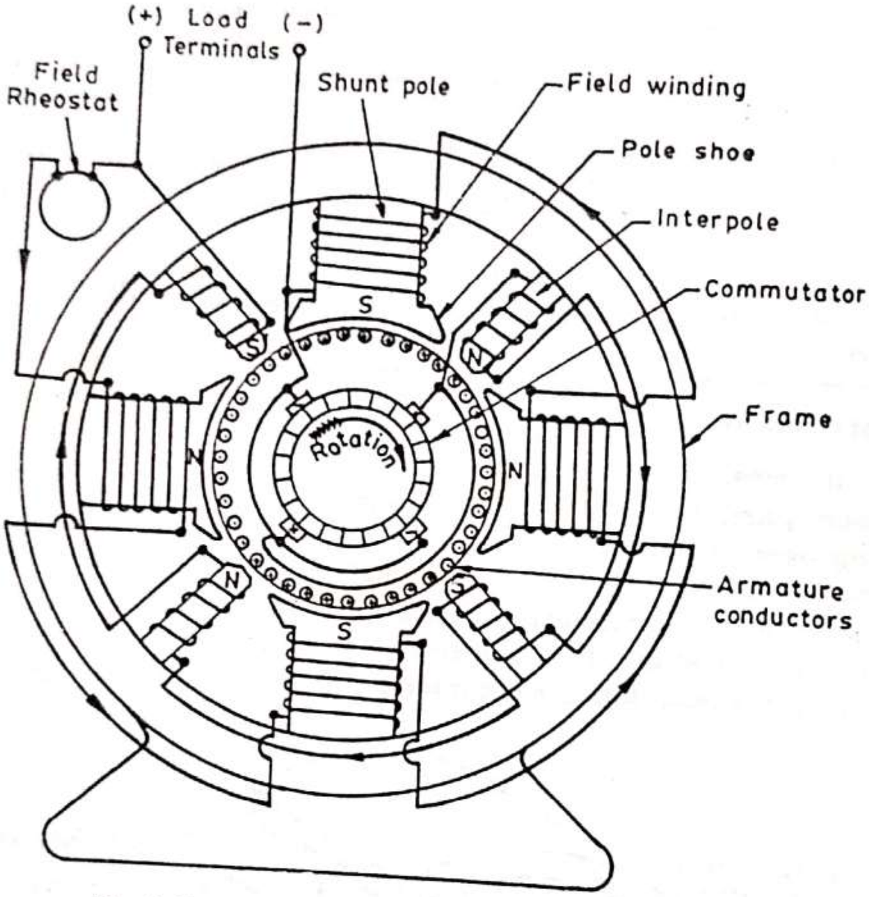


Fig. 2. Sectional view of a four pole D.C. machine.

- *The frame is the stationary part of a machine to which are fixed the main and commutating poles and by means of which the machine is bolted to its bed plate.*
- *The ring-shaped portion which serves as the path for the main and commutating pole fluxes is called the* '**yoke**'.

Cast iron used to be the material for the frame/yoke in *early machines* but now it has been *replaced by cast steel.* This is because cast iron is saturated by a flux density of about 0.8 Wb/m^2 while saturation with cast steel is at about 1.5 Wb/m^2. Thus the cross-section of a cast iron frame is about twice that of a cast steel frame for the same value of magnetic flux. Hence, if it is necessary to reduce the weight of machine, cast steel is used. Another disadvantage with the use of cast iron is that its mechanical and magnetic properties are uncertain due to the presence of blow holes in the casting. Lately, rolled steel yokes have been developed with the improvements in the welding techniques. The *advantages of fabricated yokes are that there are no pattern charges and the magnetic and mechanical properties of the frame are absolutely consistent.*

It may be advantageous to use cast iron for frames but for medium and large sizes usually rolled steel is used.

- If the armature diameter does not exceed 35 to 45 cm, then, in addition to the poles, end shields or frame-heads which carry the bearings are also attached to the frame. When the armature diameter exceeds 1 m, it is common practice to use pedestal-type bearings, mounted separately, on the machine bed plate outside the frame.
- The end shield bearings, and sometimes the pedestal bearings, are of ball or roller type. However, more frequently plain pedestal bearings are used.
- In machines with large diameter armatures a brush-holder yoke is frequently fixed to the frame.

1.2. Field Poles

- Formerly the poles were cast integral with the yoke. This practice is still being followed for small machines. But in present day machines *it is usual to use either a completely laminated pole, or solid steel poles with laminated pole shoes.*
- Laminated construction is necessary because of the pulsations of field strength that result when the notched armature rotor magnetic structure passes the pole shoe. Variations in field strength result in internal eddy currents being generated in a magnetic structure. These eddy currents cause losses ; they may be largely prevented by having laminated magnetic structures. Laminated structures allow magnetic flux to pass along the length of the laminations, but do not allow electric eddy currents to pass across the structure from one lamination to another. The assembled stack of laminations is held together as a unit by appropriately placed rivets. *The outer end of the laminated pole is curved to fit very closely into the inner surface of the main frame.*
- Fig. 3 shows the constructional details of a field pole. *The pole shoe acts as a support to the field coils and spreads out the flux in the air gap and also being of larger cross-section reduces the reluctance of the magnetic path.*

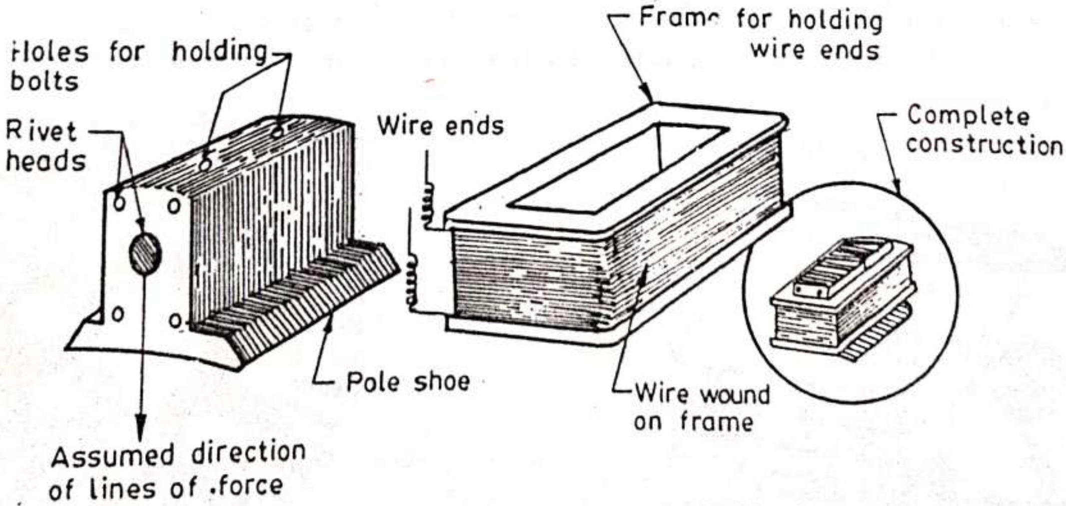


Fig. 3. Constructional details of a field pole.

- Different methods are used for attaching poles to the yoke. In case of *smaller sizes*, the back of the pole is drilled and tapped to receive pole bolts (*see* Fig. 4). In *larger sizes*, a circular or a rectangular pole bar is fitted to the pole. This pole bar is drilled and tapped and the pole bolts passing through laminations screw into the tapped bar (*see* Fig. 5).

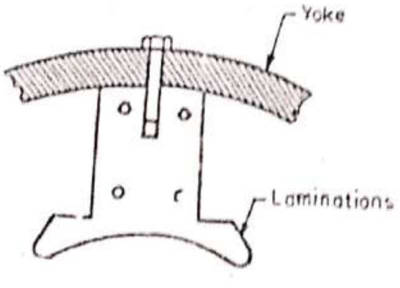


Fig. 4. Fixing pole to the yoke.

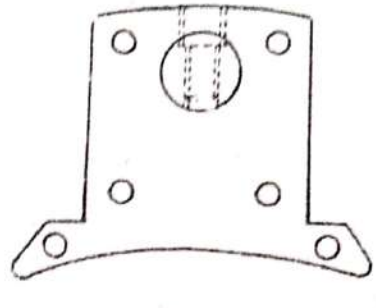


Fig. 5

1.3. Commutating Poles

- A commutating pole (also called *interpole*) is similar to a main pole and consists of core terminating in a pole shoe, which may have various shapes, and coil mounted on the core.
- The commutating poles *are arranged strictly midway between the main poles* and are bolted to the yoke.
- *Commutating poles are usually made of solid steel, but for machines operating on sharply varying loads they are made of sheet steel.*

1.4. Armature

- The armature consists of core and winding. *Iron being the magnetic material is used for armature core.* However, iron is also a good conductor of electricity. The rotation of solid iron core in the magnetic field results in eddy currents. The flow of eddy currents in the core leads to wastage of energy and creates the problem of heat dissipation. *To reduce the eddy currents the core is made of thin laminations.*
- *The armature of D.C. machines (see Fig. 6) is built up of thin laminations of low loss silicon steel.* The laminations are usually 0.4 to 0.5 mm thick and are insulated with varnish.
- The armature **laminations**, in *small machines*, are fitted directly on to the shaft and are clamped tightly between the flanges which also act as supports for the armature winding. One end flange rests against a shoulder on the shaft, the laminations are fitted and other end is pressed on the shaft and retained by a key.

The core (except in small size) is divided into number of packets by radial ventilation spacers. The spacers are usually I sections welded to thick steel laminations and arranged to pass centrally down each tooth.

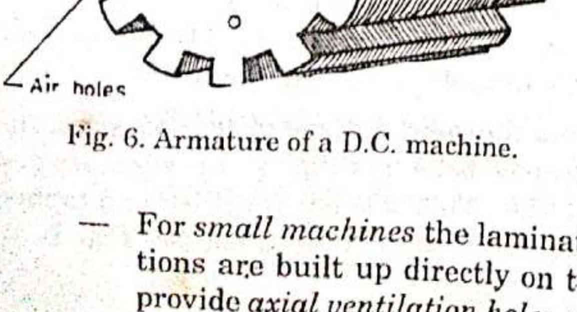


Fig. 6. Armature of a D.C. machine.

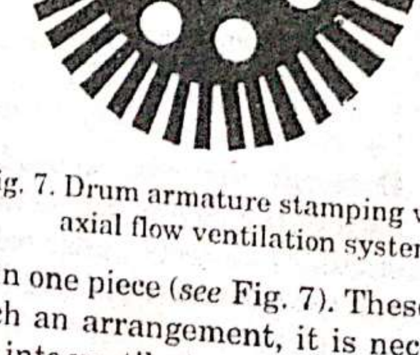


Fig. 7. Drum armature stamping with axial flow ventilation system.

— For *small machines* the laminations are punched in one piece (*see* Fig. 7). These laminations are built up directly on the shaft. With such an arrangement, it is necessary to provide *axial ventilation holes* so that air can pass into ventilating ducts.

— The armature laminations of *medium size machines* (having more than four poles) are built on a spider. The spider may be fabricated. Laminations up to a diameter of about 100 cm are punched in one piece and are directly keyed on the spider (*see* Fig. 8).

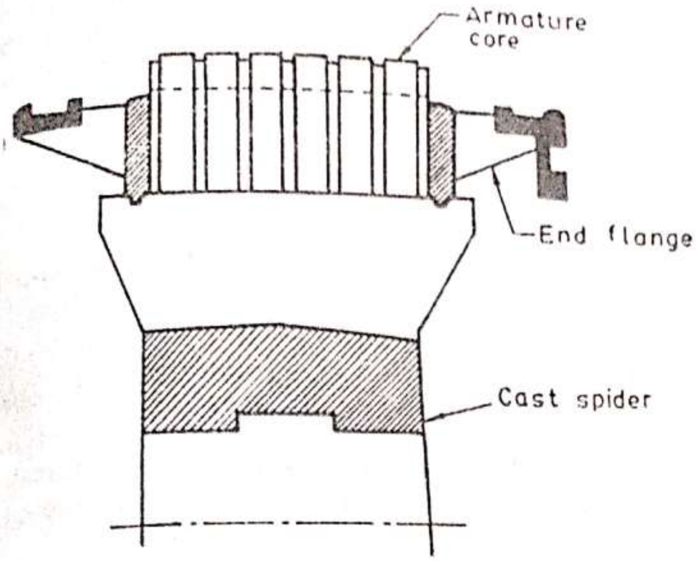


Fig. 8. Clamping of an armature core.

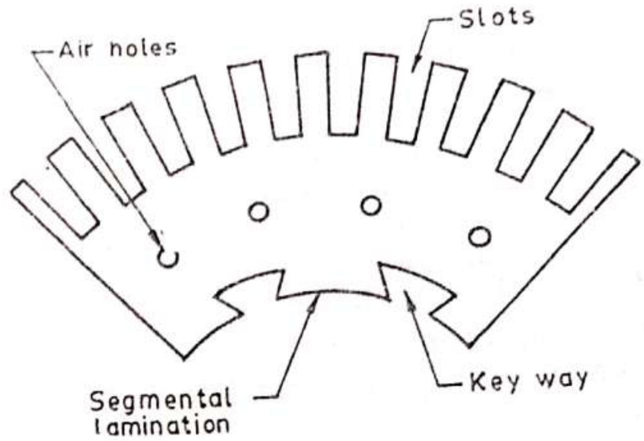


Fig. 9. Segmental stampings.

— In case of *large machines*, the laminations of such thin sections are difficult to handle because they tend to distort and become wavy when assembled together. Hence circular laminations instead of being cut in one piece are cut in a number of suitable sections or *segments* which form part of a complete ring (*see* Fig. 9). A complete circular limination is made up of four or six or even eight segmental laminations. Usually two keyways are notched in each segment and are dove-tailed or wedge shaped to make the laminations self-locking in position.

- The armature winding is housed in slots on the surface of the armature. The conductors of each coil are so spaced that when one side of the coil is under a north pole, the opposite is under a south pole.

Fig. 10 shows the arrangement of conductors and insulation in a slot.

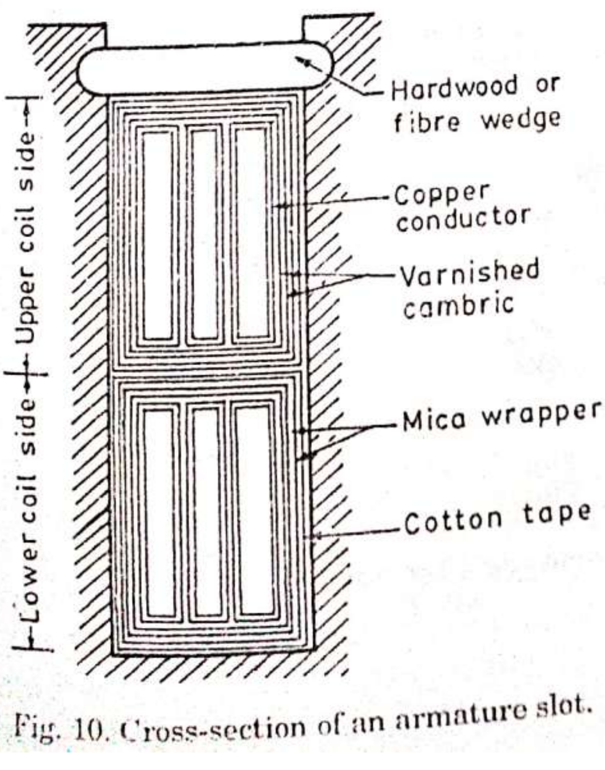


Fig. 10. Cross-section of an armature slot.

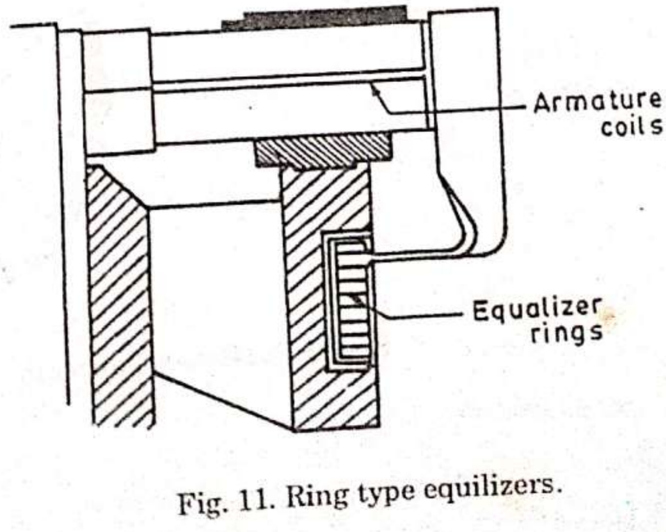


Fig. 11. Ring type equilizers.

- *In D.C. machines two layer winding with diamond shaped coils is used.* The coils are usually former wound. In *small machines,* the coils are held in position by band of steel wire, wound under tension along the core length. In *large machines*, it is useful to employ wedges of fibre or wood to hold coils in place in the slots. Wire bands are employed for holding the overhang. The *equilizer connections* are located under the overhang on the side of the commutator. Fig. 11 shows a typical arrangement for equilizers. The equilizers can be accommodated on the other end of the armature also.

1.5. Commutator

- *A commutator converts alternating voltage to a direct voltage.*
- A commutator is a cylindrical structure built up of segments made of hard drawn copper. These segments are separated from one another and from the frame of the machine by *mica strips.* The segments are connected to the winding through risers. The risers have air spaces between one another so that air is drawn across the commutator thereby keeping the commutator cool.

Fig. 12 shows the components of a commutator. The general appearance of a commutator when completed is as shown in Fig. 13 (*a*). The commutator and armature assembly is shown in Fig. 13 (*b*).

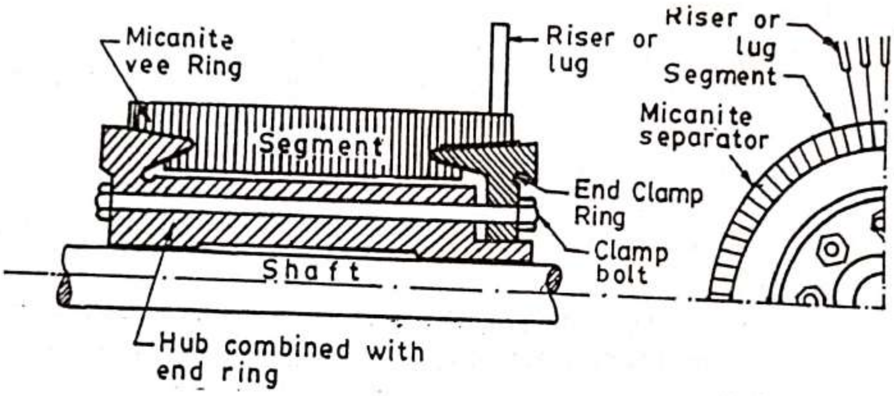


Fig. 12. Commutator components.

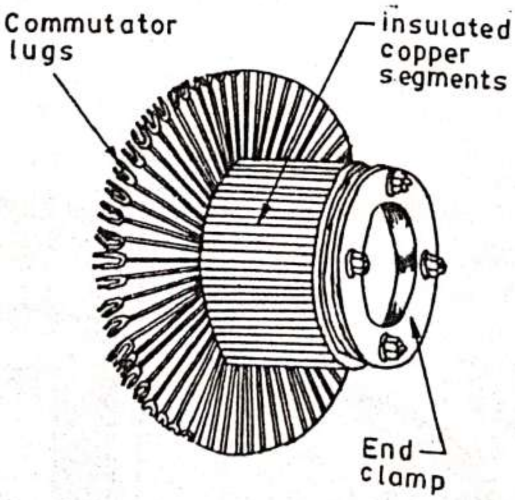


Fig. 13. (*a*) General appearance of a commutator after assembly.

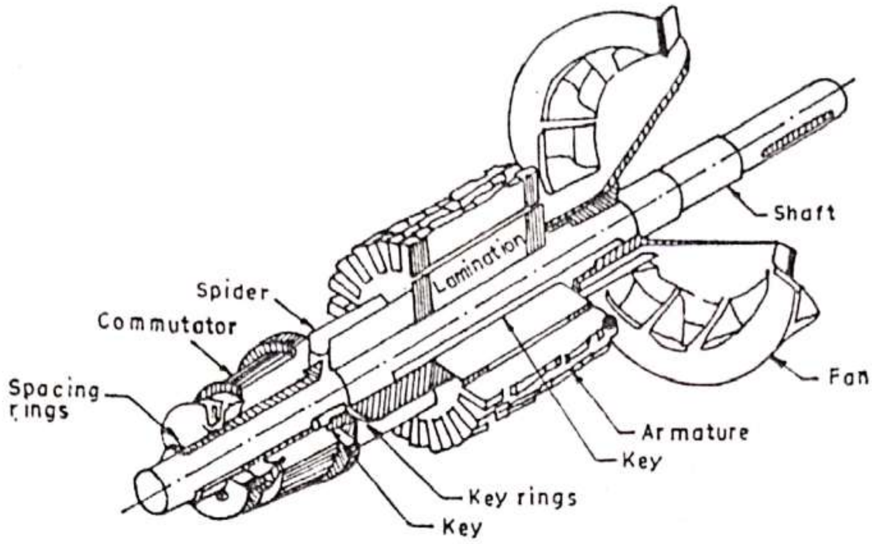


Fig. 13. (*b*) Commutator and armature assembly.

1.6. Brush Gear. To collect current from a rotating commutator or to feed current to it use is made of *brush-gear* which consists of :

(*i*) Brushes
(*ii*) Brush holders
(*iii*) Brush studs or brush-holder arms
(*iv*) Brush rocker
(*v*) Current-collecting busbars.

Brushes. The brushes used for D.C. machines are divided into five classes :

(*i*) Metal graphite
(*ii*) Carbon graphite
(*iii*) Graphite
(*iv*) Electro-graphite
(*v*) Copper.

- The ailowable *current density* at the brush contact varies from 5 A/cm^2 in case of carbon to 23 A/cm^2 in case of copper.
- The use of *copper brushes* is made for machines designed for *large currents at low voltages.* Unless, very carefully lubricated, they cut the commutator very quickly and in any case, the wear is rapid. *Graphite and carbon graphite brushes are self-lubricating and, are, therefore, widely used.* Even with the softest brushes, however, there is a gradual wearing away of the commutator, and if mica between the commutator segments does not wear down so rapidly as the segments do, the high mica will cause the brushes to make poor contact with segments, and sparking will result and consequent damage to commutator. So to prevent this, the mica is frequently '*undercut*' to a level below the commutator surface by means of a narrow milling cutter.

Brush holders. *Box type brush holders* are used in all ordinary D.C. machines. A box type brush holder is shown in Fig. 14. At the outer end of the arm, a brush box, open at top and bottom is attached. The brush is pressed on to the commutator by a *clock spring.* The *pressure can be adjusted by a lever arrangement provided with the spring.* The brush is connected to a flexible conductor called *pig tail.* The flexible conductor may be attached to the brush by a screw or may be soldered.

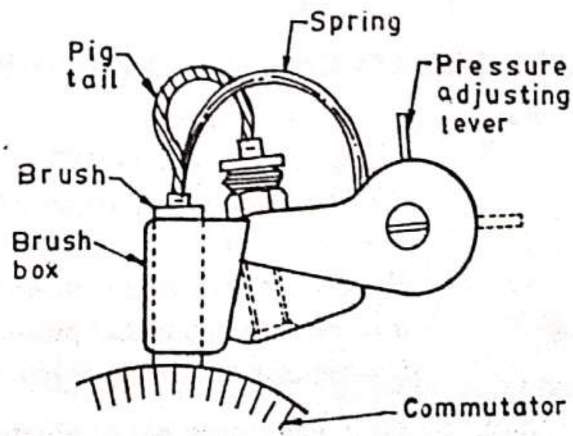


Fig. 14. Box type brush holder.

- The bush boxes are usually made of *bronze casting* or *sheet brass*. In low voltage D.C. machines where the commutation conditions are easy galvanised steel box may be used.
- Some manufacturers use individual brush holders while others use multiple holders, *i.e.*, a number of single boxes built up into one long assembly.

Brush rockers. Brush holders are fixed to brush rockers with bolts. The brush rocker is arranged concentrically round the commutator. *Cast iron is usually, used for brush rockers.*

1.7. Armature Shaft Bearings

- *With small machines roller bearings are used at both ends.*
- For *larger machines roller bearings are used for driving end and ball bearings are used for non-driving* (commutator) *end.*
- The bearings are housed in the end shields.
- For large machines pedestal bearings are used.

1.8. Armature Windings. The *armature winding* is very important element of a machine, as it directly takes part in the conversion of energy from one form into another. The requirements which a winding must meet are diverse and often of a conflicting nature. Among these requirements the following are of major importance.

- The winding must be designed with the *most advantageous utilisation of the material in respect to weight and efficiency.*
- The winding should *provide the necessary mechanical, thermal and electrical strength of the machine* to ensure the usual service life of 16-20 years.
- For D.C. machines proper current collection at the commutator (*i.e.*, absence of detrimental sparking) must be ensured.
- According to the degree of closure produced by winding, armature windings are of the following two types :

  1. Open coil winding   2. Closed coil winding.

  The closed armature windings are of two types :

  (*i*) Ring winding   (*ii*) Drum winding

  In general there are two types of drum armature windings :

  (*i*) Lap winding   (*ii*) Wave winding.

  "Lap winding" is *suitable for comparatively low voltage* but high current generators whereas **"wave of winding"** is used for high voltage, low current machines.

— In '*lap winding*' the finish of each coil is connected to the start of the next coil so that winding or commutator pitch is unity.

— In '*wave winding*' the finish of coil is connected to the start of another coil well away from the fixed coil.

2. E.M.F. EQUATION OF A GENERATOR

Let p = number of poles,

ϕ = flux/pole, webers (Wb),

Z = total number of armature conductors,

= number of slots × number of conductors/slot,

N = rotational speed of armature, r.p.m.,

a = number of parallel paths in armature, and

E_g = generated e.m.f. *per parallel path in armature.*

Average e.m.f. generated per conductor $= \dfrac{d\phi}{dt}$ volt.

Now, flux cut per conductor in one revolution, $d\phi = p\phi$ Wb.

Number of revolutions/second $= \dfrac{N}{60}$

$\therefore$ Time for one revolution, $dt = \dfrac{60}{N}$ seconds

Hence, according to Faraday's laws of electromagnetic induction,

E.m.f. generated per conductor $= \dfrac{p\phi N}{60}$ volts.

For a lap wound generator :

Number of parallel paths, $a = p$

Number of conductor (*in series*) in one path $= \dfrac{Z}{p}$

$\therefore$ E.m.f. generated *per path* $= \dfrac{\phi p N}{60} \times \dfrac{Z}{p} = \dfrac{\phi Z N}{60}$ volt.

For a wave wound generator :

Number of parallel paths, $a = p$

Number of conductor (in series) in one path $= \dfrac{Z}{2}$

$\therefore$ E.m.f. generator per path $= \dfrac{p\phi N}{60} \times \dfrac{Z}{2} = \dfrac{p\phi Z N}{120}$ volt.

In general, generated e.m.f.

$$E_g = \frac{\phi Z N}{60} \times \left(\frac{p}{a}\right) \text{volt} = \frac{p\phi Z N}{60a} \qquad ...(1)$$

where $a = p$ ...... for lap winding
$= 2$ ...... for wave winding.

Example 1. *A six pole lap wound D.C. generator has 720 conductors, a flux of 40 m Wb per pole is driven at 400 r.p.m. Find the generated e.m.f.*

Solution. Number of poles, $p = 6$

Total number of conductors, $Z = 720$

Flux per pole, $\phi = 40 \text{ m Wb} = 40 \times 10^{-3}$ Wb

Speed of rotation, $N = 400$ r.p.m.

Number of parallel paths, $a = p = 6$ [Since the generator is *lap wound.*]

Generated e.m.f. E_g :

Using the relation, $E_g = \dfrac{p\phi Z N}{60a} = \dfrac{6 \times 40 \times 10^{-3} \times 720 \times 400}{60 \times 6} = 192$ V.

Hence, **generated e.m.f. E_g = 192 V. (Ans.)**

Example 2. *A six-pole lap connected generator has a useful flux/pole of 0.045 Wb. If the no load voltage at 400 r.p.m. is 300 V, find the conductors on the armature periphery.*

Solution. Number of poles, $p = 6$

Useful flux/pole, $\phi = 0.045$ Wb

No load voltage, $E_g = 300$ V

Number of conductors, Z :

Number of parallel paths, $a = p = 6$ [Since the generator is *lap wound.*]

We know that, $E_g = \dfrac{p\phi Z N}{60a}$

$$300 = \frac{6 \times 0.045 \times Z \times 400}{60 \times 6}$$

$$\therefore \quad Z = \frac{300 \times 60 \times 6}{6 \times 0.045 \times 400} \quad i.e. \quad Z = 1000.$$

Hence, **total number of armature conductors = 1000. (Ans.)**

Example 3. *An 8-pole wave connected D.C. generator has 1000 armature conductors and flux/pole 0.035 Wb. At what speed must it be driven to generate 500 V?*

Solution. Number of poles, $p = 8$

Total number of armature conductor, $Z = 1000$

Flux/pole, $\phi = 0.035$ Wb

Generated voltage, $E_g = 500$ V

Number of parallel paths, $a = 2$ [Since the generator is wave wound.]

Speed of rotation, N :

Using the relation, $$E_g = \frac{p\phi ZN}{60a}$$

$$500 = \frac{8 \times 0.035 \times 1000 \times N}{60 \times 2}$$

$$\therefore \quad N = \frac{500 \times 60 \times 2}{8 \times 0.035 \times 1000} = 214.3 \text{ r.p.m.}$$

Hence, **speed of generator = 214.3 r.p.m. (Ans.)**

Example 4. *The armature of a 6-pole D.C. generator has a wave winding containing 650 conductors. Calculate the generated e.m.f. when the flux per pole is 0.055 Wb and the speed is 300 r.p.m.*

Calculate speed at which the armature must be driven to generate an e.m.f. of 550 V if the flux per pole is reduced to 0.05 Wb.

Solution. Number of poles, $p = 6$

Total number of conductors, $Z = 650$

Flux per pole, $\phi = 0.055$ Wb

Speed of rotation, $N = 300$ r.p.m.

E.m.f. generated, $E_g = ?$

Generated e.m.f. (2nd case) $= 550$ V

Flux per pole (2nd case) $= 0.05$ Wb

Speed of rotation, $N = ?$

Case I. E.m.f. generated, E_g :

Using the relation, $$E_g = \frac{p\phi ZN}{60a}$$

$$= \frac{6 \times 0.055 \times 650 \times 300}{60 \times 2} \quad [\because \ a = 2, \text{ as the generator is wave wound}]$$

$$= 536.25 \text{ V.}$$

Hence, **e.m.f. generated = 536.25 V. (Ans.)**

Case II. Speed of rotation, N :

$$E_g = \frac{p\phi ZN}{60a}$$

$$550 = \frac{6 \times 0.05 \times 650 \times N}{60 \times 2}$$

$$N = \frac{550 \times 60 \times 2}{6 \times 0.05 \times 650} = 338.46 \text{ r.p.m.}$$

Hence, **speed of rotation = 338.46 r.p.m. (Ans.)**