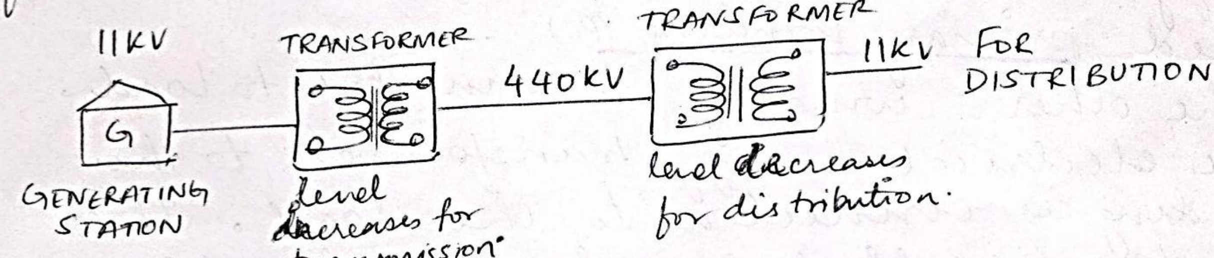
TRANSFORMERS

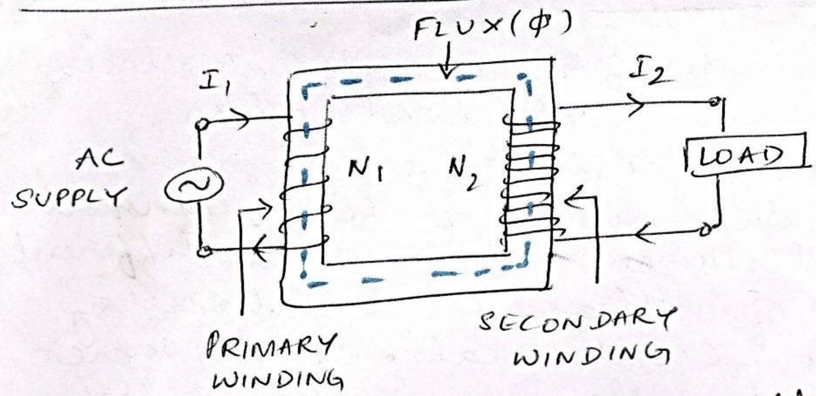
INTRODUCTION: electrical energy is generated at places where it is easier to get water head, oil or coal for hydroelectric, diesel or thermal power stations respectively. Then energy is to be transmitted at considerable distances for use in different places. Transmission of voltage electrical energy at high voltages is economical. Hence, some means are required for stepping up the voltage at generating stations and stepping down the same at the places where it is used. The machine used for this purpose is called a Transformer.

In our country, the electrical energy is usually generated at 6.6 or 11 or 33 KV, stepped up to 132, 220, 400 or 765 KV with the help of step-up transformers for transmission and then stepped down to 66 KV or 33 KV and then to 11 KV at distribution transformers; stepping down the voltage further to 400/230 V for the consumers.



"A transformer is a static electrical device which transfers electrical device, which transfers electrical power from one electrical circuit to the other, which are magnetically coupled together without any change in the frequency and power".

WORKING PRINCIPLE



→ The transformer works on the principle of mutual induction which states that when two coils are inductively coupled and if current in one coil is changed uniformly then an emf gets induced in the other coil.

→ In its elementary form, a transformer consists of two inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance.

→ One of the two coils is connected to a source of alternating voltage. This coil in which electrical energy is fed with the help of source is called primary winding (P).

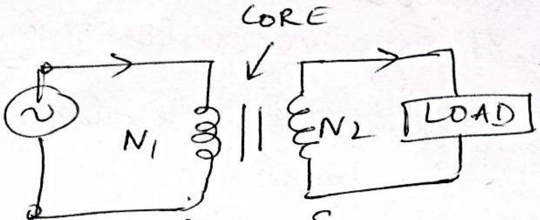
→ The other winding is connected to load. The electrical energy transformed to this winding is connected to the load. The winding is called secondary winding (S).

→ Primary winding has N_1 turns and the secondary winding has N_2 turns.

→ When primary winding is excited by an alternating vtg, it circulates an alternating current. This current produces an alternating flux (ϕ) which completes its path through the common magnetic core (as shown dotted). This alternating flux links the secondary winding.

→ As the flux is alternating, according to Faraday's law of electromagnetic induction, mutually induced emf gets developed in the secondary winding. A self induced emf also gets induced in the primary winding.

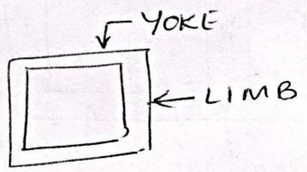
→ Symbolic Representation of a transformer :



→ The two parallel lines in between two windings represents the common magnetic core.

→ ∴ Though there is no electrical contact between the two windings, an electrical energy gets transferred from primary to the secondary.

CONSTRUCTION



→ There are two basic parts of a transformer: i) Magnetic core. ii) Winding or coils

→ Vertical portion of the core on which coils are wound is called limb. Horizontal portion is called YOKE.

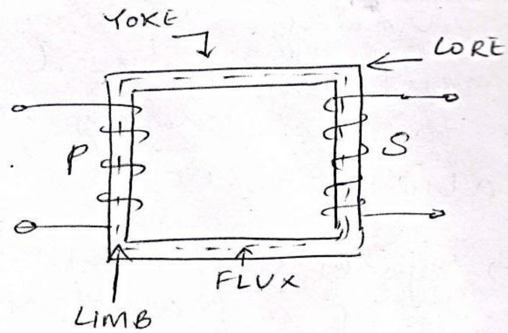
→ Core is made up of laminations to minimize eddy current losses. These laminations are insulated from each other using insulation like varnish.

→ The coils are made up of copper or other conducting material.

→ The core provides the low reluctance path to the flux produced by the primary while the windings carry the currents necessary for the functioning of the transformer

TYPES OF SINGLE PHASE TRANSFORMERS

1. CORE TYPE TRANSFORMER :-



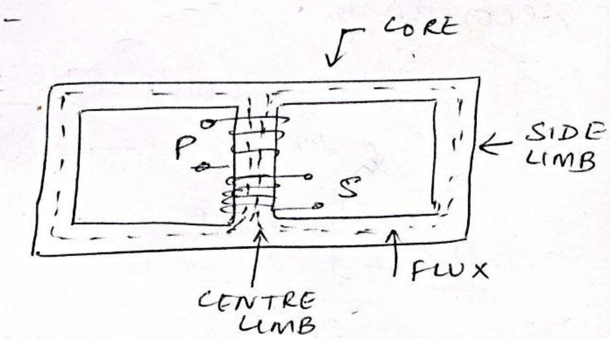
→ It has a single magnetic circuit. The core is rectangular having two limbs. The winding encircles the core

→ Both the coils are placed on both the limbs.

→ As the windings are uniformly distributed over the two limbs, the natural cooling is more effective.

→ The coils can be easily removed by removing the laminations of the top yoke for maintenance.

2. SHELL TYPE TRANSFORMER :-



→ It has a double magnetic circuit. The core has three limbs.

→ Both windings are placed on the central limb.

→ The core encircles most part of the windings, natural cooling doesnt exist.

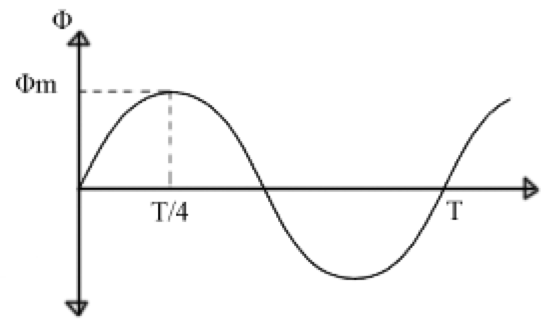
→ Generally for very high voltage transformers, the shell type construction is preferred.

→ For removing any winding for maintenance, large number of laminations are required to be removed.

EMF Equation of a Transformer

In a transformer, source of alternating current is applied to the primary winding. Due to this, the current in the primary winding (called as magnetizing current) produces alternating flux in the core of transformer. This alternating flux gets linked with the secondary winding, and because of the phenomenon of mutual induction an emf gets induced in the secondary winding. Magnitude of this induced emf can be found by using the following **EMF equation of the transformer**.

Let,
N_1 =Number of turns in primary winding
N_2 = Number of turns in secondary winding
Φ_m = Maximum flux in the core (in Wb) = (B_m x A)
f = frequency of the AC supply (in Hz)



As, shown in the fig., the flux rises sinusoidally to its maximum value Φ_m from 0. It reaches to the maximum value in one quarter of the cycle i.e in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).
Therefore,

Average rate of change of flux = $\Phi_m /_{(T/4)}$ = $\Phi_m /_{(1/4f)}$

Therefore,
average rate of change of flux = 4f Φ_m .... (Wb/s).
Now,
Induced emf per turn = rate of change of flux per turn

Therefore, average emf per turn = 4f Φ_m ....(Volts).
Now, we know, Form factor = RMS value / average value =1.11 for sine wave

Therefore, RMS value of emf per turn = Form factor * average emf per turn.

Therefore, RMS value of emf per turn = 1.11 x 4f Φ_m = 4.44f Φ_m.

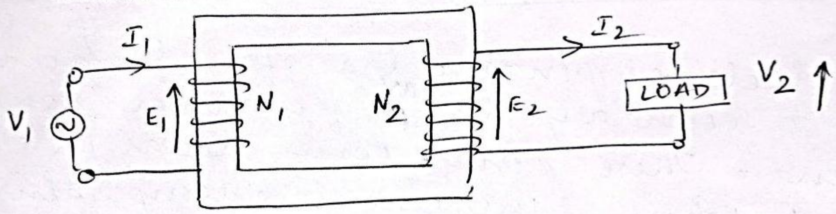
RMS value of induced emf in whole primary winding (E_1) = RMS value of emf per turn X Number of turns in primary winding

E_1 = 4.44f N_1 Φ_m

Similarly, RMS induced emf in secondary winding (E_2) can be given as

E_2 = 4.44f N_2 Φ_m.

RATIOS OF A TRANSFORMER



1. VOLTAGE RATIO :

$E_1 = 4.44 f \phi_m N_1$
$E_2 = 4.44 f \phi_m N_2$

Taking ratio of the two equations :-

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

Ratio of secondary induced emf to primary induced emf is known as voltage transformation ratio denoted as K

$$\therefore \boxed{E_2 = KE_1 \quad \text{where } K = \frac{N_2}{N_1}}$$

→ If $N_2 > N_1$ i.e $K > 1$ we get $E_2 > E_1$ then the transformer is called step-up transformer.

→ If $N_2 < N_1$ i.e $K < 1$ we get $E_2 < E_1$ then the transformer is called step-down transformer.

→ If $N_2 = N_1$ i.e $K = 1$ we get $E_1 = E_2$ then the transformer is called 1:1 or isolation transformer.

2. CURRENT RATIO :

For an ideal transformer, there are no losses.

$\therefore$ input VA = output V.A

$$V_1 I_1 = V_2 I_2$$

$$\frac{V_1}{V_2} = \frac{E_1}{E_2} \quad \text{for an ideal transformer}$$

$$\therefore \boxed{\frac{I_1}{I_2} = K = \frac{E_2}{E_1}}$$

VOLT-AMPERE RATING [VA]

→ when electrical power is transferred from primary winding to secondary there are a few power losses in between. These power losses appear in the form of heat which increase the temperature of the device.

→ The copper loss (I^2R) in the transformer depends on the current 'I' through the winding.

→ The iron or core loss depends on the voltage 'V'.

→ None of these losses depend on the power factor of the load. Hence losses decide the rating of the transformer.

→ Hence, as losses depend on V and I only, the rating of the transformer is specified as a product of these 2 parameters only called VA rating.

→ The VA rating is expressed in KVA. KVA of primary and secondary remains same.

$$\text{KVA rating of a transformer} = \frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}.$$

FULL-LOAD CURRENTS

We can obtain the full load currents of the primary and secondary I_1 & I_2 from the KVA rating of the transformer. [This is the safe maximum current limit which the transformer may carry keeping temperature rise below its limiting value]

$$I_1 \text{ full-load} = \frac{\text{KVA rating} \times 1000}{V_1}$$

$$I_2 \text{ full load} = \frac{\text{KVA rating} \times 1000}{V_2}$$

Flux in the core of a transformer

For a transformer,

$E_1 = 4.44f\, N_1\, \Phi_m$ or $E_2 = 4.44f\, N_2\, \Phi_m$

$$\Phi_m \propto \frac{E1}{f}$$

The primary voltage and frequency remain constant. Hence, for a transformer, the flux in the core remains constant and independent of the load.

DC SUPPLY FOR A TRANSFORMER

→ The transformer works on the principle of mutual induction, for which current in one coil must change uniformly. If d.c supply is given, the current will not change due to constant supply and transformer will not work.

→ Practically winding resistance is very small. For dc supply, the inductive reactance is zero as dc has no frequency. ∴ Total impedance is very low. Thus, the winding will draw very high current if dc supply is given to it. This may cause the burning of windings and may cause permanent damage of the transformer.

∴ D.C supply should not be connected to the transformers.

Losses in a transformer

As the transformer is a static apparatus and doesnt contain any rotating parts, there are no mechanical losses. The losses that occur in a transformer are:-

(i) IRON LOSS (W_i): This loss is also called as the 'CORE LOSS' and it occurs in the iron portion i.e the core of the transformer. These are of two types:-
(i) Eddy current loss (ii) Hysteresis loss.

Eddy current loss (W_e) occurs due to the flow of eddy currents in the laminations of the core. These eddy currents are induced in the laminations because the alternating flux produced by the primary winding links them. These eddy currents flow in a circular path and cause power loss in the core and heats up the core of the transformer.

$$\boxed{W_e = \beta B_m^2 f^2 t^2 V^2 \text{ watts}}$$

B_m → Maximum flux density in the core (Wb/m^2)
f → Frequency (HZ)
t → thickness of lamination (m)
V → Volume of the core (m^3)
β → Constant whose value depends on the quality of the magnetic material used for core.

To Reduce eddy current losses, the core is made of thin laminations of high permeability magnetic material such as silicon steel and they are insulated from one another by coating them with varnish.

The Hysteresis loss (W_h) occurs because the core of the transformer is subjected to cycles of magnetization.

$$\boxed{W_h = \eta\, B_m^{1.6}\, f\, V \text{ watts}}$$

$\eta \rightarrow$ constant whose value depends on the quality of the magnetic material used for making the core.

$$\boxed{W_i = W_e + W_h}$$

We observe that the iron loss depends upon B_m and frequency. All the other quantities like the thickness of laminations, volume of the core are constants. We also know that the flux in the core of the transformer is almost constant as long as supply voltage V_1 is always constant.

$\therefore$ Iron / Core losses in the transformer are considered to be constant losses

(ii) COPPER LOSS (W_{cu}) : These losses occur due to the power consumed by the resistances R_1 & R_2 of the primary and secondary windings.

$$\text{Total copper loss } (W_{cu}) = I_1^2 R_1 + I_2^2 R_2$$

$$= I_1^2 (R_1 + R_2') = I_1^2 R_{01}$$

$$\text{or} = I_2^2 (R_2 + R_1') = I_2^2 R_{02}$$

We observe that $(W_{cu}) \propto I_2^2$. At full load, I_{2FL} flows through the windings, hence we obtain full-load copper loss $(W_{cu})_{FL}$. Similarly copper losses at half load will be lesser than $(W_{cu})_{FL}$. Hence W_{cu} is termed as variable losses.

$$\boxed{\text{TOTAL LOSS IN A TRANSFORMER} = W_i + W_{cu}}$$

1ϕ TRANSFORMERS

1. A 5KVA, 50Hz, single-phase transformer has primary and secondary turns of 120 and 80. At a certain flux density, the induced emf per turn in primary is 2.5V. Determine primary and secondary voltage. (Answer: 300, 200)

Soln:

5kVA, 50Hz

$N_1 = 120$

$N_2 = 80$

emf/turn = 2.5V

E_1 & E_2 = ?

$E_1 = N_1 * \left(\frac{\text{emf}}{\text{turn}}\right)$

$\boxed{E_1 = 300\,V}$

$E_2 = N_2 * \left(\frac{\text{emf}}{\text{turn}}\right)$

$\boxed{E_2 = 200\,V}$

---

2. Find the number of turns on the primary and secondary side of a 440/230V, 50Hz, single phase transformer, if the net area of cross section of the core is 30cm^2 and the maximum value of the flux density is 1Wb/m^2. (660.67, 345.35)

Soln:

440/230V, 50Hz

$\left.\begin{array}{l} \text{Area }(A) = 30\,cm^2 \\ B_m = 1\,Wb/m^2 \end{array}\right\} \phi_m = 3\,mWb$

N_1 & N_2 = ?

$(E = 4.44 f \phi_m N)$

$E_1 = 440V$

$E_2 = 230V$

$\rightarrow$ i) $N_1 = \frac{E_1}{4.44 f \phi_m}$

$\boxed{N_1 = 660.67}$

$\rightarrow$ ii) $N_2 = \frac{E_2}{4.44 f \phi_m}$

$\boxed{N_2 = 345.35}$

---

3. A 10kVA transformer has a turns ratio of 500/200. The primary winding is connected to 1500V, 50Hz supply. Calculate:
   a. The secondary voltage on open circuit (600V)
   b. The primary and secondary full load currents (6.67A, 16.67A)
   c. The maximum value of the flux in the core (13.5mWb)

Soln:

10kVA.

$N_1/N_2 \Rightarrow 500/200$.

$E_1 = 1500V, 50Hz$.

a) $E_2 = ?$

b) I_{FL_1} & $I_{FL_2} = ?$

c) $\phi_m = ?$

a) $$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

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

$$\boxed{E_2 = 600V}$$

b) $$I_{FL_1} = \frac{kVA * 1000}{E_1}$$

$$\boxed{I_{FL_1} = 6.67A}$$

$$\frac{I_{FL_1}}{I_{FL_2}} = \frac{N_2}{N_1}$$

$$\boxed{I_{FL_2} = 16.675A}$$

c) $$E_1 = 4.44 f \phi_m N_1$$

$$\phi_m = 0.0135\ wb.$$

$$\boxed{\phi_m = 13.5 mWb}$$

— × —

4. A single phase, 20kVA transformer has 1000 primary turns and 2500 secondary turns. The net cross sectional area of the core is $100cm^2$. When the primary winding is connected to 500V, 50Hz supply. Calculate:

   a. The maximum value of the flux density in the core ($0.2252Wb/m^2$)
   b. The voltage induced in the secondary winding (1250V)
   c. The primary and secondary full load currents (40A, 16A)

Sol^n: 20kVA

$N_1 = 1000$

$N_2 = 2500$

$Area = 100\,cm^2$.

$E_1 = 500V, 50Hz$.

a) $B_m = ?$

b) $E_2 = ?$

c) I_{FL_1} & $I_{FL_2} = ?$

a) $B_m = \frac{\phi_m}{Area}$.

$\phi_m = ?$

$E_1 = 4.44 f \phi_m N_1$

$\phi_m = 2.25\,mWb$.

$B_m = \frac{2.25\,mWb}{100\,cm^2}$

$$\boxed{B_m = 0.225\,Wb/m^2}$$

b) $\frac{E_2}{E_1} = \frac{N_2}{N_1}$

$$\boxed{E_2 = 1250\,V}$$

c) $I_{FL_1} = \frac{kVA * 1000}{E_1}$

$$\boxed{I_{FL_1} = 40A}$$

$I_{FL_2} = \left(\frac{N_1}{N_2}\right) * I_{FL_1}$

$$\boxed{I_{FL_2} = 16A}$$

———— X ————

SINGLE PHASE TRANSFORMER

Theory Questions

1. With a neat diagram, explain the constructional details of i) shell type transformer, ii) core type transformer.
2. Explain the working principle of a transformer.
3. Obtain the EMF equation of a transformer with usual notations.
4. Enumerate various losses occurring in a transformer and suggest methods to reduce them.
5. Define the following terms. i) Transformer ii) Efficiency

Efficiency of Transformer :→

η is generally given as output by input.

$$\therefore \eta = \frac{\text{Output}}{\text{Input}} \times 100$$

$$\eta = \frac{\text{Power output}}{\text{Power input}} \times 100$$

Power output = Power input ~~+~~ losses (Total)

$\therefore$ Power input = Power output + Total losses

= Power output + $P_i + P_{cu}$.

$$\eta = \frac{\text{Power output}}{\text{Power output} + P_i + P_{cu}}$$

Now power output = $V_2 I_2 \cos\phi$ (where $\cos\phi$ is load power factor)

$$\therefore \eta = \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + P_i + I_2^2 R_2} \quad (\text{where } P_{cu} = I_2^2 R_2)$$

But $V_2 I_2$ is VA rating of transformer.

$$\therefore \eta = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + I_2^2 R_2}$$

$$\boxed{\eta_{\text{at full load}} = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + P_{cu \text{ at full load}}}}$$

From the η equation the only variable parameter with load is I_2 hence η at fractional load is given by

$$\boxed{\eta_{\text{at fractional load}} = \frac{x\,(\text{VA rating}) \times \cos\phi}{x\,(\text{VA rating}) \times \cos\phi + P_i + x^2 (I_2^2 R_2)}}$$

Where x is load put on transformer, for ex; if transformer is 50% loaded then $x = 0.5$ & η equation becomes

$$\eta_{\text{at 50\% of full load}} = \frac{0.5\,(\text{VA rating}) \times \cos\phi}{\ldots}$$

CHAPTER - 11
THREE PHASE INDUCTION MOTOR

11.1 Introduction:

A three phase induction motor is an a.c. motor. Of all the a.c. motors available, it is extensively used, because of the following advantages:

1. Its construction is simple, rugged and almost unbreakable.
2. Its cost is low and is highly reliable.
3. Its efficiency is high.
4. It works with reasonably good power factor at rated load.
5. Its maintenance is less.
6. Induction motors are self-starting. Hence, motors of smaller ratings do not require a starter. The starting arrangements for larger motors are simple.

The disadvantages are:

1. It is essentially a constant speed motor and the speed cannot be changed easily. The speed variation can be done at the cost of efficiency. Speed ↓ with
2. The starting torque is inferior to that of a D.C. shunt motor.

11.2 Construction:

A three phase induction motor mainly consists of two parts. (i) *stator* and (ii) *rotor*. The rotor, which is the rotating part, is separated by the stator, which is the static part, by a small air gap, which usually varies from 0.4 mm to 4 mm, depending on the rating of the motor.

11.2 (a) Stator:

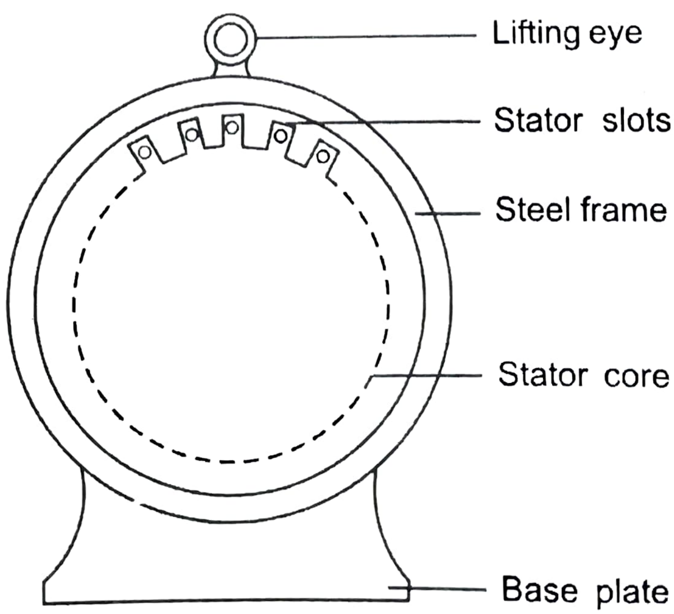


Fig. 11.1

Fig 11.1 shows the stator of the induction motor. It consists of a steel frame, which encloses a hollow, cylindrical core, made up of thin laminations of silicon steel to reduce eddy current loss and hysteresis loss. A large number of uniform slots are cut on the inner periphery of the core. The stator conductors are placed in these slots, which are insulated from one another and also from the slots. These conductors are connected as a balanced three phase star winding or delta winding. The windings are wound for a definite number of poles, depending on the requirement of speed. It is wound for more number of poles, if the speed required is less and vice-versa, according to the relation.

$$N_S = \frac{120\,f}{P} \tag{11.1}$$

Where, N_S = synchronous speed in r.p.m.

f = frequency of the supply.

and P = number of poles.

When a three phase supply is given to the stator winding, a magnetic field of constant magnitude and rotating at synchronous speed, given by the equation $N_S = 120\ f\,/\,P$ is produced. This rotating magnetic field is mainly responsible for producing the torque in the rotor, so that, it can rotate at its rated speed, which will be explained in detail in the later sections of this chapter.

11.2 (b) Rotor:

The rotor is the rotating part of the induction motor and is mounted on the shaft of the motor to which, any mechanical load can be connected. There are two types of rotors (i) *squirrel cage rotor* and (ii) *phase wound rotor*. According to the type of rotor used, three phase induction motors are classified as squirrel cage induction motors and phase wound or slip ring induction motors.

i) Squirrel cage rotor:

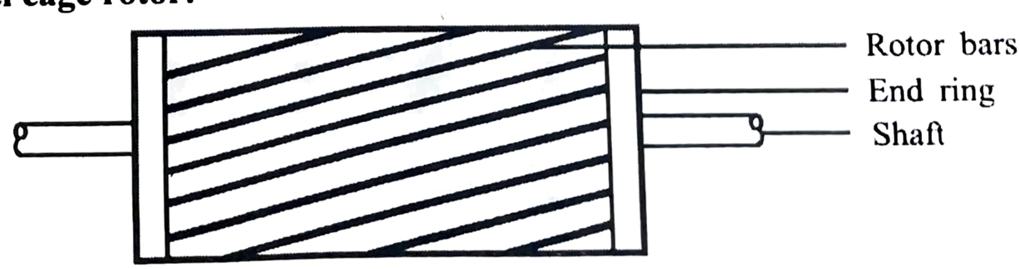


Fig.11.2

Nearly 90% of the induction motors are of squirrel cage type, as the rotor is simple and rugged in construction. This type of rotor, shown in Fig. 11.2, consists of a cylindrical laminated core with parallel slots, for carrying rotor conductors. The rotor conductors are heavy bars of copper or aluminium. One bar is placed in each slot. All the bars are brazed or welded at both ends to two copper end rings, thus short circuiting them at both ends. As the rotor bars are short circuited on themselves, it is not possible to add any external resistance in series with the rotor circuit during starting. The slots are slightly skewed, which helps in two ways (i) it reduces the noise due to magnetic hum and makes the rotor to run quietly and (ii) it reduces the locking tendency between the rotor and the stator.

ii) Phase Wound Rotor:

This rotor is a laminated, cylindrical core having uniform slots on its outer periphery. A three phase winding, which is star connected is placed in these slots. The open ends of the star winding are brought out and connected to three insulated slip rings, mounted on the shaft of the motor, with carbon brushes resting on them.

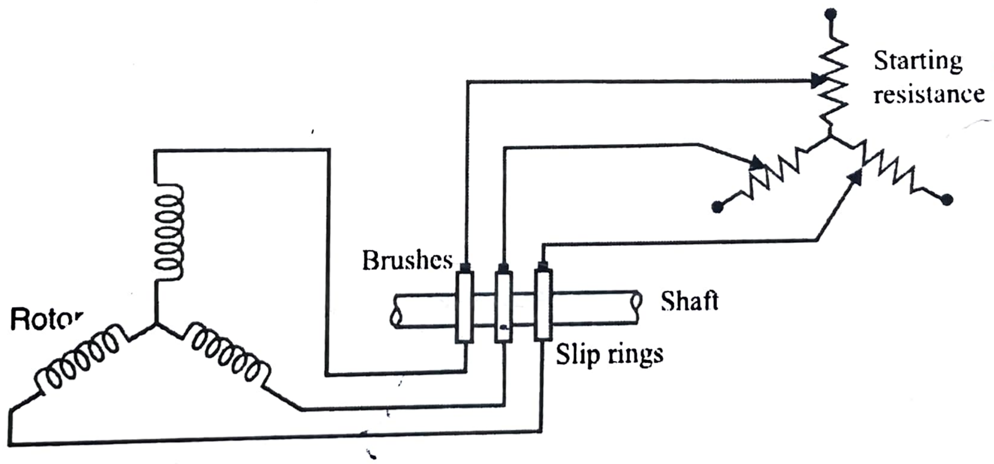


Fig.11.3

The three brushes are externally connected to a three phase star connected rheostat, which is used as a starter during the starting period. 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, wear and tear. The equivalent circuit diagram of a phase wound induction motor along with the rotor connections to the starting resistance is as shown fig.11.3.

11.2 (c) Squirrel Cage Induction Motor:

i) Advantages

...truction, rugged and can withstand rough handling.

4. A simple star-delta starter is sufficient to start the motor
5. It is explosion proof as there are no slip rings, brushes and their assembly.

ii) Disadvantages:

1. It has low starting torque.
2. The p.f. at starting is lower.
3. The starting current is high and it has no smooth running.

11.2 (d) Slip-ring Induction Motor:

i) Advantages:

1. It has external resistance in the rotor circuit which can be used as a starter, especially with load, with higher starting torque and lower starting current.
2. The external resistance can be used to control the speed and also to improve the power factor.
3. The motor is smooth running.
4. Slip-ring induction motors of very high capacity can be built.

(ii) Disadvantages:

1. The size of the slip-ring induction motor of the same capacity is more than that of squirrel cage induction motor.
2. It is costlier as the construction is complicated.
3. The maintenance and repair costs are quite high.

11.3 Rotating Magnetic Field:

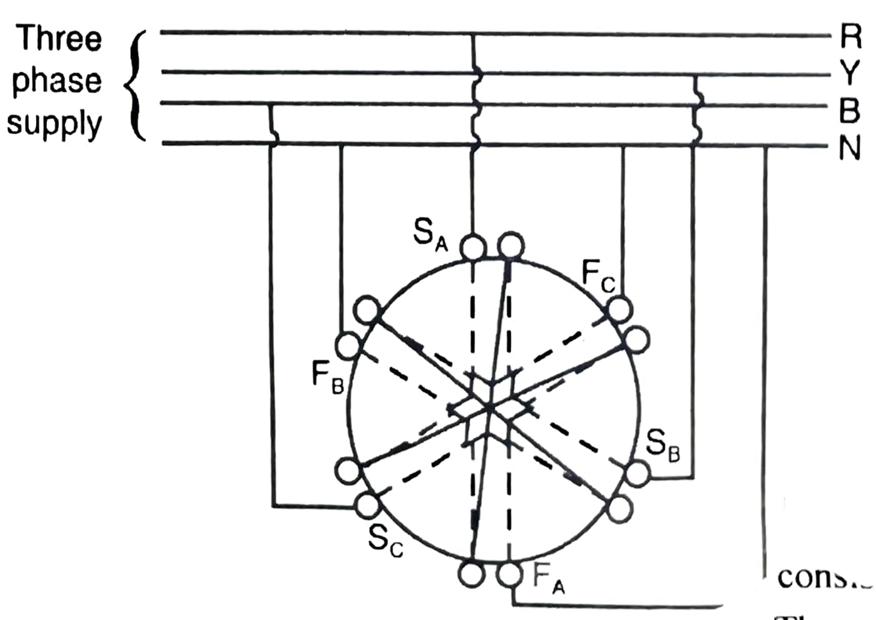


Fig.11-

cons... ...ctors. The rotor conductors are

lam...

When a three phase supply is given to the three phase winding of the stator, a rotating magnetic field of constant magnitude and rotating with synchronous speed is produced. This fact can be proved as follows.

The Fig. in 11.4, shows the three phase winding of the stator of an induction motor, which is connected to the three phase supply. The starting points of the windings S_A, S_B and S_C are connected to the three supply lines R, Y and B. The other three ends F_A, F_B and F_C are connected to the neutral N. When the supply is given, the fluxes produced in the three windings are as shown in Fig.11.5.

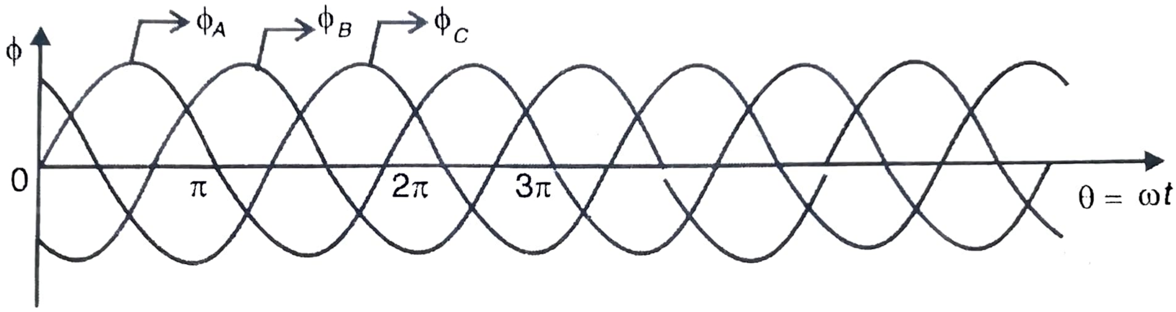


Fig.11.5

The assumed positive directions of fluxes are as shown in Fig. 11.6.

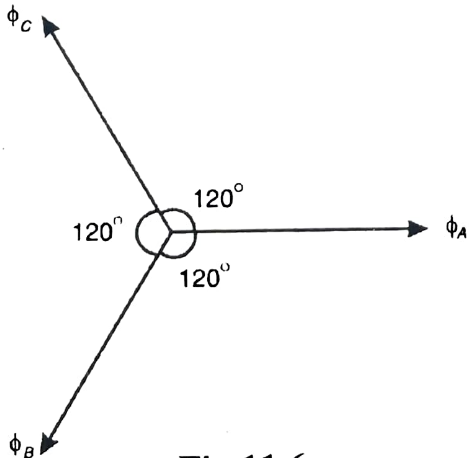


Fig.11.6

The equations for the three fluxes are:

$$\phi_A = \phi_m \sin \omega t$$

$$\phi_B = \phi_m \sin (\omega t - 120°) \text{ and}$$

$$\phi_C = \phi_m \sin (\omega t - 240°)$$

The resultant flux of these three fluxes at any instant, is given by the vector sum of the individual fluxes ϕ_A, ϕ_B and ϕ_C.

(i) When $\theta = 0°$, we find from the wave diagram of the fluxes, shown in Fig. 11.5 that

$$\phi_A = 0$$

$$\phi_B = \phi_m \sin (-120°) = -\frac{\sqrt{3}}{2}\phi_m$$

$- \sin (90+30)$

$- \cos 30$

$$\phi_C = \phi_m \sin (-240°) = \frac{\sqrt{3}}{2}\phi_m$$

These values of fluxes at this instant and their resultant are shown in Fig. 11.7. The vector ϕ_B is written opposite to its assumed positive direction, as it is negative. The resultant flux ϕ_r lies along Y–axis and its magnitude is given by,

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos 30^\circ = \frac{3}{2}\phi_m = 1.5\,\phi_m$$

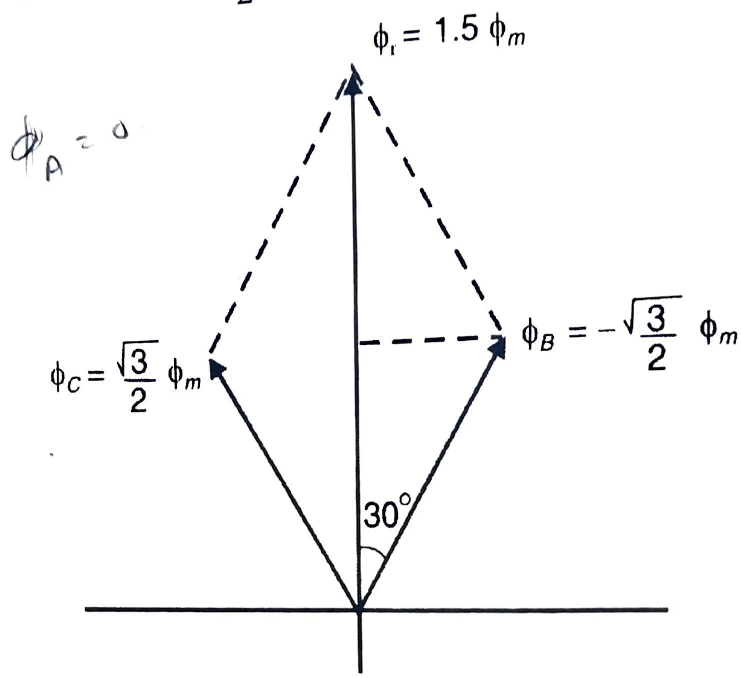


Fig. 11.7

ii) When $\theta = 60^\circ$, the values of the three fluxes are,

$$\phi_A = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_C = 0$$

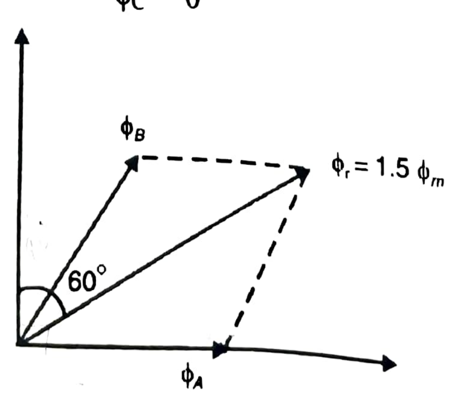


Fig.11.8

The three fluxes at this instant and their resultant are shown in Fig. 11.8. It is observed that, the resultant flux has rotated by 60° in the clockwise direction and its magnitude is 1.5 ϕ_m.

iii) When $\theta = 120°$, the values of the three fluxes are,

$$\phi_A = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = 0 \qquad \text{and} \qquad \phi_C = -\frac{\sqrt{3}}{2}\phi_m$$

The three fluxes at this instant and their resultant are shown in Fig. 11.9. It is observed that the resultant flux has rotated by another 60° i.e. through 120°, from its original position and its magnitude is 1.5 ϕ_m.

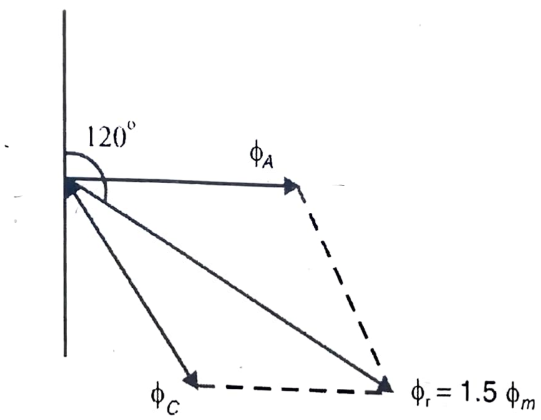
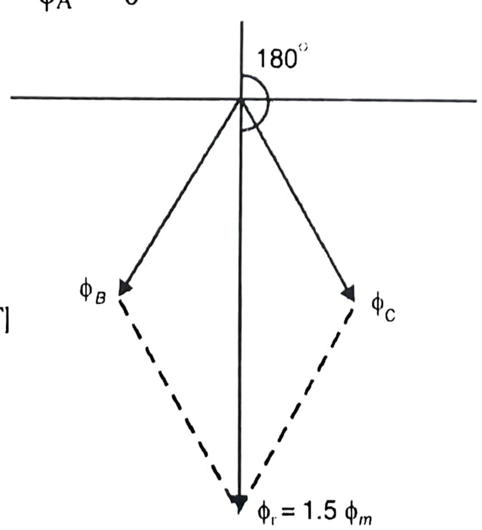


Fig. 11.9

iv) When $\theta = 180°$, the values of the three fluxes are;

$\phi_A = 0$



Tl their resultant are as shown in Fig.11.10. It is observed that the resul

From the above discussion, we can conclude that as $\theta = \omega t$ varies from $\theta = 0$ to $\theta = 2\pi$, the resultant flux also rotates with the same angular velocity ω and having a constant magnitude of 1.5 ϕ_m. Therefore, when a three phase supply is given to the stator winding, a rotating magnetic field of constant magnitude 1.5 ϕ_m and rotating with synchronous speed $N_S = 120\ f / P$ is produced.

11.4 Working Principle:

When a three phase supply is given to the three phase stator winding, a magnetic field of constant magnitude 1.5 ϕ_m and rotating with the synchronous speed N_S is produced. This rotating magnetic field sweeps across the rotor conductors and hence, an e.m.f. is induced in the rotor conductors. The direction of the induced e.m.f. is such as to oppose the very cause of it i.e. the relative speed between the rotating magnetic field and the static rotor. As the rotor conductors are short circuited on themselves, the induced e.m.f. sets up a current in the rotor conductors in such a direction as to produce a torque, which rotates the rotor in the same direction as the magnetic field, as shown in Fig. 11.11, so that the relative speed decreases. The speed of the rotor gradually increases and tries to catch up with the speed of the rotating magnetic field. But, it fails to reach the synchronous speed, because, if it catches up with the speed of the magnetic field, the relative speed becomes zero and hence, no e.m.f. will be induced in the rotor conductors, the torque becomes zero. Hence, the rotor will not be able to catch up with the speed of the magnetic field, but rotates at a speed slightly less than the synchronous speed.

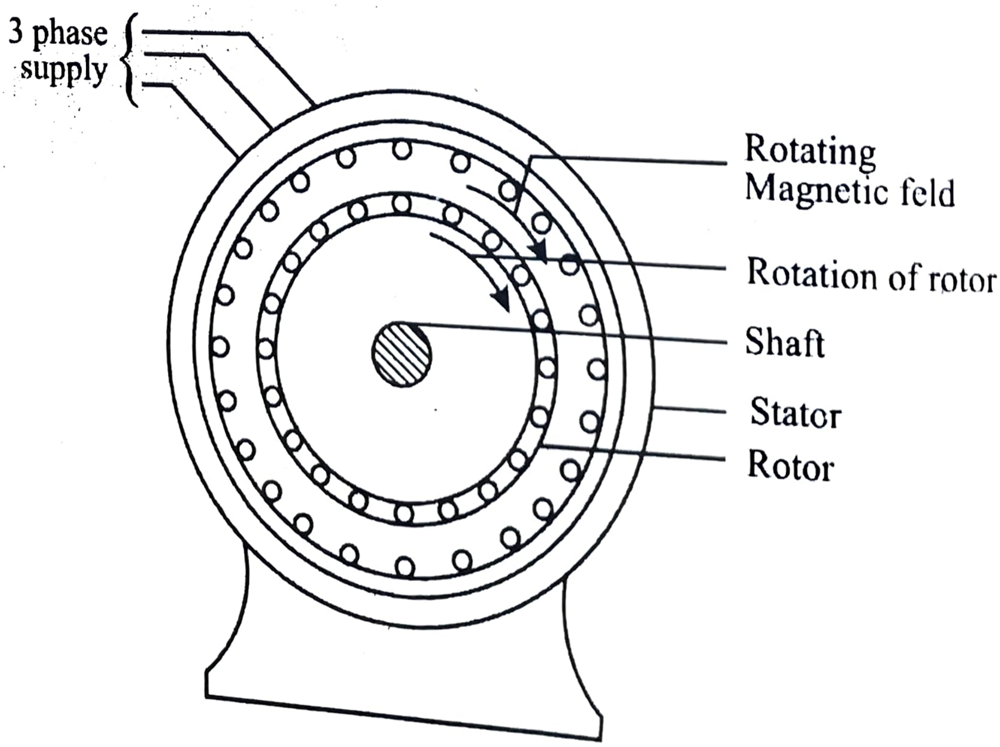


Fig.11.11

The difference between the synchronous speed N_S of the magnetic field and the actual speed of the rotor N is called as the *slip speed.*

$\therefore$ Slip speed = $N_S - N$ (11.2)

The *slip* of an induction motor is defined as the ratio of the slip speed to the synchronous speed

$$S = \frac{N_S - N}{N_S} \qquad (11.3)$$

The slip of an induction motor is usually expressed as a percentage and the percentage slip is given by,

$$\% S = \frac{N_S - N}{N_S} \times 100$$

11.5 Frequency of Rotor Current:

When the rotor is stationary, the frequency of the rotor current is the same as the supply frequency. When the induction motor is rotating, the frequency of the current induced in the rotor conductors is proportional to the relative speed or slip speed. If f^1 is the frequency of the induced current in the rotor, then

$$N_S - N = \frac{120 f^1}{P} \qquad (11.4)$$

But $$N_S = \frac{120 f}{P} \qquad (11.5)$$

Where, f = frequency of the supply

From equation (11.4) and (11.5), we get,

$$\frac{N_S - N}{N_S} = \frac{f^1}{f} = S$$

$$\therefore \; f^1 = S f \qquad (11.6)$$

The frequency of the rotor current is slip times the frequency of the supply.

$f \rightarrow$ frequency of supply

$f' \rightarrow$ frequency of the rotor current

Problems on Three Phase Induction Motor

Q. 1. A three phase induction motor is wound for four poles and is supplied from a 50Hz system. Calculate: (i) the synchronous speed, (ii) the speed of the rotor when the slip is 4% (iii) the rotor frequency when the speed of the rotor is 600rpm.

- Solution:
- Case A: $P = 4$; $f = 50$ Hz; $S = 0.04$; $N_s = ?$
- $N_s = 120 f / P = 1500$ rpm
- $N = N_s (1 – S) = 1440$ rpm
- Case B: $N' = 600$ rpm; $f = 50$ Hz; $f_r = ?$
- $S = N_s – N' / N_s = 0.6$
- $f_r = S*f = 30$ Hz

Q. 2. The frequency of emf in the stator of a 4 pole induction motor is 50Hz, and that in the rotor is 1Hz. What is the slip and speed?

- Solution:
- $P = 4$; $f = 50$ Hz; $f_r = 1$ Hz; $S = ?$; $N = ?$
- $N_s = 120\, f / P = 1500$ rpm
- $S = f_r / f = 0.02$
- $N = N_s\, (1 - S) = 1470$ rpm

Q. 3. In a 6 pole, 50Hz, 3 phase induction motor running on full load, the rotor emf makes 90 complete cycles/minute. Find the slip and full-load speed.

- Solution:
- $P = 6$; $f = 50$ Hz; $f_r = 90$ c/min = 90/60 = 1.5 c/s or Hz; $S = ?$; $N = ?$
- $N_s = 120\, f / P = 1000$ rpm
- $S = f_r / f = 0.03$
- $N = N_s\,(1 - S) = 970$ rpm

Q. 4. A 6-pole, 3 phase induction motor runs at 950rpm from a 50Hz supply. Find the slip and the number of complete cycles of the rotor emf per minute.

- Solution:
- $P = 6$; $f = 50$ Hz; $N = 950$ rpm; $S = ?$; f_r (in cycles per minute) = ?
- $N_s = 120 f / P = 1000$ rpm
- $S = N_s – N / N_s = 0.05$
- $f_r = S*f = 2.5$ Hz (cycles / second)
- f_r (in cycles per minute) = 150 c/min

THREE PHASE INDUCTION MOTOR

Theory Questions

1. Explain with a neat diagram, construction of (i) squirrel cage induction motor, (ii) slip-ring (phase wound) induction motor. Mention the merits and demerits of each type and mention their applications.
2. Explain the principle of operation of three phase induction motor.
3. Define the term slip with respect to induction motor.
4. Can an induction motor run at synchronous speed? Explain.
5. Explain the concept of Rotating Magnetic Field.