PIE Tech

POLLACHI INSTITUTE OF ENGINEERING AND TECHNOLOGY

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Department of Electrical and Electronics Engineering

Regulation 2021

II Year – IV Semester

EE3405- Electrical Machines-II

Unit-I –Synchronous Generator

INTRODUCTION

- The most commonly used machine for generation of electrical power for commercial purpose is the synchronous generator. Such a synchronous generator is also referred to as alternator since it generates alternating voltage.

CONSTRUCTION OF SYNCHRONOUS GENERATOR

Synchronous generator according to their construction, are divided into the following two classifications:

1. Rotating armature type:It has stationary field poles and rotating armature.
2. Rotating field type: It has stationary armature or stator and rotating field poles.

Most synchronous generator or alternators have rotating field and stationary armature.

The advantages of the rotating field type alternators are:

(i) A stationary armature is more easily insulted for the high voltage for which the alternator is designed.

(ii) The armature windings can be braced better mechanically against high electromagnetic forces due to large short-circuit currents when the armature windings are in the stator.

(iii) The armature windings, being stationary, are not subjected to vibration and centrifugal forces.

(iv) The output current can be taken directly from fixed terminals on the stationary armature without using slip rings, brushes.

(v) The rotating field is supplied with direct current. Only two slip rings are required to provide direct current for the rotating field, while at least three slip rings would be required for a rotating armature.

(vi) Rotating field is comparatively light and can be constructed for high speed rotation.

(vii) The stationary armature may be cooled more easily because the armature can bemade large to provide a number of cooling ducts.

For Mn The basic construction of a synchronous generator and a synchronous motor is the same. Similar to other rotating machines, an alternator consists of two main parts namely, the stator and the rotor.

- The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator.
- The rotor is the rotating part of the machine. The rotor produces the main field flux.

Construction of Stator

The stator consists of an armature made of laminations of silicon steel having slots on its inner periphery to accommodate armature windings. Fig. 1 shows a cross sectional view of the stator of a three phase two pole synchronous machine.

Double layer armature windings of three phase a, b and c are placed in the slots. The windng is star connected. The winding of each phase is distributed over several slots. Since an alternating flux is produced in the stator due to the flow of alternating current in the armature winding, the stator is made of high permeability laminated steel stampings in order to reduce hysteresis and eddy current losses. The whole structure is held in a frame made of cast steel or welded-steel plates.

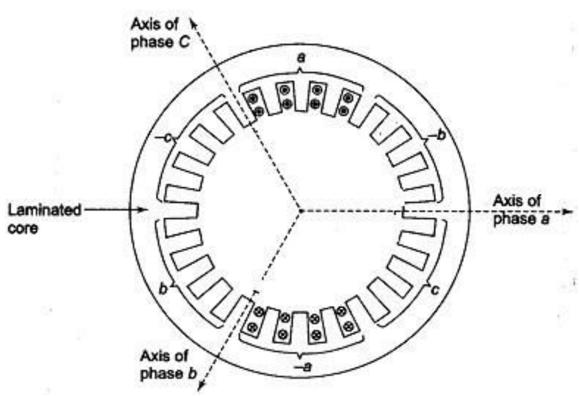


Fig.1

Slots provided on the stator core are mainly of two types: open slots and semi-closed slots. Open slots are commonly used for commercial generators. However, non-uniform air gaps due to open slots may produce ripples in the emf waveform. The use of semi-closed type slots can minimize ripples by distributing the flux as uniformly as possible. For slot insulation, leatheroid, mica folium,or manila paper of proper thickness is used.

Construction of Rotor

Two types of rotors are used in alternators. (i) Salient pole type (ii) Smooth cylindrical type

(i) Salient (or projecting) Pole Type

The term salient means projecting. Thus a salient pole rotor consists of poles projecting out from the surface of the rotor core as shown in fig. 2. Salient pole rotors are normally used for rotors with four or more poles.

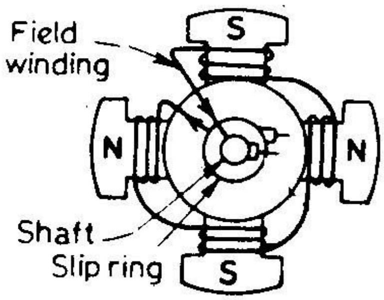


Fig.2

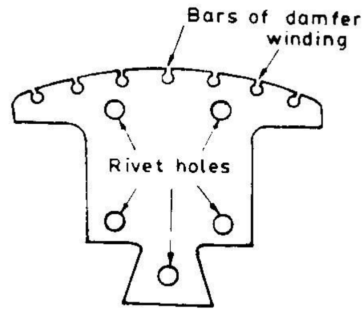


Fig. 3

Since the rotor is subjected to changing magnetic fields, it is made of steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length and then riveted together. After placing the field coil around each pole body, these poles are fitted by a dove-tail joint to a steel spider keyed to the shaft. Salient pole rotors have concentrated winding on the poles. Damper bars are usually inserted in the pole faces to damp out the rotor oscillations during sudden change in load condition as shown in fig. 3. The pole face is so shaped that the radial air gap length increases from the pole centre to pole tips. This makes the flux distribution over the armature uniform to generate sinusoidal waveform of emf.

The salient pole field structure has the following special features:

(i) They have large diameter and short axial length.

(ii) Poles are laminated to reduce eddy current losses.

(iii) These are employed with hydraulic turbines or diesel engines. The speed is 100 to 375 rpm.

(ii) Smooth Cylindrical Type

A cylindrical rotor machine is also called a non-salient pole rotor machine. It has its rotor so constructed that it forms a smooth cylinder as shown in fig.4. This type of rotor is used for alternators which are coupled to steam turbines which run at very high speeds. The number of poles of the rotor are two or four.

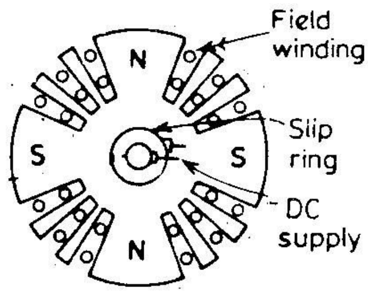


Fig.4

These rotors are made from solid forgings of alloy steel. The outer periphery of rotor has slots in which the field winding is placed. About 2/3rd of rotor pole pitch is slotted, leaving the 1/3rd unslotted for the pole centre. Heavy wedges of non-magnetic steel are forced into the grooves in the teeth outside the field coils to keep the field coils in position. Since these rotors have large lengths of core forced ventilation is necessary for proper cooling.

The non-salient field structure has the following special features:

(i) They are of small diameter and of very long axial length.

(ii) Robust construction.

(iii) High operating speed (3000 rpm)

(iv) Noiseless operation.

(v) Dynamic balancing is better.

(vi) No need to provide damper windings, except in special cases to assist synchronizing.

(vii) Better emf waveform.

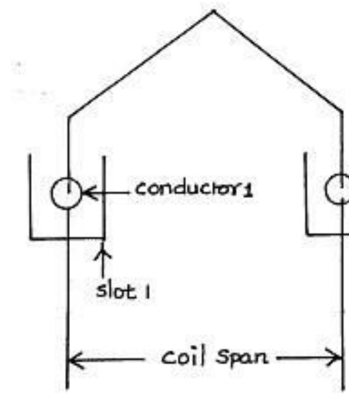
Difference between salient and cylindrical type of rotor

Salient Pole	Smooth Cylindrical
Poles are Projected	Poles are not projected
Air gap is non uniform	Air gap is uniform
Diameter is high and axial length is small	Diameter is small and axial length is large
Mechanically weak	Mechanically strong
Suitable for Low speed alternators	Suitable for High speed alternators
Separate damper winding is provided	Separate damper winding is not provided

STANDARD DEFINITION AND TERMS USED IN AC WINDINGS

1. Conductor : The part of the wire, which is under the influence of the magnetic field and responsible for the induced emf is called active length of the conductor. The conductors are placed in the armature slots.

2. Turn : A conductor in one slot, when connected to a conductor in another slot forms a turn. so two conductors consitute a turn. This is shown in fig (a).



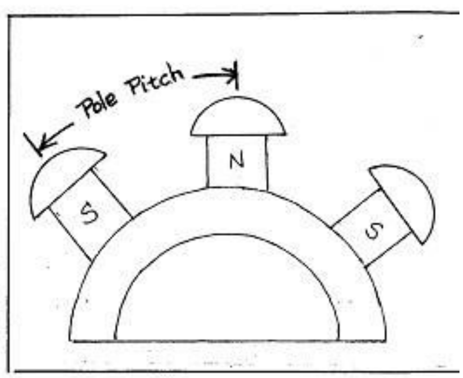
Fig(a)
Turn or coil

3. coil span : The distance between two coil sides of a coil is called as coil span.

4. Pole pitch :

The distance between the centres of two adjacent poles is called pole pitch.

Pole pitch = 180° electrical
= slots / pole



5. Relation between frequency, Speed and Number of poles

Frequency $f = \frac{PN}{120}$

where P = Number of poles
N = Synchronous speed

TYPES OF ARMATURE WINDING

In general armature winding is classified as

a) Single layer winding b) Double layer winding

c) Concentrated winding d) Distributed winding

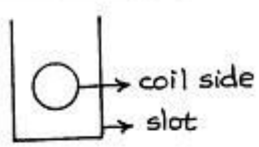
e) Full pitched winding f) short pitched winding

g) Wave winding h) Lap winding

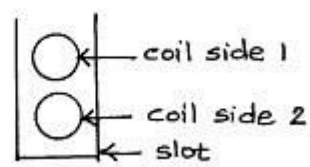
Single Layer and Double layer winding

If a slot consists of only one coil side, winding is said to be single layer winding. This is shown in fig(a).

While there are two coil sides per slot, one at the bottom and one at the top, the winding is called double layer winding as shown in Fig(b)



Fig(a) Single layer



Fig(b) Double layer

For Mn

Concentrated and Distributed winding

If slots equal to number of poles then concentrated winding is obtained. Concentrated windings gave maximum induced emfs for a given number of conductors but the wave form of emf is not exactly of sinusoidal form.

If conductors are placed in several slots under one pole, the winding is known as distributed winding. Though it reduces the induced emf it yet is most commonly employed due to its manifold advantages.

i) The harmonic emfs are reduced and so the wave form is improved.

ii) The distributed winding reduces armature reaction and armature reactance.

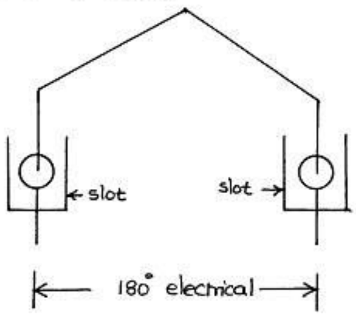
iii) The core is better utilized as a number of small slots evenly spaced are employed.

Full pitch and short pitch winding

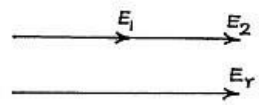
When the two coil sides forming a complete coil of a winding are 180° electrical space degrees apart, the winding is known as full pitch winding. is shown in fig(a). The induced emf differ by 180° phase, but the coil is connected in such a way that emfs add giving resultant emf E as shown in fig(b).

When the coil span of the winding is less than 180° electrical space degrees, the winding is known as

Fractional pitch or short pitch winding is shown in fig (c). In this type of winding, the induced emf in each coil side is not in phase, so the resultant emf is the phasor sum of induced emfs in the coil sides which is slightly less than their arithmetic sum, hence induced emf in short pitch winding is less than that induced emf in full pitch winding under the same condition is shown in fig (d)



Fig(a)



Fig(b)

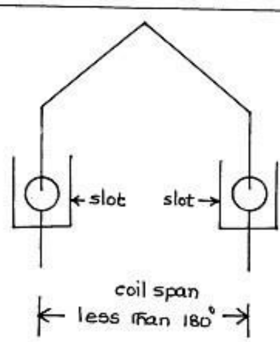
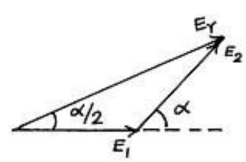


Fig (c)



Fig(d)

Advantage of short pitch coil

i) They save copper of end connections

ii) They improve wave form of the generated emf

iii) Distorting harmonics can be eliminated.

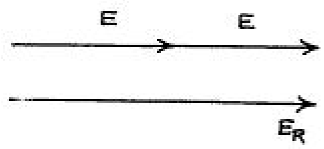
iv) Due to elimination of high frequency harmonics eddy current and hysteresis losses are reduced.

v) Efficiency is increased.

PITCH FACTOR OR COIL SPAN FACTOR (K_c)

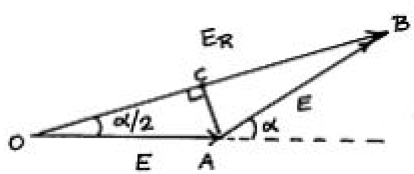
It is defined as the ratio of resultant emf when coil is short pitch to the resultant emf when coil is full pitched. It is always less than one.

$$K_c = \frac{\text{Resultant emf when coil is short pitched}}{\text{Resultant emf when coil is full pitched}}$$



Resultant emf when coil is full pitched

$$E_R = E + E = 2E \qquad (1)$$



$$\cos \alpha/2 = \frac{OC}{OA} = \frac{E_R/2}{E}$$

$$\cos \alpha/2 = \frac{E_R}{2E}$$

Resultant emf when coil is short pitched

$$E_R = 2E \cos \alpha/2 \qquad (2)$$

From equ (1) and (2)

$$\text{Pitch Factor } K_c = \frac{2E \cos \alpha/2}{2E}$$

$$\boxed{K_c = \cos \alpha/2}$$

where α = Angle of short pitch

For Mn

DISTRIBUTION FACTOR (K_d)

The distribution factor is defined as the ratio of the resultant emf when coils are distributed to the resultant emf when coils are concentrated. It is always less than one.

$$K_d = \frac{\text{Resultant emf when coils are distributed}}{\text{Resultant emf when coils are concentrated}}$$

Let β be the angular displacement between slots.

$$\beta = \frac{180^\circ}{\text{Pole pitch}} \quad ; \text{Pole pitch} = \frac{\text{No. of slots}}{\text{No. of poles}}$$

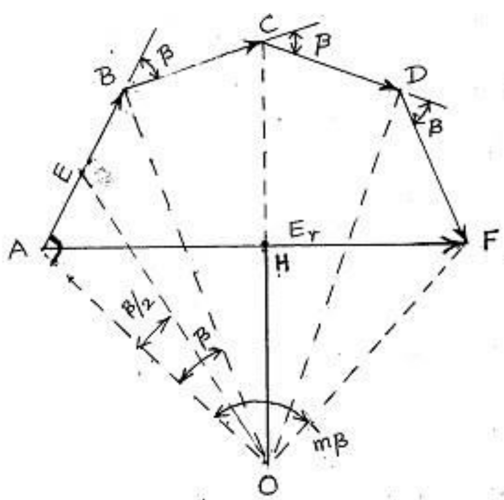
m = No. of slots/pole/phase

$m\beta$ = Phase spread angle

E = Emf induced in one coil side

If coils were bunched in one slot, then the total emf induced would be mE.

Since the coils are distributed the individual emf have a phase difference of β. This method of finding the vector sum of m voltages each of value E and having a phase difference of β is as shown in fig(a).



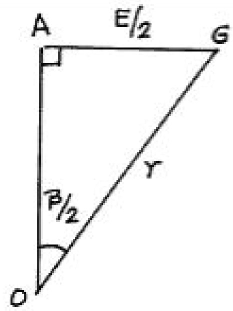
If m is large, then the curve ABCDE will become part of a circle of radius r.

$$AB = E$$

From Triangle OAB

$$OB = r$$

$$\angle AOB = \beta$$



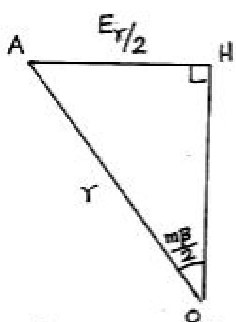
$$\sin \beta/2 = \frac{E/2}{r} = \frac{E}{2r}$$

$$\therefore E = 2r \sin \frac{\beta}{2}$$

Resultant emf when coils are concentrated $= mE$

$$= m\, 2r \sin \frac{\beta}{2} \quad \text{(1)}$$

From Triangle OAH



$$\sin \frac{m\beta}{2} = \frac{\frac{E_r}{2}}{r}$$

$$E_r = 2r \sin \frac{m\beta}{2}$$

Resultant emf when coil are distributed $= E_r$

$$= 2r \sin \frac{m\beta}{2} \quad \text{(2)}$$

From Equ. (1) and (2)

$$\text{Distribution factor } K_d = \frac{2r \sin \frac{m\beta}{2}}{m 2r \sin \frac{\beta}{2}}$$

$$\text{Distribution factor } \boxed{K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}}$$

EMF EQUATION OF AN ALTERNATOR

Let

ϕ = Flux per pole in wb

P = Number of poles

N_s = Synchronous Speed in rpm

f = Frequency of induced emf in Hz

Z = Total No. of conductors

Z_{ph} = conductors per phase connected in series

$Z_{ph} = 2T_{ph}$

T_{ph} = No. of turn/phase

K_c = coil span factor = $\cos \alpha/2$

K_d = Distribution factor = $\dfrac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}$

K_f = Form factor = 1.11 if emf is sinusoidal

The average value of emf induced in a conductor = $\dfrac{d\phi}{dt}$

In one revolution of rotor, each stator conductor is cut by a flux of ϕP webers.

$$\therefore \boxed{d\phi = \phi P}$$

Rotative speed of the rotor in rps = $\dfrac{N_s}{60}$

Time taken for one revolution of rotor = $\dfrac{1}{N_s/60}$

$$= \frac{60}{N_s}$$

$$\boxed{dt = \frac{60}{N_s}}$$

Average emf induced per conductor $= \dfrac{d\phi}{dt}$

$$= \frac{\phi P}{60/N_s}$$

$$= \frac{\phi P N_s}{60} \text{ volts}$$

we know that

$$f = \frac{PN_s}{120} \quad \text{or} \quad N_s = \frac{120f}{P}$$

substituting this value of N_s above we get

$$\text{Average emf induced per conductor} = \frac{\phi P}{60} \times \frac{120f}{P}$$

$$= 2f\phi \text{ volts}$$

If there are Z_{ph} conductors in series/phase then

$$\text{Average emf induced per phase} = \text{Average emf induced per conductor} \times Z_{ph}$$

$$= 2f\phi Z_{ph}$$

$$= 2f\phi \times 2T_{ph}$$

$$\text{Average emf induced per phase} = 4f\phi T_{ph}$$

$$\text{Rms value of emf per phase} = \text{Form factor} \times \text{Average value}$$

$$= 1.11 \times 4f\phi T_{ph}$$

$$E_{ph} = 4.44 f\phi T_{ph} \text{ volt}$$

This is the value of induced emf when all the coils in a phase are full pitched and concentrated in one slot.

SYNCHRONOUS REACTANCE

The leakage reactance X_L and the armature reactance X_a may be combined to give synchronous reactance X_S.

Hence $X_S \cdot \; X_L \cdot \; X_a$

The ohmic value of X_a varies with the power factor of the load because armature reaction depends on load power factor.

ARMATURE REACTION

Power factor	Relation between armature flux and field flux	Effect	Voltage level
Unity	Both fluxes cuts each other	Cross magnetising	Terminal voltage decreases
Lagging	Both fluxes acts opposite to each other	Demagnetising	Terminal voltage decreases more than the unity factor
Leading	Both fluxes acts in the same direction	Magnetising	Terminal voltage increases

VOLTAGE REGULATION OF ALTERNATOR

It is defined as the change in terminal voltage, expressed as a percentage (or p.u.) of the rated voltage, when the load at a given power factor is removed, with speed and field current remaining unchanged. Therefore,

$$\text{Voltage regulation} = \frac{E_0 - V}{V} \text{ in p.u.}$$
$$= \frac{E_0 - V}{V} \times 100 \text{ in percentage.}$$

Here E_0 is the no-load excitation voltage and V is the full-load terminal voltage at the same speed and field excitation.

For a lagging power-factor load, E_0 always increases and for a leading power-factor load, E_0 may decrease—consequently the voltage regulation may be positive or negative.

Though the use of automatic voltage regulators have curtailed the importance of computing the voltage regulation of synchronous machines, it is still worth-while to know its value, because of the following reasons :

(*i*) When the load is thrown off, the voltage rise must be known, since the winding insulation should be able to withstand this increased voltage.

(*ii*) Voltage regulation determines the type of automatic voltage-control equipment to be used.

(*iii*) Steady state short-circuit conditions and stability are affected by the voltage regulation.

(*iv*) Parallel operation of one alternator, with other alternators, is affected considerably by its voltage regulation.

In case of small machines, the voltage regulation can be obtained by actually loading it. In large machines, it may not be possible to obtain the voltage regulation by actual loading, because of the cost of dissipating the huge output and also providing the large input. Certain simple tests, involving only small amounts of power, are conducted and from these, the machine constants are determined to compute the voltage regulation. A few methods, for computing the voltage regulation, are described below, where per phase values are used unless otherwise stated.

Methods of Determining the Regulation

1. Electro Motive Force (EMF) or Synchronous impedance method
2. Magneto Motive Force (MMF) or Ampere-turns method
3. Zero power factor (ZPF) or Potier method
4. American Standard Association (ASA) method

EMF or SYNCHRONOUS IMPEDANCE METHOD

This method requires following data to calculate the regulation.

1. Effective Resistance of Armature (R_e)
2. Synchronous impedance (Z_S)
3. Open Circuit Test & Short Circuit Test

Open Circuit Test and Short Circuit Test:

Procedure:

The Terminals of the alternator is kept open.

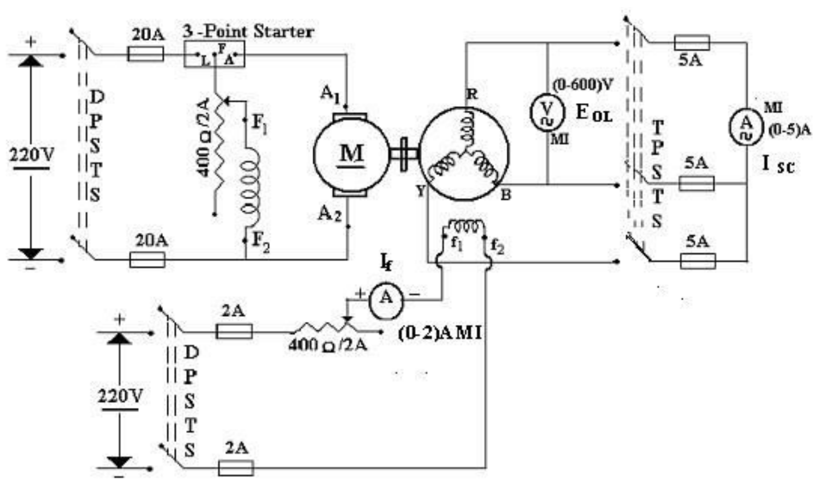
The Field Excitation is varied upto the rated voltage .

The corresponding values are obtained.

Short Circuit Test:

The output terminals are short circuited.

The field current is varied upto the rated current.



OPEN CIRCUIT & SHORT CIRCUIT TEST ON ALTERNATOR

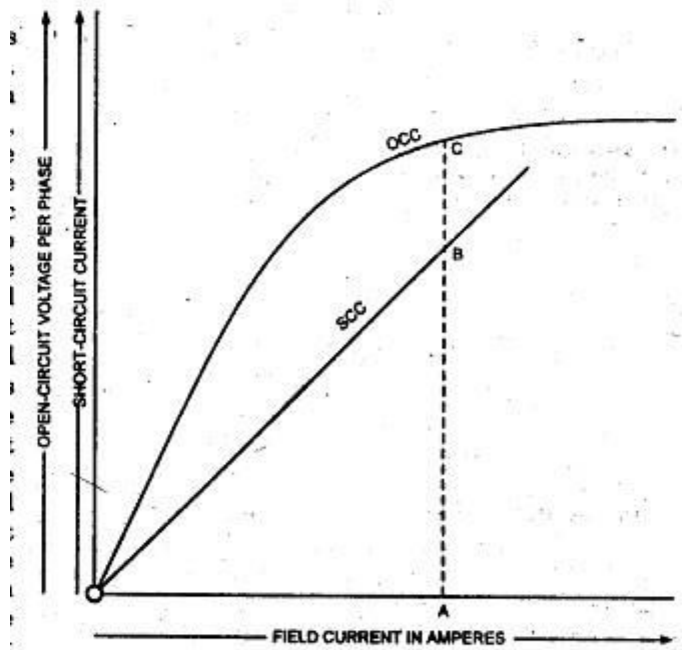
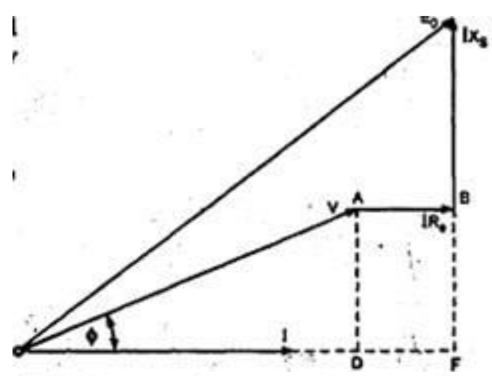


Fig.

The synchronous impedance Zs=E0/Isc =(AC(in volts)/AB(in amperes))

$X_s^{\,2} = Z_s^2 - R_a^2$



or $$E_0 = \sqrt{(V\cos\phi + IR_e)^2 + (V\sin\phi + IX_s)^2}$$ —— **For a Lagging p.f**

For a leading power-factor load, the expression for E_0 can be similarly derived and can be expressed as

$$E_0 = \sqrt{(V\cos\phi + IR_e)^2 + (V\sin\phi - IX_s)^2}$$ —— **For a Leading p.f**

Thus, in general, the expression of no-load voltage can be written as,

$$E_0 = \sqrt{(V\cos\phi + IR_e)^2 + (V\sin\phi \pm IX_s)^2}$$

where, + sign is for lagging power-factor load and, – sign is for leading power-factor load.

And $$\% \text{ regulation} = \frac{E_0 - V}{V} \times 100$$

This method is also called as pesimistic method because the regulation value obtain is always greater than actual value.

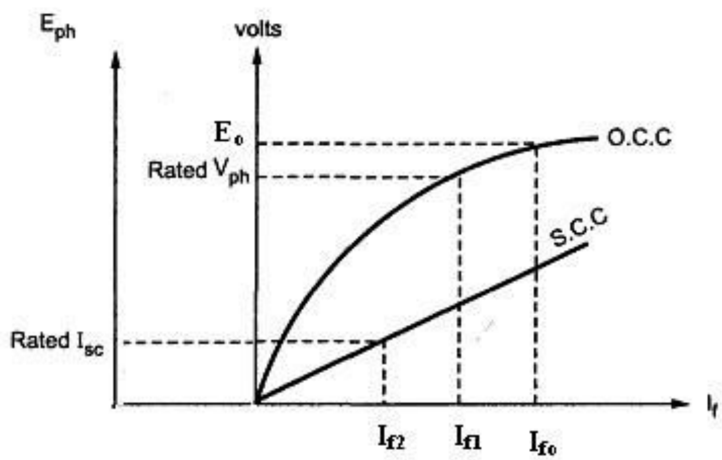
MMF or AMPERE-TURN METHOD

This method is converse method of emf method. This methos also requires open circuit test and short circuit test.

i-field ampere turns require to produce rated voltage.

ii.field ampere turns require to overcome demagnetizing effect of armature reaction.

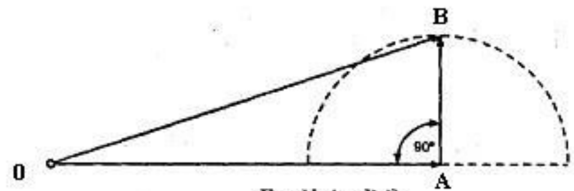
From the OC and SC tests the open circuit and short circuit characteristics are drawn, as shown in fig. From the above characteristics field current I_{f1} is determined to give rated voltage V on no load. Neglecting armature resistance drop and field current I_{f2} is determined to cause short-circuit current, equal to full load current on short circuit.



Procedure to find E_o for different power factor

a) Unity Power factor

When the alternator supplies full load current at unity p.f then the armature reaction is cross magnetizing, therefore the two currents are assumed to be perpendicular to each other. The net field current I_{fo} is vector sum of I_{f1} and I_{f2}.



For Unity P F

From the phasor diagram the various magnitudes are

$OA = I_{f1}$ $AB = I_{f2}$ $OB = I_{fo}$

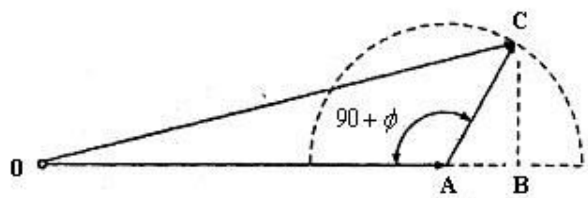
From the phasor diagram

$$I_{f0} = \sqrt{I_{f1}^2 + I_{f2}^2}$$

Now find open circuit EMF E_o, using I_{fo} from open circuit characteristics.

b) Lagging power factor

In case when alternator is supplying full load current at lagging power factor, the total current I_{f0} is shown in fig.



For Lagging P F

From the phasor diagram the various magnitudes are

$OA = I_{f1}$ $AB = I_{f2} Sin\phi$ $AC = I_{f2}$ $BC = I_{f2} Cos\phi$ $OC = I_{f0}$

Consider triangle OBC which is right angle triangle

$$I_{f0} = \sqrt{(I_{f1} + I_{f2} Sin\phi)^2 + (I_{f2} Cos\phi)^2}$$

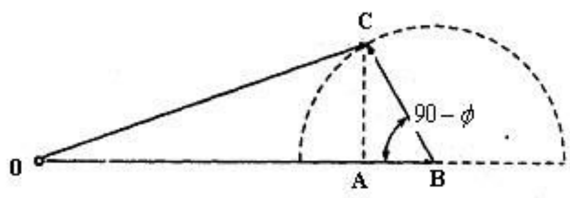
Or

$$I_{f0} = \sqrt{I_{f1}^2 + I_{f2}^2 - 2 I_{f1} I_{f2} Cos[180 - (90 + \phi)]}$$

Now find open circuit EMF E_o, using I_{fo} from open circuit characteristics.

c) Leading power factor

In case when alternator is supplying full load current at leading power factor, the total current I_{f0} is shown in fig



For Leading P F

From the phasor diagram the various magnitudes are

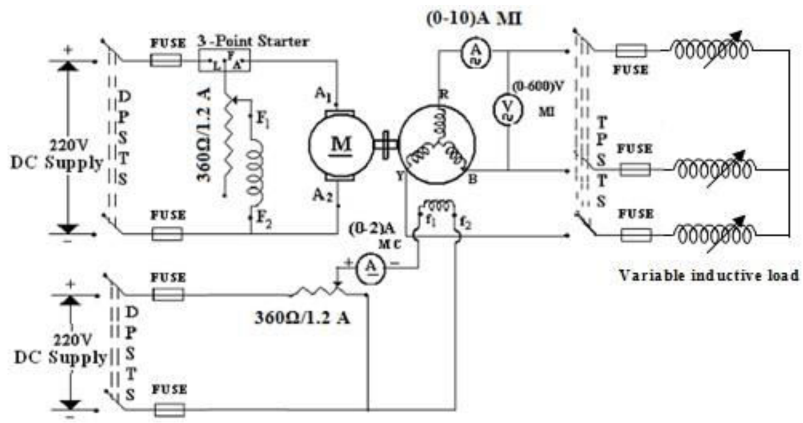
OB=I_{f1} AB=$I_{f2}Sin\phi$ CB=I_{f2} AC=$I_{f2}Cos\phi$ OC=I_{f0}

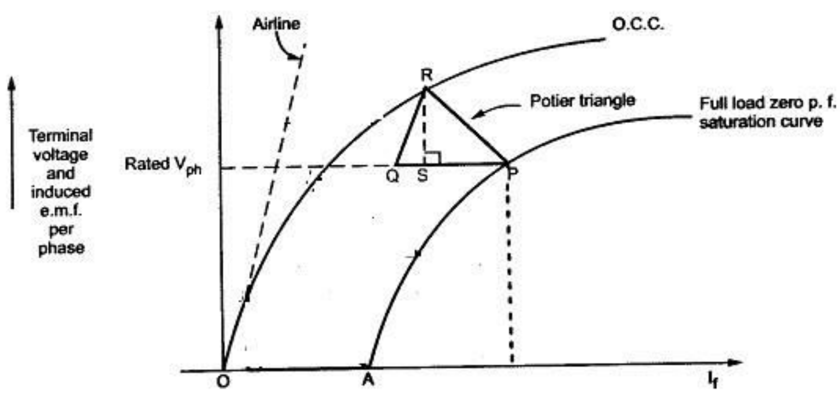
Consider triangle OAC which is right angle triangle

$$I_{f0} = \sqrt{(I_{f1} - I_{f2}Sin\phi)^2 + (I_{f2}Cos\phi)^2}$$

Or $$I_{f0} = \sqrt{(I_{f1}^2 + I_{f2}^2 - 2I_{f1}I_{f2}Cos[180 - (90 - \phi)])}$$

The first three have already been discussed. The circuit diagram for ZPF method is shown infig. to draw the zero power factor full load voltage characteristics.





1. Plot the open circuit characteristics.
2. Mark the field current corresponding to short circuit test as A along X axis.
3. Mark the field current required to produce rated voltage and rated current from ZPF test as P.
4. Join A and P to get a smooth curve called ZPF curve.
5. From P draw a line PQ equal and parallel to OA
6. Draw a tangent to OCC which is called as air line.
7. From Q draw a line parallel to air line to meet OCC at R.
8. Join RP. Triangle QPR is called potier triangle.
9. From R draw a perpendicular line to QP to meet at S.
10. From potier triangle SP=I_{f2}=Field current required to overcome demagnetizingeffect of armature reaction
11. From potier triangle RS =$I_L X_L$=Leakage reactance drop

Or $\quad X_L = \dfrac{RS \text{ (Voltage drop per phase)}}{\text{Zero powerfactor current per phase } (I_L)}$

In case of cylindrical rotor machines, Potier reactance is nearly equal to armature leakage reactance. In case of salient pole machines, the magnetizing circuit is more saturated and the armature leakage reactance is smaller than the Potier reactance.

After knowing the value of Potier reactance X_L, find the regulation by using the following formulae.

1. $E = \sqrt{(V_{ph}\cos\phi + I_L R_a)^2 + (V_{ph}\sin\phi \pm I_L X_L)^2}$
2. $I_{f0} = \sqrt{I_{f1}^2 + I_{f2}^2 + 2I_{f1}I_{f2}\cos(180 - (90 \pm \phi))}$

Note: (+) sign for lagging power factor & (–) sign for leading power factor

I_{f1} – Field current required to generate the phase e.m.f, E [measured from the graph] (Amps).

I_{f2} – Field current required for balancing armature reaction (Amps)

I_{f0} – Total field current (Amps)

Note: The voltage corresponding to I_{f0} is E_0 [Measured from the graph]

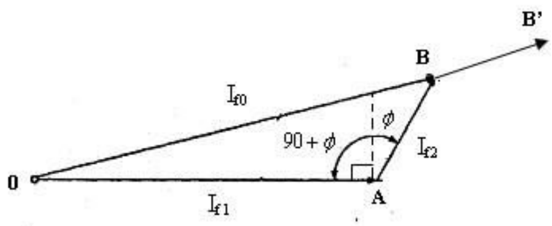
3. Percentage Regulation $\%R = \left(\dfrac{E_0 - V}{V}\right) \times 100$

ASA METHOD

We have seen that neither of the two methods, M.M.F. method and E.M.F. method is capable of giving the reliable values of the voltage regulation. The error in the results of these methods is mainly due to the two reasons,

1. In these methods, the magnetic circuit is assumed to be unsaturated. This assumption is unrealistic as in practice. It is not possible to have completely unsaturated magnetic circuit.
2. In salient pole alternators, it is not correct to combine field ampere turns and armature ampere turns. This is because the field winding is always concentrated on a pole core while the armature winding is always distributed. Similarly the field and armature m.m.f.s act on magnetic circuits having different reluctances in case of salient pole machine hence phasor combination of field and armature m.m.f. is not fully justified.

Inspite of these short comings, due to the simplicity of constructions the ASA modified form of M.M.F. method is very commonly used for the calculation of voltage regulation.



For Lagging P F

Consider the phasor diagram according to the MMF method as shown in Fig. for cosΦ lagging p.f. load. The I_{f0} is resultant excitation of I_{f1} and I_{f2} where I_{f1} is excitation required to produce rated terminal voltage on open circuit while I_{f2} is excitation required for balancing armature reaction effect.

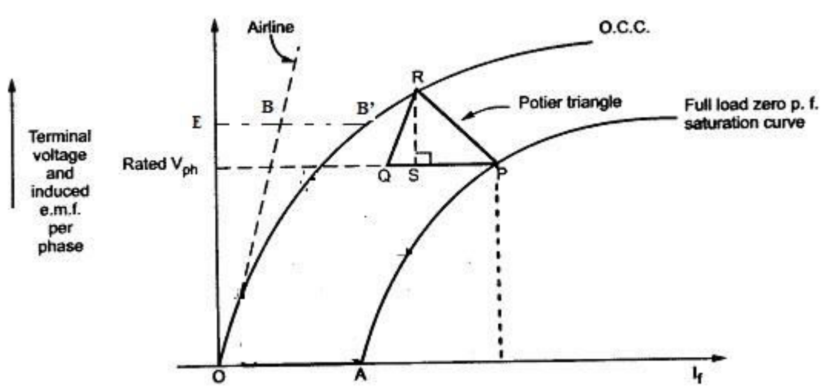
Thus $\quad OB = I_{f0}$ = resultant m.m.f.

The angle between I_{f2} and perpendicular to I_{f1} is ϕ, where $\cos\phi$ is power factor of the load.

But OB = I_{f0} = resultant is based on the assumption of unsaturated magnetic circuit which is not true in practice. Actually m.m.f. equal to BB′ is additionally required to take into account the effect of partially saturated magnetic field. Thus the total excitation required is OB′ rather than OB.

Let us see method of determining the additional excitation needed to take into account effect of partially saturated magnetic circuit.

Construct the no load saturation characteristics i.e. O.C.C. and zero power factor characteristics. Draw the potier triangle as discussed earlier and determine the leakage reactance X_L for the alternator. The excitation necessary to balance armature reaction can also be obtained from the Potier triangle. The armature resistance is known.



1. In the graph draw a line from voltage E (calculated for given p.f in step 1 of ZPF method) which is parallel to X axis which cuts the airgap line and OCC at points B and B' respectively.

2. I_{f3}=Addition excitation required to take into account effect of partially saturated field =BB' from graph.

3. Adding I_{f3} to I_{f0} we get modified field current $I_{fm}=I_{f0}+I_{f3}$ (Take the value I_{f0} from step 3 of ZPF).

4. From modified field current I_{fm}, the open circuit voltage E_0 can be determined from OCC .

Now find the regulation by using $\%R=\left(\frac{E_0 - V}{V}\right)\times 100$

The results obtained by ASA method are reliable for both salient as well as non-salient pole machine.

SYNCHRONIZING AND PARALLEL OPERATION

- The operation of connecting an alternator in parallel with another alternator or with common bus bars is known as **synchronizing**.

- Generally, alternators are used in a power system where they are in parallel with many other alternators. It means that the alternator is connected to a live system of constant voltage and constant frequency.

- Often the electrical system, to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same. In that case, the alternator is said to be connected to **infinite bus bars**.

Conditions to be satisfied:
The Terminal voltage should be same.
The speed and the frequency should be same.
The phase sequence should be same.

SYNCHRONIZING OF ALTERNATORS

SYNCHRONISING OF THREE PHASE ALTERNATORS

In case of single phase alternators, synchronization is done generally by lamp methods. It can be done by two ways:

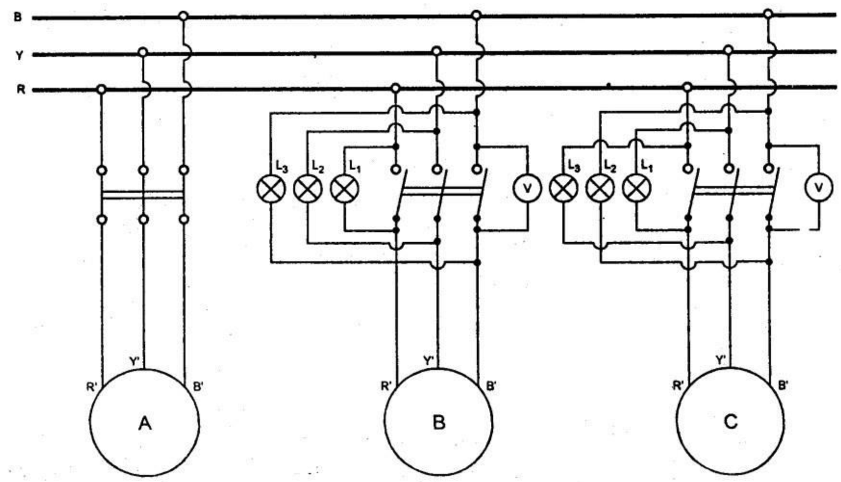
a) Dark lamp method
b) Bright lamp method

a) Dark lamp method

For Mn

SYNCHRONIZING OF THREE PHASE ALTERNATORS

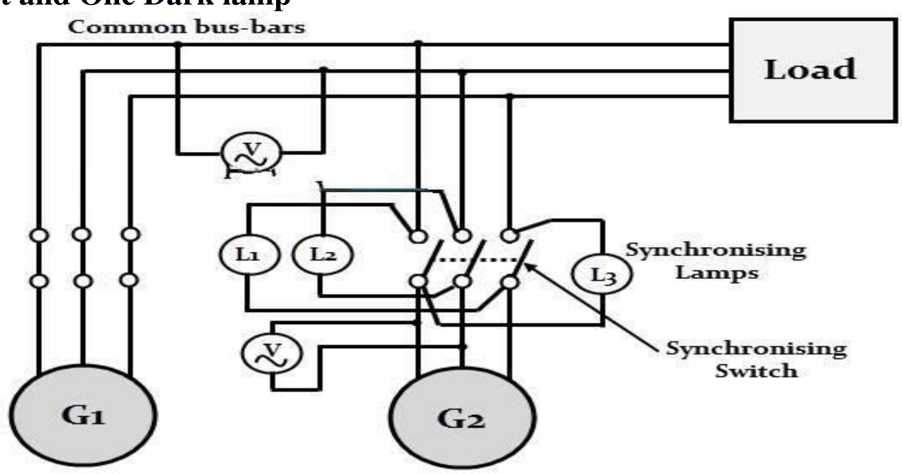
a) Three dark lamp method



Synchronising of 3-Phase Alternators
Fig. 6.2

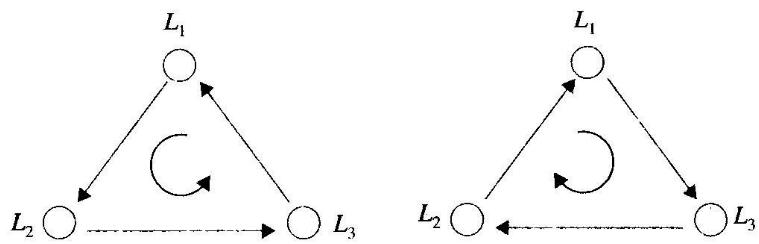
The Voltage of the incoming machine must be equal to bus bar or to the machine which is running as parallel. If the voltages are equal the resultant voltage across the voltmeter will be zero at the same time the lamps will become dark. The phase sequence can be checked when three lamps will become dark and bright in a sequence. If they are in a sequence they are out of phase then the machine has to be stopped and change the terminals. If the speed is not same lamps will started to flicker then excitation has to be adjusted to the make the speed to be same . Then the lamps will become dark and bright slower. When all the conditions are satisfied the switch is closed when the lamps become dark.

Two Bright and One Dark lamp



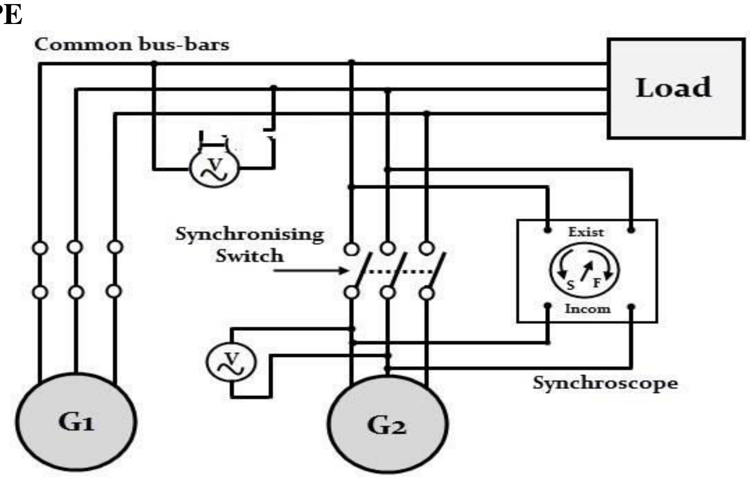
The incoming machine is faster or slower can be found by this method with respect to the sequence given it can be easily found.

For Mn



Note: With respect to above fig. light wave travelling in counter clockwise direction indicates the incoming machine is slow. Light wave travelling in clockwise direction indicates the incoming machine is slow.

SYNCHROSCOPE



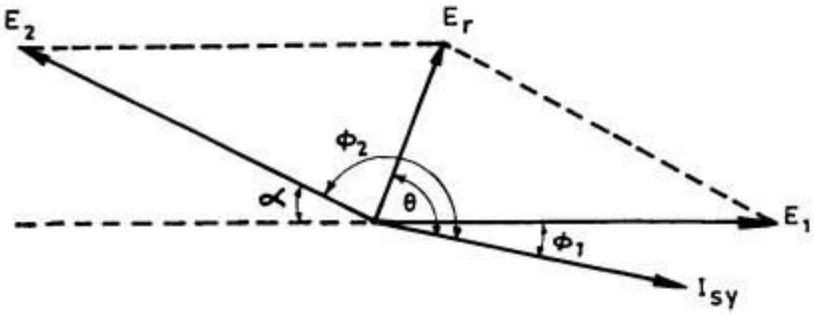
Clockwise direction – Frequency of the incoming Alternator is high.
Anti Clockwise direction – Frequency of the incoming Alternator is slow.
12'o' clock position – Frequency of the incoming alternator is exactly equal to busbar

Advantages of synchronizing alternator:

Repair and maintenance can be done easily.
The output power can be increased.
The efficiency can be increased.

SYNCHRONIZING CURRENT, POWER AND TORQUE

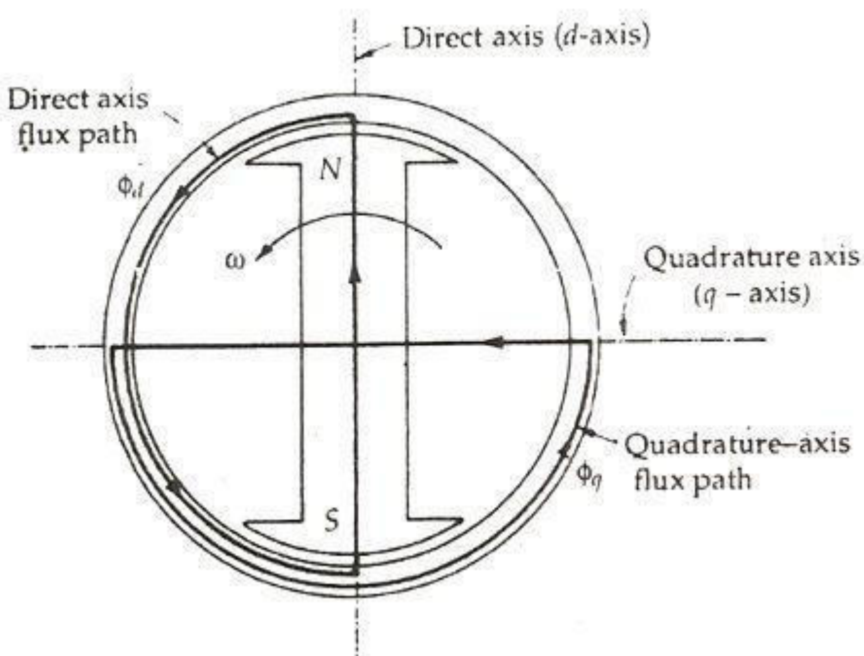
By Using the phasor diagram the Synchronizing current ,Power and Torque can be derived.



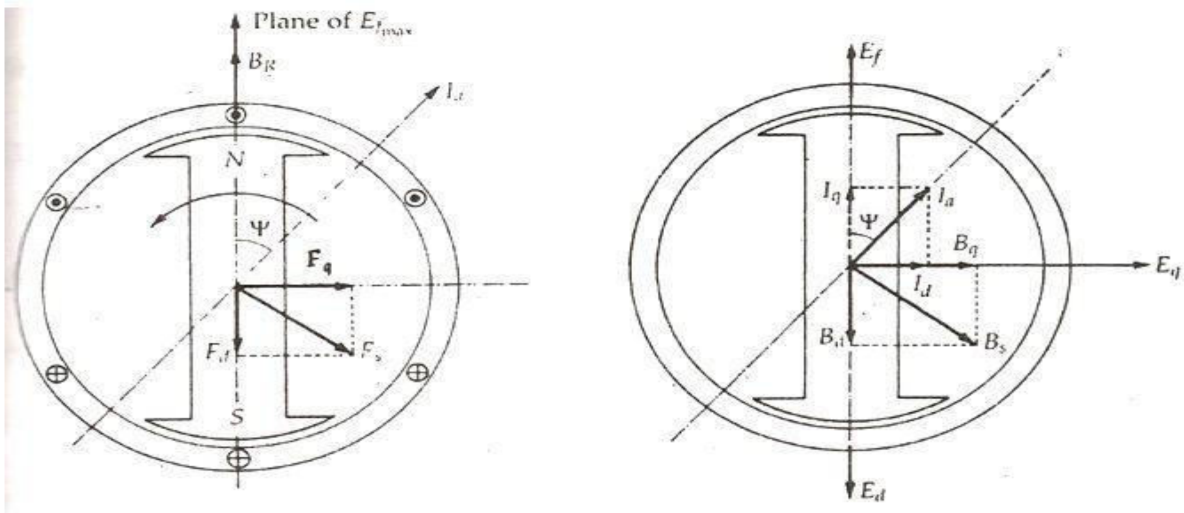
- **Syn.Current: Isy = Eα/Xs**
- **Syn.Power : Psy=3αE2/Xs**
- **Syn.Torque : Tsy = (3Psy*60)/(2*3.14*Ns)**

TWO REACTION THEORY

This theory is suitable for salinet pole alternator. The reactance effect is divided into direct axis reactance and quadrature axis reactance.

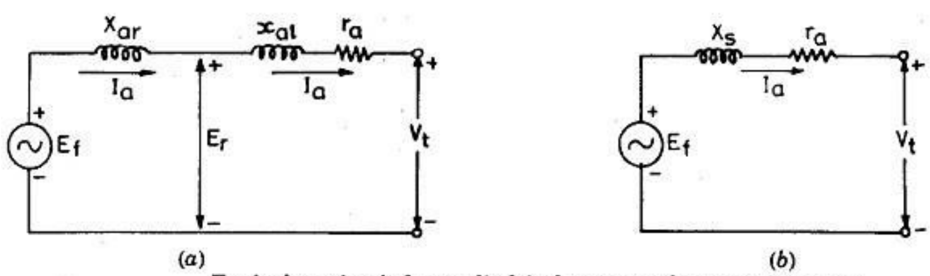


- **The axis along the axis of the rotor is called the direct or the d axis. The axis perpendicular to d axis is known as the quadrature or q axis. The direct axis flux path involves two small air gaps and is the path of the minimum reluctance. The path shown in the above figure by ϕ_q has two large air gaps and is the path of the maximum reluctance.**



- Direct axis synchronous reactance = Xd=Xad+Xl
- Quadrature axis synchronous reactance= Xq=Xaq+Xl
- Voltage V=E0-IaRa-IdXd-OPERATING CHARACTERISTICS

The steady state operating characteristics of a cylindrical rotor alternator can be obtained from its equivalent circuit shown in fig.

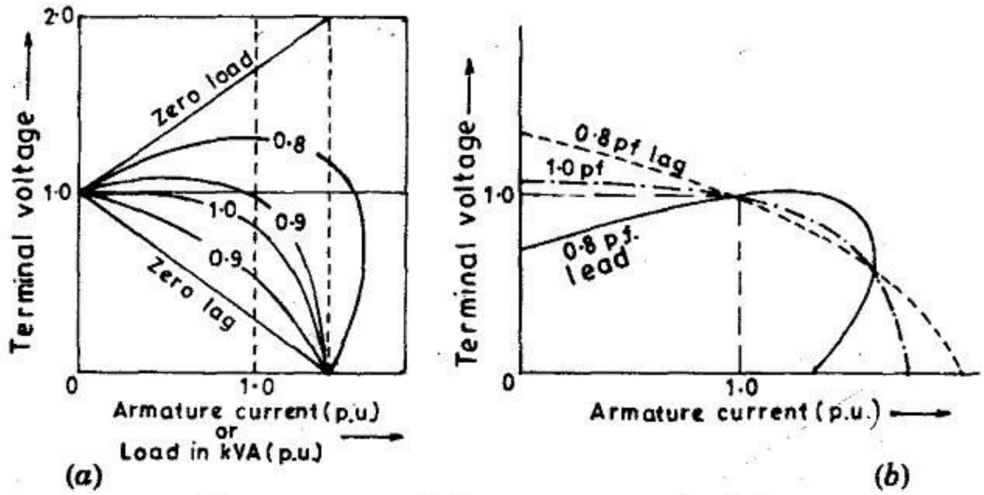


Equivalent circuit for a cylindrical-rotor synchronous generator.

1. External load characteristics

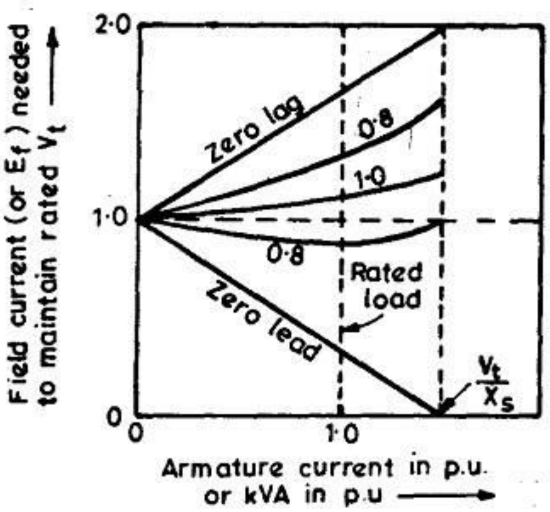
The external load characteristics or the alternator volt-ampere characteristics, represent the variation of armature terminal voltage V_t with the armature current I_a, for a constant field current.

The variation of V_t with I_a for constant E_f, is illustrated in Fig. for different power factor loads.



Alternator external characteristics with I_f held constant (*a*) at its no-load value and (*b*) at its rated V_t and rated I_a.

2.Alternator compounding characteristics



Alternator compounding curves for maintaining rated terminal voltage V_t.

For Mn

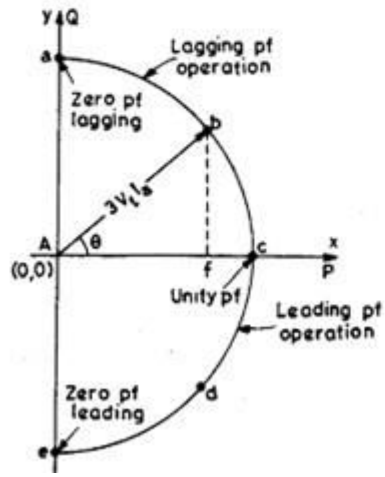
CAPABILITY CURVES

The capability curves are used to find the capacity of the alternator. The any point on the curve gives power rating of the machine. This will give the real power and reactive power. The upper half gives more leading and lower half more lagging .the lagging will increase the current this will affect the winding and losses will increase.

The x axis is the real power.

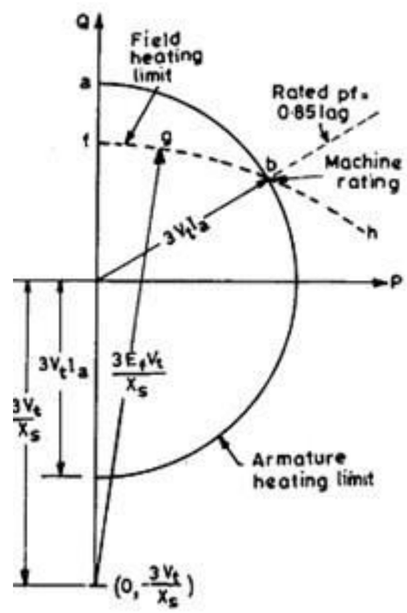
The y axis is reactive power.

The center of the circle(0,0) with the radius of 3VtIa the circle has been drawn.



The heating curve is drawn to determine upto which the loading can be done.

The centre of the circle is (0,3Vt/Xs), with the radius of 3VtEf/Xs



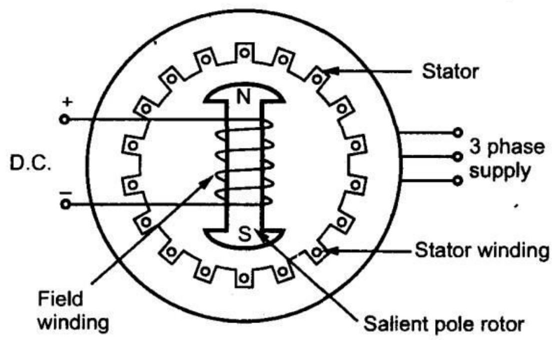
Unit-II Synchronous Motor

CONSTRUCTION OF THREE PHASE SYNCHRONOUS MOTOR

The synchronous motor construction is basically similar to rotating field type alternator. It consists of two parts :

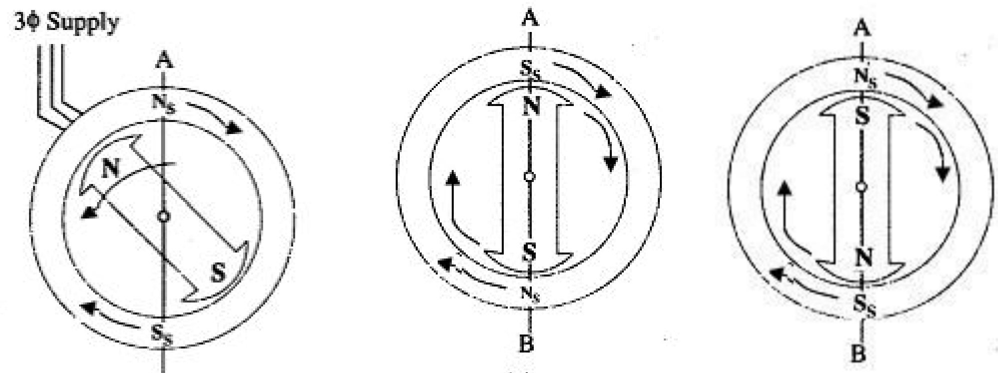
i) **Stator :** Consisting of a three phase star or delta connected winding. This is excited by a three phase a.c. supply.

ii) **Rotor :** Rotor is a field winding, the construction of which can be salient (projected pole) or non salient (cylindrical) type. Practically most of the synchronous motors use salient i.e. projected pole type construction. The field winding is excited by a separate d.c. supply through slip rings.



PRINCIPLE OF OPERATION

when a 3-ϕ winding is fed by a 3-ϕ supply, then a magnetic flux of constant magnitude but ***rotating*** at synchronous speed, is produced. Consider a two-pole stator of Fig. , in which are shown two stator poles (marked N_S and S_S) rotating at synchronous speed, say, in clockwise direction. With the rotor position as shown, suppose the stator poles are at that instant situated at points A and B. The two similar poles, N (of rotor) and N_S (of stator) as well as S and S_S will repel each other, with the result that the rotor tends to rotate in the anticlockwise direction.



But half a period later, stator poles, having rotated around, interchange their positions *i.e.* N_S is at point B and S_S at point A. Under these conditions, N_S attracts S and S_S attracts N. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction). Hence, we find that due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing *i.e.*, in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction. Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.

Now, consider the condition shown in Fig. (*a*). The stator and rotor poles are attracting each other. Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig. (*b*). Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque *i.e.*, clockwise torque, as shown in Fig. (*a*) and (*b*).

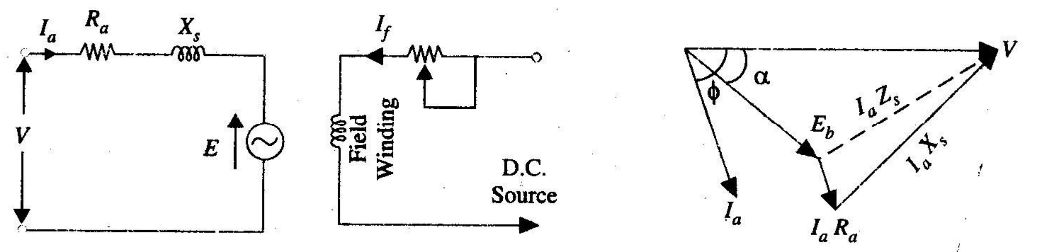
Note: 1. The average torque exerted on the rotor of synchronous motor is zero. Hence the synchronous motor is not self starting.

2. To obtain a continuous torque, the rotor should rotate at synchronous speed given by expression $N_S = \frac{120 f}{P}$

3. Different power stages in a synchronous motor are as under

Fig. 38.9 (*a*) shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. 38.9 (*b*) that the phase applied voltage V is the vector sum of reversed back e.m.f. *i.e.*, $-E_b$ and the impedance drop $I_a Z_S$. In other words, $V = (-E_b + I_a Z_S)$. The angle α* between the phasor for V and E_b is called the load angle or power angle of the synchronous motor.



(*a*) (*b*)

TORQUE EQUATION

The gross torque developed by the motor $T_g \cdot 9.55\frac{P_m}{N_s}$ N-m

Where $P_m \cdot \frac{E_b V}{X_s}\sin\cdot$

Net output of the motor then can be obtained by subtracting friction and windage i.e. mechanical losses from gross mechanical power developed.

$$P_{out} = P_m - \text{Mechanical losses}$$

The shaft torque developed by the motor $T_s \cdot 9.55\frac{P_{out}}{N_s}$

Different toques in synchronous motor

The torque required to operate the driven machine at every moment between the initial breakaway and the final shutdown is important in determination of the motor characteristics. The various torques associated with synchronous motors are termed starting torque, running torque, pull-in torque, and pull-out torque.

1. Starting Torque. It pertains to the ability of the motor to accelerate the load. The starting torque, sometimes also called the *break away torque*, required by the driven machine may be as low as 10%, as in case of centrifugal pumps, and as high as 200 or 250% of full-load torque, as in case of loaded reciprocating two-cylinder compressors.

The synchronous motor has got no self-starting torque, but in modern synchronous motors, almost any reasonable torque can be had by proper design of the damper windings (by changes in the resistance and size of the damper winding).

2. Running Torque. It is the torque developed by the motor under running conditions. It is determined by the output power and speed of the driven machine. The peak output power determines the maximum torque that would be required by the driven machine. The motor must have a breakdown or a maximum running torque greater than this value so as to avoid stalling of the machine.

3. Pull-in Torque. It refers to the ability of the motor to pull-into synchronism when changing from induction to synchronous motor operation.

4. Pull-out Torque. It pertains to the ability of the motor to remain in synchronism under rated load conditions.

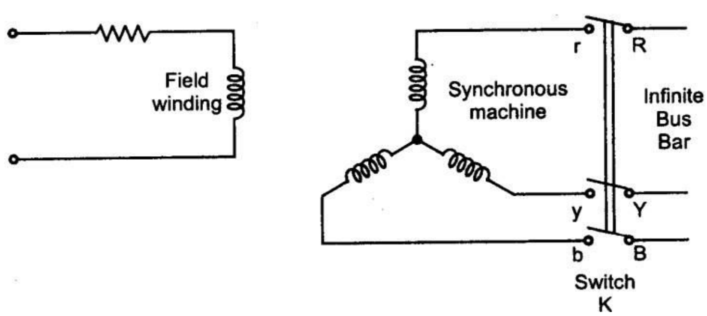
The maximum torque which the motor will develop without pulling out of step (or synchronism) is called the *pull-out torque*.

Its value varies from 1.25 to 3.5 times the full-load torque.

OPERATION ON INFINITE BUS BARS

The infinite bus represents a bus bar of constant voltage and frequency, which can deliver or absorb active and reactive power without any limitations.

The fig. shows a synchronous machine which is to be connected to the bus bars with the help of switch K. If the synchronous machine is running as a generator then its phase sequence should be same as that of bus bars. The machine speed and field current is adjusted in such a way so as to have the machine voltage same as that of bus bar voltage. The machine frequency should be nearly equal to bus bar frequency so that the machine speed is nearer to synchronous speed.



When the above conditions are satisfied, the instant of switching for synchronization should be determined. This can be determined by lamps dark methods, lamps bright method, Lamps bright and dark method or by using synchroscope.

Once switch K is closed, the stator and rotor fields of the machine lock into each other and the machine then runs at synchronous speed. The real power exchange with the mains will be now governed by the loading conditions on the shaft while the reactive power exchange will be determined by field excitation.

The same procedure is to be followed for synchronizing the synchronous motor to the infinite bus bars. The motor is run by an auxiliary device such as small dc or induction motor initially and then synchronized to the bus bars.

As we know that the synchronous motors are not self starting hence if switch K is closed when rotor is stationary, the average torque will be zero as the two fields run at synchronous speed relative to each other so the motor fails to start. They are made self starting by providing short circuited bars on the rotor which produce torque as produced in case of induction motors.

When synchronous motor is over excited it takes leading p.f. current. If synchronous motor is on no load, where load angle δ is very small and it is over excited ($E_b > V$) then power factor angle increases almost upto 90°. And motor runs with almost zero leading power factor condition. This is shown in the phasor diagram Fig. 4.31.

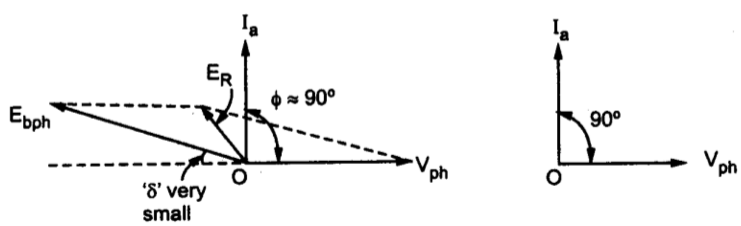


Fig. 4.31 Synchronous condenser

This characteristics is similar to a normal capacitor which always takes leading power factor current. Hence over excited synchronous motor operating on no load condition is called as **synchronous condenser or synchronous capacitor**. This is the property due to which synchronous motor is used as a phase advancer or as power improvement device.

APPLICATIONS OF SYNCHRONOUS MOTOR

Synchronous motors find extensive application for the following classes of service :

1. Power factor correction
2. Constant-speed, constant-load drives
3. Voltage regulation

(a) Power factor correction

Overexcited synchronous motors having leading power factor are widely used for improving power factor of those power systems which employ a large number of induction motors (Fig. 38.49) and other devices having lagging p.f. such as welders and flourescent lights etc.

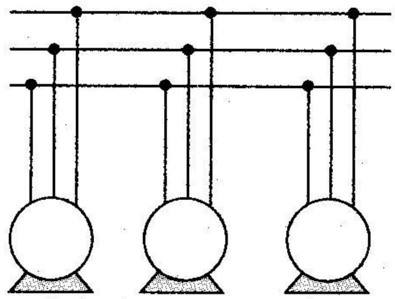


Fig. 38.49

(*b*) Constant-speed applications

Because of their high efficiency and high-speed, synchronous motors (above 600 r.p.m.) are well-suited for loads where constant speed is required such as centrifugal pumps, belt-driven reciprocating compressors, blowers, line shafts, rubber and paper mills etc.

Low-speed synchronous motors (below 600 r.p.m.) are used for drives such as centrifugal and screw-type pumps, ball and tube mills, vacuum pumps, chippers and metal rolling mills etc.

(*c*) Voltage regulation

The voltage at the end of a long transmission line varies greatly especially when large inductive loads are present. When an inductive load is disconnected suddenly, voltage tends to rise considerably above its normal value because of the line capacitance. By installing a synchronous motor with a field regulator (for varying its excitation), this voltage rise can be controlled.

When line voltage decreases due to inductive load, motor excitation is increased, thereby raising its p.f. which compensates for the line drop. If, on the other hand, line voltage rises due to line capacitive effect, motor excitation is decreased, thereby making its p.f. lagging which helps to maintain the line voltage at its normal value.

SYNCHRONOUS CONDENSER FOR POWER FACTOR CORRECTION

The low power factor increases the cost of generation, distribution and transmission of the electrical energy. Hence such low power factor needs to be corrected. Such power factor correction is possible by connecting synchronous motor across the supply and operating it on no load with over excitation.

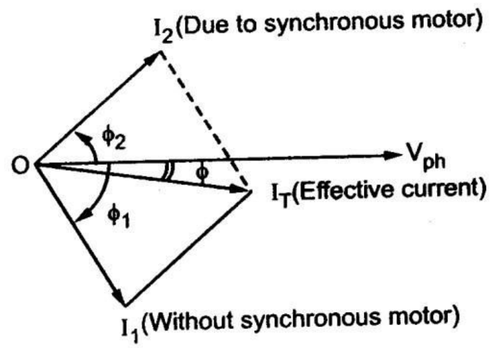


Fig. 4.32 Power factor correction by synchronous condenser

Now let V_{ph} is the voltage applied and I_{1ph} is the current lagging V_{ph} by angle ϕ_1. This power factor ϕ_1 is very low, lagging.

The synchronous motor acting as a synchronous condenser is now connected across the same supply. This draws a leading current of I_{2ph}.

The total current drawn from the supply is now phasor of I_{ph} and I_{2ph}. This total current I_T now lags V_{ph} by smaller angle ϕ due to which effective power factor gets improved. This is shown in the Fig. 4.32.

This is how the synchronous motor as a synchronous condenser is used to improve power factor of the combined load.

EFFECT OF EXCITATION ON ARMATURE CURRENT AND POWER FACTOR (V AND INVERTED V CURVES)

Consider a synchronous motor in which the *mechanical load is constant* and hence output is also constant if losses are neglected.

Case 1. 100% Excitation :

The case for 100% excitation *i.e.*, when $E_b = V$ is shown in Fig. 6.13 (*i*). Here the armature current I lags behind V by a small angle ϕ. Its angle with E_R is fixed by stator constants *i.e.*,

$$\tan\theta = \frac{X_s}{R_a}.$$

Case 2. Excitation less than 100% :

Fig. 6.13 (*ii*) represents the condition for *under-excited* motor *i.e.*, $E_b < V$. Here E_r is advanced clockwise and so is the armature current (because it lags behind E_r by a fixed angle θ). We find that :

The magnitude of I is increased, but *its power factor is decreased* ($\because$ ϕ has increased) :

— Since input as well as V are constant, hence the power component of I *i.e.*, $I\cos\phi$ remains the same as before, but wattless component $I\sin\phi$ is increased. Hence, as excitation is decreased, I will increase, but power factor will decrease so that power component *i.e.*, $I\cos\phi = OL$ will remain constant. *The locus of the extremity of current vector would be a horizontal straight line.*

Case 3. Excitation greater than 100% :

In Fig. 6.13 (*iii*) excitation is greater than 100% *i.e.*, $E_b > V$ (*i.e.*, motor is over-excited). Here the resultant voltage vector E_r is pulled-anticlockwise and so is I. It may be noted that now motor is drawing a *leading current*. It may also happen for some value of excitation, that I may be in phase

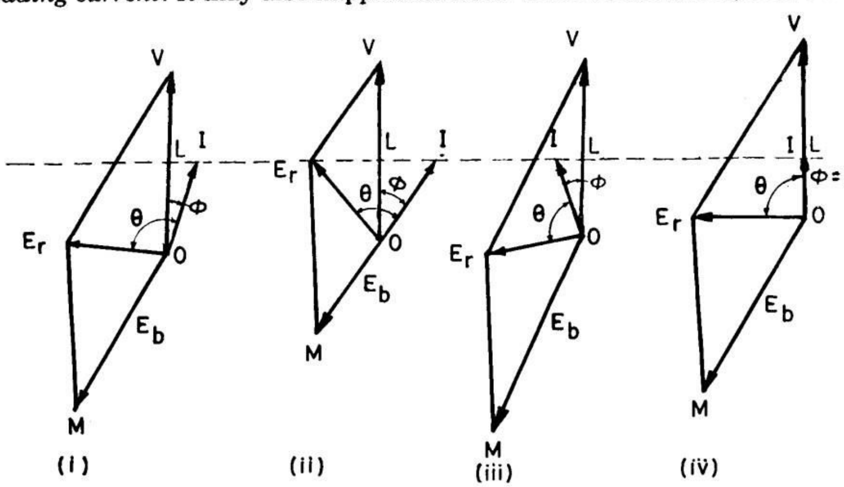


Fig. 6.13. Effect of excitation on armature current and power factor.

with *V i.e.*, power factor *is unity* [Fig. 6.13 (*iv*)]. At that time the *current drawn by motor would* be *minimum.*

V-curves of a Synchronous Motor :

- It has been stated above that, when the field current (*i.e.*, excitation) of a synchronous motor is reduced, a lagging armature current [Fig. 6.13 (*ii*)] *I* is produced which exceeds the minimum current at unity power or at normal excitation.
- Similarly, when motor is *over-excited,* the armature current also rises [Fig. 6.13 (*iii*)] and exceeds the current required at normal excitation to develop the necessary torque, at any given load.
- By applying a given *constant load* to the shaft of a synchronous motor and varying the field current from under-excitation to *over-excitation,* recording the armature current at each step, the curves of Fig. 6.14 (*a*) are obtained. The A.C. armature current is plotted against the D.C. field current for *no-load, half-load,* and *full-load* values, respectively.
- The wattmeter connections shown in Fig. 6.15 will also yield the power factor for each value of armature and field current at any given load condition. (The method employed in Fig. 6.15 is the two-wattmeters method. Since the synchronous motor is a balanced three-phase load, the one-wattmeter method, three-wattmeters method, industrial analyzer, or polyphase wattmeter would do as well in providing the power factor of the load).

Thus, as shown in Fig. 6.14. (*b*), the power factor as determined from the wattmeter readings, is plotted against the field current for the various given loads. It is worth noting that both curves show that a *slightly increased field current is required to produce normal excitation as the load is increased* (points 1, 2 and 3, respectively).

— At *no-load, the armature current at unity power factor* (normal excitation) *is not zero* but *some small value of A.C. armature current per phase, necessary to produce torque to counter balance rotational losses.* As load is applied (neglecting armature reaction) not only does the armature current rise but it is also necessary to increase the excitation to bring the armature current back in phase with the bus phase voltage. Each of the curves in the

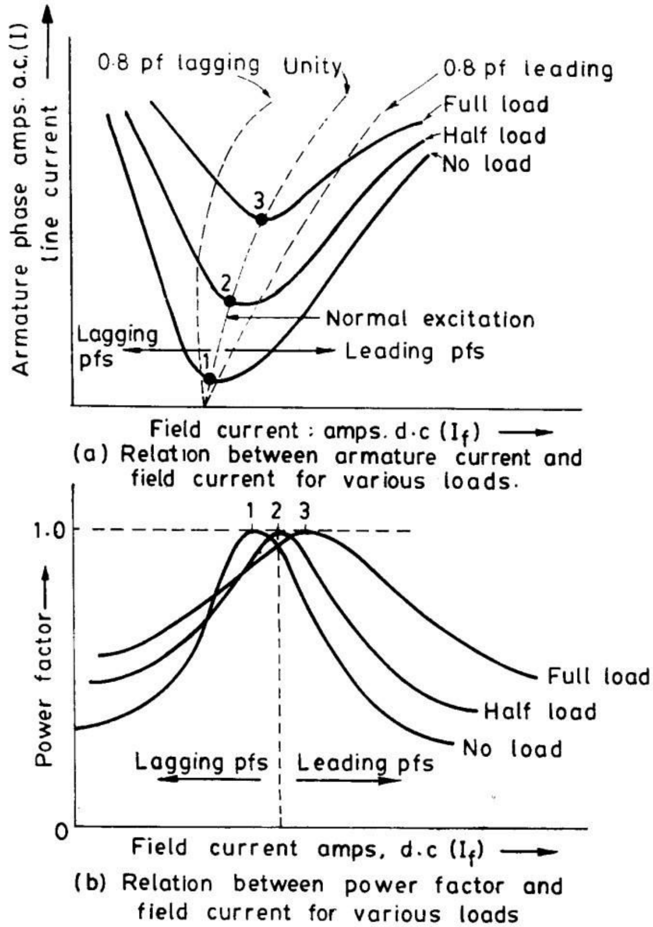


Fig. 6.14. Families of *V*-curves for a synchronous motor.

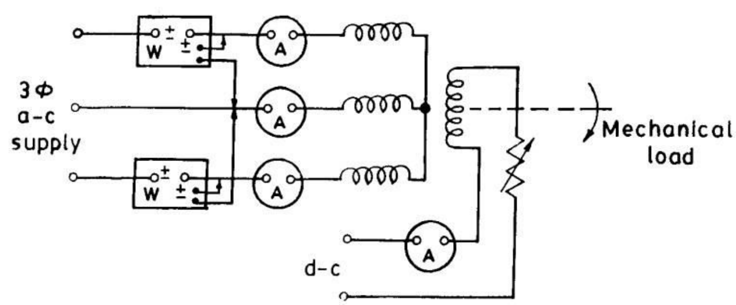


Fig. 6.15. Laboratory connections for obtaining *V*-curves.

family, therefore, will have a shift to the right as the load is increased, as shown in Figs. 6.14 (*a*) and (*b*), to provide the excitation required to obtain the same power factor (0.8 lagging, unity, or 0.8 leading) at an increased load. Thus, the *V-curves represent the phasor diagrams*, and *vice versa* for various conditions of load and power factor.

Comparison between synchronous and induction motor

S. No.	Synchronous motor	Induction motor
1.	It is inherently not self-starting and some external means are required for its starting.	It has got self-starting torque and no special means are required for starting.
2.	Requires D.C. excitation.	Does not require D.C. excitation.
3.	Speed control not possible.	Speed can be controlled but to small extent.
4.	Its average speed is constant and independent of load.	Its speeds falls with the increase in load and is always less than synchronous speed.
5.	It can be operated under a wide range of power factor, both lagging and leading.	It operates at only lagging power factor, which becomes very poor at light loads.
6.	Its torque is less sensitive to change in supply voltage.	Its torque is more sensitive to change in supply voltage.
7.	Breakdown torque is proportional to the supply voltage.	Breakdown torque is proportional to the square of the supply voltage.
8.	More complicated and more costly comparatively.	More simple and less costly comparatively.
9.	Employed for supplying mechanical load as well as for power factor improvement.	Employed for supplying mechanical load only.

HUNTING IN SYNCHRONOUS MOTOR

It is seen that, when synchronous motor is on no load, the stator and rotor pole axes almost coincide with each other.

When motor is loaded, the rotor pole axis falls back with respect to stator. The angle by which rotor retards is called load angle or angle of retardation δ.

If the load connected to the motor is suddenly changed by a large amount, then rotor tries to retard to take its new equilibrium position.

But due to inertia of the rotor, it cannot achieve its final position instantaneously. While achieving its new position due to inertia it passes beyond its final position corresponding to new load. This will produce more torque than what is demanded. This will try to reduce the load angle and rotor swings in other direction. So there is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load. Such a swing is shown in the Fig. 4.27.

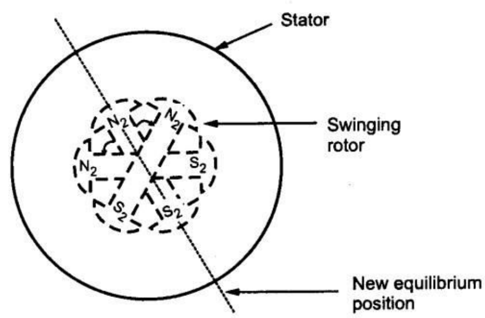


Fig. 4.27 Hunting in synchronous motor

Such oscillations of the rotor about its new equilibrium position, due to sudden application or removal of load is called swinging or **hunting** in synchronous motor.

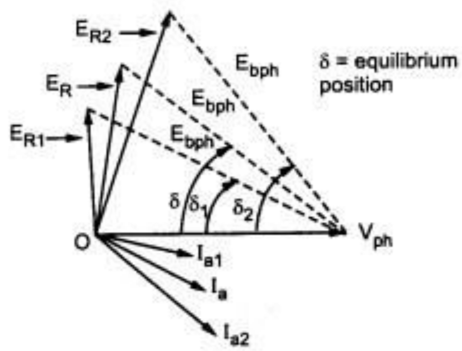


Fig. 4.28 Current variations during hunting

Due to such hunting, the load angle δ changes its value about its final value. As δ changes, for same excitation i.e. E_{bph} the current drawn by the motor also changes. Hence during hunting there are changes in the current drawn by the motor which may cause problem to the other appliances connected to the same line. The changes in armature current due to hunting is shown in the Fig. 4.28.

If such oscillations continue for longer period, there are large fluctuations in the current. If such variations synchronise with the natural period of oscillation of the rotor, the amplitude of the swing may become so great that motor may come out of synchronism. At this instant mechanical stresses on the rotor are severe and current drawn by the motor is also very large. So motor gets subjected to large mechanical and electrical stresses.

Use of damper winding to prevent hunting

It is mentioned earlier that in the slots provided in the pole faces, a short circuited winding is placed. This is called damper winding.

When rotor starts oscillating i.e. when hunting starts a relative motion between damper winding and the rotating magnetic field is created. Due to this relative motion, e.m.f. gets induced in the damper winding. According to Lenz's law, the direction of induced e.m.f. is always so as to oppose the cause producing it. The cause is the hunting. So such induced e.m.f. oppose the hunting. The induced e.m.f. tries to damp the oscillations as quickly as possible. Thus hunting is minimised due to damper winding.

The time required by the rotor to take its final equilibrium position after hunting is called as **setting time** of the rotor. If the load angle δ is plotted against time, the schematic representation of hunting can be obtained as shown in the Fig. 4.29. It is shown in the diagram that due to damper winding the setting time of the rotor reduces considerably.

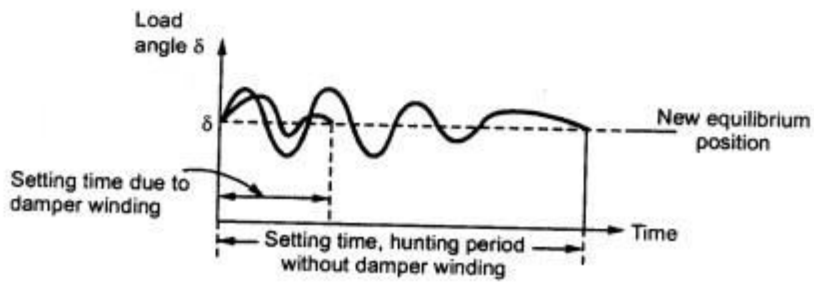


Fig. 4.29 Effect of damper

MERITS AND DEMERITS OF SYNCHRONOUS MOTOR

Merits. (*i*) The ease with which the power factor can be controlled. An over-excited synchronous motor having a leading power factor can be operated in parallel with induction motors and other power apparatus operating at lagging power factors, thereby improving the power factor of the supply system.

(*ii*) The speed is constant and independent of load. This characteristic is mainly of use when the motor is required to drive another alternator to generate a supply at a different frequency as in frequency changers.

(*iii*) Electro-magnetic power varies linearly with the voltage.

(*iv*) These motors can be constructed with wider air gaps than induction motors, which make them better mechanically.

(*v*) These motors usually operate at higher efficiencies, especially in the low speed unity pf ranges.

Demerits (*i*) The cost per kw output is generaly higher than that of an induction motor.

(*ii*) It requires dc excitation which must be supplied from external source.

(*iii*) The synchronous motor is inherently not self-starting motor and needs some arrangement for its starting and synchronizing.

(*iv*) It cannot be used for variable speed jobs as there is no possibility of speed adjustment.

(*v*) It cannot be started under load. Its starting torque is zero.

(*vi*) It has a tendency to hunt.

(*vii*) It may fall out of synchronism and stop when over-loaded.

(*viii*) Collector rings and brushes are required.

(*ix*) For some purposes synchronous motors are not desirable as for driving shafts in small workshops having no other power available for starting and in cases where frequent starting or strong starting torque is required.

For Mn

STARTING METHODS OF SYNCHRNOUS MOTOR

As seen earlier, synchronous motor is not self starting. It is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible by various methods in practice. The various methods to start the synchronous motor are,

1. Using pony motors
2. Using damper winding
3. As a slip ring induction motor
4. Using small d.c. machine coupled to it.

4.7.1 Using Pony Motors

In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called **'Pony Motor'**.

Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as a synchronous motor.

4.7.2 Using Damper Winding

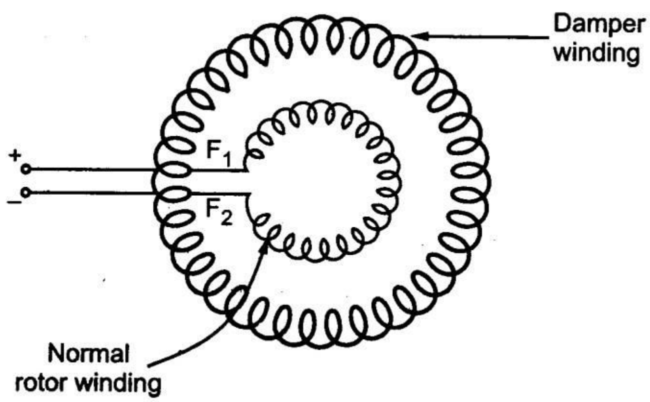


Fig. 4.8 (a) Starting as a squirrel cage I.M.

In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called **damper winding**. This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor. The schematic representation of such damper winding is shown in the Fig.4.8(a).

Once the stator is excited by a three phase supply, the motor starts rotating as an induction motor at sub synchronous speed. Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed. As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero. Hence when motor is running as synchronous motor, there cannot be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit. As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

4.7.3 As a Slip Ring Induction Motor

The above method of starting synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper winding, it is designed to form a three phase star or delta connected winding. The three ends of this winding are brought out through slip rings. An external rheostat then can be introduced in series with the rotor circuit. So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque. The resistance is then gradually cut off, as motor gathers speed. When motor attains speed near synchronous, d.c. excitation is provided to the rotor, then motor gets pulled into synchronism and starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a rotor resistance starter.

The synchronous motor started by this method is called a slip ring induction motor is shown in the Fig. 4.8 (b).

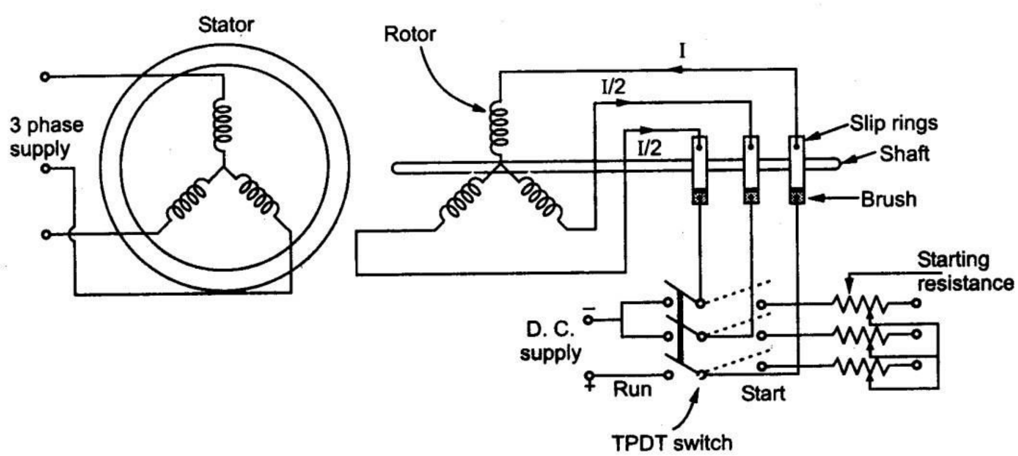


Fig. 4.8 (b) Starting as a slip ring I.M.

It can be observed from the Fig. 4.8 (b) that the same three phase rotor winding acts as a normal rotor winding by shorting two of the phases. From the positive terminal, current 'I' flows in one of the phases, which divides into two other phases at start point as I/2 through each, when switch is thrown on d.c. supply side.

4.7.4 Using Small D.C. Machine

Many a times, a large synchronous motors are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.

- The salient pole synchronous motor has the following two axes :
  — Field pole axis, called the *direct axis* or *d-axis* ; and
  — The axis passing through the centre of interpolar space, called *quadrature axis* or *q-axis* (as in case of an alternator).

I_d and I_q are the components of the armature current resolved along d-axis and q-axis respectively.

In the Fig. 6.11 and 6.12 are shown the complete phasor diagrams of a salient pole synchronous motor, for a leading power factor, considering and neglecting armature resistance respectively.

From Fig. 6.12, using E_b as reference phasor, we have

$$V \cos \alpha = E_b - I_d X_d \quad ...(6.6)$$

and

$$V \sin \alpha = I_q X_q \quad ...(6.7)$$

$\therefore$

$$I_d = \frac{E_b - V \cos \alpha}{X_d} \quad ...(6.8)$$

and

$$I_q = \frac{V \sin \alpha}{X_q} \quad ...(6.9)$$

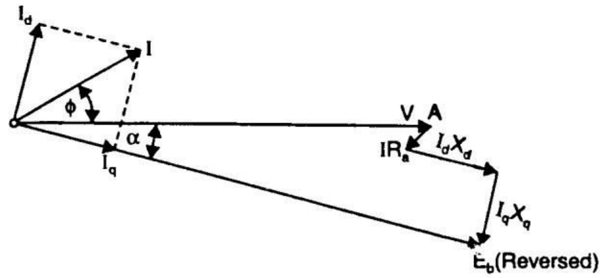


Fig. 6.11. Phasor diagram for synchronous motor-leading p.f. (Considering armature resistance).

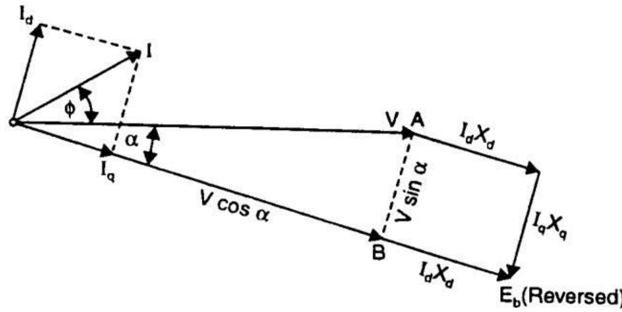


Fig. 6.12. Phasor diagram for synchronous motor-leading p.f. (Neglecting armature resistance).

Regardless of the axis of reference, power input is given by the product of the in-phase components of the current and voltage plus the product of the quadrature component.

$\therefore \qquad P_{in} = I_q V \cos\alpha + I_d V \sin\alpha$

Substituting the values of I_d and I_q from eqns. (6.8) and (6.9), we get

$$P_{in(per\ phase)} = \frac{V \sin\alpha}{X_q} \times V\cos\alpha + \frac{E_b - V\cos\alpha}{X_d} \times V \sin\alpha$$

$$= \frac{V^2 \sin\alpha\cos\alpha}{X_q} + \left[\frac{E_b V \sin\alpha - V^2 \sin\alpha\cos\alpha}{X_d}\right]$$

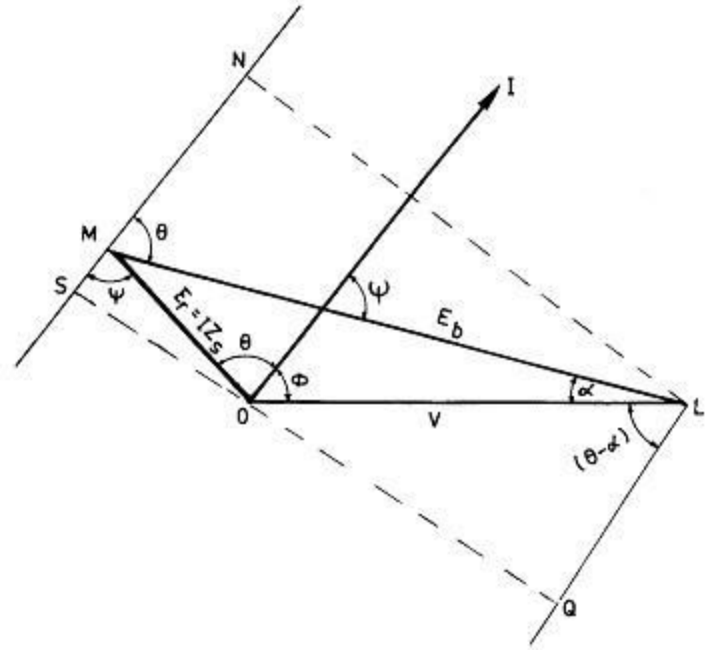
$$= \frac{E_b V}{X_d}\sin\alpha + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\alpha \qquad ...(6.10)$$

Total power input (3 times of the above)

$$= \frac{3E_b V}{X_d}\sin\alpha + \frac{3V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\alpha$$

$$= \frac{E_{bL} V_L}{X_d}\sin\alpha + \frac{{V_L}^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\alpha \qquad ...(6.11)$$

POWER DEVELOPED BY SYNCHRONOUS MOTOR



OL = supply voltage/phase
I = armature current
LM = back e.m.f. at a load angle of α
OM = resultant voltage, $E_r = IZ_s$ (or IX_s if R_a is negligible)

- I lags/leads V by an angle ϕ and lags behind E_r by an angle θ (internal angle)

$$= \tan^{-1}\left(\frac{X_s}{R_a}\right).$$

- Line NS is drawn at angle θ to LM.
- LN and QS are perpendicular to NS (hence to LQ also).

Mechanical power developed *per phase* in the rotor,

$$P_{\text{mech}} = E_b I \cos\psi \qquad \text{...(6.1)}$$

In ΔOMS, $\quad MS = IZ_s \cos\psi$

Now, $\quad MS = NS - NM = LQ - NM$

$\therefore \quad IZ_s \cos\psi = V\cos(\theta - \alpha) - E_b \cos\theta$

$\therefore \quad I\cos\psi = \dfrac{V}{Z_s}\cos(\theta-\alpha) - \dfrac{E_b}{Z_s}\cos\theta$

Putting this value in (6.1), we get

$$P_{\text{mech}}/\text{phase} = E_b\left[\frac{V}{Z_s}\cos(\theta-\alpha) - \frac{E_b}{Z_s}\cos\theta\right]$$

or

$$P_{\text{mech}}/\text{phase} = \frac{E_b V}{Z_s}\cos(\theta-\alpha) - \frac{E_b^2}{Z_s}\cos\theta \qquad \text{...(6.2)}$$

This is the expression for the mechanical power developed in terms of load angle (α) and the internal angle (θ) of the motor for a constant voltage V and E_b (or excitation because E_b depends on excitation only).

excitation only).

Maximum power developed. Condition for maximum power developed can be found by differentiating the above expression (eqn. 6.2) with respect to load angle and then equating it to zero.

$$\therefore \quad \frac{dP_{\text{mech}}}{d\alpha} = -\frac{E_b V}{Z_s}\sin(\theta-\alpha) = 0 \quad \text{or} \quad \sin(\theta-\alpha) = 0$$

$\therefore \quad \theta = \alpha$

$\therefore$ Value of maximum power,

$$(P_{\text{mech}})_{\max} = \frac{E_b V}{Z_s} - \frac{E_b^2}{Z_s}\cos\alpha$$

or

$$\frac{E_b V}{Z_s} - \frac{E_b^2}{Z_s}\cos\theta \qquad \text{...(6.3)}$$

- This shows that the *maximum power and hence torque* ($\because$ speed is constant) *depends on V and E_b i.e., excitation.*
- Maximum value of θ and hence α is 90°. For *all values of V and E_b, this limiting value of α is the same but maximum torque will be proportional to the maximum power developed* as given in eqn. (6.3).
- In Fig. 6.10 eqn. (6.2) is plotted.
- If R_a is neglected, then

$$Z_s \simeq X_s \text{ and } \theta = 90°$$

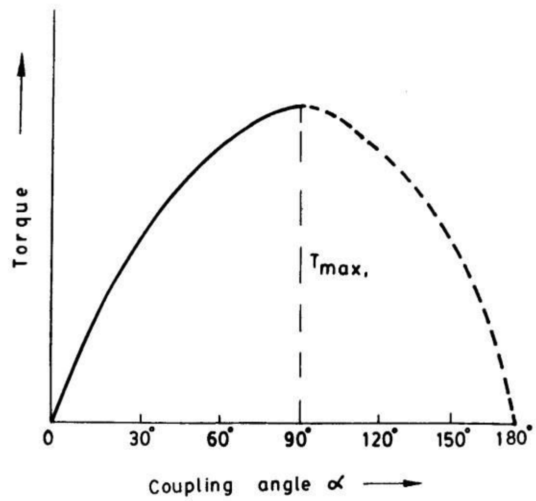


Fig. 6.10

$$\therefore \qquad \cos\theta = 0$$

$$P_{mech} = \frac{E_b V}{X_s} \cos(90° - \alpha) \qquad \text{[from eq. (6.2)]}$$

i.e.,

$$P_{mech} = \frac{E_b V}{X_s} \sin\alpha \qquad ...(6.4)$$

This gives the value of mechanical power developed in terms of α—the basic variable of a synchronous machine.

$$\therefore \qquad (P_{mech})_{max} = \frac{E_b V}{X_s} \qquad \text{[from eqn. (6.3)]}$$

This corresponds to the *'pull-out'* torque.

The above value can be obtained by putting α = 90° in eqn. (6.4).

PROBLEM: 01

Example 6.2. *A 2200 V, 3-phase star-connected synchronous motor has a resistance of 0.22 Ω/phase and a synchronous reactance of 2.4 Ω / phase. The motor is operating at 0.6 power factor leading with a line current of 180 A.*

Determine the value of the generated e.m.f./phase. **(Bangalore University Nov., 1996)**

Solution. Phase voltage, $V = \frac{2200}{\sqrt{3}} = 1270$ V

Resistance/phase, $R = 0.22\ \Omega$

Synchronous reactance/phase, $X_s = 2.4\ \Omega$

Power factor, $\cos\phi = 0.6$ (leading)

Line current, $I = 180$ A

Generated e.m.f./phase, E_b :

Here, $\cos\phi = 0.6$

$\therefore$ $\phi = \cos^{-1} = (0.6) = 53.13°$ (lead)

Also $\tan\theta = \frac{X_s}{R} = \frac{2.4}{0.22} = 10.91$

$\therefore$ $\theta = 84.8°$

$\therefore$ $(\theta + \phi) = 53.13 + 84.8° = 137.93°$

$\cos(\theta + \phi) = \cos 137.93° = -0.7423$

Synchronous impedance, $Z_s = \sqrt{(0.22)^2 + (2.4)^2} = 2.41\ \Omega$/phase

Impedance drop/phase, $E_r = IZ_s = 180 \times 2.41 = 433.8$ V

The vector diagram is shown in Fig. **6.18**.

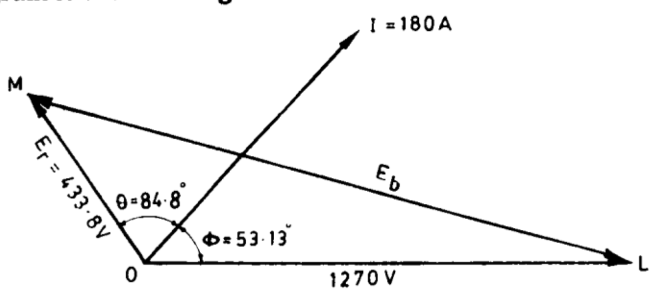


Fig. 6.18

$\therefore$ **Generated e.m.f./phase,** $E_b = \sqrt{V^2 + (E_r)^2 - 2V \times E_r \cos(\theta + \phi)}$

$= \sqrt{(1270)^2 + (433.8)^2 - 2 \times 1270 \times 433.8 \cos(53.31° + 84.8°)}$

$= 1618.3$ V

Hence, **synchronous e.m.f. (line)** = $\sqrt{3} \times$ **1618.3 = 2803 V. (Ans.)**

For Mn

PROBLEM: 02

☞**Example 6.3.** *A 6600 V, 3-phase, star-connected synchronous motor draws a full-load current of 80 A at 0.8 p.f. leading. The armature resistance is 2.2 Ω and reactance 22 Ω per phase. If the stray losses of the machine are 3200 W, find :*

(i) E.m.f. induced, *(ii) Output power, and*

(iii) Efficiency of the machine.

Solution. Phase voltage, $V = \frac{6600}{\sqrt{3}} = 3810$ V

Full-load current, $I = 80$ A at 0.8 p.f. leading

Armature resistance per phase, $R_a = 2.2\ \Omega$

Synchronous reactance/phase, $X_s = 22\ \Omega$

Stray loss $= 3200$ W

(*i*) **E.m.f. induced, E_b :**

Power factor, $\cos\phi = 0.8$

$\therefore$ $\phi = \cos^{-1}(0.8) = 36.9°$

Synchronous impedance/phase,

$$Z_s = \sqrt{R_a^2 + X_s^2} = \sqrt{(2.2)^2 + (22)^2} = 22.11\ \Omega$$

$$\tan\theta = \frac{X_s}{R_a} = \frac{22}{2.2} = 10 \quad \text{or} \quad \theta = \tan^{-1} 10 = 84.3°$$

Impedance drop/phase, $E_r = IZ_s = 80 \times 22.11 = 1768.8$ V

The vector diagram is shown in Fig. 6.19.

Induced e.m.f, E_b/phase, $E_b = \sqrt{V^2 + E_r^2 - 2VE_r\cos(\theta + \phi)}$

$$= \sqrt{(3810)^2 + (1768.8)^2 - 2 \times 3810 \times 1768.8 \cos(84.3° + 36.9°)}$$

$$= 4962.5 \text{ V}$$

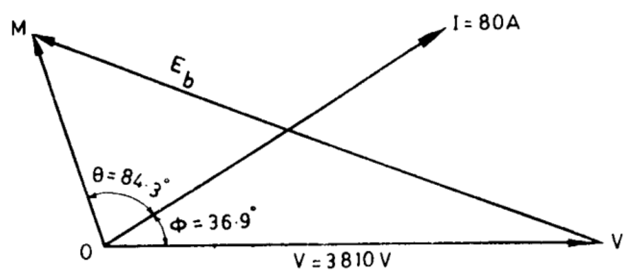


Fig. 6.19

Induced line e.m.f. $= \sqrt{3} \times 4962.5 =$ **8595 V. (Ans.)**

(*ii*) **Power output :**

Total input $= \sqrt{3}E_L I_L \cos\phi = \sqrt{3} \times 6600 \times 80 \times 0.8 = 731618$ W

Total copper losses $= 3I^2R_a = 3 \times (80)^2 \times 2.2 = 42240$ W

Total stray losses $= 3200$ W

$\therefore$ **Power output** = power input – copper losses – stray losses

$= 731618 - 42240 - 3200 =$ **686178 W. (Ans.)**

(*iii*) **Efficiency :**

Efficiency, $\eta = \frac{\text{output}}{\text{input}} = \frac{686178}{731618} \times 100 =$ **93.79%. (Ans.)**

PROBLEM: 03

Example 6.4. *A 11 kV, 3-phase star-connected synchronous motor draws a current of 45 A. The effective resistance and synchronous reactance per phase are 0.9 Ω and 28 Ω respectively. Calculate the power supplied to the motor and induced e.m.f. for a power factor of :*

(*i*) *0.8 lagging* (*ii*) *0.8 leading.*

Solution. Supply voltage/phase $= \frac{E_L}{\sqrt{3}} = \frac{11 \times 1000}{\sqrt{3}} = 6351$ V

Current drawn, $I = 45$ A

Effective resistance/phase, $R_a = 0.9\ \Omega$

Synchronous resistance/phase, $X_s = 28\ \Omega$

Synchronous impedance/phase,

$$Z_s = \sqrt{R_a^2 + X_s^2} = \sqrt{(0.9)^2 + (28)^2} = 28\ \Omega \text{ (app.)}$$

$$\tan\theta = \frac{X_s}{R_a} = \frac{28}{0.9} = 31.111$$

$\therefore$ $\theta = 88.1°$

Impedance drop/phase, $E_r = IZ_s = 45 \times 28 = 1260$ V.

(*i*) **0.8 p.f. lagging :**

$\cos\phi = 0.8$

or $\phi = \cos^{-1} 0.8 = 36.9°$

Power supplied to the motor

$= \sqrt{3} E_L I_L \cos\phi$

$= \sqrt{3} \times 11000 \times 45 \times 0.8$

$= 685892$ or **685.892 kW. (Ans.)**

Refer Fig. 6.20.

Induced e.m.f./phase,

$$E_b = \sqrt{V^2 + E_r^2 - 2VE_r \cos(\theta - \phi)}$$

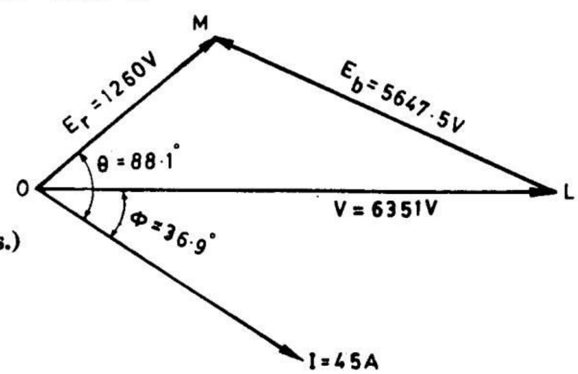


Fig. 6.20

$= \sqrt{(6351)^2 + (1260)^2 - 2 \times 6351 \times 1260 \times \cos(88.1° - 36.9°)}$

$= 5647.5$ V

Induced line e.m.f. $= \sqrt{3} \times 5647.5 =$ **9781.7 V. (Ans.)**

(*ii*) **0.8 p.f. leading :**

Power supplied to the motor

$= \sqrt{3} E_L I_L \cos\phi = \sqrt{3} \times 11000 \times 45 \times 0.8$

= 685892 W or **685.892 kW. (Ans.)**

Refer Fig. 6.21.

Induced e.m.f./phase,

$$E_b = \sqrt{V^2 + E_r^2 - 2VE_r \cos(\theta + \phi)}$$

$$= \sqrt{(6351)^2 + (1260)^2 - 2 \times 6351 \times 1260 \cos(88.1° + 36.9°)}$$

= 7148.6 V

Induced line e.m.f. $= \sqrt{3} \times 7148.6 =$ **12381.7 V. (Ans.)**

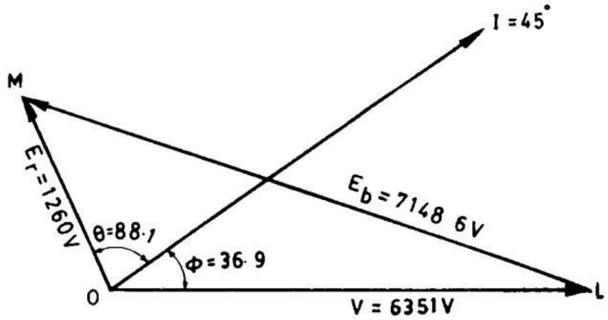


Fig. 6.21

PROBLEM: 04

☞**Example 6.6.** *The synchronous reactance per phase of a 3-phase star-connected 6600 V synchronous motor is 20 Ω. For a certain load input, the input is 915 kW at normal voltage and the induced line e.m.f. is 8942 V. Neglecting resistance, determine :*

(*i*) *line current, and* (*ii*) *power factor.* **(S.C.E.T.E. W.B., 1996)**

Solution. Synchronous reactance/phase, $X_s = 20\ \Omega$

Input to motor = 915 kW

Supply phase voltage, $V = \frac{6600}{\sqrt{3}} = 3810$ V

Induced e.m.f./phase, $E_b = \frac{8942}{\sqrt{3}} = 5163$ V

Resistance, $R_a = 0.$

Since induced e.m.f. is greater than the supply voltage, therefore the motor must be operating with a leading power factor.

Since power input $= \sqrt{3} V_L I_L \cos\phi = \sqrt{3} V_L I \cos\phi$

[∵ In star-connection : phase current = line current]

$$\therefore \qquad I\cos\phi = \frac{\text{power input}}{\sqrt{3}V_L} = \frac{915 \times 1000}{\sqrt{3} \times 6600} = 80 \text{ A}$$

Internal angle, $\theta = \tan^{-1}\frac{X_s}{R_a} = \tan^{-1}\frac{20}{0} = \tan\infty = 90°$

Impedance drop, $E_r = IZ_s = I\sqrt{R_a^2 + X_s^2} = I\sqrt{0^2 + 20^2} = 20I$

Refer Fig. 6.23.

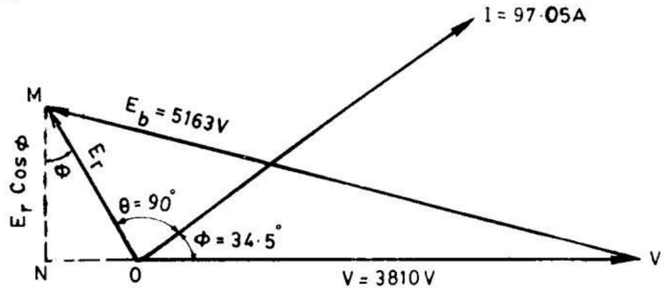


Fig. 6.23

From right angle ΔLMN, we have

$$LM^2 = LN^2 + MN^2$$

$$(5163)^2 = LN^2 + (E_r\cos\phi)^2 = LN^2 + (20I\cos\phi)^2$$

$$= LN^2 + (20 \times 80)^2 \qquad [\because \; I\cos\phi = 80 \text{ A ..... calculated above}]$$

$$\therefore \qquad LN^2 = (5163)^2 - (1600)^2$$

$$\therefore \qquad LN = 4909 \text{ V}$$

But $\qquad ON = LN - OL = 4909 - 3810 = 1099$ V

Now $\qquad E_r = (OM) = \sqrt{(ON)^2 + MN^2} = \sqrt{(1099)^2 + (20 \times 80)^2} = 1941$ V

(*i*) **Line current,** $\qquad I_L$ = phase current, I

$$= \frac{E_r}{Z_s} = \frac{1941}{20} = \mathbf{97.05\ A.} \quad \textbf{(Ans.)}$$

(*ii*) **Power factor,** $\qquad \cos\phi = \frac{I\cos\phi}{I} = \frac{80}{97.05} =$ **0.8243 (leading). (Ans.)**

$[\phi = \cos^{-1} 0.8243 = 34.5°]$.

PROBLEM: 05

Example 6.9. *A 2000 V, 3-phase, 4-pole star-connected synchronous motor runs at 1500 r.p.m. The excitation is constant and corresponding to an open-circuit voltage of 2000 V. The resistance is negligible in comparison with synchronous reactance of 3.5 Ω/phase. For an armature current of 200 A, determine :*

(*i*) *Power factor,* (*ii*) *Power input, and*

(*iii*) *Torque developed.*

Solution. Supply voltage/phase, $V = \frac{2000}{\sqrt{3}} = 1155$ V

Armature current $= 200$ A

Synchronous speed, $N_s = 1500$ r.p.m.

Induced e.m.f./phase, $E_b = \frac{2000}{\sqrt{3}} = 1155$ V

Synchronous reactance/phase, $X_s = 3.5\ \Omega$/phase

Resistance/phase = negligible

∴ Synchronous impedance, $Z_s = X_s = 3.5\ \Omega$

∴ Internal angle, $\theta = 90°$

Impedance drop, $E_r = IZ_s = 200 \times 3.5 = 700$ V

Assuming armature current lagging behind the supply voltage, as shown in Fig. 6.27.

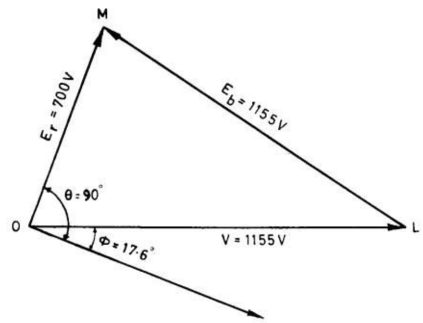


Fig. 6.27

In ΔLOM, we have $E_b^2 = V^2 + E_r^2 - 2VE_r \cos(\theta - \phi)$

$$(1155)^2 = (1155)^2 + (700)^2 - 2 \times 1155 \times 700 \cos(90 - \phi)$$

∴ $2 \times 1155 \times 700 \sin \phi = 700^2$

∴ $\sin \phi = \frac{(700)^2}{2 \times 1155 \times 700} = 0.303$

∴ $\phi = \sin^{-1}(0.303) = 17.6°$.

(*i*) **Power factor,** $\cos \phi = \cos 17.6° = \mathbf{0.9532}$. **(Ans.)**

(*ii*) **Power input,** $= \sqrt{3} V_L I_L \cos \phi = \sqrt{3} \times 2000 \times 200 \times 0.9532$

$= 660396$ W or **660.396 kW. (Ans.)**

(*iii*) Torque developed $= \frac{\text{power input} - \text{copper losses}}{2\pi N_s/60}$

$$= \frac{660396 \times 60}{2\pi \times 1500}$$

[∵ Copper losses are negligible as resistance is negligible]

$=$ **4204.2 N-m. (Ans.)**

For Mn

For Mn

/

Example 6.15. *A 400 V, 8 kW 3-phase synchronous motor has negligible resistance and synchronous reactance of 8 Ω/phase. Determine the minimum current and the corresponding induced e.m.f. for full-load condition.*

Assume an efficiency of 88%.

Solution. Supply voltage/phase,

$$V = \frac{400}{\sqrt{3}} = 231 \text{ V}$$

Motor output = 8 kW or 8000 W

Synchronous reactance/phase,

$$X_s = 8\ \Omega$$

Efficiency = 88%

$$\text{Motor input} = \frac{\text{output}}{\text{efficiency}} = \frac{8000}{0.88} = 9091 \text{ W}$$

Since motor input $= \sqrt{3} V_L I \cos\phi$

$$\therefore \quad I\cos\phi = \frac{\text{motor input}}{\sqrt{3} V_L} = \frac{9091}{\sqrt{3} \times 400} = 13.12 \text{ A.}$$

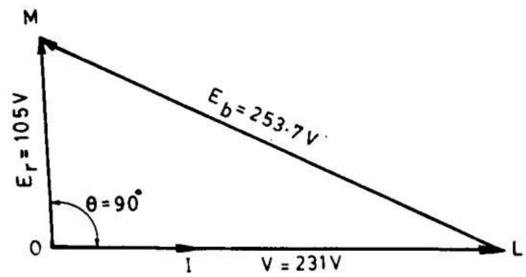


Fig. 6.34

The *current is minimum when power factor is unity*. In such a condition,

$$I = I\cos\phi = \mathbf{13.12\ A.} \quad \textbf{(Ans.)}$$

Impedance drop, $E_r = IZ_s = 13.12 \times 8 = 105$ V

Refer Fig. 6.34.

$$E_b^2 = V^2 + E_r^2 = (231)^2 + (105)^2$$

$$\therefore \quad E_b = \sqrt{(231)^2 + (105)^2} = \mathbf{253.7\ V.} \quad \textbf{(Ans.)}$$

If developed power has to achieve maximum value, then

$$\frac{dP_m}{d\delta} = 1025.59 \times 10^3 \cos\delta + 2 \times 177.54 \times 10^3 \cos 2\delta = 0$$

$$\therefore\ 1025.59 \times 10^3 \cos\delta + 355.08 \times 10^3 \left(2\cos^2\delta - 1\right) = 0$$

or $$710.16 \times 10^3 \cos^2\delta + 1025.59 \times 10^3 \cos\delta - 355.08 \times 10^3 = 0$$

$$\cos\delta = \frac{-1025.59 \times 10^3 \pm \sqrt{\left(1025.59 \times 10^3\right)^2 + 4 \times 710.16 \times 10^3 \times 355.08 \times 10^3}}{2 \times 710.16 \times 10^3}$$

$$= \frac{-1025.59 \times 10^3 \pm 1435.44 \times 10^3}{1420.32 \times 10^3} = 0.288$$

$$\delta = 73.22^\circ$$

Maximum $P_m = 1025.59 \times 10^3 \sin\left(73.22^\circ\right) + 177.54 \times 10^3 \sin\left(2 \times 73.22^\circ\right)$

$P_m = 1080$ kW

Maximum Power developed for three phases $= 3 \times P_m$

$= 3 \times 1080 = 3240$ kW

For Mn

Unit III-Three Phase Induction Motor:

INTRODUCTION

The three phase induction motor runs on three phase AC supply. It is an ac motor. The power is transferred by means of induction. So it is also called as rotating transformer.

Advantages:

1. It has very simple and extremely rugged, almost unbreakable construction (especially squirrel-cage type).
2. Its cost is low and it is very reliable.
3. It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
4. It requires minimum of maintenance.
5. It starts up from rest and needs no extra starting motor and has not to be synchronised. Its starting arrangement is simple especially for squirrel-cage type motor.

Disadvantages:

1. Its speed cannot be varied without sacrificing some of its efficiency.
2. Just like a d.c. shunt motor, its speed decreases with increase in load.
3. Its starting torque is somewhat inferior to that of a d.c. shunt motor.

CONSTRUCTIONAL DETAILS OF THREE PHASE INDUCTION MOTOR

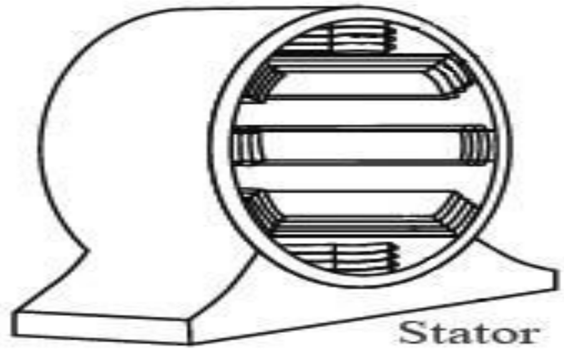
An induction motor consists essentially of two main parts :

(a) a stator and

(b) a rotor.

(a) Stator

The stator of an induction motor is, in principle, the same as that of a synchronous motor or generator. It is made up of a number of stampings, which are slotted to receive the windings [Fig. (*a*)]. The stator carries a 3-phase winding and is fed from a 3-phase supply. It is wound for a definite number of poles , the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and ***vice versa***. The stator windings, when supplied with 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves (or rotates) at synchronous speed (given by $N_s = 120 f/P$). This revolving magnetic flux induces an e.m.f. in the rotor by mutual induction.



(b) Rotor

(i) ***Squirrel-cage rotor* :** Motors employing this type of rotor are known as squirrel-cage induction motors.

(ii) ***Phase-wound or wound rotor* :** Motors employing this type of rotor are variously known as 'phase-wound' motors or 'wound' motors or as 'slip-ring' motors.

Squirrel cage Rotor

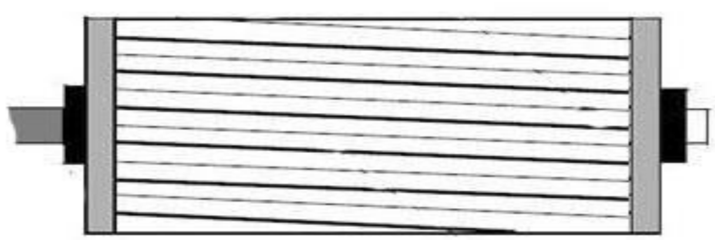
Almost 90 per cent of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminium or alloys. One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short-circuiting end-rings, thus giving us, what is so picturesquely called, a squirrel-case construction

It should be noted that the ***rotor bars are permanently short-circuited on themselves***, hence it is not possible to add any external resistance in series with the rotor circuit for starting purposes.

The rotor slots are usually not quite parallel to the shaft but are purposely given a slight skew This is useful in two ways :

(i) it helps to make the motor run quietly by reducing the magnetic hum and

(ii) it helps in reducing the locking tendency of the rotor *i.e.* the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

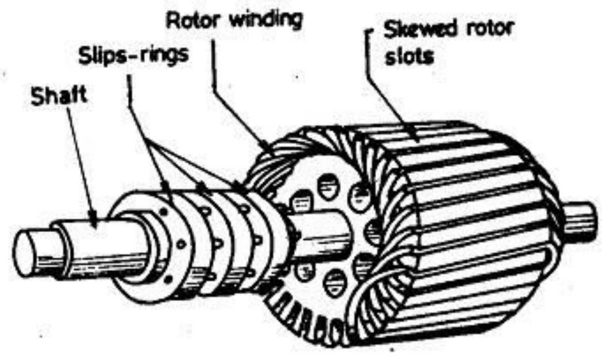


Squirrel Cage Rotor

Phase -Wound Rotor

This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils as used in alternators. The rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even ***when the stator is wound two-phase***

The three phases are starred internally. The other three winding terminals are brought out and connected to three insulated slip-rings mounted on the shaft with brushes resting on them .



These three brushes are further externally connected to a 3-phase star-connected rheostat [Fig. (*a*)]. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor, for changing its speed-torque/current characteristics. When running under normal conditions, the ***slip-rings are automatically short-circuited*** by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip-rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel-case rotor.

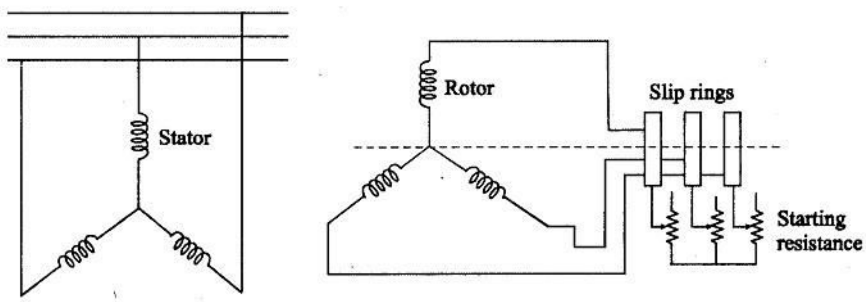


Fig (*a*) External Resistance Connection

For Mn

PRINCIPLE OF OPERATION

When the 3-phase stator windings, are fed by a 3-phase supply then, as seen from above, a magnetic flux of constant magnitude, but rotating at synchronous speed, is set up.

The flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary.

Due to the relative speed between the rotating flux and the stationary conductors, an e.m.f. is induced in the latter, according to Faraday's laws of electro-magnetic induction.

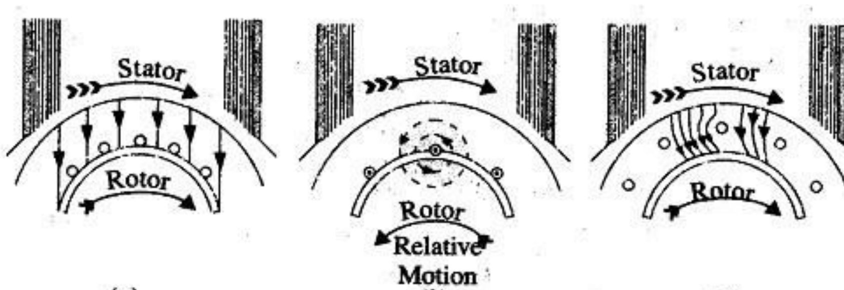
The frequency of the induced e.m.f. is the same as the supply frequency.

Its magnitude is proportional to the relative velocity between the flux and the conductors and its direction is given by Fleming's Right-hand rule. Since the rotor bars or conductors form a closed circuit, rotor current is produced whose direction, as given by Lenz's law, is such as to oppose the very cause producing it.

In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the ***same*** direction as that of the flux and tries to catch up with the rotating flux.

The setting up of the torque for rotating the rotor is explained below :

In Fig (*a*) is shown the stator field which is assumed to be rotating clockwise. The relative motion of the rotor with respect to the stator is ***anticlockwise***. By applying Right-hand rule, the direction of the induced e.m.f. in the rotor is found to be outwards. Hence, the direction of the flux due to rotor current *alone*, is as shown in Fig. (*b*). Now, by applying the Left-hand rule, or by the effect of combined field [Fig. (*c*)] it is clear that the rotor conductors experience a force tending to rotate them in clockwise direction. Hence, the rotor is set into rotation in the same direction as that of the stator flux (or field).



(*a*) (*b*) (*c*)

Fig.

SLIP

The difference between synchronous speed and rotor speed and expressed as a percentage of synchronous speed

Though it may be expressed in so many revolutions/second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term '*slip*' is descriptive of the way in which the rotor 'slips back' from synchronism.

$$\% \text{ slip} \quad s = \frac{N_s - N}{N_s} \times 100$$

Sometimes, $N_s - N$ is called the ***slip speed.***

Obviously, rotor (or motor) speed is $N = N_s(1 - s)$

It may be kept in mind that revolving flux is rotating synchronously, relative to the stator (*i.e.* stationary space) but at slip speed relative to the rotor.

When the rotor is stationary, the frequency of rotor current is *the same as the supply frequency.* But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip-speed. Let at any slip-speed, the frequency of the rotor current be f'. Then

$$N_S \cdot N \cdot \frac{120 f'}{P} \quad \text{Also} \quad N_S \cdot \frac{120 f}{P}$$

Note

When rotor starts rotating, it tries to catch the speed of rotating magnetic field.

If it catches the speed of the rotating magnetic field, the relative motion between rotor and the rotating magnetic field will vanish ($N_s - N = 0$). In fact the relative motion is the main cause for the induced e.m.f. in the rotor. So induced e.m.f. will vanish and hence there cannot be rotor current and the rotor flux which is essential to produce the torque on the rotor. Eventually motor will stop. But immediately there will exist a relative motion between rotor and rotating magnetic field and it will start. But due to inertia of rotor, this does not happen in practice and rotor continues to rotate with a speed slightly less than the synchronous speed of the rotating magnetic field in the steady state. The **induction motor never rotates at synchronous speed**. The speed at which it rotates is hence called **subsynchronous speed** and motor sometimes called **asynchronous motor**.

$$\therefore \qquad N < N_s$$

So it can be said that rotor slips behind the rotating magnetic field produced by stator. The difference between the two is called **slip speed** of the motor.

$$N_s - N = \text{slip speed of the motor in r.p.m.}$$

Relation between torque and rotor power factor

In induction motor, the torque is proportional to the product of flux per pole and the rotor current, power factor of the rotor.

$$\boxed{T \propto \phi_2 I_2 \cos\phi_2}$$

Denoting rotor emf at standstill by E_2 we have that $E_2 \propto \phi_2$

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

$$\boxed{T = K E_2 I_2 \cos\phi_2}$$

where K = constant

From the equ it is clear that as ϕ_2 increases (and hence, $\cos\phi_2$ decreases) the torque decreases and vice versa.

Starting Torque

The torque developed by the motor at the instant of starting is called starting torque.

Let

E_2 = Rotor emf per phase at standstill

R_2 = Rotor resistance/phase at standstill

X_2 = Rotor Reactance /phase at standstill

Z_2 = Rotor impedance /phase at standstill

$$Z_2 = \sqrt{R_2^2 + X_2^2}$$

$$I_2 = \frac{E_2}{Z_2} \quad \text{——— (1)}$$

$$\cos\phi_2 = \frac{R_2}{Z_2} \quad \text{——— (2)}$$

starting Torque $T_{st} = K E_2 I_2 \cos\phi_2$ ——— (3)

Substitute Equ (1), (2) in (3)

$$T_{st} = K E_2 \cdot \frac{E_2}{Z_2} \cdot \frac{R_2}{Z_2}$$

$$T_{st} = K \frac{E_2^2 R_2}{R_2^2 + X_2^2} \quad \text{(or)} \quad K \frac{E_2^2 R_2}{Z_2^2}$$

If the supply voltage V is constant, then the flux ϕ and hence E_2 both are constant.

$$\therefore \; T_{st} = K_1 \frac{R_2}{Z_2^2} \qquad (\because \; K_1 = K E_2)$$

Rotor emf and reactance under running condition

Let

E_2 = standstill rotor induced emf / phase

X_2 = standstill rotor reactance / phase

f_2 = Rotor current frequency at standstill

when rotor is stationary i.e. $s = 1$, the frequency of rotor emf is the same as that of the stator frequency. i.e $f_2 = f$

When rotor starts running, the relative speed between it and the rotating stator flux is decreased. Hence the rotor induced emf which is directly proportional to this relative speed, is also decreased. Hence for a slip 's' the rotor induced emf will be 's' times the induced emf at standstill.

Under running condition

Rotor emf $\boxed{E_r = s E_2}$

Rotor frequency $\boxed{f_r = s f_2}$

and Rotor reactance $\boxed{X_r = s X_2}$

Rotor torque

Torque is the twisting force and this Force is being produced by the rotor current and the rotor current is produced by the stator flux per pole. Rotor current depends on the rotor power factor and so torque equation can be given by

$$T \propto \phi I_r \cos\phi_2 \quad \text{——— (1)}$$

$$\phi \propto E_2 \quad \text{and} \quad I_r = \frac{E_r}{Z_r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$\cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Substituting I_r and $\cos\phi_2$ in equ (1)

$$T \propto E_2 \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$T \propto \frac{SE_2^2 R_2}{\left(\sqrt{R_2^2 + (SX_2)^2}\right)^2}$$

$$T \propto \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

$$\boxed{T = K \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}} \longrightarrow \text{Torque Equation of Rotor under Running Condition}$$

where K is a constant.

The constant K is proved to be

$$K = \frac{3}{\omega_s} \quad \text{and} \quad \omega_s = \frac{2\pi N_s}{60}$$

when s=1 i.e at starting

$$\boxed{T_{st} = K \frac{E_2^2 R_2}{R_2^2 + X_2^2}}$$ → Equation of starting Torque

Condition for maximum torque

Mathematically for maximum torque we can write

$$\frac{dT}{ds} = 0$$

where $$T = \frac{K s E_2^2 R_2}{R_2^2 + (sX_2)^2} \quad \text{———} \quad (2)$$

While carrying out differentiation remember that E_2, R_2, X_2 and K are constants. The only variable is slip s.

As both numerator and denominator contains s terms, differentiate T with respect to 's' using the rule of differentiation for u/v.

$$\therefore \frac{dT}{ds} = \frac{(KsE_2^2R_2)\frac{d}{ds}(R_2^2 + s^2X_2^2) - (R_2^2 + s^2X_2^2)\frac{d}{ds}(KsE_2^2R_2)}{(R_2^2 + s^2X_2^2)^2}$$

$$\frac{dT}{ds} = 0$$

$$\therefore KsE_2^2R_2(2sX_2^2) - (R_2^2+s^2X_2^2)(KE_2^2R_2) = 0$$

$$KE_2^2R_2[2s^2X_2^2 - s^2X_2^2 - R_2^2] = 0$$

$$s^2X_2^2 = R_2^2$$

$$s^2 = \frac{R_2^2}{X_2^2}$$

$$\boxed{s = \frac{R_2}{X_2}}$$

This is the slip at which the torque is maximum.

Substitute $s = \frac{R_2}{X_2}$ in equ (2)

Then $$T_{max} = \frac{K\frac{R_2}{X_2}E_2^2R_2}{R_2^2 + \frac{R_2^2}{X_2^2}X_2^2}$$

$$T_{max} = \frac{KR_2^2E_2^2}{2R_2^2X_2}$$

$$\boxed{T_{max} = \frac{KE_2^2}{2X_2}} \rightarrow \text{Maximum Torque Equation}$$

SYNCHRONOUS WATT

The torque produced in the induction motor is given by,

$$T = \frac{\dfrac{3(I'_{2r})^2 R'_2}{s}}{\dfrac{2\pi N_s}{60}} = \frac{P_2}{\dfrac{2\pi N_s}{60}} \text{ N-m}$$

Thus torque is directly proportional to the rotor input. By defining new unit of torque which is synchronous watt we can write,

$$T = P_2 \quad \text{synchronous-watts}$$

If torque is given in synchronous-watts then it can be obtained in N-m as,

$$1 \text{ syn-watt} = \frac{60}{2\pi N_s} \text{ N-m}$$

i.e.

$$1 \text{ N-m} = \frac{2\pi N_s}{60} \text{ syn-watt}$$

PROBLEM: 01

A 24 pole, 50 Hz, star connected induction motor has rotor resistance of 0.016 Ω per phase and rotor reactance of 0.265 Ω per phase at standstill. It is achieving its full load torque at a speed of 247 rpm. calculate the ratio of

i) Full load torque to maximum torque (ii) Starting torque to maximum torque.

Given data

$P = 24 \quad f = 50\,Hz \quad R_2 = 0.016\,\Omega/\text{phase}$

$X_2 = 0.265\,\Omega/\text{phase} \quad N = 247\ \text{rpm}$

Solution

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{24} = 250\ \text{rpm}$$

$$S_f = \frac{N_s - N}{N_s} = \frac{250-247}{250} = 0.012 = \text{full load slip}$$

$$\boxed{S_f = 0.012}$$

$$S_m = \frac{R_2}{X_2} = \frac{0.016}{0.265} = 0.06037$$

$$\boxed{S_m = 0.06037}$$

i) $$\frac{T_{FL}}{T_m} = \frac{2 S_m S_f}{S_m^2 + S_f^2} = \frac{2 \times 0.06037 \times 0.012}{(0.06037)^2 + (0.012)^2}$$

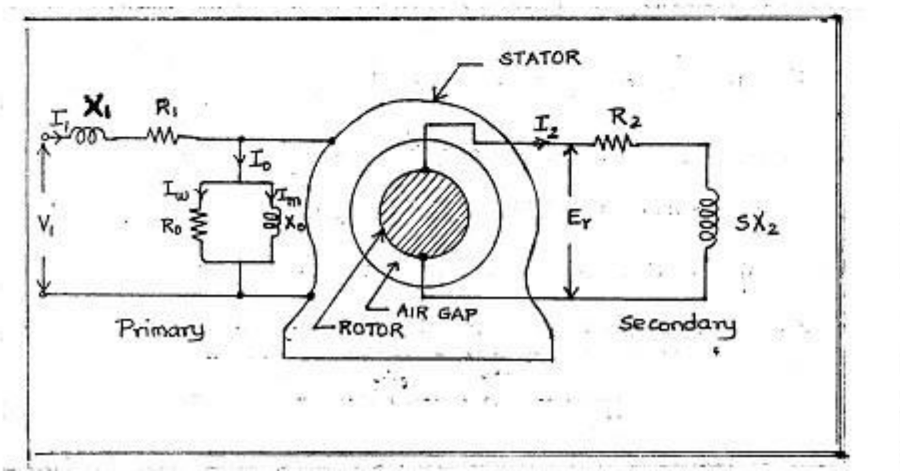
$$\boxed{\frac{T_{FL}}{T_m} = 0.3824}$$

(ii) $$\frac{T_{st}}{T_m} = \frac{2 S_m}{1 + S_m^2} = \frac{2 \times 0.06037}{1 + (0.06037)^2} = 0.1203$$

$$\boxed{\frac{T_{st}}{T_m} = 0.1203}$$

EQUIVALENT CIRCUIT OF INDUCTION MOTOR

The transfer of energy from stator to the rotor of an induction motor takes place entirely inductively with the help of a flux mutually linking the two. Hence an induction motor is essentially a transformer with stator forming the primary and rotor forming (the short circuited) rotating secondary as shown in fig(a)



When motor is loaded, the rotor current I_2 is given by

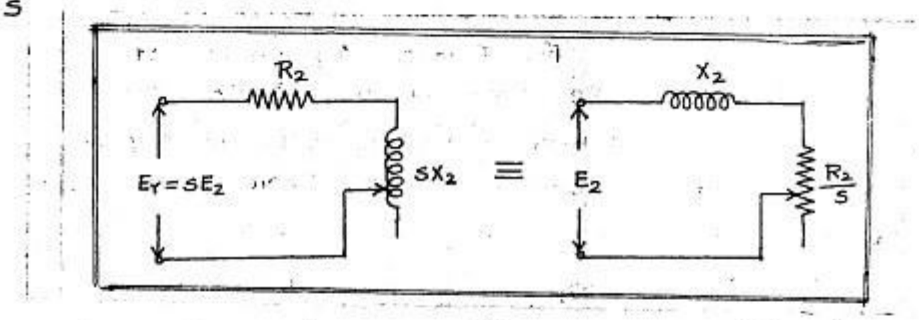
$$I_2 = \frac{E_r}{Z_r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Divide both numerator and denominator by 's', we get

$$I_2 = \frac{E_2}{\sqrt{\left(\frac{R_2}{S}\right)^2 + X_2^2}}$$

From the above relation it appears that the rotor circuit which actually consists of fixed resistance R_2 and a variable reactance sX_2 connected across E_r can be looked upon as equivalent to a rotor circuit having a fixed reactance X_2 connected in series with a variable resistance

$\frac{R_2}{s}$ is shown in Fig (b).



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

It consists of two parts.

(i) The first part R_2 is the rotor resistance itself and represents the rotor cu loss.

(ii) The second part is $R_2\left(\frac{1}{s} - 1\right)$. This is known as the load resistance R_L and is electrical equivalent of the mechanical load on the motor.

The equivalent rotor circuit along with the load resistance R_L may be drawn as shown in fig (c)

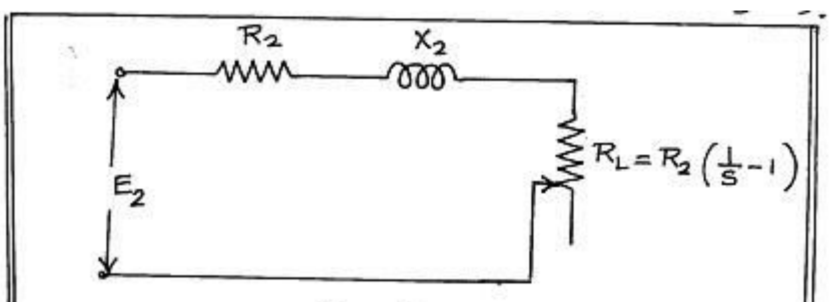
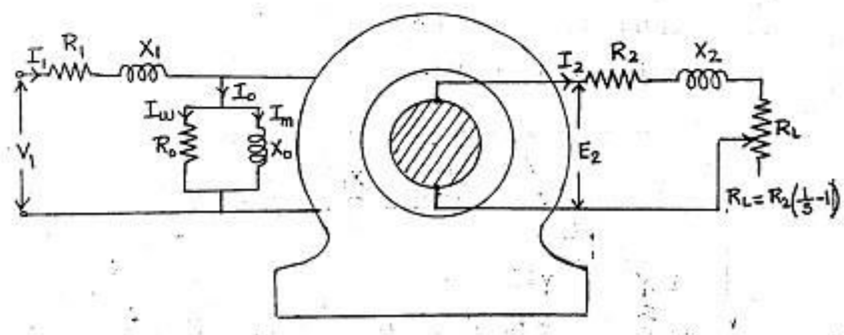


Fig (c)

So the equivalent circuit of an induction motor can be modified as follows.



As in the case of a transformer, in this case also, the secondary value may be transferred to the primary and vice versa. As before it should be remembered that when shifting impedance or resistance from secondary to primary, it should be divided by K^2 whereas current should be multiplied by K. The equivalent circuit of an induction motor where all values have been referred to primary i.e stator is shown in Fig (d)

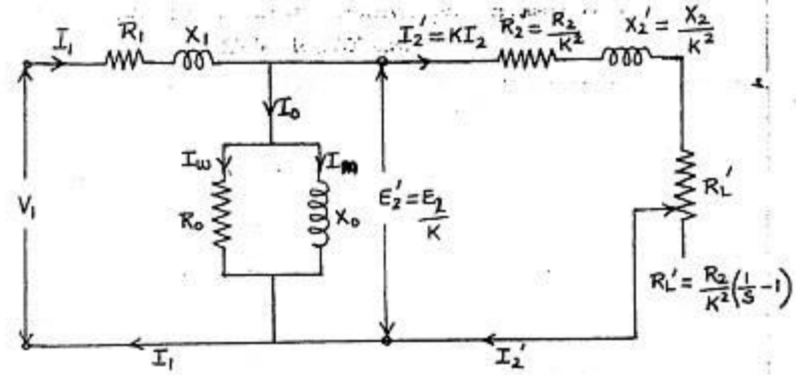
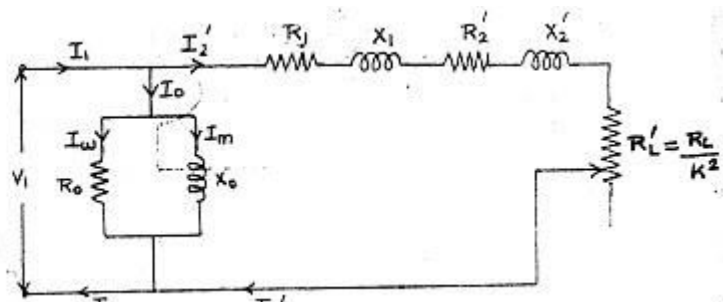
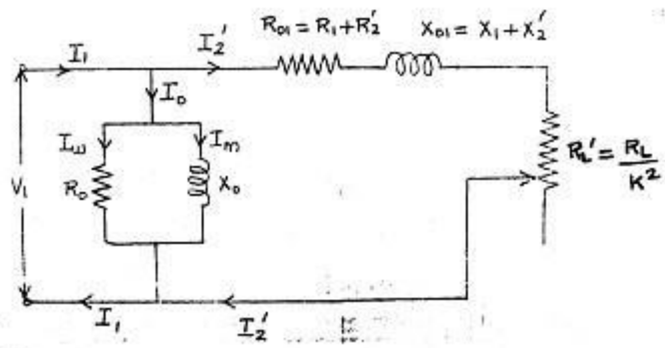


fig (d)

As shown in Fig (e), the exciting circuit may be transferred to the left, because inaccuracy involved is negligible but the circuit and hence the calculation are very much simplified. This is known as the approximate equivalent circuit of the induction motor.



fig(b)



APPROXIMATE EQUIVALENT CIRCUIT OF AN INDUCTION MOTOR

LOSSES AND EFFICIENCY

1. LOSSES

The various power losses in an induction motor can be classified as,

i) Constant losses

ii) Variable losses

i) Constant losses :

These can be further classified as core losses and mechanical losses.

Core losses occur in stator core and rotor core. These are also called iron losses. These losses include eddy current losses and hysterisis losses. The eddy current losses are minimised by using laminated construction while hysterisis losses are minimised by selecting high grade silicon steel as the material for stator and rotor.

The iron losses depends on the frequency. The stator frequency is always supply frequency hence stator iron losses are dominant. As against this in rotor circuit, the frequency is very very small which is slip times the supply frequency. Hence rotor iron losses are very small and hence generally neglected, in the running condition.

The mechanical losses include frictional losses at the bearings and windage losses. The friction changes with speed but practically the drop in speed is very small hence these losses are assumed to be the part of constant losses.

ii) Variable losses :

This include the copper losses in stator and rotor winding due to current flowing in the winding. As current changes as load changes, these losses are said to be variable losses.

Generally stator iron losses are combined with stator copper losses at a particular load to specify total stator losses at particular load condition.

Rotor copper loss = $3 I_{2r}^2 R_2$ ... analysed separately

where I_{2r} = Rotor current per phase at a particular load

R_2 = Rotor resistance per phase

2. EFFICIENCY

The ratio of net power available at the shaft (P_{out}) and the net electrical power input (P_{in}) to the motor is called as overall efficiency of an induction motor.

$$\therefore \quad \% \eta = \frac{P_{out}}{P_{in}} \times 100$$

The maximum efficiency occurs when variable losses become equal to constant losses. When motor is on no load, current drawn by the motor is small. Hence efficiency is low. As load increases, current increases so copper losses also increase. When such variable losses achieve the same value as that of constant losses, efficiency attains its maximum value. If load is increased further, variable losses become greater than constant losses hence deviating from condition for maximum, efficiency starts decreasing. Hence the nature of the curve of efficiency against output power of the motor is shown in the Fig.

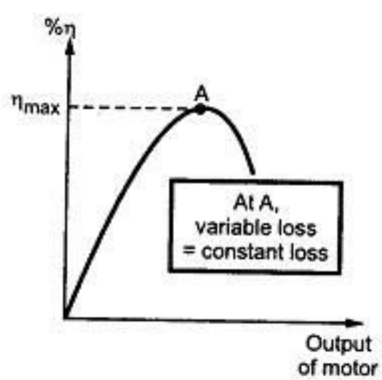


Fig. Efficiency curve for an induction motor

Power flow diagram for an induction motor

Induction motor converts an electrical power supplied to it into mechanical power. The various stages in this conversion is called **power flow** in an induction motor.

The three phase supply given to the stator is the **net electrical input** to the motor. If motor power factor is cos ϕ and V_L, I_L are line values of supply voltage and current drawn, then net input electrical power supplied to the motor can be calculated as,

$$P_{in} = \sqrt{3}\, V_L I_L \cos\phi$$

where P_{in} = Net input electrical power.

This is nothing but the **stator input**.

The part of this power is utilised to supply the losses in the stator which are stator core as well as copper losses.

The remaining power is delivered to the rotor magnetically through the air gap with the help of rotating magnetic field. This is called **rotor input** denoted as $\mathbf{P_2}$.

So

$$P_2 = P_{in} - \text{stator losses (core + copper)}$$

The rotor is not able to convert its entire input to the mechanical as it has to supply **rotor losses**. The rotor losses are dominantly copper losses as rotor iron losses

are very small and hence generally neglected. So rotor losses are **rotor copper losses** denoted as P_c.

So

$$P_c = 3 \times I_{2r}^2 \times R_2$$

where I_{2r} = Rotor current per phase in running condition

R_2 = Rotor resistance per phase.

After supplying these losses, the remaining part of P_2 is converted into mechanical which is called **gross mechanical power** developed by the motor denoted as $\mathbf{P_m}$.

$$\therefore \quad P_m = P_2 - P_c$$

Now this power, motor tries to deliver to the load connected to the shaft. But during this mechanical transmission, part of P_m is utilised to provide **mechanical losses** like friction and windage.

And finally the power is available to the load at the shaft. This is called **net output** of the motor denoted as $\mathbf{P_{out}}$. This is also called shaft power.

$$\therefore \quad P_{out} = P_m - \text{Mechanical losses.}$$

The rating of the motor is specified in terms of value of P_{out} when load condition is full load condition. This is expressed in horse powers and called **H.P. rating** of the motor.

The above stages can be shown diagramatically called **power flow diagram** of an induction motor.

This is shown in the Fig.

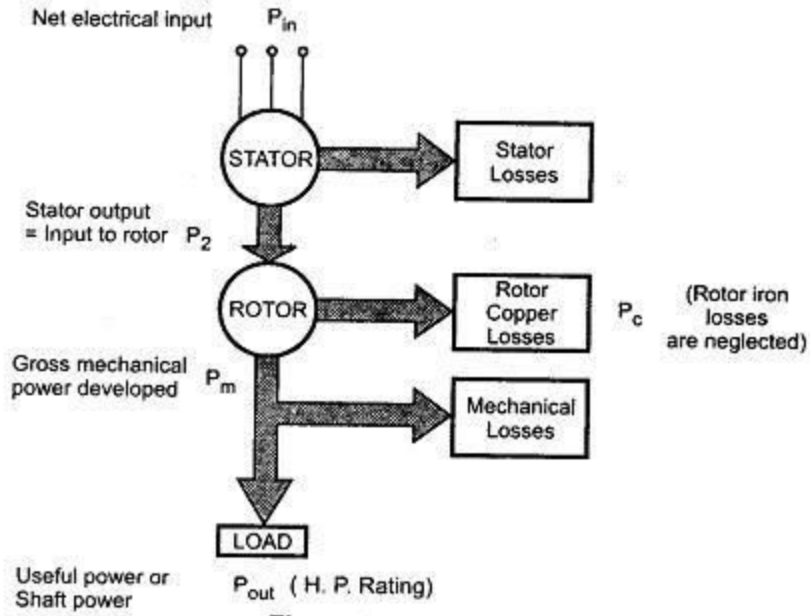


Fig. Power flow diagram

From the power flow diagram we can define,

$$\text{Rotor efficiency} = \frac{\text{Rotor output}}{\text{Rotor input}} = \frac{\text{Gross mechanical power developed}}{\text{Rotor input}}$$

$$= \frac{P_m}{P_2}$$

$$\text{Net motor efficiency} = \frac{\text{Net output at shaft}}{\text{Net electrical input to motor}}$$

$$\% \ \eta = \frac{P_{out}}{P_{in}} \times 100$$

Important formulae

1. $\frac{P_c}{P_2} = S$

2. $(1-S) P_2 = P_m$

3. $P_2 : P_c : P_m = 1 : s : 1-S$

4. $\omega = \frac{2\pi N}{60}$

5. $P_{out} = \frac{2\pi N T}{60}$

PROBLEM: 01

The power supplied to a 3 phase induction motor is 40 kW and the corresponding stator losses are 2 kW. Calculate the total Mech. power developed and rotor copper loss if slip is 0.04.

Given data :

$P_{in} = 40$ KW stator losses = 2 KW

$S = 0.04$

solution

$P_2 = P_{in}$ - stator losses

$P_2 = 40 - 2 = 38$ KW

Mech. Power developed

$P_m = (1-S) P_2$

$P_m = (1-0.04) \times 38$

$P_m = 36.48$ KW

Rotor cu loss $P_c = P_2 - P_m$

$P_c = 38 - 36.48$

$P_c = 1.52$ KW

PROBLEM: 02

A 3 phase, 50 Hz induction motor draws 50 KW from the mains. If the stator losses are 1 KW and the rotor emf is observed to make 120 complete oscillations per minute, determine i) the rotor loss ii) Gross mechanical output.

Given data

$f = 50\ Hz$ $P_{in} = 50\ KW$ Stator losses = 1 KW

$f' = \frac{120}{60}$ oscillation /sec = 2 Hz

solution

$$f' = sf$$

$$\therefore s = \frac{f'}{f} = \frac{2}{50} = 0.04$$

$P_2 = P_{in}$ - stator losses = 50-1 = 49 KW

Rotor loss $P_c = sP_2 = 0.04 \times 49 = 1.96\ KW$

$$\boxed{P_c = 1.96\ KW}$$

Gross Mechanical output

$$P_m = (1-s)P_2 = (1-0.4) \times 49 = 47.04\ KW$$

$$\boxed{P_m = 47.04\ KW}$$

PROBLEM: 03

The power input to a 500V, 50Hz 6 pole 3phase induction motor running at 975 rpm is 40 KW. The stator losses are 1 KW and friction and windage losses toal 2 KW. calculate i) the slip ii) the rotor cu loss 3) the output horse power iv) The efficiency.

Given data

$V_L = 500\ V$ $f = 50\ Hz$ $P = 6$ $N = 975\ rpm$

$P_{in} = 40\ KW$ Stator losses = 1 KW

Friction and windage losses = 2 KW.

Solution

i) $S = \frac{N_s - N}{N_s} = \frac{1000 - 975}{1000} = 0.025$

$$\boxed{S = 0.025}$$

ii) Rotor input $P_2 = P_{in}$ - stator losses $= 40 - 1$

$$P_2 = 39 \text{ KW}$$

Rotor cu loss $P_c = sP_2 = 0.025 \times 39 = 0.975 \text{ KW}$

$$\boxed{P_c = 0.975 \text{ KW}}$$

(iii) Gross mech. Power $P_m = (1-s)P_2$

$$P_m = (1-0.025) \times 39 = 38.025 \text{ KW}$$

output power $P_{out} = P_m$ - friction & windage loss

$$P_{out} = 38.025 - 2 = 36.025 \text{ KW}$$

output horse power $= \frac{P_{out} \text{ in watts}}{735.5} = \frac{36.025 \times 10^3}{735.5}$

$$\boxed{\text{output horse power} = 48.98 \text{ h.p.}}$$

(iv) The efficiency

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{36.025}{40} \times 100$$

$$\boxed{\% \eta = 90.0625}$$

PROBLEM: 04

The active power input to a 415 V, 50 Hz, 6 pole, 3 phase induction motor running at 970 rpm is 41 KW. The input power factor is 0.9 The stator losses amount to 1.1 KW and the mechanical losses total 1.2 KW. calculate line current, slip, rotor copper loss, mechanical power output and efficiency.

Given data

$V_L = 415$ V $f = 50$ Hz $P = 6$ $N = 970$ rpm

$P_{in} = 41$ KW $\cos\phi = 0.9$ Stator losses $= 1.1$ KW

Mechanical losses $= 1.2$ KW

Solution

i) $P_{in} = \sqrt{3}\, V_L I_L \cos\phi$

$$41 \times 10^3 = \sqrt{3} \times 415 \times I_L \times 0.9$$

$$\boxed{I_L = 63.3771\ A}$$

ii) $N_s = \frac{120 f}{P} = \frac{120 \times 50}{6} = 1000\ rpm$

$$S = \frac{N_s - N}{N_s} = \frac{1000 - 970}{1000} = 0.03$$

$$\boxed{S = 0.03}$$

(iii) $P_2 = P_{in} - \text{Stator loss} = 41 - 1.1 = 39.9\ kW$

$$P_c = SP_2 = 0.03 \times 39.9 = 1.197\ kW$$

$$\boxed{P_c = 1.197\ kW}$$

(iv) $P_m = (1-S) P_2 = (1-0.03) \times 39.9 = 38.703\ kW$

$$P_{out} = P_m - \text{Mech. loss} = 38.703 - 1.2$$

$$\boxed{P_{out} = 37.503\ kW}$$

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{37.503}{41} \times 100 = 91.47$$

$$\boxed{\% \eta = 91.47}$$

PROBLEM: 05

A 3 phase, 400V, 50 Hz 4 pole induction motor has star connected stator winding, the rotor resistance and reactance per phase are 0.1 Ω and 4 Ω respectively. The full load speed is 40 rpm. calculate the synchronous speed, slip, rotor emf / phase and torque developed by the motor at full load.

For Mn

Given data

$V = 400\ V \quad f = 50\ Hz \quad P = 4 \quad R_2 = 0.1\ \Omega$

$X_2 = 4\ \Omega \quad N = 40\ rpm$

solution

Synchronous speed $N_s = \frac{120 f}{P} = \frac{120 \times 50}{4}$

$$N_s = 1500\ rpm$$

Slip

$$S = \frac{N_s - N}{N_s} = \frac{1500-40}{1500}$$

$$S = 0.9733$$

Rotor emf/phase

$$E_2 = \frac{400}{\sqrt{3}} = 230.94\ V$$

rotor emf/phase under full load conditions

$$E_r = S E_2 = 0.973\ (230.94)$$

$$E_r = 224.70\ V$$

Torque developed by motor on full load

$$T_f = \frac{3}{2\pi N_s} \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

$$T_f = \frac{3}{2\pi \left(\frac{1500}{60}\right)} \times \frac{0.973\ (230.94)^2 \times 0.1}{0.1^2 + (0.973 \times 4)^2}$$

$$T_f = \frac{15567.99}{157 \times 15.157664} = 6.541\ N\text{-}m$$

$$T_f = 6.541\ N\text{-}m$$

SLIP-TORQUE CHARACTERISTICS

The curve drawn between torque and slip from s=1 (at start) to s=0 (synchronous speed) is called torque-slip characteristics of the induction motor.

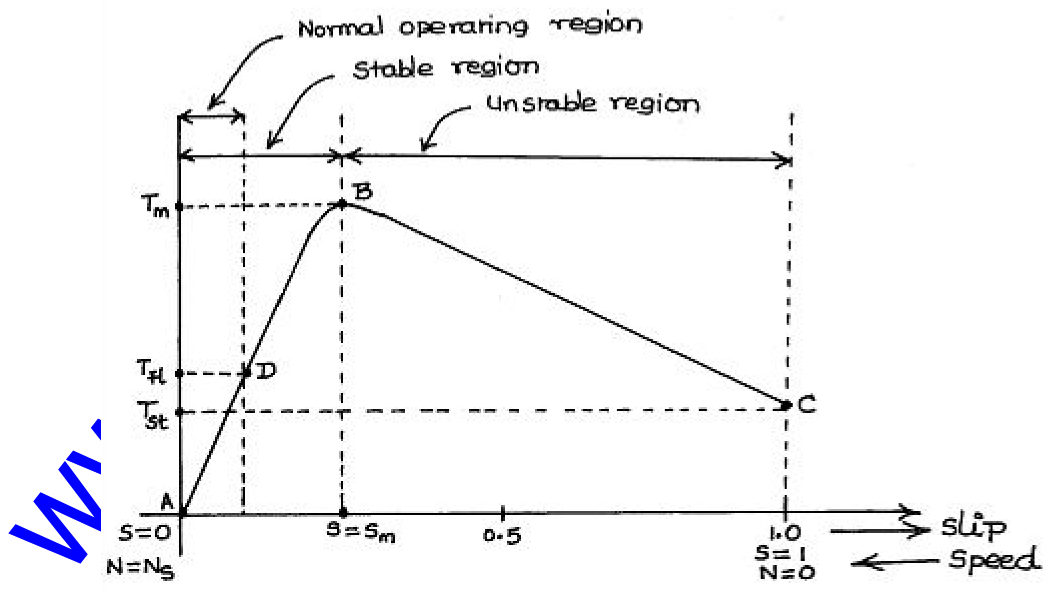
The torque equation of 3 phase induction motor is given by

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

Here the input voltage is constant. i.e E_2 is also constant. So the above equation becomes

$$T \propto \frac{s R_2}{R_2^2 + (s X_2)^2} \quad \text{——— (1)}$$

Fig (a) shows torque-slip characteristics of three phase induction motor.



It consists of three regions.

1. Stable operating region
2. Unstable operating region
3. Normal operating region.

Stable Region (AB)

In stable region, the slip value 'S' is very small i.e the term $(SX_2)^2$ is very small as compared to R_2^2. Hence neglecting $(SX_2)^2$ in equation (1)

$$T \propto \frac{SR_2}{R_2^2} \Rightarrow T \propto \frac{S}{R_2}$$

$$\boxed{T \propto S} \text{ as } R_2 \text{ is constant}$$

The slip value is directly proportional to the torque. In this region, as the load increases speed decreases which increases the slip.

$$T\uparrow, S\uparrow$$

So the characteristics is approximately a straight line. It is indicated as shown in curve AB. Hence, the slip value between $S=0$ to $S=S_m$.

Unstable region (BC)

When the slip is further increased from S_m, the region is unstable region. Hence, the slip value is high i.e the value between S_m to 1. The term R_2^2 may be neglected as compared to $(SX_2)^2$ in equation (1).

$$T \propto \frac{S}{(SX_2)^2} \propto \frac{1}{S} \quad \text{where } X_2 \text{ is constant.}$$

$$\therefore \boxed{T \propto \frac{1}{S}}$$

In this region, torque is inversely proportional to slip.

$$S\uparrow, T\downarrow$$

The torque-slip curve is similar to the rectangular hyperbola. By increasing the load, the motor speed decreases, Hence slip increases and so torque must increase to satisfy the load demand. But again increasing the load, speed further decreases finally the motor comes to standstill condition.

In the unstable region, the motor should not be operated

Normal operating region (AD)

The Region AD is Normal operating region and also called as low slip region. The motor is continuously operated in this region.

NOTE: Generally full load torque is less than the maximum Torque.

$$T_{Full\text{-}load} < T_m$$

GENERATING AND BRANKING REGION

Motoring Mode:

In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The induction motor torque varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip.

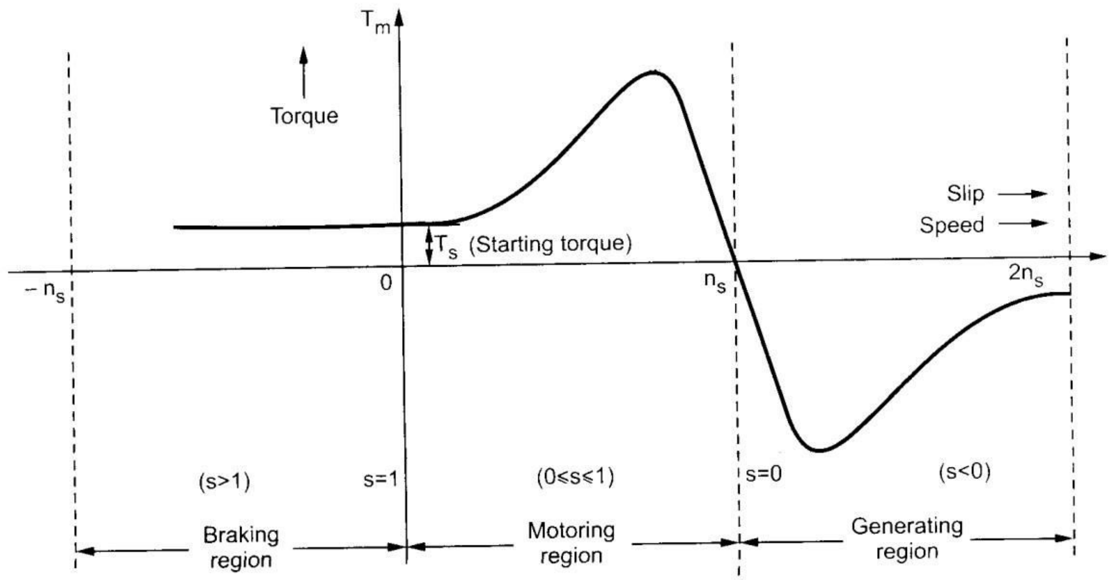
Generating Mode

- **In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation**

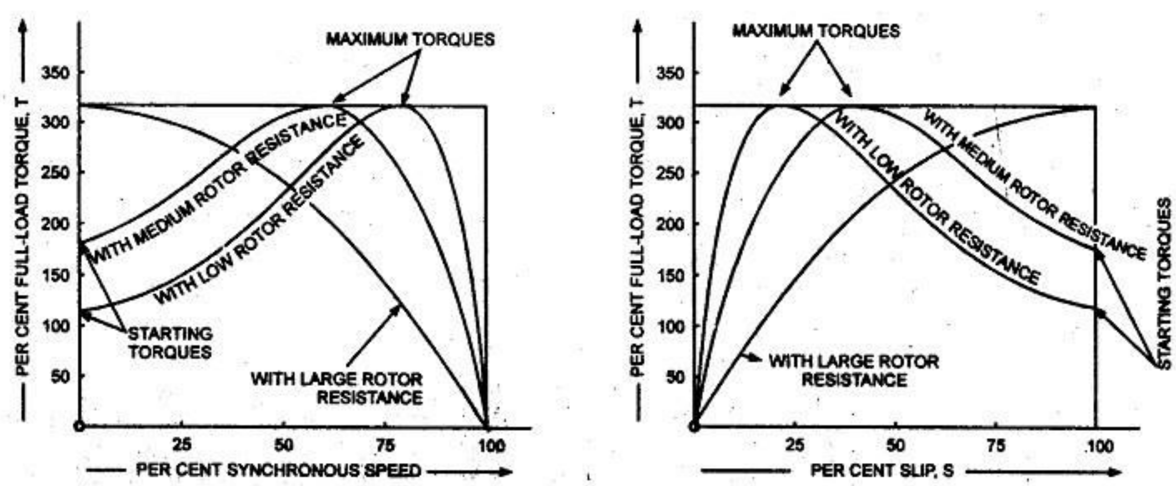
Braking Mode

- **In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time.**

For Mn



Effect of rotor resistance upon torque slip or torque speed relationship



(a) Torque-Speed Curves

(b) Torque-Slip Curves

PROBLEM: 01

A 3ϕ induction motor having a star connected rotor has an induced emf of 80V between slip-rings at standstill on open circuit. The rotor has a resistance and reactance per phase of 1Ω and 4Ω respectively. calculate current/phase and power factor when a) slip-rings are short circuited b) slip-rings are connected to star-connected rheostat of 3Ω per phase.

solution

Stand still emf of rotor/phase = $80/\sqrt{3}$ = 46.2 V

a) $R_2 = 1\Omega$ $X_2 = 4\Omega$

Rotor impedance/phase = $\sqrt{1^2+4^2}$ = 4.12Ω

Rotor current/phase = $\frac{E_2}{Z_2} = \frac{46.2}{4.12}$ = 11.2 A

Power factor = $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{1}{4.12} = 0.243$

As p.f is low, the starting torque is also low

b) Rotor resistance/phase = 3+1 = 4 Ω

Rotor impedance/phase = $\sqrt{4^2+4^2}$ = 5.66 Ω

Rotor current/phase = $\frac{E_2}{Z_2} = \frac{46.2}{5.66}$ = 8.16 A

Power factor = $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{4}{5.66} = 0.707$

Hence, the starting torque is increased due to improvement in the power factor.

PROBLEM: 02

A 3 phase, 400/200 V, Y-Y connected wound-rotor induction motor has 0.06 Ω rotor resistance and 0.3 Ω stand still reactance per phase. Find the additional resistance required in the rotor circuit to make the starting torque equal to the maximum torque of the motor

$$\frac{T_{st}}{T_m} = \frac{2 S_m}{1 + S_m^2} \quad \text{since} \quad T_{st} = T_{max}$$

$$1 = \frac{2 S_m}{1 + S_m^2} \quad (\text{or}) \quad 1 + S_m^2 - 2 S_m = 0$$

$$S_m^2 - 2 S_m + 1 = 0$$

$$S_m = 1$$

Now $S_m = \frac{R_2 + r}{X_2}$

where r = external resistance / phase

$$\therefore \quad 1 = \frac{0.06 + r}{0.3} \Rightarrow r = 0.3 - 0.06 = 0.24\Omega$$

$$r = 0.24\Omega$$

PROBLEM: 03

A 12 pole, 3 phase, 600 V, 50 Hz, Star-connected Induction motor has motor resistance and stand-still reactance of 0.03 and 0.5 Ω per phase respectively. calculate a) speed of full-load torque to maximum torque b) ratio of full-load torque to maximum torque if the full load speed is 495 rpm.

Solution

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{12} = 500 \text{ rpm}$$

$R_2 = 0.03\Omega$ $X_2 = 0.5\ \Omega$

$$S_m = \frac{R_2}{X_2} = \frac{0.03}{0.5} = 0.06$$

a) Speed of full-load torque to maximum Torque

$$= N_s (1 - S_m) = 500 (1 - 0.06) = 470 \text{ rpm}$$

b) Full-load speed = 495 rpm $S = 0.01$ at full load

$$\frac{\text{Full load torque}}{\text{Maximum Torque}} = \frac{2 S_f S_m}{S_f^2 + S_m^2} = \frac{2 \times 0.01}{(0.01)^2 + (0.06)^2}$$

$$= 0.324$$

LOAD TEST

By conducting the load test on three phase induction motor, the performance of the motor viz. slip, power factor, input, efficiency etc. at various loads can be studied.

The induction motor is loaded by any of the following methods :

1. Brake test
2. By connecting a d.c. generator

In case of loading by connecting a d.c. generator, the induction motor is connected to a d.c. generator. The generator is loaded by a lamp bank. Thus inturn an induction motor is loaded. The Fig. shows the experimental set up for conducting load test on three phase induction motor using a d.c. generator.

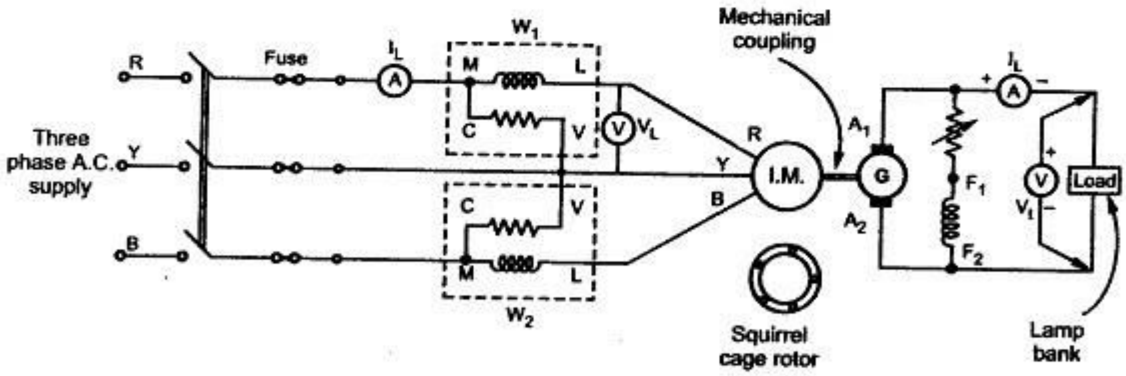


Fig. Load test on three phase induction motor

On induction motor side, ammeter reads line current I_L and voltmeter reads line voltage V_L. The two wattmeters are connected as per the two wattmeter method hence,

$$P_{in} = \text{power input} = W_1 + W_2$$

On generator side, the ammeter reads load current I_L and voltmeter reads terminal voltage V_t.

By varying the lamp bank, load on generator i.e. load on induction motor can be varied. The induction motor can be star or delta connected and can be squirrel cage or slip ring type. The speed readings are taken using tachometer. The load is increased till induction motor carries rated line current. The following observation table is prepared,

Measure:
Vl,IL,W1,W2

Calculations : The output of induction motor is input to a d.c. generator.

Output of d.c. generator $= V_t \times I_L$ W

Assume $\eta_{gen} = 80\ \%$

$\therefore$ P_{out} of induction motor $= P_{in}$ of d.c. generator

$$= \frac{P_{out}\ \text{of d.c. generator}}{\eta_{gen}} = \frac{V_t I_L}{\eta_{gen}}\ \text{W}$$

P_{in} of induction motor $= W_1 + W_2$ W

$$\cos\phi = \frac{P_{in}}{\sqrt{3} V_L I_L} = \frac{W_1 + W_2}{\sqrt{3} V_L I_L} = \text{Power factor}$$

$$\%\ \eta_{motor} = \frac{P_{out}\ \text{of motor}}{P_{in}\ \text{of motor}} \times 100$$

$$\%\ \text{slip} = \frac{N_s - N}{N_s} \times 100$$

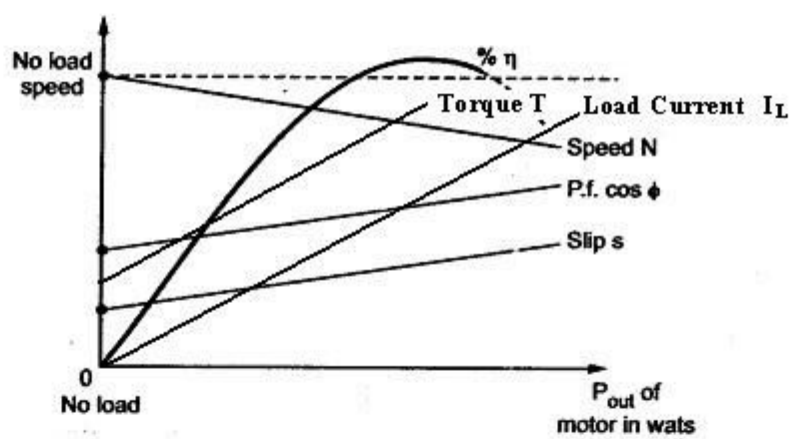
where $N_S = \frac{120f}{P}$ for a given motor

For various loads above parameters are obtained.

As the load on the induction motor increases,

1. The output of motor increases.
2. The power factor increases.
3. The efficiency increases upto certain load and then decreases.
4. The speed decreases marginally.
5. The slip increases.
6. The input current increases.

The various performance characteristics can be obtained as shown in the Fig.



NO-LOAD TEST

In this test, the motor is made to run without any load i.e. no load condition. The speed of the motor is very close to the synchronous speed but less than the synchronous speed. The rated voltage is applied to the stator. The input line current and total input power is measured. The two wattmeter method is used to measure the total input power. The circuit diagram for the test is shown in the Fig.

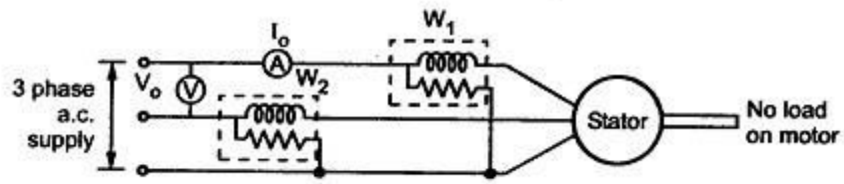


Fig. No load test

As the motor is on no load, the power factor is very low which is less than 0.5 and one of the two wattmeters reads negative. It is necessary to reverse the current coil or pressure coil connections of such a wattmeter to get the positive reading. This reading must be taken negative for the further calculations.

The total power input W_o is the algebraic sum of the two wattmeter readings. The observation table is,

V_o volts Rated line voltage	I_o Amp No load current	$W_o = W_1 + W_2$ (Algebraic sum) in watts

The calculations are,

$$W_o = \sqrt{3}\, V_o\, I_o \cos\phi_o$$

$$\therefore \quad \cos\phi_o = \frac{W_o}{\sqrt{3}\, V_o\, I_o} \qquad \text{where } V_o, I_o \text{ are line values}$$

This is **no load power factor.**

Thus we are now in a position to obtain magnitude and phase angle of no load current I_o, which is required for the circle diagram.

From the knowledge of I_o and ϕ_o, the parameters of the equivalent circuit can be obtained as,

$$I_c = I_o \cos\phi_o = \text{active component of no load current}$$

$$I_m = I_o \sin\phi_o = \text{magnetising component of no load current}$$

$$R_o = \frac{V_o\,(\text{per phase})}{I_c\,(\text{per phase})} = \text{no load branch resistance}$$

$$X_o = \frac{V_o\,(\text{per phase})}{I_m\,(\text{per phase})} = \text{no load branch reactance}$$

The power input W_o consists of following losses,

1. Stator copper loss i.e. $3\, I_o^2\, R_1$ where I_o is no load per phase current and R_1 is stator resistance per phase.

2. Stator core loss i.e. iron loss.

3. Friction and windage loss.

The no load rotor current is very small and hence rotor copper loss is negligibly small. The rotor frequency is s times supply frequency and on no load it is very small. Rotor iron losses are proportional to this frequency and hence are negligibly small.

Thus W_o consists of stator iron loss and friction and windage loss which are constants for all load conditions. Hence W_o is said to give fixed losses of the motor.

$\therefore$ W_o = no load power input

= fixed loss ... neglecting stator copper loss

BLOCKED ROTOR TEST

In this test, the rotor is locked and it is not allowed to rotate. Thus the slip s = 1 and $R'_L = R'_2\ (1-s)/s$ is zero. If the motor is slip ring induction motor then the windings are short circuited at the slip rings.

The situation is exactly similar to the short circuit test on transformer. If under short circuit condition, if primary is excited with rated voltage, a large short circuit current can flow which is dangerous from the windings point of view. So similar to the transformer short circuit test, the reduced voltage (about 10 to 15% of rated voltage) just enough such that stator carries rated current is applied. Now the applied voltage V_{SC}, the input power W_{SC} and a short circuit current I_{SC} are measured.

As $R'_L = 0$, the equivalent circuit is exactly similar to that of a transformer and hence the calculations are similar to that of short circuit test on a transformer.

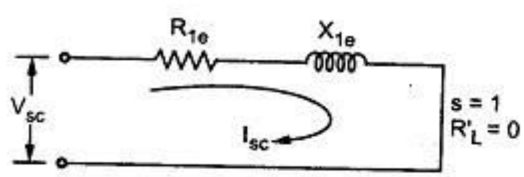
V_{SC} = Short circuit reduced voltage (line value)

I_{SC} = Short circuit current (line value)

W_{SC} = Short circuit input power

Now $W_{SC} = \sqrt{3}\, V_{SC} I_{SC} \cos\phi_{SC}$ ... line values

$$\therefore \quad \cos\phi_{SC} = \frac{W_{SC}}{\sqrt{3}\, V_{SC} I_{SC}}$$



This gives us short circuit power factor of a motor.

Now the equivalent circuit is as shown in the Fig.

$\therefore$ $W_{SC} = 3\,(I_{SC})^2 R_{1e}$ where I_{SC} = Per phase value

$$\therefore \quad R_{1e} = \frac{W_{SC}}{3\,(I_{SC})^2}$$

This is equivalent resistance referred to stator.

$$Z_{1e} = \frac{V_{SC}\text{ (Per phase)}}{I_{SC}\text{ (Per phase)}}$$

= Equivalent impedance referred to stator

$$\therefore \quad X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}$$

= Equivalent reactance referred to stator

During this test, the stator carries rated current hence the stator copper loss is also dominant. Similarly the rotor also carriers short circuit current to produce dominant rotor copper loss. As the voltage is reduced, the iron loss which is proportional to voltage is negligibly small. The motor is at standstill hence mechanical loss i.e. friction and windage loss is absent. Hence we can write,

$$W_{SC} = \text{Stator copper loss + Rotor copper loss}$$

But it is necessary to obtain **short circuit current when normal voltage** is applied to the motor. This is practically not possible. But the reduced voltage test results can be used to find current I_{SN} which is short circuit current if normal voltage is applied.

If $\quad V_L$ = normal rated voltage (line value)

$\quad V_{SC}$ = Reduced short circuit voltage (line value)

then
$$I_{SN} = \left(\frac{V_L}{V_{SC}}\right) \times I_{SC}$$

where $\quad I_{SC}$ = Short circuit current at reduced voltage

Thus, $\quad I_{SN}$ = Short circuit current at normal voltage

Now power input is proportional to square of the current

So $\quad W_{SN}$ = Short circuit input power at normal voltage

This can be obtained as,

$$W_{SN} = \left(\frac{I_{SN}}{I_{SC}}\right)^2 W_{SC}$$

But at normal voltage core loss can not be negligible hence,

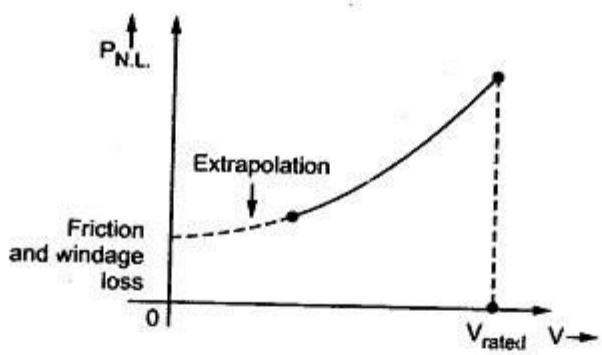
$$W_{SN} = \text{core loss + stator and rotor copper loss}$$

SEPERATION OF NO-LOAD LOSSES

The no load losses are the constant losses which include core loss and friction and windage loss. The separation between the two can be carried out by the no load test conducted from variable voltage, rated frequency supply.

When the voltage is decreased below the rated value, the core loss reduces as nearly square of voltage. The slip does not increase significantly the friction and windage loss almost remains constant.

The voltage is contineously decreased till the machine slip suddenly begins to increase and the motor tends to stall. At no load, this takes place at a sufficiently reduced voltage. The graph showing no load losses $P_{N.L.}$ versus V as shown in the Fig. is extrapolated to V = 0 which gives friction and windage loss as iron or core loss is zero at zero voltage.



CIRCLE DIAGRAM

Circle diagram of an induction motor can be drawn by using the data obtained from

(1) no-load

(2) short-circuit test

and **(3) stator resistance test**, as shown below.

Step No. 1

From no-load test, I_0 and ϕ_0 can be calculated. Hence, as shown in Fig. 35.9, vector for I_0 can be laid off lagging ϕ_0 behind the applied voltage V.

Step No. 2

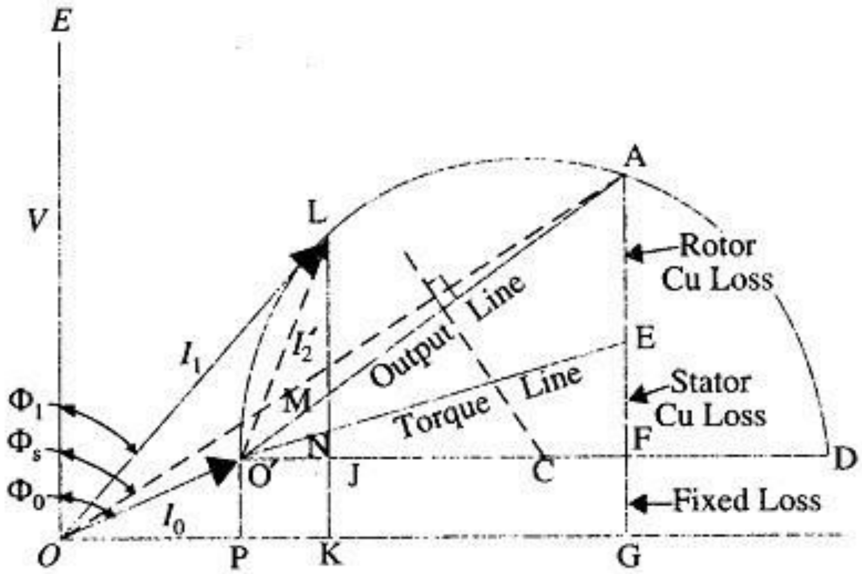
Next, from blocked rotor test or short-circuit test, short- circuit current I_{SN} ***corresponding to normal voltage*** and ϕ_S are found. The vector ***OA*** represents $I_{SN} = (I_S V/V_S)$ in magnitude and phase.

Vector $O'A$ represents rotor current I_2' as referred to stator.

Clearly, the two points O' and A lie on the required circle.

For finding the centre C of this circle, chord $O'A$ is bisected at right angles–its bisector giving point C.

The diameter $O'D$ is drawn perpendicular to the voltage vector.



As a matter of practical contingency, it is recommended that the scale of current vectors should be so chosen that the diameter is more than 25 cm, in order that the performance data of the motor may be read with reasonable accuracy from the circle diagram.

With centre C and radius = CO', the circle can be drawn.

The line $O'A$ is known as **out-put line.**

It should be noted that as the voltage vector is drawn vertically, all vertical distances represent the active or power or energy components of the currents.

For example, the vertical component $O'P$ of no-load current OO' represents the no-load input, which supplies core loss, friction and windage loss and a negligibly small amount of stator I^2R loss. Similarly, the vertical component AG of short-circuit current OA is proportional to the motor input on short-circuit or if measured to a proper scale, may be said to equal power input.

Step No. 3

Torque line. ***This is the line which separates the stator and the rotor copper losses.*** When the rotor is locked, then all the power supplied to the motor goes to meet core losses and Cu losses in the stator and rotor windings. The power input is proportional to AG. Out of this, FG (= $O'P$) represents fixed losses *i.e.* stator core loss and friction and windage losses. AF is proportional to the sum of the stator and rotor Cu losses. The point E is such that

$$\frac{AE}{EF} = \frac{\text{rotor Cu loss}}{\text{stator Cu loss}}$$

As said earlier, line $O'E$ is known as torque line.

How to locate point E ?

(i) ***Squirrel-cage Rotor.*** Stator resistance/phase *i.e.* R_1 is found from stator-resistance test. Now, the short-circuit motor input W_s is approximately equal to motor Cu losses (neglecting iron losses).

Stator Cu loss = $3I_S^2 R_1$ $\quad\therefore$ rotor Cu loss = $W_S - 3I_S^2 R_1$ $\quad\therefore \dfrac{AE}{EF} = \dfrac{W_S - 3I_S^2 R_1}{3I_S^2 R_1}$

***(ii)* Wound Rotor.** In this case, rotor and stator resistances per phase r_2 and r_1 can be easily computed. For any values of stator and rotor currents I_1 and I_2 respectively, we can write

$$\therefore \quad K = \frac{I_1}{I_2} = \text{transformation ratio}$$

Now
$$\frac{AE}{EF} = \frac{\text{rotor copper loss}}{\text{stator copper loss}} = \frac{I_2^2 R_2}{I_1^2 R_1} = \frac{R_2}{R_1}\left(\frac{I_2}{I_1}\right)^2 = \frac{R_2}{R_1}\cdot\frac{1}{K^2}$$

But
$$R_2' = \frac{R_2}{K^2} = \text{rotor resistance referred to stator}$$

$$\therefore \quad \frac{AE}{EF} = \frac{R_2'}{R_1}$$

Thus point E can be obtained by dividing line AF in the ratio R_2' to R_1.

Let us assume that the motor is running and taking a current OL .

Then, the perpendicular JK represents fixed losses,
JN is stator Cu loss,
NL is the rotor input,
NM is rotor Cu loss,
ML is rotor output and
LK is the total motor input.

From our knowledge of the relations between the above-given various quantities, we can write :

$\sqrt{3} \,.\, V_L \,.\, LK$ = motor input
$\sqrt{3} \,.\, V_L \,.\, JK$ = fixed losses
$\sqrt{3} \,.\, V_L \,.\, JN$ = stator copper loss
$\sqrt{3} \,.\, V_L \,.\, MN$ = rotor copper loss
$\sqrt{3} \,.\, V_L \,.\, MK$ = total loss
$\sqrt{3} \,.\, V_L \,.\, ML$ = mechanical output
$\sqrt{3} \,.\, V_L \,.\, NL$ = rotor input $\propto$ torque

1. ML / LK = output/input = efficiency
2. MN / NL = (rotor Cu loss)/(rotor input) = slip, s.
3. $$\frac{ML}{NL} = \frac{\text{rotor output}}{\text{rotor input}} = 1 - s = \frac{N}{N_S} = \frac{\text{actual speed}}{\text{synchronous speed}}$$
4. $$\frac{LK}{OL} = \text{power factor}$$

Maximum Quantities

It will now be shown from the circle diagram that the maximum values occur at the positions stated below :

***(i)* Maximum Output**

It occurs at point M where the tangent is parallel to output line $O'A$. Point M may be located by drawing a line *CM* from point *C* such that it is perpendicular to the output line *O′A*. Maximum output is represented by the vertical MP.

(*ii*) Maximum Torque or Rotor Input

It occurs at point *N* where the tangent is parallel to torque line *O′E*. Again, point *N* may be found by drawing *CN* perpendicular to the torque line. Its value is represented by *NQ* . Maximum torque is also known as stalling or pull-out torque.

(*iii*) Maximum Input Power

It occurs at the highest point of the circle *i.e.* at point R where the tangent to the circle is horizontal. It is proportional to RS. As the point R is beyond the point of maximum torque, the induction motor will be unstable here. However, the maximum input is a measure of the size of the circle and is an indication of the ability of the motor to carry short-time over-loads. Generally, RS is twice or thrice the motor input at rated load.

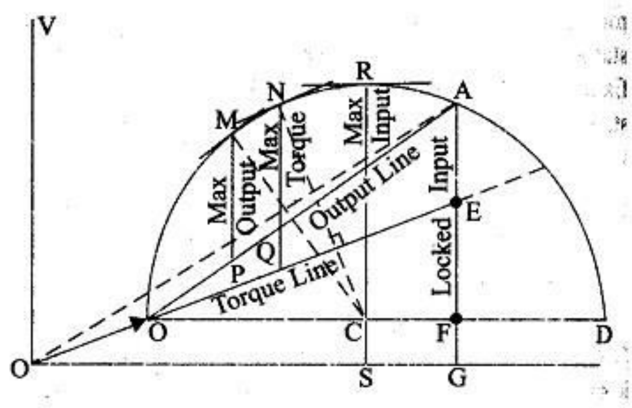
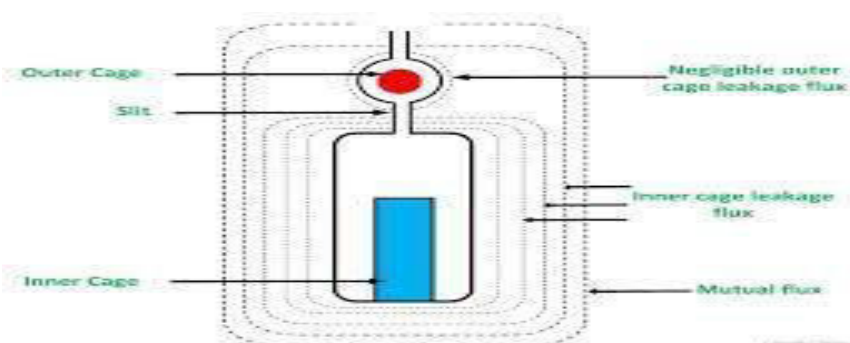


Fig. 35.10

DOUBLE CAGE CONSTRUCTION

Rotor of a double squirrel cage motor has two independent cages on the same rotor. The figure at left shows the cross sectional diagram of a double squirrel cage rotor.
Bars of high resistance and low reactance are placed in the outer cage, and bars of low resistance and high reactance are placed in the inner cage. The outer cage has high 'reactance to resistance ratio' whereas, the inner cage has low 'reactance to resistance ratio'



Working:

At starting of the motor, frequency of induced emf is high because of large slip (slip = frequency of rotor emf / supply frequency). Hence the reactance of inner cage ($2\pi fL$ where, f = frequency of rotor emf) will be very high, increasing its total impedance. Hence at starting most of the current flows through outer cage despite its large resistnace (as total impedance is lower than the inner cage). This will not affect the outer cage because of its low reactance. And because of the large resistance of outer cage starting torque will be large. As speed of the motor increases, slip decreases, and hence the rotor frequency decreases. In this case, the reactance of inner cage will be low, and most of the current will flow through the inner cage which is having low resistance. Hence giving a good efficiency.

When the double cage motor is running at normal speed, frequency of the rotor emf is so low that the reactance of both cages is negligible. The two cages being connected in parallel, the combined resistance is low.

SYNCHRONOUS INDUCTION MOTOR

In the applications where high starting torque and constant speed are desired then synchronous induction motors can be used. It has the advantages of both synchronous and induction motors. The synchronous motor gives constant speed whereas induction motors can be started against full load torque.

Consider a normal slip ring induction motor having three phase winding on the rotor as shown in the Fig. 5.51. (See Fig. on next page)

The motor is connected to the exciter which gives d.c. supply to the rotor through slip rings. One phase carries full d.c. current while the other two carries half of the full d.c. current as they are in parallel. Due to this d.c. excitation, permanent poles (N and S) are formed on the rotor.

Initially it is run as an slip ring induction motor with the help of starting resistances. When the resistance is cut out the motor runs with a slip. Now the connections are changed and the exciter is connected in series with the rotor windings which will remain in the circuit permanently.

As the motor is running as induction motor initially high starting torque (upto twice full load value) can be developed. When d.c. excitation is provided it is pulled into synchronism and starts running at constant speed. Thus synchronous induction motor provides constant speed, large starting torque, low starting current and power factor correction.

It may be possible that the a.c. winding is put on the rotor and the d.c. excitation is provided on the stator. This simplifies control gear. It also gives better facilities for insulation which permits higher voltages and lower d.c. excitations.

The d.c. winding must be designed in such a way as to give high mmf with moderate d.c. excitation power. The excitation loss must be distributed evenly over the winding. The mmf distribution should be nearly sinusoidal. It should also provide damping against hunting and it should be satisfactorily started as an induction motor.

When the machine is running as an induction motor there are induced alternating currents in the rotor and it runs below synchronous speed. When the rotor carries d.c. currents the rotor field and hence the rotor must run at synchronous speed. This means that slip must be reduced to zero. But if there is any departure from this speed during normal operation then again induced currents are there in the rotor. The rotor is of low resistance so its windings act as damping winding. Hence no separate damping windings are required.

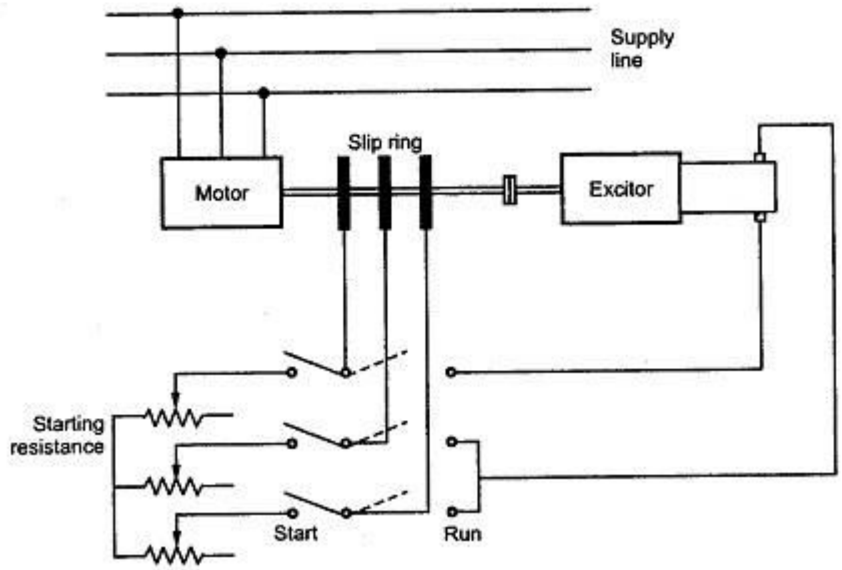


Fig. 5.51

While studying the performance characteristics of synchronous induction motor, three different types of torques are to be considered. These are viz. the starting torque which indicates capacity of motor to start against load, pull in torque which indicates the ability of the motor to maintain operation during change over from induction motor to synchronous motor, pull out torque which represents the running of motor synchronously at peak load. The first two torques are closely related with each other and are the characteristics of the machine running as induction motor. The pull out torque is characterisics when it is running synchronously. The characteristics curves for synchronous induction motor operating at full load unity p.f. and at 0.8 p.f. leading is shown in Fig. 5.53.

When the load exceeds the synchronous pull out torque, the machine looses synchronism and runs as an induction motor with fluctuation in torque and slip due to d.c. excitation. With reduction in load torque the motor is automatically resynchronized.

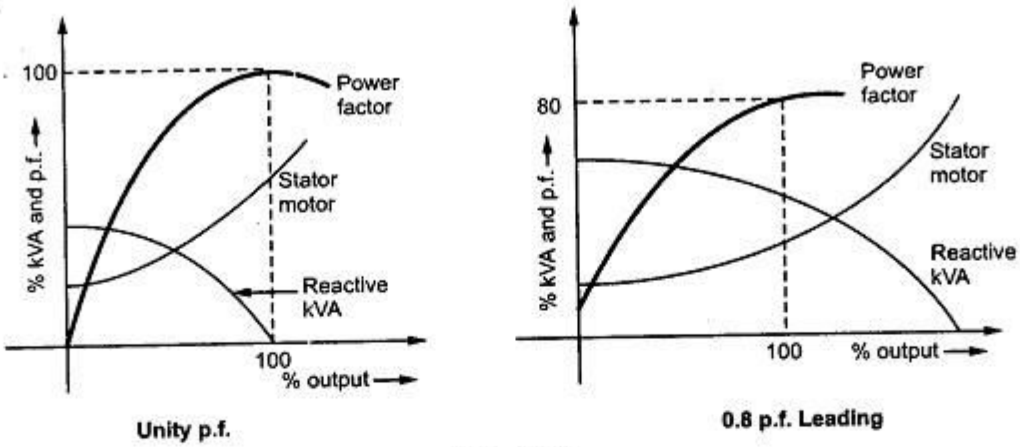


Fig. 5.53

Advantages

Following are the advantages of synchronous induction motor over salient pole synchronous motor.

i) The synchronous induction motor can start and synchronize against more than full load torque which is not possible with salient pole synchronous motor which must be started against light load.

ii) The exciter required for synchronous induction motor is of smaller capacity as the gap is not long as compared to normal salient pole motor.

iii) The rotor winding in synchronous induction motor can function as providing excitation and required damping. So no separate damper winding is required.

iv) No separate starting and control equipments are required.

Disadvantages

i) As the gap is small as compared to normal salient pole synchronous motor it will not give large overload capacity.

ii) The variation of power factor is large as compared to normal synchronous motor.

iii) The speed variation is not possible for synchronous induction motor as it runs at constant motor.

The applications where mechanical load is to be driven alongwith phase advancing properties of synchronous motors are to be used then use of synchronous induction motor is better option. Also the applications where in load torque is remaining nearly constant, this motor can be used.

UNIT IV-

STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR:

NEED FOR STARTING

When a 3-ϕ Induction motor is switched on at normal supply voltage, heavy current will flow through the motor because at the time of starting, there is no back emf. An induction motor, when directly switched on, takes five to seven times its full load current and it develops only 1.5 to 2.5 times full load torque. This initial inrush of excessive current is objectionable because it will produce large line voltage drop. This will affect the operation of other electrical equipments connected to the same line. Due to this, starters are used for starting the three phase induction motors.

TYPES OF STARTERS

Squirrel cage Motors

1. DOL starter
2. Stator resistance starter
3. Auto-transformer starter
4. Stat-Delta starter

Slip-ring Motors

5. Rotor resistance starter

DIRECT ON LINE (DOL) STARTER

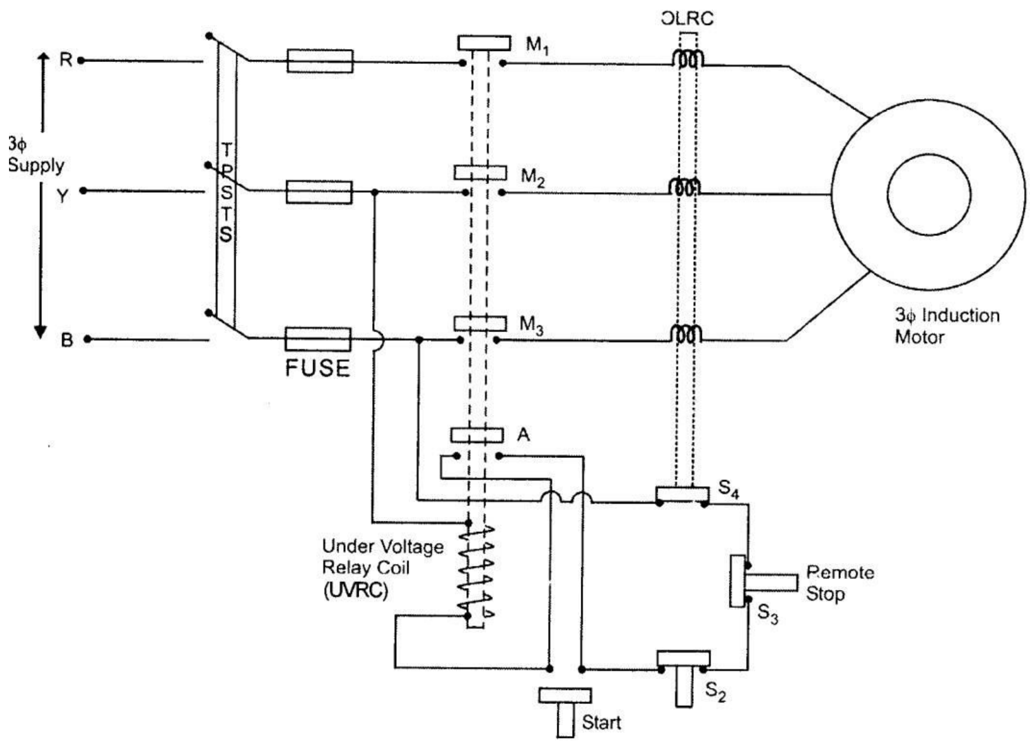
A motor of small capacity and which gathers normal speed quickly can be started with this starter. A small capacity motor (below 2 kW) draws only small amount of current. This may not cause much voltage drop in the supply line.

Figure 4.1 shows a 3-ϕ induction motor with a DOL starter. M_1, M_2, M_3 are main contactors normally open (NO) type making and breaking the motor line current.

These contactors are operated by a relay coil. S_2, S_3 and S_4 are normally closed (NC) type and are connected in series with relay coil. Over load relay coil (OLRC) is connected in series with motor line supply.

Operation

When TPST switch is closed, the Under Voltage Relay Coil (UVRC) is energized and it will operate the main contactors to close. Hence the full voltage is given to the motor and it runs. Closing of contactor A retains the supply to the UVRC.



Contactor S_2 is used to disconnect the supply from the motor by manually pressing it. Remote operation of the same can be achieved with the help of contactor S_3.

No Voltage Protection

When the supply voltage either fails totally or falls below certain value, the holding power given by UVRC comes down causing the main contactor to be opened. Thus the motor is protected from low voltage operation.

Over Load Protection

When the line current exceeds the preset value, OLRC is energized more and causes the contactor S_4 to open. When S_4 opens, the UVRC is disconnected from the supply. Therefore it will release the main contactors.

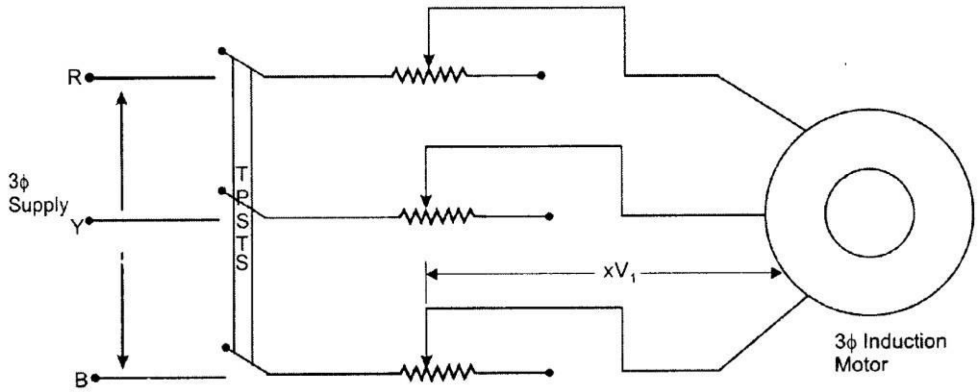
The relation between starting torque (T_{st}) and full load torque ($T_{f\ell}$) is given by

$$\frac{T_{st}}{T_{f\ell}} = \left(\frac{I_{SC}}{I_{f\ell}}\right)^2 s_f$$

where $I_{SC} = I_{st}$ = Short circuit current, s_f = full load slip

STATOR RESISTANCE STARTER

A variable resistor (or) reactor is connected in series with the supply terminals of the motor. The purpose of this resistance is to reduce the supply voltage. This reduced voltage is given to the motor terminals. Figure 4.2 shows primary resistance starter.



Stator side resistance

The reduced voltage limits the starting current. If the voltage across the terminal is reduced by 50%, then the starting current is reduced by 50%, but torque is reduced to 25% of the full voltage value.

Let reduced per phase voltage $= xV_1$

Per phase starting current $I_{st} = \frac{xV_1}{Z_{SC}} = x I_{SC}$

We know that $\frac{T_{st}}{T_{f\ell}} = \left(\frac{I_{SC}}{I_{f\ell}}\right)^2 s_f$

$$= \left(\frac{xI_{SC}}{I_{f\ell}}\right)^2 s_f$$

$$\boxed{\frac{T_{st}}{T_{f\ell}} = x^2 \left(\frac{I_{SC}}{I_{f\ell}}\right)^2 s_f}$$

In an induction motor, torque α (voltage)^2.

$$\therefore \frac{\text{Starting torque with reactor starting}}{\text{Starting torque with direct switching}} = \left(\frac{xV_1}{V_1}\right)^2 = x^2$$

Advantages

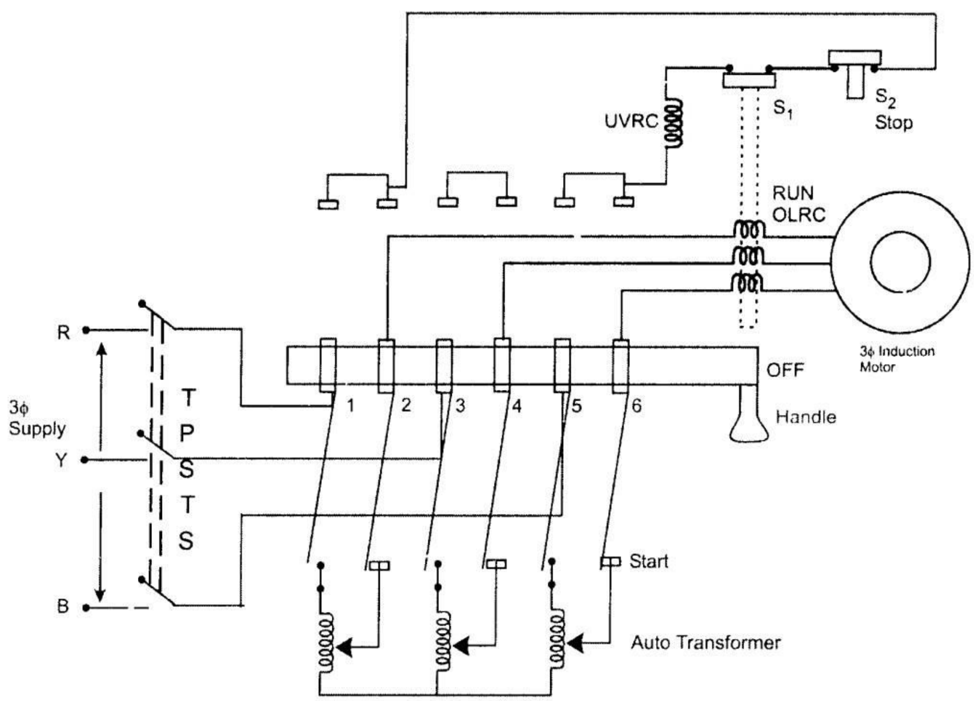
1. Smooth acceleration
2. High power factor during start
3. Less expensive
4. Closed transition starting

Disadvantages

1. Power lost in resistors
2. Low starting torque
3. Less efficiency

AUTO TRANSFORMER STARTER

Figure 4.3 shows an autotransformer starter. This starter is used to give a reduced voltage to the 3-phase induction motor to limit the starting current. The reduced voltage is obtained by an auto transformer.



The supply is given to terminals 1, 3 and 5 of the movable handle and the motor is connected to 2, 4 and 6 of handle through an OLRC (Over Load Release Coil). Low voltage protection is given to the motor by UVRC.

Operation

When the handle is at start position, the motor is connected through the auto transformer. Therefore a reduced voltage is applied and hence starting current is reduced. When the motor gets 80% of the normal speed, the handle is moved to RUN position. At this position, the motor receives full line voltage.

Over Load Protection

When motor current exceeds the preset value, the over load relay coil (OLRC) is energized high enough to operate the contactor S_1. Hence supply is switched off.

Low voltage protection

The Under Voltage Relay Coil (UVRC) is connected across two lines. When supply voltage goes low or fails, UVRC de-energizes and releases the handle to OFF position.

In general, if the reduction in applied voltage is a fraction x of the rated voltage V, then the starting current of the motor is given by

$$I_{st} = x\, I_{sc}$$

The starting current drawn from the supply

$$= x\,(I_{st}) = x\,(xI_{sc}) = x^2\, I_{sc}$$

Thus, the line current drawn from the supply is very less in this case, compared to primary resistance starting though the initial starting current is reduced by same fraction.

The torque developed by the motor,

$$T = \frac{3I_2^{\,2} R_2}{s} \text{ (synchronous watts)}$$

Full load torque $$T_{f\ell} = \frac{3I_{f\ell}^2 R_2}{s_f}$$

Starting torque $$T_{st} = \frac{3I_{st}^2 R_2}{1.0} \qquad [s = 1] \text{ at start}$$

Thus $$\frac{\text{starting torque}}{\text{full load torque}} = \frac{T_{st}}{T_{f\ell}} = \left(\frac{I_{st}}{I_{f\ell}}\right)^2 s_f$$

Hence, in auto transformer starters,

$$\frac{T_{st}}{T_{f\ell}} = \left(\frac{xI_{sc}}{I_{f\ell}}\right)^2 s_f = x^2 \left(\frac{I_{sc}}{I_{f\ell}}\right)^2 s_f$$

Advantages

1. Reduced line current.
2. Smooth starting.
3. High acceleration.

Disadvantages

1. Cost is high.
2. It is not used for large motors.

TAR-DELTA STARTER

Figure 4.4 shows a star-delta starter. This method is used in motors which are meant to run normally with a delta connected stator winding. It consists of a two way switch which connects the motor in star for starting and then in delta for normal running.

When the two way switch is at START position, the stator windings are connected in star. Therefore the applied voltage is reduced by a factor of $\frac{1}{\sqrt{3}}$ (For star connection $V_{ph} = \frac{V_L}{\sqrt{3}}$). Hence the starting current is reduced. When the motor speed reaches 70 to 80% of normal value, the switch is changed to RUN position where the motor is connected in delta. Therefore full voltage is applied to the motor in the running condition.

Star – delta starter is also provided with no – volt release and over load release, which protect the motor against sudden failure of supply and over load on the motor. A locking arrangement is also provided, so that the motor can be started only in star connection. Figure 4.4 shows the diagram of a star – delta starter without safety devices and locking arrangement for clarity of the diagram.

Since at starting instant, the stator windings are connected in star, so voltage across each phase winding is reduced to $\frac{1}{\sqrt{3}}$ of line voltage and, therefore, starting current per phase becomes equal to $I_{sc}/\sqrt{3}$.

Starting line current by connecting the stator windings in star at the starting instant = starting motor current per phase = $I_{sc}/\sqrt{3}$.

Starting line current by direct switching with stator windings connected in delta = $\sqrt{3}$ I

$$\therefore \frac{\text{Line current with star-delta starting}}{\text{Line current with direct switching}} = \frac{I_{sc}/\sqrt{3}}{\sqrt{3}\, I} = \frac{1}{3}$$

PROBLEM: 01

A 3-phase, 6 pole, 50 Hz induction motor takes 60 A at a full load speed of 940 rpm and develops a torque of 150 N-m. The starting current at rated voltage in 300 A. What is the starting torque? If a star/delta starter is used, determine the starting torque and starting current.

Given data:

Number of poles P = 6, Supply frequency f = 50 Hz,

Full load torque $T_{f\ell}$ = 150 N-m, Full load current $I_{f\ell}$ = 60 A,

Full load speed N = 940 rpm, Starting current I_{st} = 300 A.

To find:

Starting torque (T_{st})

Starting current and starting torque, when star / delta starter is used.

Solution:

For direct - switching of induction motors

$$\frac{T_{st}}{T_{f\ell}} = \left(\frac{I_{st}}{I_{f\ell}}\right)^2 s_f$$

Synchronous speed $$N_s = \frac{120f}{P} = \frac{120\times 50}{6} = 1000 \text{ rpm}$$

$$s_f = \frac{N_s - N}{N} = \frac{1000-940}{1000} = 0.06$$

$$\frac{T_{st}}{150} = \left(\frac{300}{60}\right)^2 0.06$$

$$\boxed{T_{st} = 225 \text{ N-m}}$$

When star/delta starter is used, starting current

I_{st} = 1/3 × Starting current when direct switching

= 300/3 = 100 A

I_{st} = 100 A

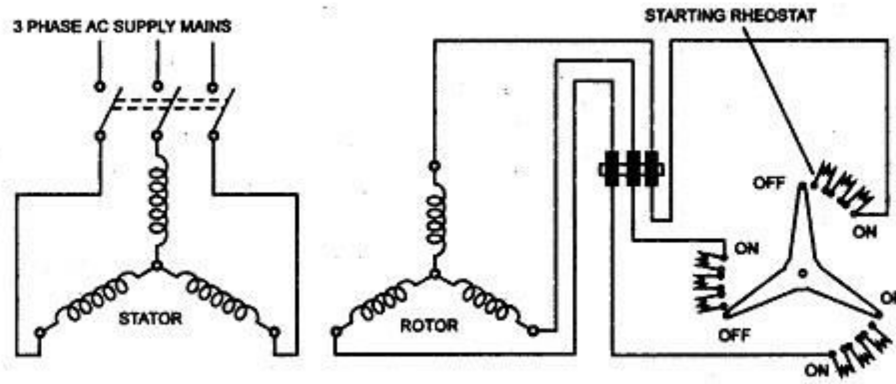
Starting torque $$T_{st} = \frac{\text{Starting torque with direct switching}}{3}$$

$$= \frac{225}{3} = 75\ N-m$$

$$\boxed{T_{st} = 75\ \text{N}-\text{m}}$$

ROTOR RESISTANCE STARTER

To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor circuit at start. This addition of the resistance in rotor in the form of 3 phase star connected rheostat.



Slip-Ring Induction Motor With Starting Rheostat

The external resistance is inserted in each phase of the rotor winding through slip ring and brush assembly. Initially maximum resistance is in the circuit. As motor gather speed, the resistance is gradually cut-off. The operation may be manual or automatic.

We have seen that the starting torque is proportional to the rotor resistance. Hence important advantage of this method is not only the starting current is limited but starting torque of the motor also gets improved.

Note : The only limitation of the starter that it can be used only for slip ring induction motors as in squirrel cage motors, the rotor is permanently short circuited.

1.1 Calculation of Steps of Rotor Resistance Starter

The calculation of steps of rotor resistance starter is based on the assumptions that,

1. The motor starts against a constant torque
2. The rotor current fluctuates between two fixed values, a maximum and a minimum, denoted as I_{2max} and I_{2min}.

The Fig. 2, shows a single phase of a three phase of a three phase rheostat to be inserted in the rotor. The starter has n steps, equally divided into the section AB. The contact point after each step is called stud. The total resistances upto each stud from the star point of star connected rotor as denoted as R_1, R_2, ...R_{n-1}.

PROBLEM: 01

A 4 pole, 50 Hz, 3-phase slip ring induction motor when fully loaded runs with a slip of 3%. Determine the value of the resistance to be inserted in series per phase in the rotor circuit to reduce the speed by 10% and the new slip. The rotor resistance per phase is 0.2 Ω.

Given data:

Number of poles P = 4, Supply frequency f = 50 Hz,

Slip s_1 = 3% (or) 0.03, Rotor resistance R_2 = 0.2 Ω/phase

To find:

The value of resistance to be connected in series per phase in the rotor circuit to reduce the speed by 10% and the new slip.

Solution:

Synchronous speed $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

Speed $N_1 = N_s(1 - s_1) = 1500\,(1 - 0.03)$

$= 1455$ rpm

$N_2 = 0.9 \times N_1 = 0.9 \times 1455$

$= 1309.5$ rpm

$$s_2 = \frac{N_s - N_2}{N_s} = \frac{1500 - 1309.5}{1500} = 0.127$$

Torque $T = \frac{KsE_2^2 R_2}{R_2^2 + (SX_2)^2}$

Neglecting X_2

$$T_1 = \frac{Ks_1E_2^2R_2}{R_2^2} = \frac{Ks_1E_2^2}{R_2}$$

$$T_2 = \frac{Ks_2E_2^2}{R_2 + r}$$

Given $T_1 = T_2$

$$\therefore \quad \frac{Ks_1E_2^2}{R_2} = \frac{Ks_2E_2^2}{R_2 + r}$$

i.e.,

$$\frac{s_1}{R_2} = \frac{s_2}{R_2 + r}$$

$$\frac{0.03}{0.2} = \frac{0.127}{0.2 + r}$$

$$\boxed{r = 0.646\ \Omega}$$

PROBLEM: 02

The rotor of an eight pole, 50 Hz, three-phase induction motor has a resistance of 0.2 Ω / phase and runs at 720 rpm. If the load torque remains unchanged, calculate the additional rotor resistance that will reduce its speed by 10%. Neglect stator impedances.

Given data:

Numnber of poles P = 8, Supply frequency f = 50 Hz,

Rotor resistance / phase $R_2 = 0.2\ \Omega$, Motor speed $N_1 = 720$ rpm

Load torque constant

To find:

The additional rotor resistance that will reduce its speed by 10%.

Solution:

Motor torque $$T = \frac{KsR_2E_2^2}{R_2^2 + (sX_2)^2}$$

Here, X_2 is not given, then the equation becomes

$$T_1 = \frac{Ks_1R_2E_2^2}{R_2^2} = \frac{Ks_1E_2^2}{R_2} \quad .. (1)$$

When an external resistance (r) is connected in the rotor circuit, the equation (1) becomes

$$T_2 = \frac{Ks_2E_2^2}{R_2 + r}$$

Since $T_1 = T_2$

$$\frac{Ks_1E_2^2}{R_2} = \frac{Ks_1E_2^2}{R_2 + r}$$

$$\frac{s_1}{R_2} = \frac{s_2}{R_2 + r}$$

Synchronous speed $$N_s = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

Slip $$s_1 = \frac{N_s - N_1}{N_s} = \frac{750 - 720}{750} = 0.04$$

Speed $$N_2 = 720 \times 0.9 = 648 \text{ rpm}$$

Slip $$s_2 = \frac{N_s - N_2}{N_s} = \frac{750 - 648}{750} = 0.136$$

$$\frac{0.04}{0.2} = \frac{0.136}{0.2 + r}$$

$$\boxed{r = 0.48\ \Omega}$$

PROBLEM: 03

A 3-phase, squirrel cage induction motor has a short circuit current equal to 4 times the full load current. Find the starting torque as a percentage of full load torque if the motor is started by (i) Direct switching to the supply mains (ii) A star-delta starter (iii) An auto-transformer (iv) A resistance in the stator circuit.

Solution:

$$I_{sc} = 4I_{f\ell}, \text{ Assume full slip } s_f = 0.01$$

i) Using DOL starter

$$\frac{T_{st}}{T_{f\ell}} = \left(\frac{I_{sc}}{I_{f\ell}}\right)^2 s_f$$

$$T_{st} = \left(\frac{4I_{f\ell}}{I_{f\ell}}\right)^2 \times 0.01 \times T_{f\ell} = 0.16\,T_{f\ell}$$

$$\boxed{T_{st} = 16\%\ T_{f\ell}}$$

ii) Star-delta startor

$$\frac{T_{st}}{T_{f\ell}} = \frac{1}{3}\left(\frac{I_{sc}}{I_{f\ell}}\right)^2 s_f$$

$$T_{st} = \frac{1}{3}\left(\frac{4I_{f\ell}}{I_{f\ell}}\right)^2 \times 0.01 \times T_{f\ell}$$

$$\boxed{T_{st} = 5.33\ \%\text{ of } T_{f\ell}}$$

iii) Auto-transformer starter

$$\frac{T_{st}}{T_{f\ell}} = x^2\left(\frac{I_{sc}}{I_{f\ell}}\right)^2 s_f$$

Assume x = 1, $T_{st} = 1^2\left(\frac{4I_{f\ell}}{I_{f\ell}}\right)^2 \times 0.01 \times T_{f\ell} = 0.16\,T_{f\ell}$

$$\boxed{T_{st} = 16\%\text{ of } T_{f\ell}}$$

iv) Resistance in the stator circuit

$$\frac{T_{st}}{T_{f\ell}} = x^2\left(\frac{I_{SC}}{I_{f\ell}}\right)^2 s_f$$

Assume x = 1

$$T_{st} = 1^2\left(\frac{4\,I_{f\ell}}{I_{f\ell}}\right) \times 0.01 \times T_{f\ell} = 0.16\,T_{f\ell}$$

$$\boxed{\therefore\ T_{st} = 16\ \%\text{ of full load torque}}$$

SPEED CONTROL

A three phase induction motor is practically a constant speed machine, more or less like a dc shunt motor. However, there is one difference of practical importance between the two whereas dc shunt motors can be made to run at any speed within wide limits, with good efficiency and speed regulation, merely by manipulating a simple field rheostat, the same is not possible with induction motors, In their case, speed reduction is accompanied by a corresponding loss of efficiency and good speed regulation.

The equation for rotor (motor) speed N of a 3-phase induction motor is

$$N = (1 - s)\, N_S = (1 - s)\,\frac{120f}{P}\ \text{rpm}$$

Different methods of speed control may be grouped under 2 main headings.

CONTROL FROM STATOR SIDE

1. by changing the applied voltage
2. by changing the supply frequency
3. by changing the number of stator poles

CONTROL FROM ROTOR SIDE

1. rotor rheostat control (by changing the slip)
2. by operating 2 motors in concatenation or cascade
3. by injection of emf in the rotor circuit. (slip power recovery scheme)

CONTROL FROM STATOR SIDE

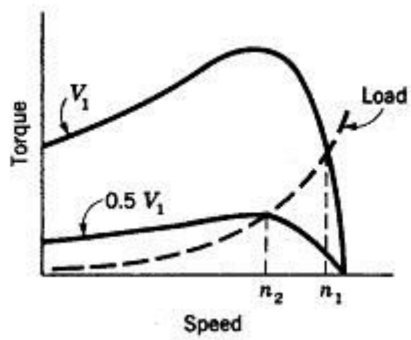
1. **By changing the applied voltage**

It is seen that the electro-magnetic torque of a polyphase induction motor is proportional to square of the supply voltage [$T \propto V^2$].

The torque-speed characteristics of a 3 phase induction motor for varying supply voltage are shown in Fig. 3.28 from which it can be observed that for a given load, the speed of the motor can be varied within a small range by this method.

But in this method, due to reduction in voltage, current drawn by the motor increased. Due to increased current, the motor may get overheated.

The variable voltage may be obtained by means of either saturable reactors, variac, or tap-changing transformers.



Advantages

1. Cheap
2. Easy method

Disadvantages

1. A large change in voltage is required for a relatively small change in speed.
2. A large change in voltage will result in a large change in the flux density thereby seriously disturbing the magnetic conditions of the motor.
3. The developed torque reduces greatly with the reduction in supply voltage.
4. The range of speed control is very limited in the downward direction i.e., from rated speed to lower speeds.

Applications

Application of this method is restricted to very small motors, particularly to those driving fan type loads.

2. **By Changing Supply Frequency**

The synchronous speed of the induction motor can be controlled in a stepless way over a wide range by changing the supply frequency.

The resultant air-gap flux per pole is given by

$$\Phi_r = \frac{1}{4.44\, K_{w1}\, N_{ph1}} \cdot \left(\frac{V}{f}\right)$$

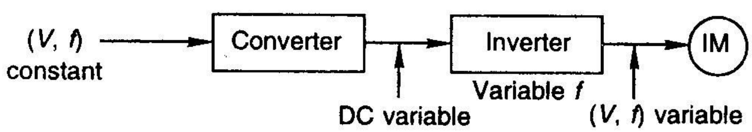
Therefore, in order to avoid saturation in stator and rotor cores which would cause sharp increase in magnetization current, the flux Φ_r must be kept constant as f is varied.

To achieve this, it follows from Eq. that when f is varied, V must also be varied such that (V/f) remains constant.

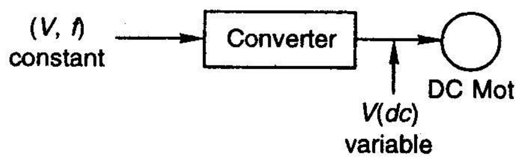
Variable (V, f) supply from constant (V, f) supply can be arranged by the converter-inverter arrangement shown schematically in Fig. (a) which employs SCR circuitry

Figure (b) shows an alternative speed-control scheme using a converter and dc motor (shunt).

The chief attraction of employing induction motor for speed control is its ruggedness, low cost and maintenance-free operation as compared to dc motor. Because of the cost of the inverter involved in the induction motor speed-control scheme, the dc motor scheme as of today is more economical. However, the induction motor scheme is a strong candidate for speed control and is likely to take over in the near future with further improvement and cost reduction in SCR technology.



(a)



(b)

The torque-slip characteristics of the motor can be sketched at frequencies above and below the nominal as shown in Fig.

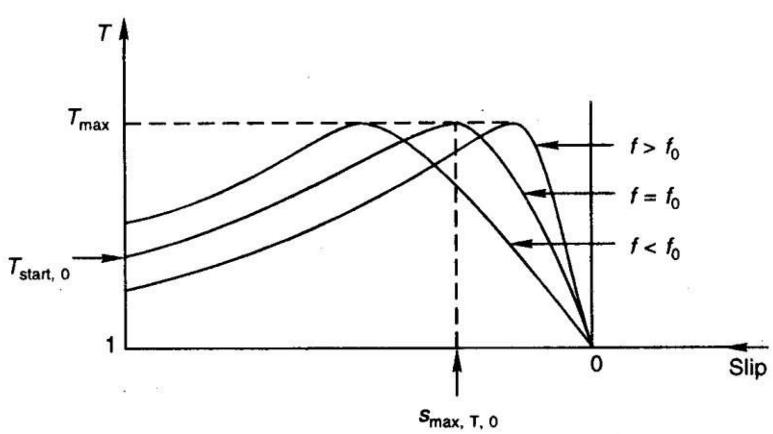


Fig. 9.50 Torque-slip characteristics; variable f, constant (V/f)

3. By Changing the number of Stator Poles

This method of speed control provides change in speed at 2 or 4 discrete levels by changing the number of poles of the rotating magnetic field. The squirrel cage rotor can adjust itself to the rotating magnetic field for different poles whereas the slip ring rotor is to be wound for the same number of poles as that of the stator winding. Hence this method of speed control is applicable only for SCIM.

We know that $N_s = \frac{120f}{p}$, from this equation it becomes evident that the synchronous speed (and hence the running speed) of an induction motor could also be changed by changing the number of stator poles.

The number of stator poles can be changed by

(a) Multiple stator winding and

(b) Method of consequent poles.

(a) Multiple stator winding

The stator has 2 or more entirely independent windings with different number of poles in the same slot and only one winding is energised at a time. For example, a 36 slot stator may have two, $3-\phi$ windings with 4 and 6 poles respectively. With a supply frequency of 50 Hz, 4 pole winding will give $N_s = \frac{120 \times 50}{4} = 1500$ rpm and the 6 pole winding will give $N_s = \frac{120 \times 50}{6} = 1000$ rpm. Hence the motor can be operated at two different speed.

Demerits

1. Such a machine tends to be more costly
2. Less efficient and hence used only when absolutely necessary.

Applications

Elevator motor, traction motor, motors for machine tools.

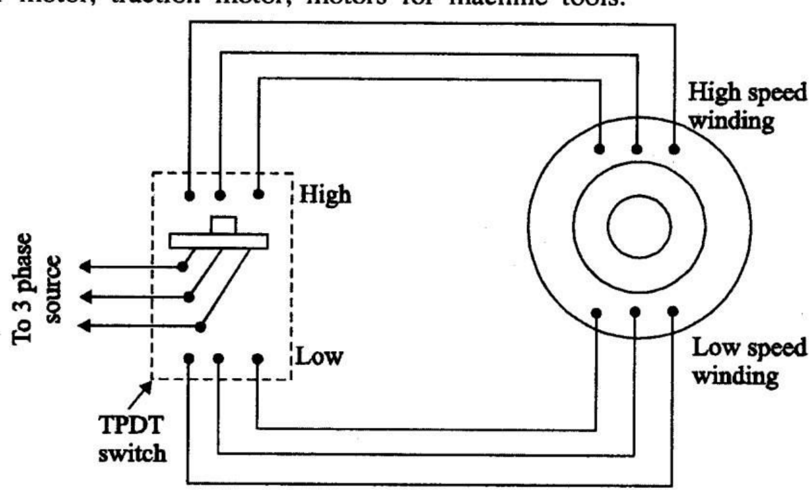


Fig. 3.29 Multiple Stator Winding

(b) Method of consequent poles

To vary the number of poles, stator windings is split into number of groups and the terminals of these groups are brought out. By making simple variations in the terminal connection the numbers of poles are varied as shown in the figure below.

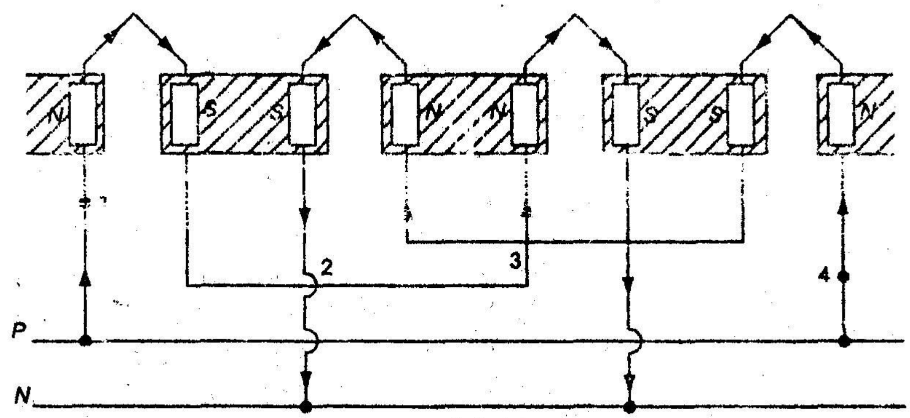


Fig. 3.28 Consequent pole winding connection for $P = 4$.

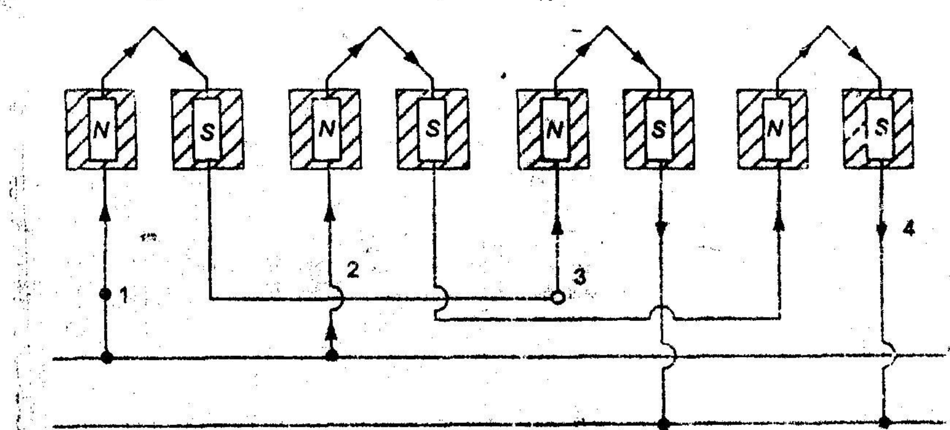


Fig. 3.29 Consequent pole winding connection for $P = 8$

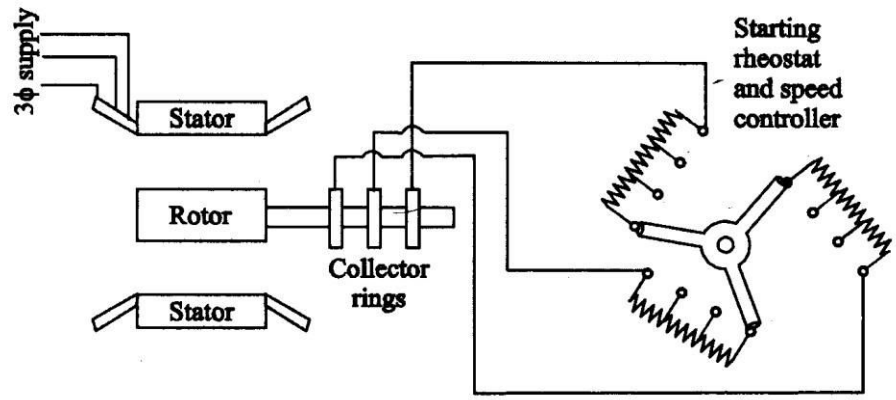
In this method, it is possible to change the number of poles only in the ratio 1:2. In the above fig. when terminals 1 and 4 are connected to phase and, 2 and 3 to neutral the number of poles obtained is 4 as shown in fig (a).

Altering the connections in such a way that 1 and 2 are connected to phase and, 3 and 4 to neutral the number of poles obtained is 8 as shown in fig (b). Thus two different speed can be obtained. No smooth variation of speed is possible in this method.

CONTROL FROM ROTOR SIDE

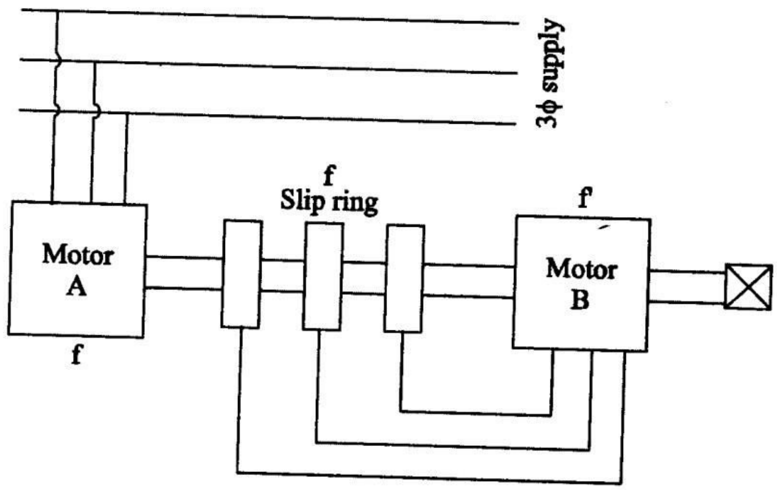
1. **Rotor Rheostat Control or Slip Control**

This can be accomplished by introducing resistance in the rotor circuit, which causes as increase in slip, thereby bringing down the speed of the motor.



2. **Cascade or Tandem or Concatenation method**

This method requires 2 motors, the first of which must have a wound rotor. It should also have a one-to-one voltage ratio. So that in addition to cascading, each motor may be run from the supply mains separately. That is, at standstill with rotor circuit open, the voltage across the slip-rings should be equal to that across the stator terminals. The stators of both motors should be wound for the same voltage. The second motor may be of the squirrel cage type or have a wound rotor with external resistance. The rotor shafts are directly coupled, so that both run at the same speed.



The stator of the first motor, A is connected to the $3-\phi$ supply. Then the rotor of the first motor is connected to the stator of the second motor B. The starting resistance is connected to the rotor circuit of the second motor.

In cascade method, there are 4 ways to obtain different speeds by the combination of the motors.

Motor 1 may be run separately from the supply,

Synchronous speed, $N_{SA} = \frac{120f}{P_A}$ [for motor A]

where

f = supply frequency

P_A = no. of stator poles of the motor A

Motor 2 may be allowed to run separately from the supply,

Synchronous speed of motor B, $N_{SB} = \frac{120f}{P_B}$ [for motor B]

where

P_B = no. of stator poles of the motor B.

Cumulative Cascade

Motor A and motor B are allowed to operate in cumulative cascade. In this, the stator fields of the motor A and B are having the phase rotation in the same direction. The synchronous speed of the cascaded set can be derived as follows.

$N_{SA} = \frac{120f}{P_A}$ [synchronous speed of motor A]

Running speed, $N = (1 - s_A)\, N_{SA} = (1 - s_A)\, \frac{120f}{P_A} \rightarrow (A)$

Rotor frequency of motor A, $f' = s_A f$

Synchronous speed of motor B, $N_{SB} = \frac{120f'}{P_B}$

Running speed $N = (1 - s_B)\, N_{SB} = (1 - s_B)\, \frac{120f'}{P_B}$

$$N = (1 - s_B)\, \frac{120\, s_A f}{P_B} \rightarrow (B)$$

Equating (A) and (B)

$$(1 - s_A)\, \frac{120f}{P_A} = (1 - s_B)\, \frac{120\, s_A f}{P_B}$$

$$\frac{(1 - s_A)}{P_A} = (1 - s_B)\, \frac{s_A}{P_B}$$

On no load the speed of rotor B is almost equal to its synchronous speed, so that the slip S_B=0 and the above equation becomes

$$\therefore \frac{1 - s_A}{P_A} = \frac{s_A}{P_B}$$

$$s_A = \frac{P_B}{P_A + P_B}$$

But $$s_A = \frac{N_{SA} - N}{N_{SA}}$$

$$\frac{P_B}{P_A + P_B} = \frac{N_{SA} - N}{N_{SA}}$$

$$\frac{P_B}{P_A + P_B} = 1 - \frac{N}{N_{SA}}$$

$$N = N_{SA}\, \frac{P_A}{P_A + P_B}$$

$$N = \frac{120f}{P_A}\, \frac{P_A}{P_A + P_B}$$

$$\boxed{\therefore N_{sc}\ \underline{\Omega}\ N = \frac{120f}{P_A + P_B}}$$

Differential Cascade

In this case, the rotating magnetic fields of motors A and B are in opposite directions. i.e, the phase rotation of stator field of A and B are opposing. This reversal of phase rotation is obtained by inter-changing any of its 2 leads.

In this case, the synchronous speed obtained is

$$N_{SC} = \frac{120f}{P_A - P_B}$$

From this equation, the number of poles is equal to the sum of the number of poles of two machines.

This method can give four different speeds.

1. Main motor alone : $N_S = \frac{120\,f}{P_1}$
2. Auxiliary motor alone : $N_S = \frac{120\,f}{P_2}$
3. Cumulative cascade connection : $N = \frac{120\,f}{P_1 + P_2}$
4. Differential cascade connection : $N = \frac{120\,f}{P_1 - P_2}$ [*Note:* $P_2 < P_1$]

The main disadvantages are

1. This method requires two motors.
2. More expensive.
3. Wide range of speed control is not possible.
4. It cannot be operated when $P_1 = P_2$ (or) $P_1 < P_2$.

For More

PROBLEM: 01

Example 7.7 : *A 4 pole induction motor and a 6 pole induction motor are connected in cumulative cascade arrangement. The supply frequency is 50 Hz while the frequency in rotor circuit of 4 pole motor is 1 Hz. Determine the slip of each machine and combined speed of the set.*

Solution : The arrangement is shown in the Fig. 7.17.

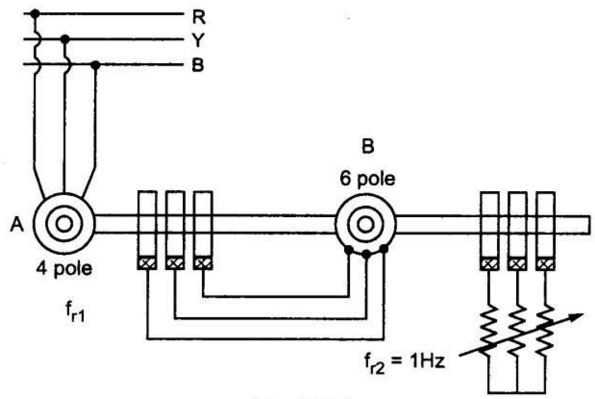


Fig. 7.17

Let f_{r1} = rotor frequency of motor A

f_{r2} = rotor frequency of motor B = 1 Hz

P_A = poles of A = 4

P_B = poles of B = 6

The set is cumulatively coupled.

Hence the synchronous speed of the set can be obtained as,

$$N_{sc} = \frac{120 f}{P_A + P_B} = \frac{120 \times 50}{4+6} = 600 \text{ r.p.m.}$$

Now $f_{r2} = s f$

and $s = \frac{N_{sc} - N}{N_{sc}}$ = slip of the set

$$\therefore \quad 1 = \frac{600 - N}{600} \times 50$$

$$\therefore \quad 12 = 600 - N$$

$$\therefore \quad N = 588 \text{ r.p.m.}$$

This is the combined speed of the set

$$N_{SA} = \frac{120 f}{P_A} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$\therefore \quad s_A = \frac{1500 - 588}{1500} = 0.608 \text{ i.e. } 60.8\ \%$$

$$N_{SB} = \frac{120 f_{r1}}{P_B}$$

and $f_{r1} = s_A f = 0.608 \times 50 = 30.4$ Hz

$$\therefore \quad N_{SB} = \frac{120 \times 30.4}{6} = 608 \text{ r.p.m.}$$

$$\therefore \quad s_B = \frac{N_{SB} - N}{N_{SB}} = \frac{608 - 588}{608} = 0.033 \text{ i.e. } 3.3\%.$$

The s_A and s_B are the slip values of machine A and B respectively.

PROBLEM: 02

Example 7.6 : *Two induction motor are used for the cascade control. The main motor has 4 poles while the auxillary motor has 6 poles. Determine the various synchronous speeds possible for the set. Assume supply frequency 50 Hz.*

Solution : $P_A = 4$, $P_B = 6$ and f = 50 Hz.

1) $$N_s = \frac{120f}{P_A} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$ ... 'A' running alone

2) $$N_s = \frac{120f}{P_B} = \frac{120 \times 50}{6} = 1000 \text{ r.p.m}$$ ... 'B' running alone

3) $$N_s = \frac{120f}{P_A + P_B} = \frac{120 \times 50}{10} = 600 \text{ r.p.m.}$$ ... Cumulative cascade

4) $$N_s = \frac{120f}{P_A - P_B} = \frac{120 \times 50}{2} = 3000 \text{ r.p.m.}$$ ... Differential cascade

Though $P_A - P_B$ is negative, in practice the effective poles are 2 only. The negative sign indicates the direction of torque.

3. By injection of emf in rotor circuit (slip power recovery scheme)

The slip power recovery system can be classified into two types.

1. Kramer system
2. Scherbius system

These two systems can further be classified into two methods.

1. Conventional method
2. Static method

4.11.6 Kramer System

The Kramer system is applicable only for sub-synchronous speed operation. The classification of Kramer system is

a. Conventional Kramer system. b. Static Kramer system.

4.11.6.1 Conventional Kramer System

Figure 4.17 shows conventional Kramer system. The system consists of a 3 phase rotary converter and a dc motor. The slip power is converted into dc power by a rotary converter and fed to the armature of a dc motor.

The slip ring induction motor is coupled to the dc motor. The slip rings are connected to the rotary converter. The dc output of rotary converter is used to drive a dc motor. The rotary converter and dc motor are excited from the dc bus bars or from an exciter. The speed of slip ring induction motor is adjusted by adjusting the speed of dc motor with the help of a field regulator.

This system is also called the electromechanical cascade, because the slip frequency power is returned as mechanical power to the slip ring induction motor shaft by the dc motor.

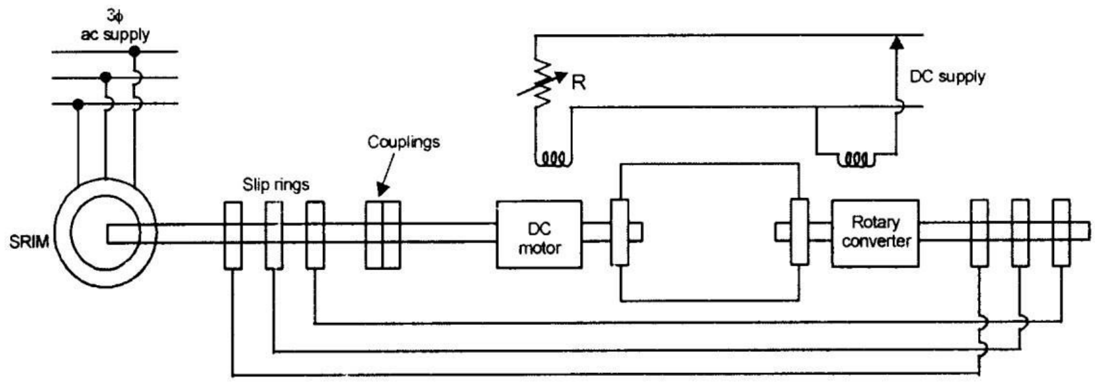


Figure 4.17: Conventional Kramer system

If the mechanical losses in cascade system are neglected the shaft power output of the SRIM motor is

$$P_m = (1-s)\ P_{in}$$

where P_{in} = Input power to the stator

The slip power $P_s = sP_{in}$ is added to P_m by converting it to mechanical power by the dc motor. This mechanical power is fed to the slip-ring induction motor shaft. Thus, irrespective of the value of the slip and consequently the speed of the SRIM, the power output remains more or less constant. Hence, it is also called the constant - power cascade. This method is used only for large motors of capacity 4000 kW or above.

Advantages

1. The main advantage of this method is that any speed, within the working range can be obtained.

2. If the rotary converter is over excited, it will take a leading current which compensates for the lagging current drawn by SRIM and hence improves the power factor of the system.

The slip power is converted into dc by a 3-phase diode bridge rectifier figure 4.18. This dc power is fed to the dc motor. This dc motor is mechanically coupled to SRIM. The slip power is converted to mechanical power and fed back to the SRIM shaft.

The torque supplied to the load is shared by SRIM and DC motor. The SRIM speed can be controlled by controlling the field regulator (field current) of the dc motor. In this method the speed control range is synchronous speed to around half of the synchronous speed.

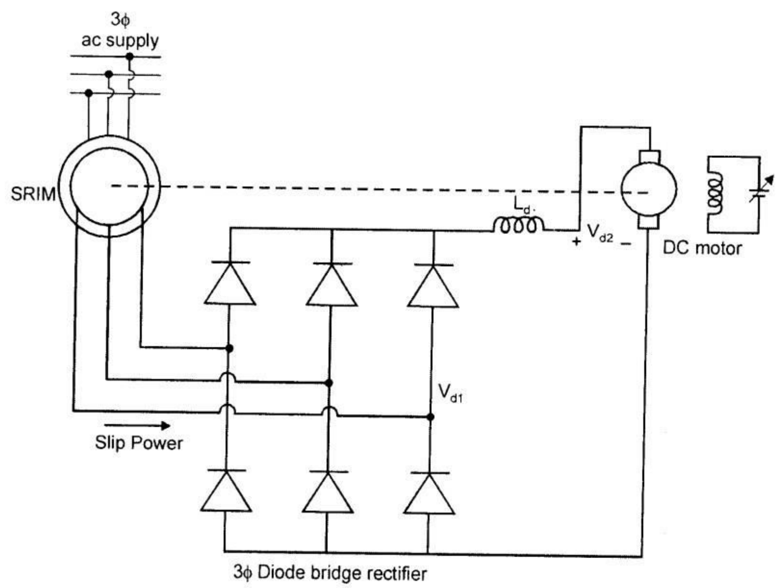


Figure 4.18: Improved version of Kramer system

In the figure 4.19 the diode bridge rectifier is replaced by thyristor bridge rectifier. The speed of SRIM can be controlled from zero to around synchronous speed, by varying the firing angle of thyristor rectifier.

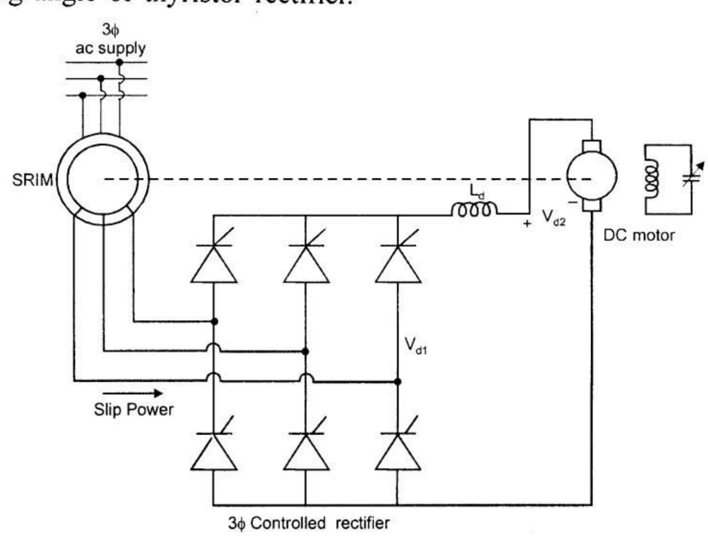


Figure 4.19: Improved version of Kramer system

4.11.6.2 Static Kramer System

In the rotor resistance control method, the slip power is wasted in the rotor circuit resistance. Instead of wasting the slip power in the rotor circuit resistance, it can be converted to 50 Hz ac and pumped back to the line.

Here, the slip power can flow only in one direction. This method of drive is called static Kramer drive. It is shown in figure 4.20. The static Kramer drive offers speed control for sub synchronous speed only. i.e. speed can be controlled less than the synchronous speed only.

In this method, the slip power is taken from the rotor and it is rectified to dc voltage by 3-phase diode bridge rectifier. Inductor L_d smoothens the ripples in the rectified voltage V_d. This dc power is converted into ac power by using line – commutated inverter. The rectifier and inverter are both line commutated by alternating emfs appearing at the slip rings and supply bus bars respectively. Here, the slip power flows from rotor circuit to supply. This method is also called constant – torque drive.

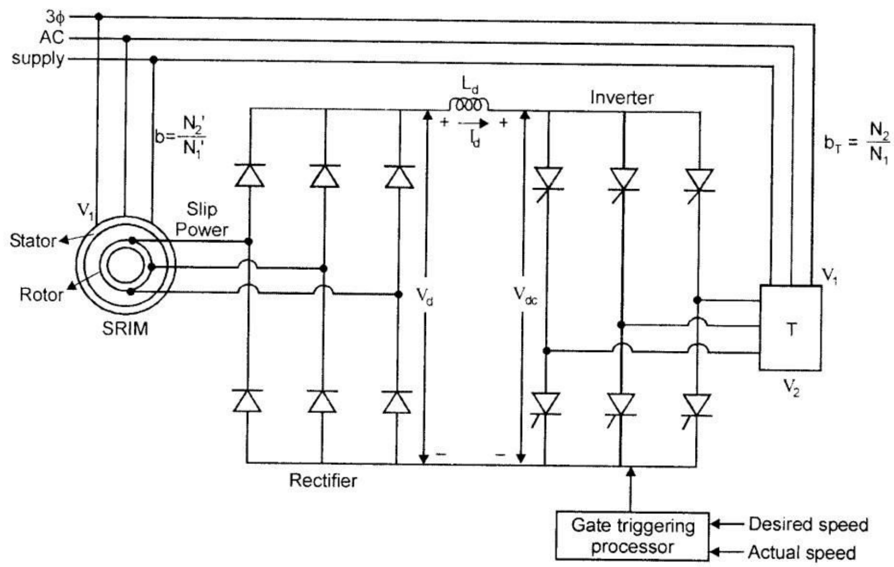


Figure 4.20: Static Kramer system

The static Kramer drive has been very popular in large power pump and fan type drives, where the range of speed control is limited, but less than the synchronous speed.

This method of speed control is economical because the rectifier and inverter have to carry only the slip power of the rotor, which is considerably less than the input power to the stator.

4.11.7 Scherbius System

The Scherbius system is similar to Kramer system but only difference is that in the Kramer system the feedback is mechanical and in the Scherbius system the return power is electrical. The different types of Scherbius systems are

a) Conventional Scherbius drive

b) Static Scherbius drive

4.11.7.1 Conventional Scherbius Drive

Figure 4.21 shows conventional method of Scherbius drive. This method consists of SRIM, rotary converter, dc motor and induction generator. Here, the rotary converter converts slip power into dc power and the dc power fed to the dc motor.

The dc motor is coupled with induction generator. The induction generator converters the mechanical power into electrical power and returns it to the supply line. The SRIM speed can be controlled by varying the field regulator of the dc motor.

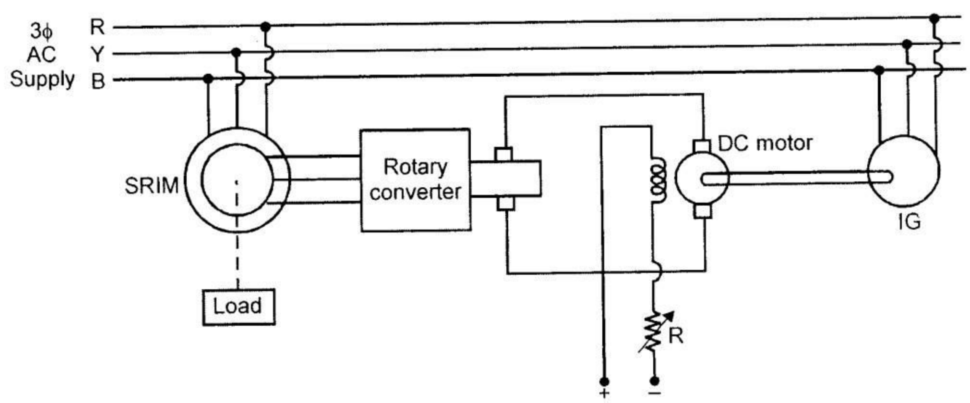


Figure 4.21: Conventional Scherbius system

4.11.7.2 Static Scherbius System

For the speed control of SRIM both below and the above synchronous speed, static Scherbius drive system is used. This system can again be classified as

1) DC link static Scherbius drive

2) Cycloconverter static Scherbius drive

DC link static Scherbius drive

This system consists of SRIM, two numbers of phase controlled bridges, smoothing inductor and step up transformer. This system is used for both sub-synchronous speed and super-synchronous speed operation. It is shown in the figure 4.22.

i) Sub-synchronous speed operation

In sub-synchronous speed control of SRIM, slip power is removed from the rotor circuit and is pumped back into the ac supply. Figure 4.22 shows the dc link static Scherbius system.

In the Scherbius system, when the machine is operated at sub-synchronous speed, phase controlled bridge 1 operates in the rectifier mode and bridge 2 operates in the inverter mode. In other words, bridge 1 has firing angle less than 90° whereas bridge 2 has firing angle more than 90°.

The slip power flows from rotor circuit to bridge 1, bridge 2, transformer and returned to the supply i.e.

Slip Power → Rectifier (bridge 1) → Inverter (bridge 2) → Transformer → Supply

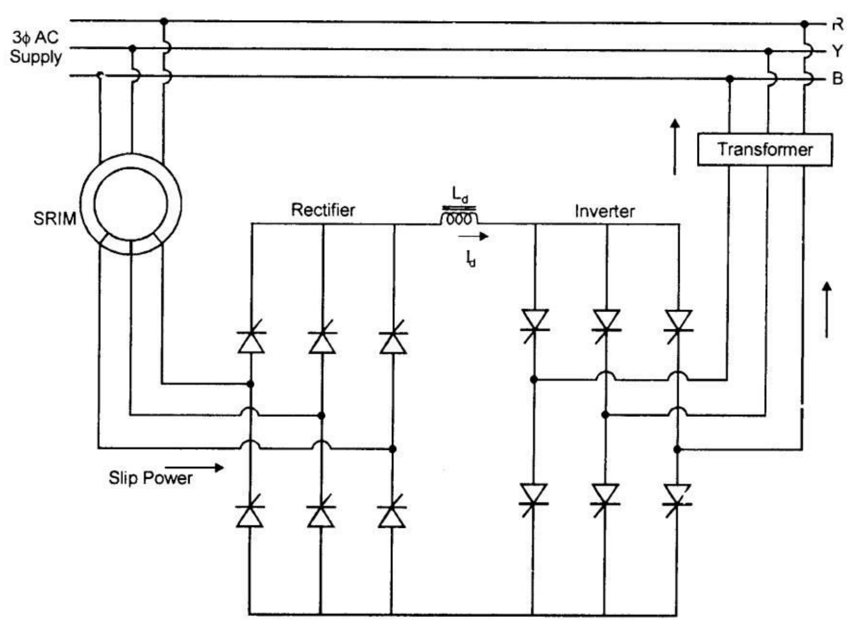


Figure 4.22: Static Scherbius drive-sub synchronous speed operation

ii) Super synchronous speed operation

In super synchronous speed operation, the additional power is fed into the rotor circuit at slip frequency. Figure 4.23 shows super synchronous speed operation of a DC link static Scherbius system. In the Scherbius system, when the machine is operated at super synchronous speed, phase controlled bridge 2 should operate in rectifier mode and bridge 1 in inverter mode. In other words, the bridge 2 has firing angle less than 90° whereas bridge 1 has firing angle more than 90°. The slip power flows from the supply to transformer, bridge 2 (rectifier), bridge 1 (line commutated inverter) and to the rotor circuit.

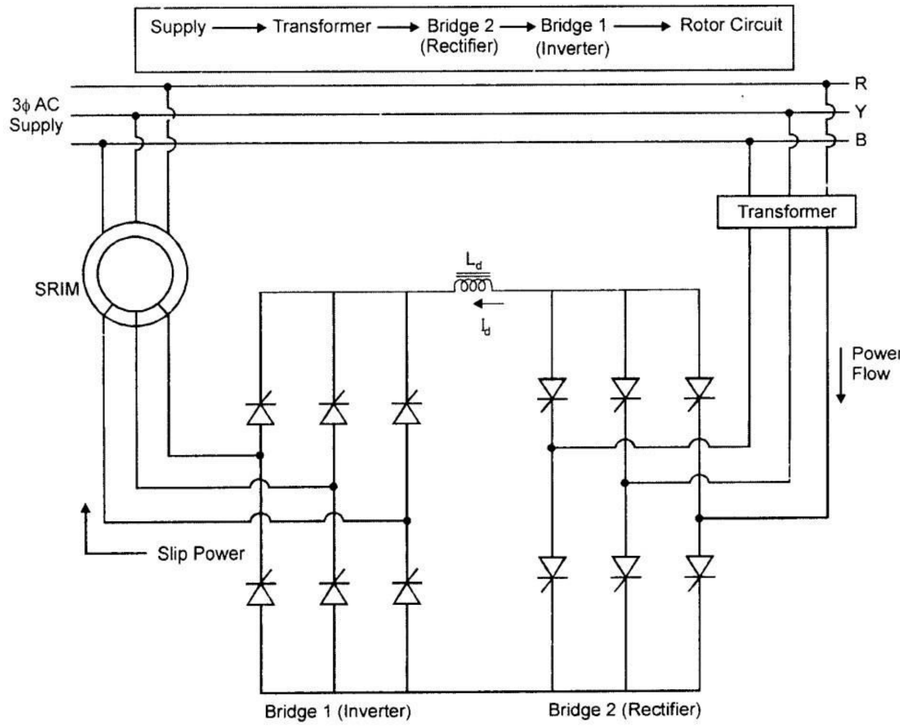


Figure 4.23: Static Scherbius drive – super synchronous speed operation

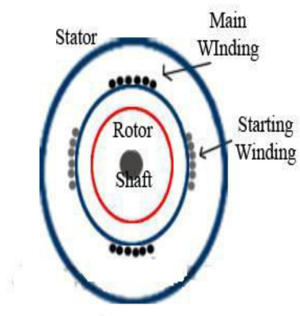
Near synchronous speed, the rotor voltage is low, and forced commutation must be employed in the inverter, which makes the scheme less attractive. The replacement of six diodes by six thyristors increases the converter cost and also necessitates the introduction of slip frequency gating circuit.

Difficulty is experienced near synchronous speed when the slip frequency emfs are insufficient for line or natural commutation, and special connections or forced commutation methods are necessary for the passage through synchronism. Thus, the provision of super synchronous speed control unduly complicates the static converter cascade system and nullifies the advantages of simplicity and economy.

UNIT V- SINGLE PHASE INDUCTION MOTOR AND SPECIAL MOTORS:

CONSTRUCTIONAL DETAILS OF SINGLE PHASE INDUCTION MOTOR:

Construction of a single phase induction motor is similar to the construction of three phase induction motorhaving squirrel cage rotor, except that the stator is wound for single phase supply. Stator is also provided with a 'starting winding' which is used only for starting purpose.



Working Principle Of Single Phase Induction Motor

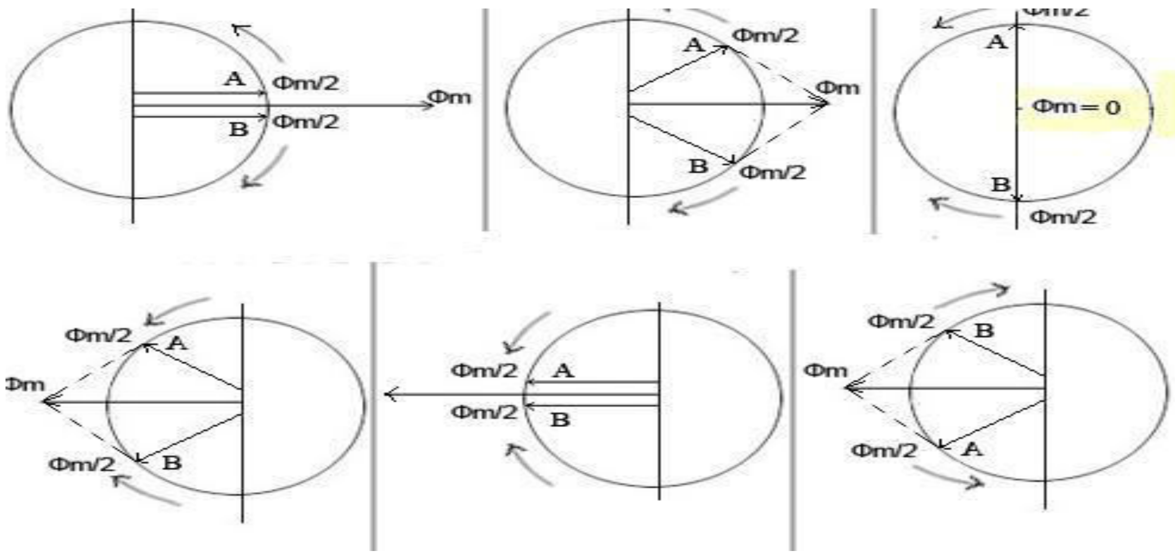
When the stator of a single phase motor is fed with single phase supply, it produces alternating flux in the stator winding. The alternating current flowing through stator winding causes induced current in the rotor bars accordingto Faraday's law of electromagnetic induction. This induced current in the rotor will also produce alternating flux. Even after both alternating fluxes are set up, the motor fails to start (the reason is explained below). However, if the rotor is given a initial start by external force in eitherdirection, then motor accelerates to its final speed and keeps running with its rated speed. This behavior of a single phase motor can be explained by double-field revolving theory.

Single Phase Induction Motor Is Not Self Starting:

The stator of a single phase induction motor is wound with single phase winding. When the stator is fed with a single phase supply, it produces alternating flux (which alternates along one space axis only). Alternating flux acting on a squirrel cage rotor can not produce rotation, only revolving flux can. That is why a single phase induction motor is not self starting.

Double-Field Revolving Theory

The double-field revolving theory states that, any alternating quantity (here, alternating flux) can be resolved into two components having magnitude half of the maximum magnitude of the alternating quantity, and both these components rotating in opposite direction.



Starting Methods of Single Phase Induction Motor:

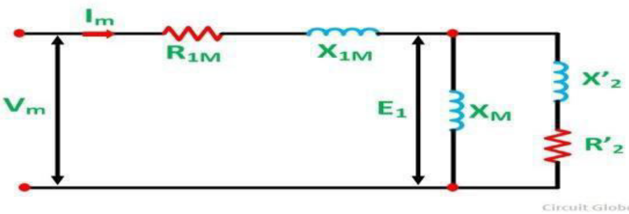
To make it self-starting, it can be temporarily converted into a two-phase motor while starting. This can be achieved by introducing an additional 'starting winding' also called as auxillary winding.

- Hence, stator of a single phase motor has two windings: (i) Main winding and (ii) Starting winding (auxillary winding). These two windings are connected in parallel across a single phase supply and are spaced 90 electrical degrees apart. Phase difference of 90 degree can be achieved by connecting a capacitor in series with the starting winding.
- Hence the motor behaves like a two-phase motor and the stator produces revolving magnetic field which causes rotor to run. Once motor gathers speed, say upto 80 or 90% of its normal speed, the starting winding gets disconnected form the circuit by means of a centrifugal switch, and the motor runs only on main winding.

EQUIVALENT CIRCUIT OF SINGLE PHASE INDUCTION MOTOR:

The **Equivalent circuit** of a **Single Phase Induction Motor** can be obtained by two methods named as the Double Revolving Field Theory and Cross Field Theory. Firstly the equivalent circuit is developed on the basis of double revolving field theory when only its main winding is energized.

Considering the case when the rotor is stationary and only the main winding is excited. The motor behaves as a single phase transformer with its secondary short circuited. The equivalent circuit diagram of the single phase motor with only its main winding energized the is shown
below



R_{1m} is the resistance of the main stator winding.

- X_{1m} is the leakage reactance of the main stator winding.
- X_M is the magnetizing reactance.
- R'_2 is the standstill rotor resistance referred to the main stator winding.
- X'_2 is the standstill rotor leakage reactance referred to the main stator winding.
- V_m is the applied voltage.
- I_m is the main winding current
  - The core loss will be assumed to be lumped with the mechanical and stray losses as a part of the rotational losses of the rotor. The pulsating air gap flux in the motor at the standstill is resolved into two equal and opposite fluxes with the motor. The standstill impedance of each of the rotor referred to the main stator winding is given as

$$\frac{R'_2}{2} + j\,\frac{X'_2}{2}$$

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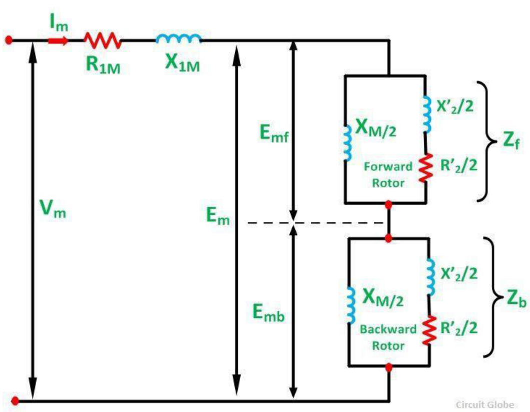
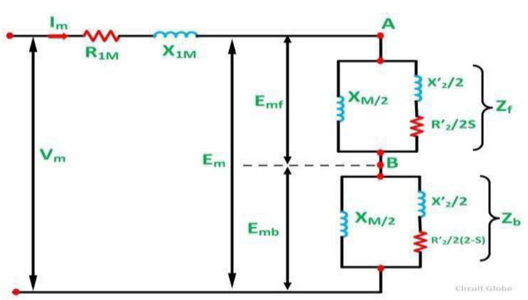


When both forward and backward slips are taken into account, the equivalent circuit shown below is formed. In this condition, the motor is running on the main winding alone.



The rotor impedance representing the effect of the forward field referred to the stator winding m is given by an impedance shown below.

$$\frac{R'_2}{2s} + j\frac{1}{2}X'_2 \text{ parallel with } j\frac{X_M}{2}$$

The rotor impedance of a single phase induction motor representing the effect of the backward field referred to the stator winding m is given by an impedance shown below.

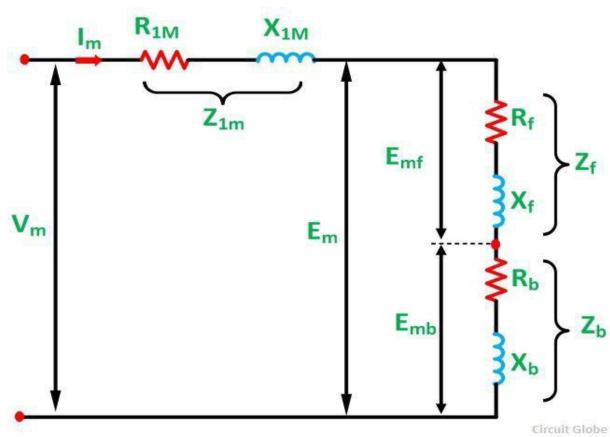
$$\frac{R'_2}{2(2-s)} + j\frac{1}{2}X'_2 \text{ parallel with } j\frac{1}{2}X_M$$

Therefore,

$$Z_f = \frac{\left(\frac{R'_2}{2s} + j\frac{1}{2}X'_2\right)\left(j\frac{1}{2}X_M\right)}{\frac{R'_2}{2s} + j\frac{1}{2}X'_2 + j\frac{1}{2}X_M} \quad \ldots\ldots\ldots (1) \text{ and}$$

$$Z_b = \frac{\left(\frac{R'_2}{2(2-s)} + j\frac{1}{2}X'_2\right)\left(j\frac{1}{2}X_M\right)}{\frac{R'_2}{2(2-s)} + j\frac{1}{2}X'_2 + j\frac{1}{2}X_M} \quad \ldots\ldots\ldots (2)$$

The simplified equivalent circuit of a single phase induction motor with only its main winding energized is shown in the figure below.



TYPES OF SINGLE PHASE INDUCTION MOTOR:

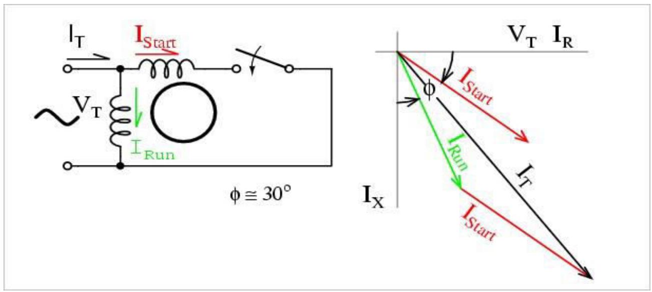
The single phase induction motors are made self starting by providing an additional flux by some additional means. Now depending upon these additional means the single phase induction motors are classified as:

1. **Split phase induction motor**.
2. **Capacitor startinductor motor**.
3. **Capacitor start capacitor runinduction motor (two value capacitor method)**.
4. **Shaded pole induction motor**.

Split Phase Induction Motor

In addition to the main winding or running winding, the stator of single phase induction motor carries another winding called auxiliary winding or starting winding. A centrifugal switch is connected in series with auxiliary winding. The purpose of this switch is to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to 75 to 80% of the synchronous speed. We know that the running winding is inductive in nature. Our aim is to create the phase difference between the two winding and this is possible if the starting winding carries high resistance.

I_{run} is the current flowing through the main or running winding, I_{start} is the current flowing in starting winding, and V_T is the supply voltage.



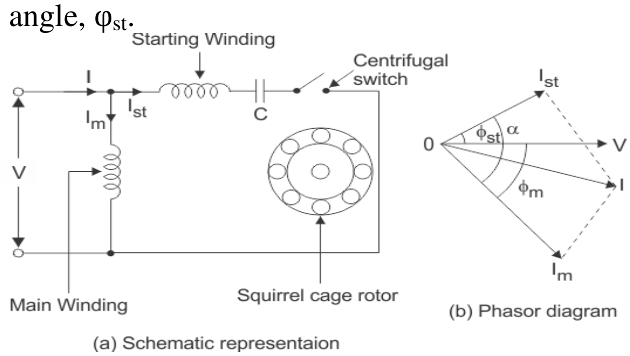
The highly resistive winding the current is almost in phase with the voltage and for highly inductive winding the current lag behind the voltage by large angle. The the applied voltage by very small angle and the running winding is highly inductive in nature so, the current flowing in running winding lags behind applied voltage by large angle. The resultant of these two current is I_T. The resultant of these two starting winding is highly resistive so, the current flowing in the starting winding lags behind current produce rotating magnetic field which rotates in one direction. In **split phase induction motor** the starting and main current get splitted from each other by some angle so this motor got its name as split phase induction motor.

Applications of Split Phase Induction Motor

Split phase induction motors have low starting current and moderate starting torque. So these motors are used in fans, blowers, centrifugal pumps, washing machine, grinder, lathes, air conditioning fans, etc. These motors are available in the size ranging from 1/20 to 1/2 KW.

Capacitor Start IM and Capacitor Start Capacitor Run :

The working principle and construction of Capacitor start inductor motors and capacitor start capacitor run induction motors are almost the same. The single phase induction motor is not self starting because the magnetic field produced is not rotating type. In order to produce rotating magnetic field there must be some phase difference. In case of split phase induction motor we use resistance for creating phase difference but here we use capacitor for this purpose. We are familiar with this fact that the current flowing through the capacitor leads the voltage. So, in **capacitor start inductor motor** and **capacitor start capacitor run induction motor** we are using two winding, the main winding and the starting winding. With starting winding we connect a capacitor so the current flowing in the capacitor i.eI_{st} leads the applied voltage by some angle, φ_{st}.



The running winding is inductive in nature so, the current flowing in running winding lags behind applied voltage by an angle, φ_m. Now there occur large phase angle differences between these two currents which produce an resultant current, I and this will produce a rotating magnetic field. Since the torque produced by these motors depends upon the phase angle difference,which is almost 90^o. So, these motors produce very high starting torque. In case of **capacitor start induction motor**, the centrifugal switch is provided so as to disconnect the starting winding when the motor attains a speed up to 75 to 80% of the synchronous speed but in case of

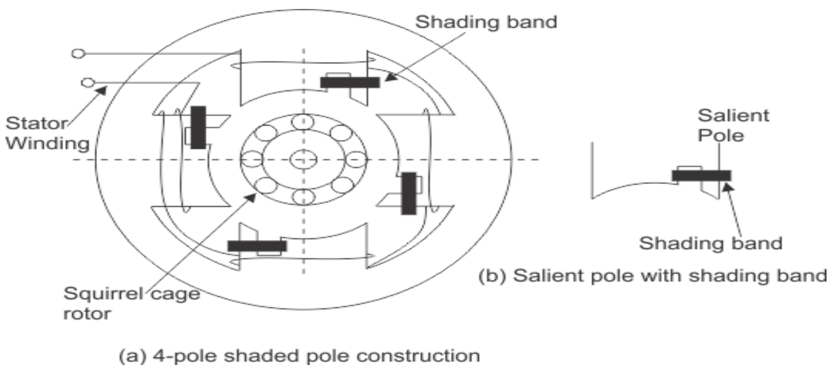
capacitor start capacitors run induction motor there is no centrifugal switch so, the capacitor remains in the circuit and helps to improve the power factor and the running conditions of single phase induction motor.

Application of Capacitor Start IM and Capacitor Run IM:

These motors have high starting torque hence they are used in conveyors, grinder, air

conditioners, compressor, etc. They are available up to 6 KW.

Shaded Pole Single Phase Induction Motors



The stator of the **shaded pole single phase induction motor** has salient or projected poles.These poles are shaded by copper band or ring which is inductive in nature. The poles are divided into two unequal halves. The smaller portion carries the copper band and is called as shaded portion of the pole.

ACTION: When a single phase supply is given to the stator of shaded pole induction motor an alternating flux is produced. This change of flux induces emf in the shaded coil. Since this shaded portion is short circuited, the current is produced in it in such a direction to oppose the main flux. The flux in shaded pole lags behind the flux in the unshaded pole. The phase difference between these two fluxes produces resultant rotating flux. We know that the stator winding current is alternating in nature and so is the flux produced by the stator current. In order to clearly understand the working of shaded pole induction motor consider three regions-

1. When the flux changes its value from zero to nearly maximum positive value.
2. When the flux remains almost constant at its maximum value.
3. When the flux decreases from maximum positive value to zero.

REGION 1: When the flux changes its value from zero to nearly maximum positive value – In this region the rate of rise of flux and hence current is very high. According to Faraday's law whenever there is change in flux emf gets induced. Since the copper band is short circuit the current starts flowing in the copper band due to this induced emf. This current in copper band produces its own flux. Now according to Lenz's law the direction of this current in copper band is such that it opposes its own cause i.e rise in current. So the shaded ring flux opposes the main flux, which leads to the crowding of flux in non shaded part of stator and the flux weaken in shaded part. This non uniform distribution of flux causes magnetic axis to shift in the middle of the non shaded part.

REGION 2: When the flux remains almost constant at its maximum value- In this region the rate of rise of current and hence flux remains almost constant. Hence there is very little induced emf in the shaded portion. The flux produced by this induced emf has no effect on the main flux and hence distribution of flux remains uniform and the magnetic axis lies at the center of the pole.

REGION 3: When the flux decreases from maximum positive value to zero - In this region the rate of decrease in the flux and hence current is very high. According to Faraday's law whenever there is change in flux emf gets induced. Since the copper band is short circuit the current starts flowing in the copper band due to this induced emf. This current in copper band produces its own flux. Now according to Lenz's law the direction of the current in copper band is such that it opposes its own cause i.e decrease in current. So the shaded ring flux aids the main flux, which leads to the crowding of flux in shaded part of stator and the flux weaken in non shaded part. This non uniform distribution of flux causes magnetic axis to shift in the middle of the shaded part of the pole. This shifting of magnetic axis continues for negative cycle also and leads to the production of rotating magnetic field. The direction of this field is from non shaded part of the pole to the shaded part of the pole.

Advantages and Disadvantages of Shaded Pole Motor

The advantages of shaded pole induction motor are

1. Very economical and reliable.
2. Construction is simple and robust because there is no centrifugal switch.

The disadvantages of shaded pole induction motor are

1. Low power factor.
2. The starting torque is very poor.
3. The efficiency is very low as, the copper losses are high due to presence of copper band.
4. The speed reversal is also difficult and expensive as it requires another set of copper rings.

Applications of Shaded Pole Motor

Applications of Shaded pole motors induction motor are- Due to their low starting torques and reasonable cost these motors are mostly employed in small instruments, hair dryers, toys, record players, small fans, electric clocks etc. These motors are usually available in a range of 1/300 to 1/20 KW.

LINEAR INDUCTION MOTOR:

A **linear induction motor** (**LIM**) is an alternating current (AC), asynchronous linear motor that works by the same general principles as other induction motors but is typically designed to directly produce motion in a straight line. Characteristically, linear induction motors have a finite primary or secondary length, which generates end-effects, whereas a conventional induction motor is arranged in an endless loop.[1]

As with rotary motors, linear motors frequently run on a three-phase power supply and can support very high speeds. However, there are end-effects that reduce the motor's force, and it is often not possible to fit a gearbox to trade off force and speed. Linear induction motors are thus frequently less energy efficient than normal rotary motors for any given required force output.

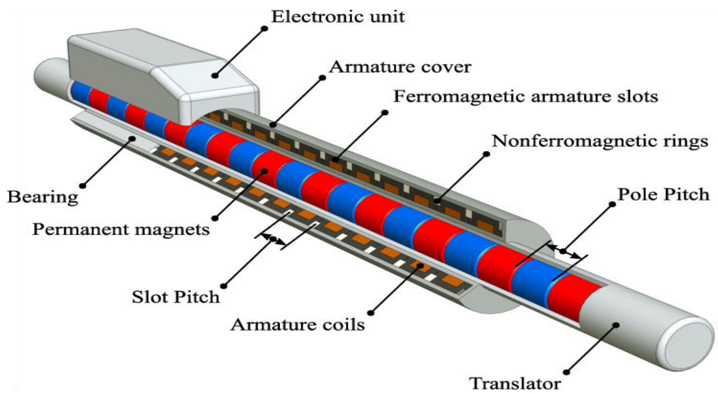
LIMs, unlike their rotary counterparts, can give a levitation effect. They are therefore often used where contactless force is required, where low maintenance is desirable, or where the duty cycle is low. Their practical uses include magnetic levitation, linear propulsion, and linear actuators.

They have also been used for pumping liquid metals.

CONSTRUCTION:

A linear electric motor's primary typically consists of a flat magnetic core (generally laminated) with transverse slots that are often straight cut[6]with coils laid into the slots, with each phase giving an alternating polarity so that the different phases physically overlap.

The secondary is frequently a sheet of aluminium, often with an iron backing plate. Some LIMs are double sided with one primary on each side of the secondary, and, in this case, no iron backing is needed.



Two types of linear motor exist: a *short primary*, where the coils are truncated shorter than the secondary, and a *short secondary*, where the conductive plate is smaller. Short secondary LIMs are often wound as parallel connections between coils of the same phase, whereas short primaries are usually wound in series.[7]

The primaries of transverse flux LIMs have a series of twin poles lying transversely side-by-side with opposite winding directions. These poles are typically made either with a suitably cut laminated backing plate or a series of transverse U-cores.

PRINCIPLE:

In this electric motor design, the force is produced by a linearly moving magnetic field acting on conductors in the field. Any conductor, be it a loop, a coil, or simply a piece of plate metal, that is placed in this field will have eddy currents induced in it thus creating an opposing magnetic field in accordance with Lenz's law. The two opposing fields will repel each other, creating motion athe

magnetic field sweeps through the metal.
where f_s is supply frequency in Hz, p is the number of poles, and n_s is the synchronous speed of the magnetic field in revolutions per second.
The travelling field pattern has a velocity of
where v_s is velocity of the linear travelling field in m/s, and t is the pole pitch.
For a slip of s, the speed of the secondary in a linear motor is given byVr= (1-s)Vs.

Hysteresis Motor

A **Hysteresis Motor** is a synchronous motor with a uniform air gap and without DC excitation. It operates both in single and three phase supply. The Torque in a Hysteresis Motor is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of thes s stator.

The working of the motor depends on the working of the continuously revolving magnetic flux. For the split phase operation, the stator winding of the motor has two single phase supply. This stator winding remains continuously connected to the single phase supply both at the starting as well as the running of the motor.

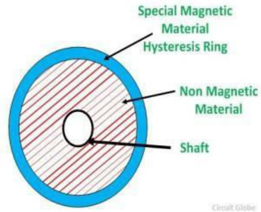
The rotor of the motor is made up of smooth chrome steel cylinder and it has no winding. It has high retentivity and because of this, it is very difficult to change the magnetic polarities once they are caused by the revolving flux of the rotor. The rotor of the hysteresis motor moves synchronously because the pole of the motor magnetically locks with the stator which has opposite polarities.

Construction of Stator of Hysteresis Motor

The stator of the hysteresis motor produces a rotating magnetic field and is almost similar to the stator of the induction motor. Thus, the stator of the motor is connected either to single supply or to the three phase supply. The three phase motor produces more uniform rotating field as compared to that of the single phase supply. The stator winding of the single-phase hysteresis motor is made of permanent split capacitor type or shaded pole type.The capacitor is used with an auxiliary winding in order to produce a uniform field.

Construction of Rotor of Hysteresis Motor

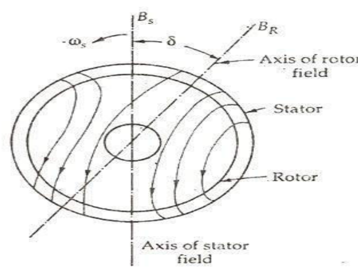
The rotor of the hysteresis motor consists of the core of aluminium or some other non-magnetic material which carries a layer of special magnetic material. The figure below shows the rotor of the hysteresis motor.



The outer layer has a number of thin rings forming a laminated rotor. The rotor of the motor is a smooth cylinder, and it does not carry any windings. The ring is made of hard chrome or cobalt steel having a large hysteresis loop.

Operationof aHysteresisMotor

The following illustration shows the basic functioning of a hysteresis motor.



When supply is given applied to the stator, a rotating magnetic field is produced. This magnetic field magnetises the rotor ring and induces pole within it. Due to the hysteresis loss in the rotor, the induced rotor flux lags behind the rotating stator flux. The angle δ between the stator magnetic field B_S and the rotor magnetic field B_R is responsible for the production of the torque. The angle δ depends on the shape of the hysteresis loop and not on the frequency.

Thus, the value of Coercive force and residual flux density of the magnetic material should be large. The ideal material would have a rectangular hysteresis loop as shown by loop 1 in the hysteresis loop figure. The stator magnetic field produces Eddy currents in the rotor. As a result, they produce theirown magnetic field.

The eddy current loss is given by the equation shown below.

$$p_e = k_e f_2^2 B^2$$

Where,

- k_e is a constant
- f_2 is the eddy current frequency
- B is the flux density

As we know,

$$f_2 = sf_1$$

Where s is the slip and f1 are the frequency of the stator.

Therefore,

$$p_e = k_e s^2 f_1^2 B^2$$

The torque is given by the equation shown below.

$$T_e = \frac{p_e}{s\,\omega_s} \quad \text{or}$$

$$T_e = k's \quad \ldots\ldots\ldots(1)$$

Where,

$$k' = \frac{k_e f_1^2 B^2}{\omega_s} = \text{constant}$$

Now, the torque due to hysteresis loss is given by the equation shown below.

$$p_h = k_h f_2 B^{1.6} \quad \text{or}$$

$$p_h = k_h s f_1 B^{1.6} \quad \ldots\ldots\ldots(2)$$

The Torque due to hysteresis is given as

$$\tau_h = \frac{p_h}{s\,\omega_s} \quad \text{or}$$

$$\tau_h = \frac{k_h f_1 B^{1.6}}{\omega_s} = k'' = \text{constant} \;\dots\dots\dots\; (3)$$

From the equation (1) it is clear that the torque is proportional to the slip. Therefore, as the speed of the rotor increases the value of τ_e decreases. As the speed of the motor reaches synchronous speed, the slip becomes zero and torque also become zero.

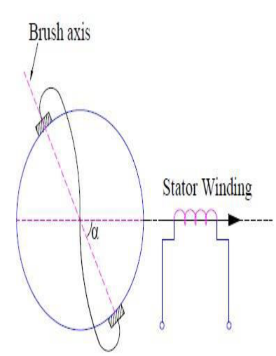
As the electromagnet torque is developed by the motor is because of the hysteresis loss and remains constant at all rotor speed until the breakdown torque. At the synchronous speed, the eddy current torque is zero and only torque due to hysteresis loss is present.

REPULSION MOTOR:

Repulsion Motor is a special kind of single phase AC motor which works due to the repulsion of similar poles. The stator of this motor is supplied with 1 phase AC supply and rotor circuit is shorted through carbon brush.

Construction of RepulsionMotor:

The main components of repulsion motor are stator, rotor and commutator brush assembly. The stator carries a single phase exciting winding similar to the main winding of single phase induction motor. The rotor has distributed DC winding connected to the commutator at one end just like in DC motor. The carbon brushes are short circuited on themselves.

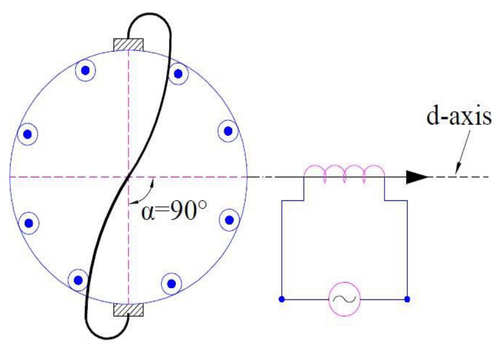


In the above figure, the stator winding have single phase AC winding which produces the working mmf in the air gap. The brushes on rotor are shown to be shorted. As the rotor circuit is shorted, the rotor receives power from stator bytransformer action.

Workingprinciple of Repulsion Motor:

The basic principle behind the working of repulsion motor is that "similar poles repel each other." This means two North poles will repel each other. Similarly, two South poles will repel each other.

When the stator winding of repulsion motor is supplied with single phase AC, it produces a magnetic flux along the direct axis as shown in figure above by arrow mark. This magnetic flux when link with the rotor winding, creates an emf. Due to this emf, a rotor current is produced. This rotor current in turn produces a magnetic flux which is directed along the brush axis due to commutator assembly. Due to the interaction of stator and rotor produced fluxes, an electromagnetic torque is produced. Let us discuss this aspect in detail.



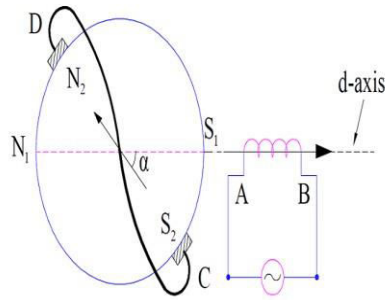
In the above figure, the angle α between the stator produced field and brush axis is 90°. This means, the brush axis is in quadrature with the direct. Under this condition, there will not be any mutual induction between the stator and rotor windings. Therefore, no emf and hence no rotor current is produced. Thus no electromagnetic torque is developed.

This means that motor will not run when $\alpha = 90°$. As the stator produced flux is unaffected by the zero rotor mmf, this condition is similar to the open circuittransformer. This is the reason, the brush position of $\alpha = 90°$ is called open-circuit, no-load, high impedance or neutral position.

Let us now consider the case when $\alpha = 0°$ as shown in figure below.

Thus in repulsion motor, no electromagnetic torque is developed when the angle between the stator and rotor magnetic flux axis is either 0 or 90°.

But actually the brush axis occupies a position somewhere in between $\alpha = 0°$ and $\alpha = 90°$ as
shown in figure below.



If the stator produced flux is assumed to be directed from A to B, then rotor produced flux must also have a component in a direction opposite to stator produced flux. This is just because of Lenz's Law. Therefore the rotor flux will be directed from C to D. Notice that it cannot be directed from D to C otherwise it will have a flux component directed toward A to B which is violation of Lenz's Law.

Since stator flux is toward A to B, South Pole (S1) is generated at A. Similarly South Pole (S2) is generated on rotor at C. Since similar poles repel each other, S1 will repel S2. Due to this repulsion between the like poles, motor will rotate in clockwise direction. ***This is the reason; this motor is called Repulsion Motor***. It is clear from the above figure and discussion that, the direction of rotation of repulsion motor can be reversed by simply changing the brush axis to the other side of filed winding (stator winding).

Stepper Motor:

A stepper motor (or step motor) is a brushless DC electric motor that can divide a full rotation into a large number of steps. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence, and the motor's position can be controlled precisely without any feedback mechanism (an open-loop controller), as long as the motor is carefully sized to the application.

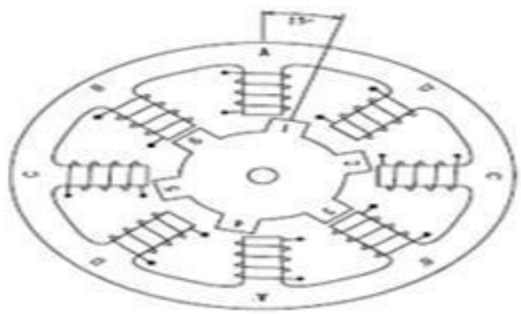
Stepper motors may be used for locomotion, movement, positioning, and many other functions where we need precise control of the position of a shaft, lever or other moving part of a mechatronic device.

Stepper motors are formed by coils and magnets and incorporate a shaft that moves when power is applied. The difference between stepper and DC motors is the way the shaft moves. The rotor moves by applying power to different coils in a predetermined sequence. The stepper motor can also hold their position and resist rotation.

Types:
Variable Reluctance Stepper Motor
Permanent Magnet Stepper Motor
Hybrid Stepper Motor:

Variable Reluctance Stepper Motor:

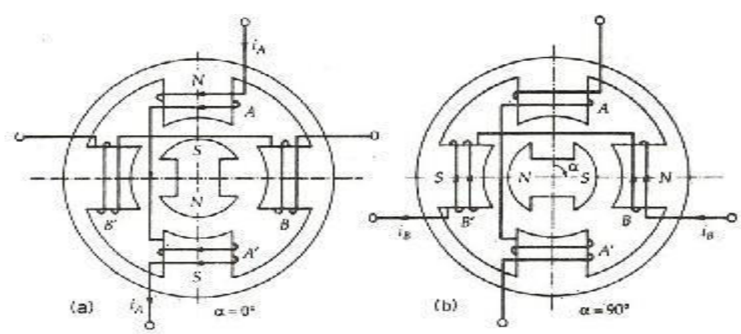
Variable-reluctance type stepper motors, that are the simplest type of steppers, consist of a soft iron multi-toothed rotor and a wound stator. When DC is applied to the stator windings, the poles become magnetized. Rotation occurs when the rotor teeth are attracted to the energized stator poles. Since the magnets of the variable reluctance step motors are smaller and lighter than those of permanent magnet step motors, they are faster. The smaller the area between the rotor and thestator gears of VR type stepper motors, the less the loss of the magnetic force.



Permanent MagnetStepper Motor

The **Permanent Magnet Stepper Motor** has a stator construction similar to that of the single stack variable reluctance motor. The rotor consists of permanent magnet poles of high retentivity steel and is cylindrical in shape. The concentrating windings on diametrically opposite poles are connected in series to form a two phase winding on the stator.

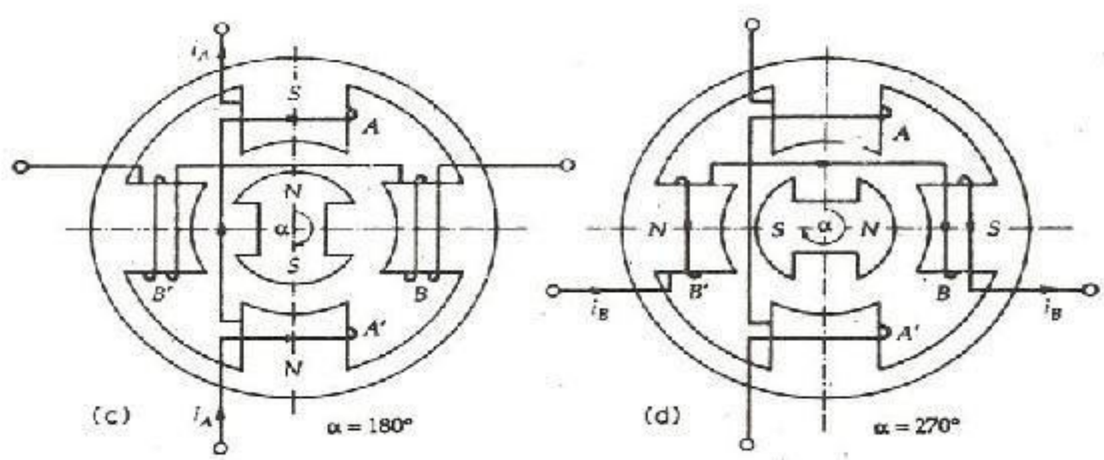
The rotor poles align with the stator teeth depending on the excitation of the winding. The two coils AA' connected in series to form a winding of Phase A. Similarly the two coil BB' is connected in series forming a phase B windings.The figure below shows 4/2 Pole Permanent Magnet Stepper Motor.



In figure (a) the current flows start to the end of phase A. The phase winding is denoted by A^+ and the current by i^+_A. The figure shows the condition when the phase winding is excited with the current i^+_A. The south pole of the rotor is attracted by the stator phase A. Thus, the magnetic axis of the stator and rotor coincide and α = 0^0

Similarly, in the figure (b) the current flows from the start to the end at phase B. The current is denoted by i^+_B and the winding by B^+. Considering the figure (b), the windings of phase A does not carry any current and the phase B is excited by the i^{+}_{B} current. The stator pole attracts the rotor pole and the rotor moves by 90^0 in the clockwise direction. Here $\alpha = 90^0$

The figure (c) below shows that the current flows from the end to the start of the phase A. This current is denoted by i^{-}_{A} and the winding is denoted by A^{-}. The current i^{-}_{A} is opposite to the current i^{+}_{A}. Here, phase B winding is de-energized and phase A winding is excited by the current i^{-}_{A}. The rotor moves further 90^0 in clockwise direction and the $\alpha = 180^0$



In the above figure (d), the current flows from end to starting point of phase B. The current is represented by i^{-}_{B} and the winding by B^{-}. Phase A carries no current and the phase B is excited. The rotor again moves further 90^0 and the value of $\alpha = 270^0$

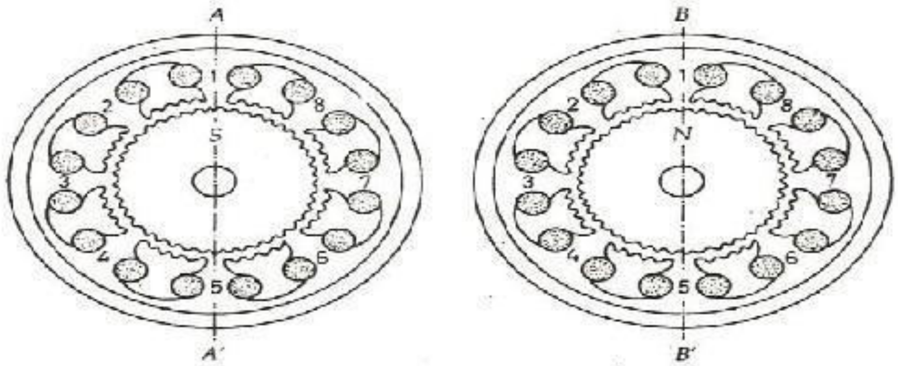
Completing the one revolution of the rotor for making $\alpha = 360^0$ the rotor moves further 90 degrees by de-energizing the winding of phase B and exciting the phase A. In the permanent magnet stepper motor the direction of the rotation depends on the polarity of the phase current.The sequence A^+, B^+, A^-, B^-, A^+ is followed by the clockwise movement of the rotor and for the anticlockwise movement, the sequence becomes A^+ B^-, A^-, B^+, A^+.

The permanent magnet rotor with large number of poles is difficult to make, therefore, stepper motors of this type are restricted to large step size in the range of 30 to 90^0. They have higher inertia and therefore, lower acceleration than variable stepper motors. The Permanent Magnet stepper motor produces more torque than the Variable Reluctance Stepper Motor.

HybridStepper Motor

The word Hybrid means combination or mixture. The **Hybrid Stepper Motor**is a combination of the features of the Variable Reluctance Stepper Motor and Permanent Magnet Stepper Motor. In the center of the rotor, an axial permanent magnet is provided. It is magnetized to produce a pair of poles as North (N) and South (S) as shown in the figure below.

At both the end of the axial magnet the end caps are provided, which contains an equal number of teeth which are magnetized by the magnet. The figure of the cross section of the two end caps of the rotor is shown below.



The stator has 8 poles, each of which has one coil and S number of teeth. There are 40 poles on the stator, and each end cap has 50 teeth. As the stator and rotor teeth are 40 and 50 respectively, the step angle is expressed as shown below.

The rotor teeth are perfectly aligned with the stator teeth. The teeth of the two end caps are displaced from each other by half of the pole pitch. As the magnet is axially magnetized, all the teeth on the left and right end cap acquire polarity as south and north pole respectively.

The coils on poles 1, 3, 5 and 7 are connected in series to form phase A. Similarly, the coils on the poles 2, 4, 6 and 8 are connected in series to form phase B.

When Phase is excited by supplying a positive current, the stator poles 1 and 5 becomes South poles and stator pole 3 and 7 becomes north poles.

Now, when the Phase A is de-energized, and phase B is excited, the rotor will turn by a full step angle of 1.8^0 in the anticlockwise direction. The phase A is now energized negatively; the rotor moves further by 1.8^0 in the same anti-clockwise direction. Further rotation of the rotor requires phase B to be excited negatively.

Thus, to produce anticlockwise motion of the rotor the phases are energized in the following sequence +A, +B, -A, -B, +B, +A…….. For the clockwise rotation, the sequence is +A, -B, +B,
+A……..

One of the main advantages of the Hybrid stepper motor is that, if the excitation of the motor is removed the rotor continues to remain locked in the same position as before the removal of the excitation. This is because of theDetent Torque produced by the permanent magnet.

Advantages of Hybrid Stepper
Motor

The advantages of the Hybrid Stepper Motor are as follows:-

- The length of the step is smaller.
- It has greater torque.
- Provides Detent Torque with the de-energized windings.
- Higher efficiency at lower speed.
- Lower stepping rate.

Disadvantages of Hybrid Stepper Motor

The Hybrid Stepper Motor has the following drawbacks.

- Higher inertia.
- The weight of the motor is more because of the presence of the rotor magnet.
- If the magnetic strength is varied, the performance of the motor is effected.
- The cost of the Hybrid motor is more as compared to the Variable Reluctance Motor.

Servo Motor – Types and Working Principle

The servo motor is most commonly used for high technology devices in the industrial application like automation technology. It is a self contained electrical device, that rotate parts of a machine with high efficiency and great precision. The output shaft of this motor can be moved to a particular angle. Servo motors are mainly used in home electronics, toys, cars, airplanes, etc.This article discusses about what is a servo motor, servo motor working, servo motor types and its applications.

Types of Servo Motor

Servo motors are classified into different types based on their application, such as AC servo motor, DC servo motor, brushless DC servo motor, positional rotation, continuous rotation and linear servo motor etc. Typical servo motors comprise of three wires namely, power control and ground. The shape and size of these motors depend on their applications. RC servo motor is the most common type of servo motor used in hobby applications, robotics due to their simplicity, affordability and reliability of control by microprocessors.

DC Servo Motor

The motor which is used as a DC servo motor generally have a separate DC source in the field of winding & armature winding. The control can be archived either by controlling the armature current or field current. Field control includes some particular advantages over armature control. In the same way armature control includes some advantages over field control. Based on the applications the control should be applied to the DC servo motor. DC servo motor provides very accurate and also fast respond to start or stop command signals due to the low armature inductive reactance. DC servo motors are used in similar equipments and computerized numerically controlled machines.

AC Servo Motor

AC servo motor is an AC motor that includes encoder is used with controllers for giving closed loop control and feedback. This motor can be placed to high accuracy and also controlled precisely as compulsory for the applications. Frequently these motors have higher designs of tolerance or better bearings and some simple designs also use higher voltages in order to accomplish greater torque. Applications of an AC motormainly involve in automation, robotics, CNC machinery, and other applications a high level of precision and needful versatility.

Servo Motor Working

A unique design for servo motors are proposed in controlling the robotics and for control applications. They are basically used to adjust the speed control at high torques and accurate positioning. Parts required are motor position sensor and a highly developed controller. These motors can be categorized according the servo motor controlled by servomechanism. If DC motor is controlled using this mechanism, then it is named as a DC servo motor. Servo motors are available in power ratings from fraction of a watt to 100 watts.The rotor of a servo motor is designed longer in length and smaller in diameter so that it has low inertia. To know more about this, please follow the link: Servo motor working principle and interfacing with 8051 microcontroller