1.1. Unit – I - 3-Phase Induction Motors

1.1.1. Teaching Material / Teaching Aids as per above lecture plan.

1.1.1.1. Lecture-1

Three Phase Induction Motor

The most common type of AC motor being used throughout the work today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. They are found everywhere from a small workshop to a large manufacturing industry.

The advantages of three-phase AC induction motor are listed below:

1. Simple design
2. Rugged construction
3. Reliable operation
4. Low initial cost
5. Easy operation and simple maintenance
6. Simple control gear for starting and speed control
7. High efficiency.

Induction motor is originated in the year 1891 with crude construction (The induction machine principle was invented by *NIKOLA TESLA* in 1888.). Then an improved construction with distributed stator windings and a cage rotor was built.

The slip ring rotor was developed after a decade or so. Since then a lot of improvement has taken place on the design of these two types of induction motors. Lot of research work has been carried out to improve its power factor and to achieve suitable methods of speed control.

Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

1. Squirrel cage Induction Motors
2. Slip ring Induction Motors 3.2.1 *Squirrel cage Induction Motors*

(a) Stator Construction

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig: 3.1(a).

The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor. When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.

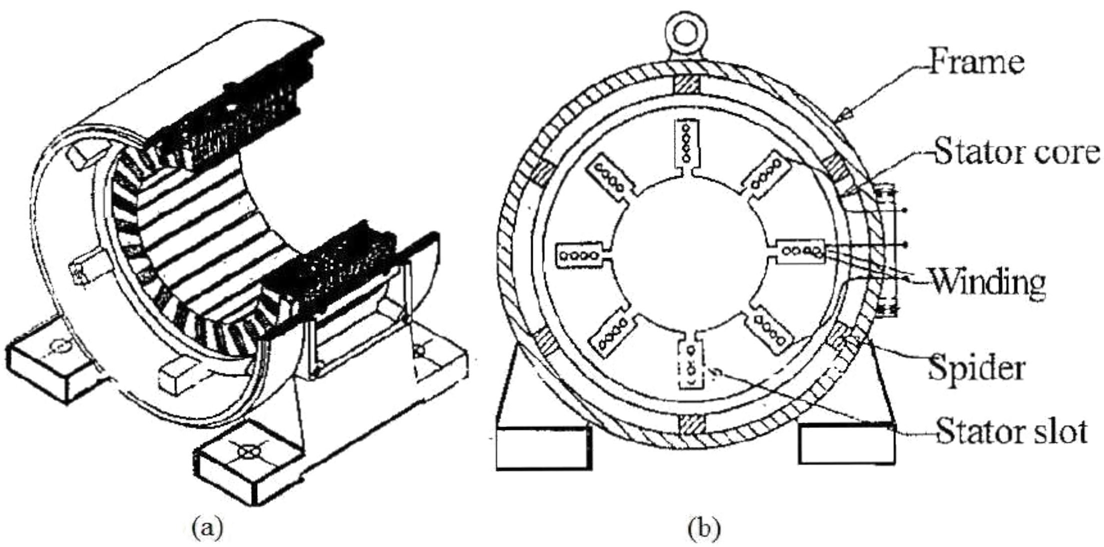


Fig: 3.1

(b) Rotor Construction

The rotor of the squirrel cage motor shown in Fig: 3.1(b) contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in Fig: 3.1(b).In small machines the conductor bars and end rings are sometimes made of aluminum with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

(c) End Shields

The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

3.2.2 *Slip ring Induction Motors*

(a) Stator Construction

The construction of the slip ring induction motor is exactly similar to the construction of squirrel cage induction motor. There is no difference between squirrel cage and slip ring motors.

(b) Rotor Construction

The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.

Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.

The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig: 3.2.

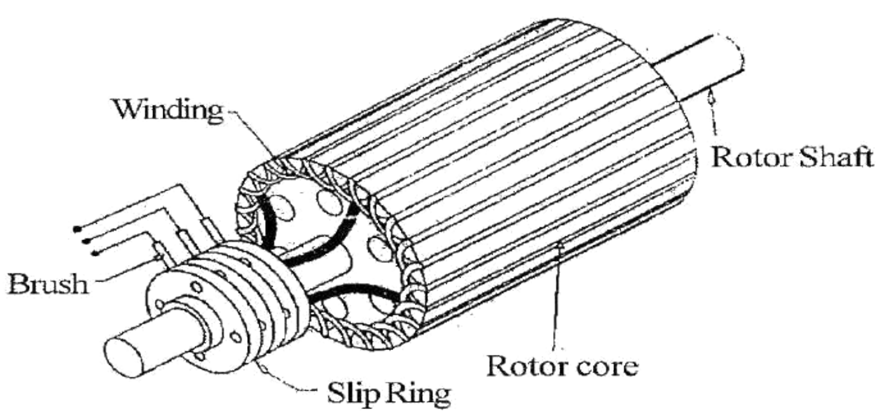


Fig: 3.2

<u>THE ADVANTAGES OF THE SLIPRING MOTOR ARE</u>

- It has susceptibility to speed control by regulating rotor resistance.
- High starting torque of 200 to 250% of full load value.
- Low starting current of the order of 250 to 350% of the full load current.

Hence slip ring motors are used where one or more of the above requirements are to be met.

Comparison of Squirrel Cage and Slip Ring Motor

Sl.No.	Property	*Squirrel cage motor*	*Slip ring motor*
1.	**Rotor Construction**	*Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes*	*Winding wire is to be used.* *Wound rotor required attention.* *Slip ring and brushes are needed also need frequent maintenance.*
2.	**Starting**	*Can be started by D.O.L., star-delta, auto transformer starters*	*Rotor resistance starter is required.*
3.	**Starting torque**	*Low*	*Very high*
4.	**Starting Current**	*High*	*Low*
5.	**Speed variation**	*Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.*	*Easy to vary speed.* *Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.*
6.	**Maintenance**	*Almost ZERO maintenance*	*Requires frequent maintenance*
7.	**Cost**	*Low*	*High*

1.1.1.2. *Lecture-2*

Rotating Magnetic Field and Induced Voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.3.4). Coils that are diametrically opposite are connected in series by means of three jumpers

that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoidally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.3.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

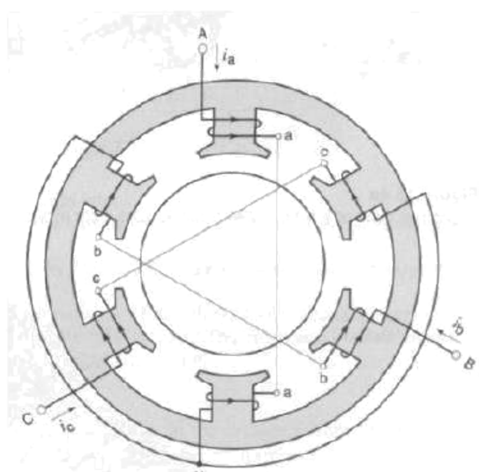


Fig: 3.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

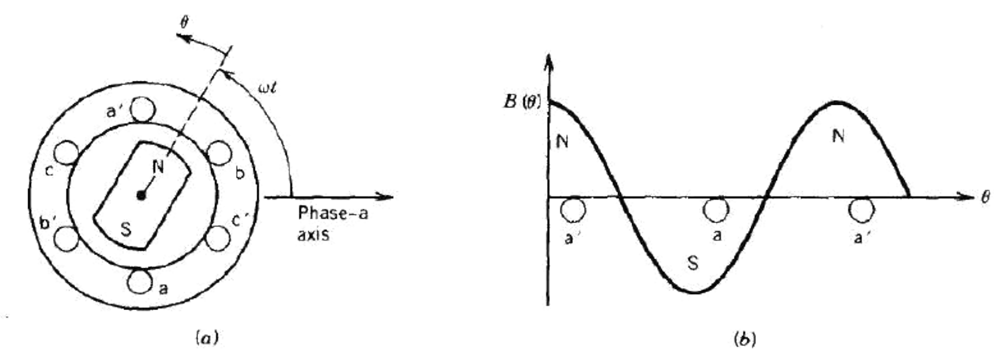


Fig: 3.5 Air gap flux density distribution.

The flux density distribution in the air gap can be expressed as:

$$B(\theta) = B_{\max} \cos \theta$$

The air gap flux per pole, ϕ_P, is:

$$\phi_p = \int_{-\pi/2}^{\pi/2} B(\theta) lr d\theta = 2B_{\max} lr$$

Where,

l is the axial length of the stator.

r is the radius of the stator at the air gap.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.3.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.

($= N\phi_P$ at $\omega t = 0^o$) (Fig.3.5a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,

$$\lambda_a(\omega t) = N\phi_p \cos \omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin \omega t = E_{\max} \sin \omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max} \sin(\omega t - 120)$$

$$e_c = E_{\max} \sin(\omega t + 120).$$

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N\phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full -pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor KW, called the winding factor, must therefore be applied. For most three-phase machine windings KW is about 0.85 to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$Erms = 4.44fNph\varphi pKW$

Where *Nph* is the number of turns in series per phase.

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, ØP represents the flux per pole of the machine.

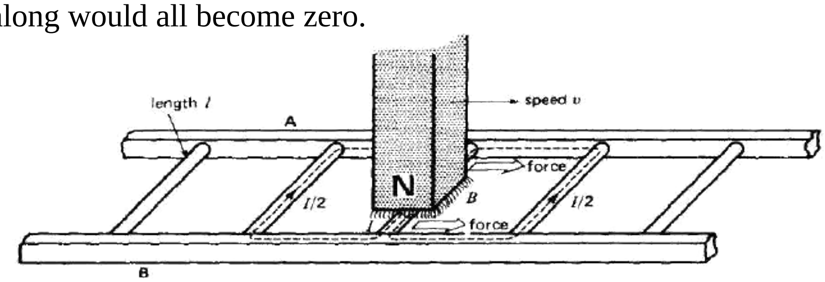
1.1.1.3. Lecture-3

Principle of Operation

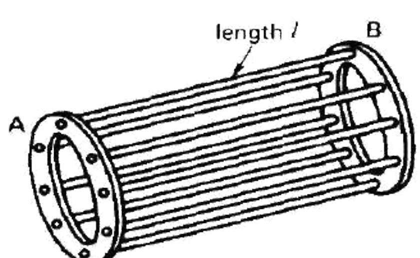
The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz force on a conductor. The behaviour can readily be understood by means of the following example.

Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig.3.3 a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:

1. A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).
2. The induced voltage immediately produces a current I, which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.
3. Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).
4. The force always acts in a direction to drag the conductor along with the magnetic field. If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors wilt also decreases. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.



(a)



(b)

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig.3.3b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings.

1.1.1.4. Lecture-4

The torque produced by three phase induction motor depends upon the following three factors:Firstly the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor, lastly the power factor of rotor of the three phase induction motor.

Combining all these factors together we get the equation of torque as-

$$T \propto \phi I_2 \cos\theta_2$$

Where, T is the torque produced by induction motor,

φ is flux responsible for producing induced emf,

I_2 is rotor current,

$\cos\theta_2$ is the power factor of rotor circuit.

The flux φ produced by the stator is proportional to stator emf E_1.

i.e $\varphi \propto E_1$

We know that transformation ratio K is defined as the ratio of secondary voltage (rotor voltage) to that of primary voltage (stator voltage).

Rotor current I_2 is defined as the ratio of rotor induced emf under running condition , sE_2 to total impedance, Z_2 of rotor side,

$$i.e\ I_2 = \frac{sE_2}{Z_2}$$

and total impedance Z_2 on rotor side is given by ,

$$Z_2 = \sqrt{R_2^2 + (sX_2)^2}$$

Putting this value in above equation we get,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

s= slip of Induction motor

We know that power factor is defined as ratio of resistance to that of impedance. The power factor of the rotor circuit is

$$\cos\theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Putting the value of flux φ, rotor current I_2, power factor $\cos\theta_2$ in the equation of torque we get,

$$T \propto E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Combining similar term we get,

$$T \propto sE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Removing proportionality constant we get,

$$T = KsE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$This\ comstant\ K = \frac{3}{2\pi n_s}$$

Where n_s is synchronous speed in r. p. s, $n_s = N_s / 60$. So, finally the equation of torque becomes,

$$T = sE_2^2 \times \frac{R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s} N - m$$

Derivation of K in torque equation.

In case of three phase induction motor, there occur copper losses in rotor. These rotor copper losses are expressed as

$Pc = 3I^2 R_2$

We know that rotor current,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Substitute this value of I_2 in the equation of rotor copper losses, P_c. So, we get

$$P_c = 3R_2 \left(\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \right)^2$$

$$On\ simplifying\ P_c = \frac{3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

1.1.1.5. Lecture-5

Ques1: A 3 φ 4 pole 50 hz induction motor runs at 1460 r.p.m. find its %age slip.

Solution

N_s = 120f/p = 120*50/4 = 1500r.p.m.

Running speed of motor = n= 1460r.p.m.

Slip S=(N_s–N)/ N_s*100 =(1500-1460) x 100 / 1500 = 2.667%

Ques2: A 12 pole 3 φ alternator driver at speed of 500 r.p.m. supplies power to an 8 pole 3 φ induction motor. If the slip of motor is 0.03p.u, calculate the speed.

Solution

Frequency of supply from alternator, f=PN/120

=12*500/120 = 50hz

where P= no of poles on alternator

N=alternator speed is r.p.m.

Synchronous speed of 3 φ induction motor

N=120f/Pm

=120*50/8 = 750 r.p.m.

Speed of 3 φ induction motor N=Ns (1-s)

=750(1-0.03) = 727.5 r.p.m.

Ques3: A motor generates set used for providing variable frequency ac supply consists of a 3-φ synchronous and 24 pole 3 φ synchronous generator. The motor generate set is fed from 25hz, 3 φ ac supply. A 6 pole 3 φ induction motor is electrically connected to the terminals of the synchronous generator and runs at a slip of 5%. Find

i) the frequency of generated voltage of synchronous generator

ii) the speed at which induction motor is running

Solution

Speed of motor generator set

Ns=(120*f1(supply freq))/(no of pole on syn motor)

=120*25/10 = 300 r.p.m.

frequency of generated voltage

fz=speed of motor gen set voltage *no of poles on syn gen/120

= 300*24/120 = 60hz

Speed of induction motor , Nm=Ns(1-s)

=120 fz /Pm(1-s) = 120*60/6(1-0.05) = 1140r.p.m.

Ques4: A 3-φ 4 pole induction motor is supplied from 3φ 50Hz ac supply. Find

(1) synchronous speed

(2) rotor speed when slip is 4%

(3) the rotor frequency when runs at 600r.p.m.

Sulution

1) Ns =120f/p

=120*50/4 = 1500 r.p.m.

2) speed when slip is 4% or .04

N=Ns (1-s)

=1500(1-0.04) = 1440 r.p.m.

3) slip when motor runs at 600 r.p.m.

S'=(Ns –N)/Ns

=(1500-600)/1500 = 0.6

Rotor frequency f' = S'f = 0.6*50 = 30Hz.

Ques5: A 12 pole 3-φ alternator is coupled to an engine running at 500r.p.m. If supplied a 3φ induction motor having full speed of 1440r.p.m.

Find the %age slip, frequency of rotor current and no of poles of rotor.

Ans

Frequency of supply from alternator f=Pa*Na/120

=12*500/120 = 50Hz

Full load speed Nf =1440 r.p.m.

The no of poles (nearest to and higher than full load speed of motor =1440) should be in even nos.

P=120f/n = 120*50/1440 = 4

Ns = 120f/Pm = 120*50/4 = 1500 r.p.m.

% Slip s = (Ns-N)/Ns x 100 =(1500-1440) x 100 / 1500 = 4%

Rotor frequency f’ = sf = 0.04*50 = 2Hz

No A poles of the motor = 4

Ques6: The rotor of 3φ induction motor rotates at 900r.p.m. when states is connected to 3φ supply .find the rotor frequency.

Solution

Nr =980 r.p.m., f=50Hz, Ns=120f/p

When P=2, Ns=3000r.p.m.,P=4, Ns=1500

P=6, Ns=1000, P=8, Ns=750r.p.m.

As we know that synchronous speed is slightly greater than rotor speed.

Ns=1000 r.p.m. P=6

Fr=Sf=(Ns-N)/Ns*f=Sf = (1000-980) x 50 / 1000

Ques7: A 3 φ 50Hz induction motor has a full load speed of 960 r.p.m

(a) find slip

(b) No of poles

(c) Frequency of rotor induced e.m.f

(d) Speed of rotor field w.r.t. rotor structure

(e) Speed of rotor field w.r.t. Stator structure

(f) Speed of rotor field w.r.t. stator field

Solution:

Given f = 50 Hz(supply frequency)

N = 960r.p.m

The no. of pole will be 6 only(because at P=6, Ns = 1000 which is nearer and greater then 960 r.p.m.)

(a) Slip, S = (Ns-N)/Ns * 100 = (1000 – 960) / 1000 * 100 = 4%

(b) No of poles = 6

(c) Frequency of rotor induced emf = fr = SF = .04 * 50 = 2Hz

(d) Speed of rotor field w.r.t rotor structure = 120fr/p = 120*2/6 = 40 r.p.m.

(e) Speed of rotor field w.r.t. stator structure os actually the speed of stator filed w.r.t stator structure, Ns = 1000r.p.m

(f) Speed of rotor field w.r.t stator field is zero

1.1.1.6. *Lecture-6*

Power Stages in an Induction Motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1. Fixed losses

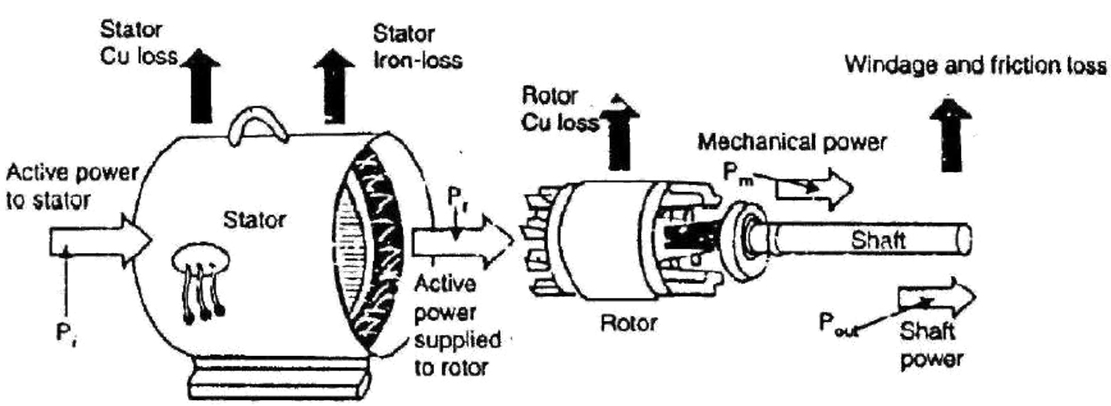
a. Stator iron loss
b. Friction and windage loss

The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

2. Variable losses

- Stator copper loss
- Rotor copper loss

Fig: shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.



The following points may be noted from the above diagram:

1. Stator input, Pi = Stator output + Stator losses + Stator output + Stator Iron loss + Stator Cu loss
2. Rotor input, Pr = Stator output

It is because stator output is entirely transferred to the rotor through air-gap by electromagnetic induction

3. Mechanical power available, Pm = Pr - Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque Tg.

4. Mechanical power at shaft, Pout = Pm - Friction and windage loss

Mechanical power available at the shaft produces a shaft torque Tsh.

5. Clearly, Pm - Pout = Friction and windage loss.

1.1.1.7. Lecture-7

Equivalent Circuit of Three Phase Induction Motor

Fig. 3.10 (i) shows the equivalent circuit per phase of the rotor at slip s. The rotor phase current is given by;

$$I'_2 = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

Mathematically, this value is unaltered by writing it as:

$$I'_2 = \frac{E_2}{\sqrt{(R_2/s)^2 + (X_2)^2}}$$

As shown in Fig. 3.10 (ii), we now have a rotor circuit that has a fixed reactance X2 connected in series with a variable resistance R2/s and supplied with constant voltage E2. Note that Fig. 3.10 (ii) transfers the variable to the resistance without altering power or power factor conditions.

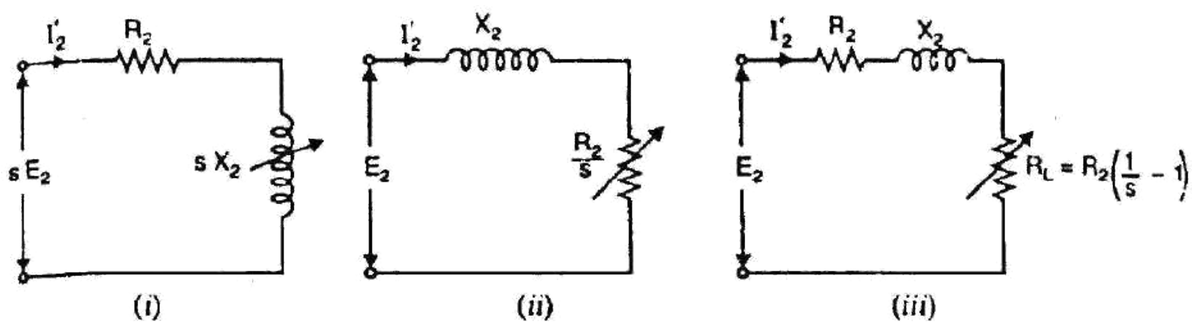


Fig: 3.10

The quantity R_2/s is greater than R_2 since s is a fraction. Therefore, R_2/s can be divided into a fixed part R_2 and a variable part $(R_2/s - R_2)$ i.e.,

$$\frac{R_2}{s} = R_2 + R_2\left(\frac{1}{s} - 1\right)$$

(i) The first part R_2 is the rotor resistance/phase, and represents the rotor Cu loss.

(ii) The second part $R_2\left(\frac{1}{s} - 1\right)$ is a variable-resistance load. The power delivered to this load represents the total mechanical power developed in the rotor. Thus mechanical load on the induction motor can be replaced by a variable-resistance load of value $R_2\left(\frac{1}{s} - 1\right)$. This is

$$\therefore \quad R_L = R_2\left(\frac{1}{s} - 1\right)$$

Fig. 3.10 (iii) shows the equivalent rotor circuit along with load resistance RL.

Now Fig: 3.11 shows the equivalent circuit per phase of a 3-phase induction motor. Note that mechanical load on the motor has been replaced by an equivalent electrical resistance RL given by;

$$R_L = R_2\left(\frac{1}{s} - 1\right) \qquad \text{----- (i)}$$

The circuit shown in Fig. 3.11 is similar to the equivalent circuit of a transformer with secondary load equal to R2 given by eq. (i). The rotor e.m.f. in the equivalent circuit now depends only on the transformation ratio K (= E2/E1).

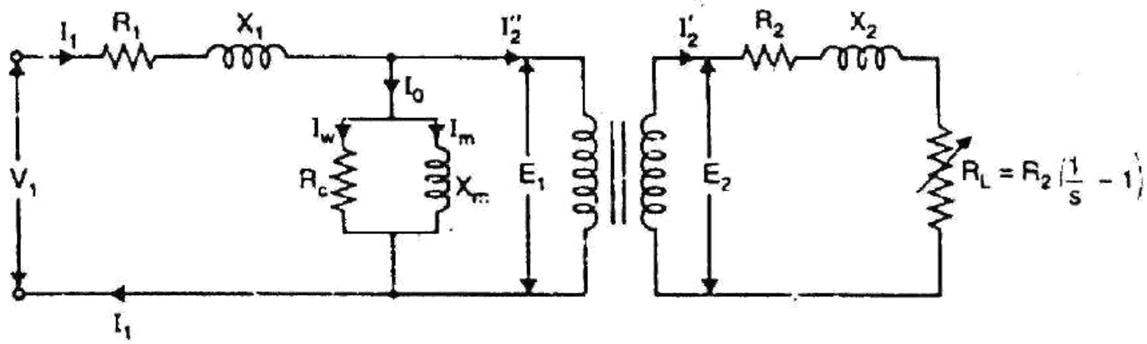


Fig: 3.11

Therefore; induction motor can be represented as an equivalent transformer connected to a variable-resistance load RL given by eq. (i). The power delivered to R L represents the total mechanical power developed in the rotor. Since the equivalent circuit of Fig. 3.11 is that of a transformer, the secondary (i.e., rotor) values can be transferred to primary (i.e., stator) through the appropriate use of transformation ratio K. Recall that when shifting resistance/reactance from secondary to primary, it should be divided by K2 whereas current should be multiplied by K. The equivalent circuit of an induction motor referred to primary is shown in Fig. 3.12

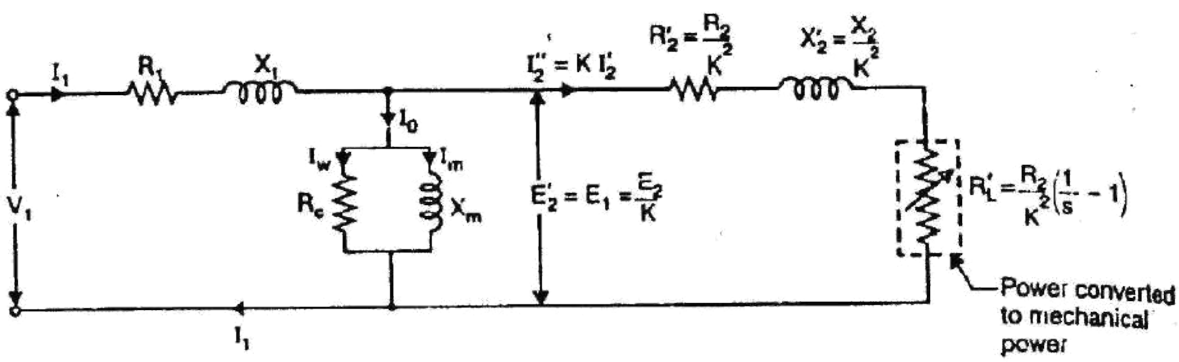


Fig: 3.12

Note that the element (i.e., R'L) enclosed in the dotted box is the equivalent electrical resistance related to the mechanical load on the motor. The following points may be noted from the equivalent circuit of the induction motor:

(i) At no-load, the slip is practically zero and the load R'L is infinite. This condition resembles that in a transformer whose secondary winding is open-circuited.

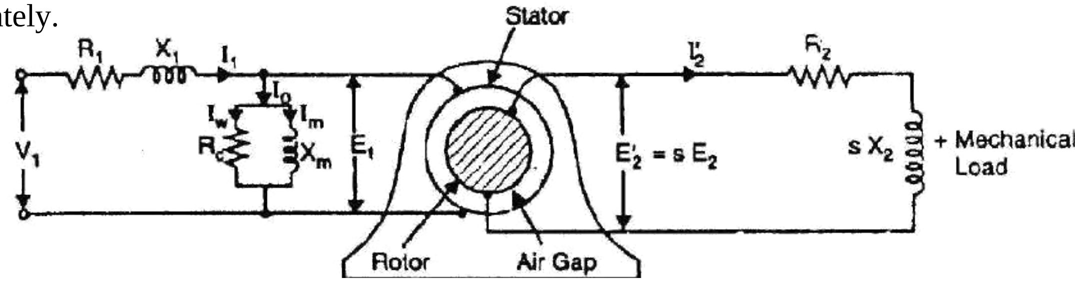
(ii) At standstill, the slip is unity and the load R'L is zero. This condition resembles that in a transformer whose secondary winding is short-circuited.

(iii) When the motor is running under load, the value of R'L will depend upon the value of the slip s. This condition resembles that in a transformer whose secondary is supplying variable and purely resistive load.

(iv) The equivalent electrical resistance R'L related to mechanical load is slip or speed dependent. If the slip s increases, the load R'L decreases and the rotor current increases and motor will develop more mechanical power. This is expected because the slip of the motor increases with the increase of load on the motor shaft.

Phasor Diagram of Three Phase Induction Motor

In a 3-phase induction motor, the stator winding is connected to 3-phase supply and the rotor winding is short-circuited. The energy is transferred magnetically from the stator winding to the short-circuited, rotor winding. Therefore, an induction motor may be considered to be a transformer with a rotating secondary (short-circuited). The stator winding corresponds to transformer primary and the rotor finding corresponds to transformer secondary. In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer. Fig. 3.8 shows the equivalent circuit per phase for an induction motor. Let discuss the stator and rotor circuits separately.



Stator circuit. In the stator, the events are very similar to those in the transformer primary. The applied voltage per phase to the stator is V1 and R1and X1 are the stator resistance and leakage reactance per phase respectively. The applied voltage V1 produces a magnetic flux which links the stator winding (i.e., primary) as well as the rotor winding (i.e., secondary). As a result, self-induced e.m.f. E1 is induced in the stator winding and mutually induced e.m.f.

E'2(= s E2 = s K E1 where K is transformation ratio) is induced in the rotor winding. The flow of stator current I1 causes voltage drops in R1 and X1.

∴ V1 = −E1 + I1 (R1+ j X1) ...phasor sum

When the motor is at no-load, the stator winding draws a current I0. It has two components viz.,

(i) which supplies the no-load motor losses and (ii) magnetizing component Im which sets up magnetic flux in the core and the air gap. The parallel combination of Rc and Xm, therefore, represents the no-load motor losses and the production of magnetic flux respectively.

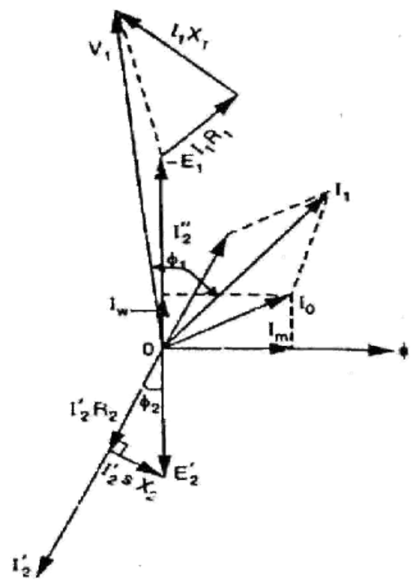
∴ I0 = Iw + Im

Rotor circuit. Here R2 and X2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be X2 .The induced voltage/phase in the rotor is E'2 = s E2 = s K **E1**. Since the rotor winding is short-circuited, the whole of e.m.f. E'2 is used up in circulating the rotor current I'2.

∴ E'2 = I'2 (R2 + j s X2)

The rotor current I'2 is reflected as I"2 (= K I'2) in the stator. The phasor sum of I"2 and I0 gives the stator current I1.

It is important to note that input to the primary and output from the secondary of a transformer are electrical. However, in an induction motor, the inputs to the stator and rotor are electrical but the output from the rotor is mechanical. To facilitate calculations, it is desirable and necessary to replace the mechanical load by an equivalent electrical load. We then have the transformer equivalent circuit of the induction motor.



It may be noted that even though the frequencies of stator and rotor currents are different, yet the magnetic fields due to them rotate at synchronous speed Ns. The stator currents produce a magnetic flux which rotates at a speed Ns. At slip s, the speed of rotation of the rotor field relative to the rotor surface in the direction of rotation of the rotor is

$$= \frac{120\, f'}{P} = \frac{120\, s\, f}{P} = s\, N_s$$

But the rotor is revolving at a speed of N relative to the stator core. Therefore, the speed of rotor field relative to stator core

$$= sN_s + N = (N_s - N) + N = N_s$$

Thus no matter what the value of slip s, the stator and rotor magnetic fields are synchronous with each other when seen by an observer stationed in space. Consequently, the 3-phase induction motor can be regarded as being equivalent to a transformer having an air-gap separating the iron portions of the magnetic circuit carrying the primary and secondary windings. Fig. shows the phasor diagram of induction motor.

1.1.2. Test Questions

a. Fill in the blanks type of questions

1. **<u>Stator core</u>** is usually fabricated out of silicon steel.
2. The frame of an induction motor is usually made of **<u>cast iron</u>**
3. The shaft of an induction motor is made of **<u>stiff</u>**
4. The shaft of an induction motor is made of **<u>carbon steel</u>**
5. In an induction motor, noload the slip is generally **<u>less than 1%</u>**
6. In medium sized induction motors, the slip is generally around **<u>4%</u>**
7. In squirrel cage induction motors, the rotor slots are usually given slight skew in order to **<u>reduce magnetic hum</u>**
8. In case the air gap in an induction motor is increased **<u>the power factor will decrease</u>**
9. Slip rings are usually made of **<u>phospor bronze</u>**
10. A 3phase 440 V, 50 Hz induction motor has 4% slip. The frequency of rotor e.m.f. will be **<u>2 Hz</u>**

b. Multiple choice questions

1. If **Ns** is the synchronous speed and **S** the slip, then actual running speed of an induction motor will be

(a) Ns (b) s.Ns **(c) (ls)Ns** (d) (Nsl)s

2. The efficiency of an induction motor can be expected to be nearly

(a) 60 to 90% **(b) 80 to 90%** (c) 95 to 98% (d) 99%

3. The number of slip rings on a squirrel cage induction motor is usually

(a) two (b) three (c) four **(d) none**

4. The starting torque of a squirrelcage induction motor is

(a) low (b)negligible (c) same as fullload torque (d) slightly more than fullload torque

5. An induction motor with 1000 r.p.m. speed will have

(a) 8 poles **(b) 6 poles** (c) 4 poles (d) 2 poles

6. The good power factor of an induction motor can be achieved if the average flux density in the air gap is

(a) absent **(b) small** (c) large (d) infinity

7. An induction motor is identical to

(a) D.C. compound motor (b) D.C. series motor (c) synchronous motor **(d)asynchronous motor**

8. Which of the following methods is easily applicable to control the speed of the squirrel cage induction motor ?

(a)By changing the number of stator poles (b) Rotor rheostat control

(c) By operating two motors in cascade (d) By injecting e.m.f. in the rotor circuit

9. If any two phases for an induction motor are interchanged

(a) the motor will run in reverse direction (b) the motor will run at reduced speed

(c) the motor will not run (d) the motor will burn

10. In threephase squirrelcage induction motors

(a)rotor conductor ends are shortcircuited through slip rings

(b) rotor conductors are shortcircuited through end rings

(c) rotor conductors are kept open

(d) rotor conductors are connected to insulation

c. True or False questions

1. In a threephase induction motor, the number of poles in the rotor winding is always **equal to number of poles in stator**
2. The power factor of an induction motor under noload conditions will be closer to **0.2 lagging**
3. Slip of an induction motor is negative when **rotor speed is more than the synchronous speed of the field and are in the same direction**
4. In an induction motor the relationship between stator slots and rotor slots is that **stator slots are not exact multiple of rotor slots**
5. Slip ring motor is recommended where **high starting torque is needed**
6. As load on an induction motor goes on increasing **its power factor goes on increasing upto full load and then it falls again**

7. If a 3phase supply is given to the stator and rotor is short circuited rotor will move **in the same direction as the direction of the field**
8. The speed characteristics of an induction motor closely resemble the speed load characteristics of which of the following machines **D.C. shunt motor**
9. A 3phase slip ring motor has **wound rotor**
10. In a threephase induction motor **power factor at starting is low as compared to that while running**

1.1.3. Review Questions

d. Objective type of questions

1. Describe the principle construction and operation of Induction motor.
2. Discuss the various losses taking place in IM. Explain the effect of slip on the Performance of IM.
3. Derive the torque equation of an induction motor. Mention the condition for maximum torque.
4. Describe how rotating magnetic field is developed in induction motor.
5. Discuss the following

(a) How torque is developed in the rotor of a induction motor.

(b) Why in some induction motors double cages are provided?

6. Why the rotor of a poly phase induction motor can never attain synchronous speed? Discuss.
7. Describe the constructional features of both slip ring and squirrel cage induction motor. Discuss the merits of one over the other.
8. With neat diagram describe the equivalent circuit of 3phase Double Cage IM.
9. Draw the phasor diagram of an Induction motor and explain.
10. With a neat sketch discuss the principle of operation of double cage Induction motor, Briefly explain the torque slip characteristics of an Induction motor.

e. Analytical type questions

1. The frequency of stator EMF is 50 Hz for an 8-pole induction motor. If the rotor frequency is 2.5 hz, calculate the slip and the actual speed of rotor.

2. An 8 pole, 3phase alternator is coupled to a prime mover running at 750 rpm. It supplies an induction motor which has a full load speed of 960 rpm. Find the number of poles of IM and slip.

3. In case of an 8-pole induction motor the supply frequency was 50 Hz and the shaft speed was 735 rpm. Compute (i) Synchronous speed (ii) Slip speed per unit slip (iii) Percentage slip.

4. A 3- φ induction motor is wound for 4 poles and is supplied from 50Hz system. Calculate i) Synchronous speed ii) Rotor speed, when slip is 4% iii) Rotor frequency when rotor runs at 60 rpm.

5. The emf in the stator of an 8 pole induction motor has a frequency f 50 Hz and that in the rotor is 1.5Hz. At what speed the motor is running and what is the slip?

6. An 8-pole, 50 Hz, 3 phase slip ring IM has effective resistance of 0.08 /phase. The speed correspond to maximum torque is 650 rpm. What is the value of resistance to be inserted in rotor circuit to obtain maximum torque at starting?

7. A 4 pole, 400 V, 3phase IM has a standstill rotor EMF of 100 V per phase. The rotor has resistance of 50 Ώ/ph and standstill reactance of 0.5 Ώ/ph. Calculate the maximum torque & slip at which it occurs. Neglect stator impedance.

8. The power input to a 500V, 50Hz, 6 -pole, 3 -phase induction motor running at 975 rpm is 40 KW. The stator losses are 1KW and the friction and windage losses total to 2KW, Calculate i) The slip ii) Rotor copper loss iii) Shaft power.

9. An 8 pole, 3 phase alternator is coupled to an engine running at 750 rpm. The alternator supplies power to an induction motor which has a full load speed of 1425 rpm. Find the percentage slip and the number of poles of the motor

10. 500HP, 30, 440V, 50Hz induction motor has a speed of 950 rpm on full load. The machine has 6 poles. Calculate
    i. Slip, and Speed of rotor field w.r.t rotor.
    ii. Speed of rotor field w.r.t stator.
    iii. Complete alternations of rotor voltage per minute.
    iv. Relative speed between stator field w.r.t rotors.

f. Essay type Questions

1. Describe the principle construction and operation of Induction motor.
2. Discuss the various losses taking place in IM. Explain the effect of slip on the Performance of IM.
3. Derive the torque equation of an induction motor. Mention the condition for maximum torque.
4. Describe how rotating magnetic field is developed in induction motor.
5. Discuss the following
   (a) How torque is developed in the rotor of a induction motor.
   (b) Why in some induction motors double cages are provided?

6. Why the rotor of a poly phase induction motor can never attain synchronous speed? Discuss.
7. Describe the constructional features of both slip ring and squirrel cage induction motor. Discuss the merits of one over the other.
8. With neat diagram describe the equivalent circuit of 3phase Double Cage IM.
9. Draw the phasor diagram of an Induction motor and explain.
10. With a neat sketch discuss the principle of operation of double cage Induction motor, Briefly explain the torque slip characteristics of an Induction motor.

g. Problems

1.1.4. Skill Building Exercises/Assignments

Eg:- -Prepare a model of something
-Trace something
-Prepare a report on something etc.,

1.1.5. Previous Questions (Asked by JNTUK from the concerned Unit)

1.1.6. GATE Questions (Where relevant)

1.1.7. Interview questions (which are frequently asked in a Technical round - Placements)

1.1.8. Real-Word (Live) Examples / Case studies wherever applicable

1.1.9. Suggested “Expert Guest Lectures” (both from in and outside of the campus)

1.1.10. Literature references of Relevant NPTEL Videos/Web/You Tube videos etc.

1.1.11. Any Lab requirements; if so link it to Lab Lesson Plan.

1.1.12. Reference Text Books / with Journals Chapters etc.

1. The performance and design of alternating current machines – M.G. Say, CBS publishers & distributors, New Delhi.
2. Electrical Machines – P.S. Bimbra, Khanna Publishers.
3. Electrical Machines by J.B.Guptha, S.K.Kataria & Sons.
4. Electrical Machines by D. P.Kothari, I. J. Nagarth, Mc Graw Hill Publications, 4th edition.
5. Electrical Machines by R.K.Rajput, Lakshmi publications,Fifth edition.
6. Electrical Machines by Smarajit Ghosh, Pearson Publications.