VISHNU INSTITUTE OF TECHNOLOGY
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Vishnupur, BHIMAVARAM – 534 202

ELECTRICAL & ELECTRONICS ENGINEERING

II B. Tech. II Semester EEE R20 Autonomous

Electrical Machines – II

Material for Unit I & II

UNIT-I: 3-phase Induction Motors:

Construction of cage and wound rotor machine – production of rotating magnetic field – principle of operation – rotor EMF and rotor frequency – rotor current and PF at standstill and running conditions – rotor power input, rotor copper loss, mechanical power developed and their interrelationship – equivalent circuit – Phasor diagram – Numerical problems.

UNIT-II: Characteristics, Starting and Testing Methods of Induction Motors:

Torque equation –expressions for maximum torque and starting torque – torque-slip characteristics – double cage and deep bar rotors – crawling and cogging – speed control of induction motor with V/f method– methods of starting – starting current and torque calculations– No load and Blocked rotor tests – circle diagram – induction generator operation (Qualitative treatment only).

1. Construction and Principle of Squirrel Cage or Cage Rotor Motor

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

The advantages of three-phase AC induction motor are

- ✓ Simple design
- ✓ Rugged construction
- ✓ Reliable operation
- ✓ Low initial cost
- ✓ Easy operation and simple maintenance
- ✓ Simple control gear for starting and speed control
- ✓ High efficiency

Types of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

- ✓ Squirrel cage Induction Motors
- ✓ Slip ring Induction Motors

Construction of Squirrel Cage Motor (Stator)

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame. The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor (**Fig. 1**). When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.

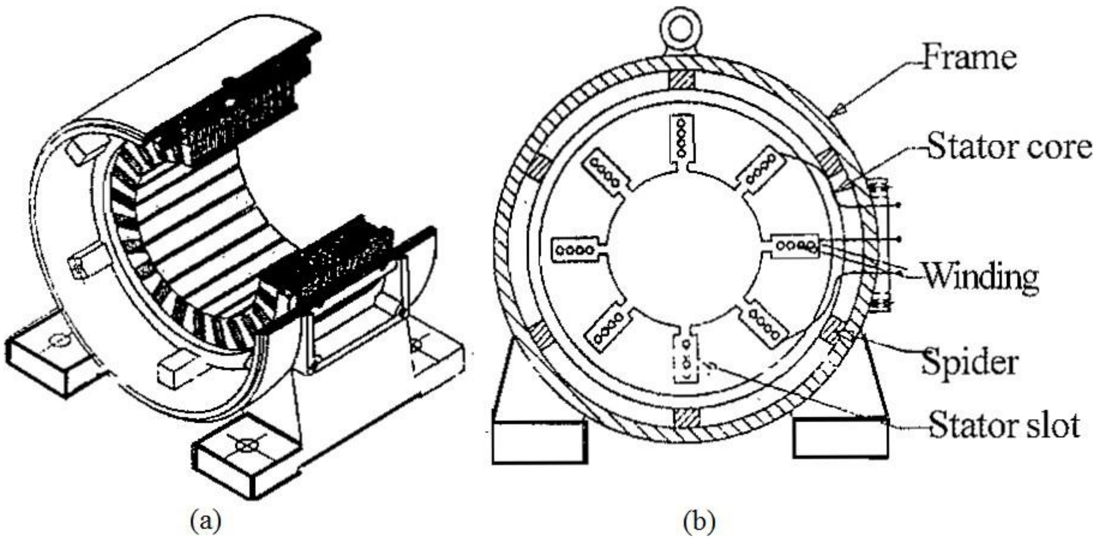


Fig 1. Stator of squirrel cage induction motor

Construction of Squirrel Cage Motor (Rotor)

The rotor of the squirrel cage motor shown in Fig: contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core. These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in **Fig. 2.**

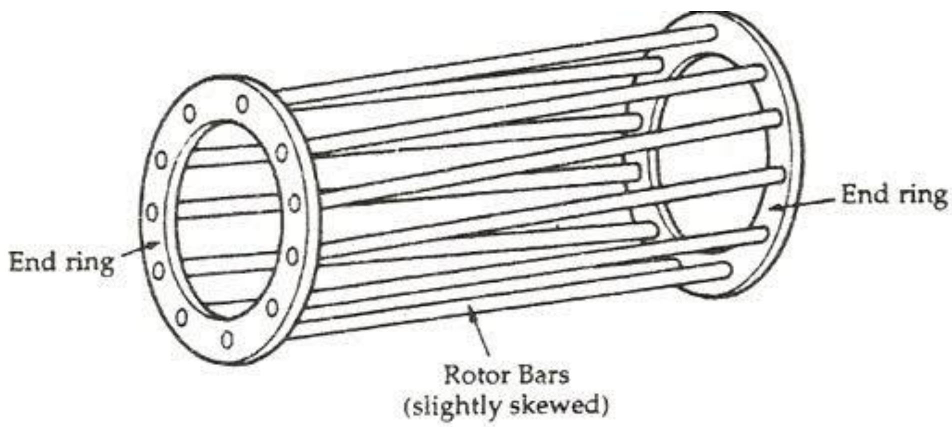


Fig. 2. Rotor of Squirrel cage induction motor

In small machines the conductor bars and end rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived. The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used. The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running. The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

Construction of Slip Ring Motor (Stator)

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

Construction of Slip Ring Motor (Rotor)

The rotor of the slip ring induction motor is also cylindrical or constructed of lamination. Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star. The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig. 3. To increase the phase difference the motor is provided with some rings through which high resistance is connected in series with the circuit. Because of this high resistance, the inductive reactance is decreased such that the phase differences the current and voltage is also decreased. Therefore, due to the decrease in phase difference the motor can able to develop high starting torque

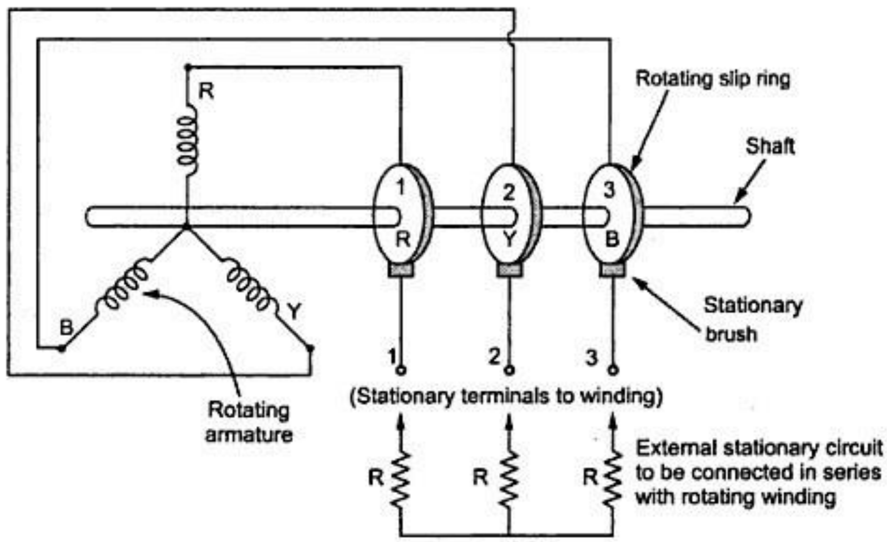


Fig. 3. Rotor circuit of slip ring induction motor

Squirrel cage and slip ring rotor

Property	Squirrel cage motor	Slip ring motor
Rotor Construction	Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes	Slip ring and brushes are required
Staring methods	Can be start with star-delta, auto-transformer, DOL etc.	Can be start with rotor resistance starter
Starting current	High	Low
Maintenance	Easy	Requires frequent maintenance
Cost	Low	High

Principle Operation of 3 Phase Induction Motor

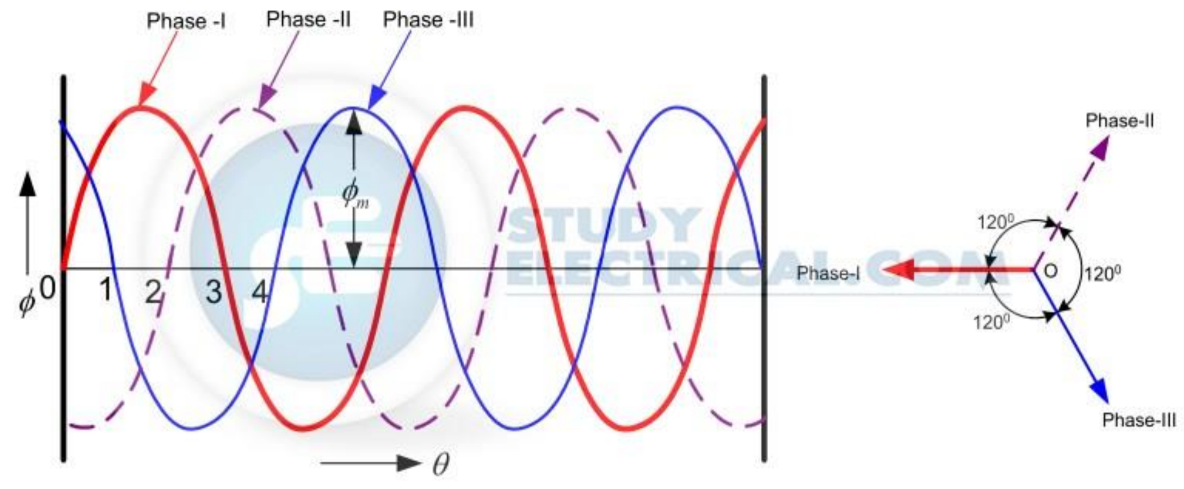
When the motor is excited with three-phase supply, three-phase stator winding produce a rotating magnetic field with 120 displacements at constant magnitude which rotates at synchronous speed. This changing magnetic field cuts the rotor conductors and induces a current in them according to the principle of Faraday's laws of electromagnetic induction. As these rotor conductors are shorted, the current starts to flow through these conductors. In the presence of magnetic field of stator, rotor conductors are placed, and therefore, according to the Lorenz force principle, a mechanical force acts on the rotor conductor. Thus, all the rotor conductors force, i.e., the sum of the mechanical forces produces torque in the rotor which tends to move it in the same direction of rotating magnetic field. This rotor conductor's rotation can also be explained by Lenz's law which tells that the induced currents in the rotor oppose the cause for its production, here this opposition is rotating magnetic field. This result the rotor starts rotating in the same direction of the stator rotating magnetic field. If the rotors speed more than stator speed, then no current will induce in the rotor because the reason for rotor rotation is the relative speed of the rotor and stator magnetic fields. This stator and the rotor field's difference is called as slip. This is how 3-phase motor is called as asynchronous machine due to this relative speed difference between the stator and the rotors. As we discussed above, the relative speed between the stator field and the rotor conductors causes to rotate the rotor in a particular direction. Hence, for producing the rotation, the rotor speed Nr must always be less than the stator field speed Ns, and the difference between these two parameters depends on the load on the motor.

$$Ns = \frac{120f}{P}$$

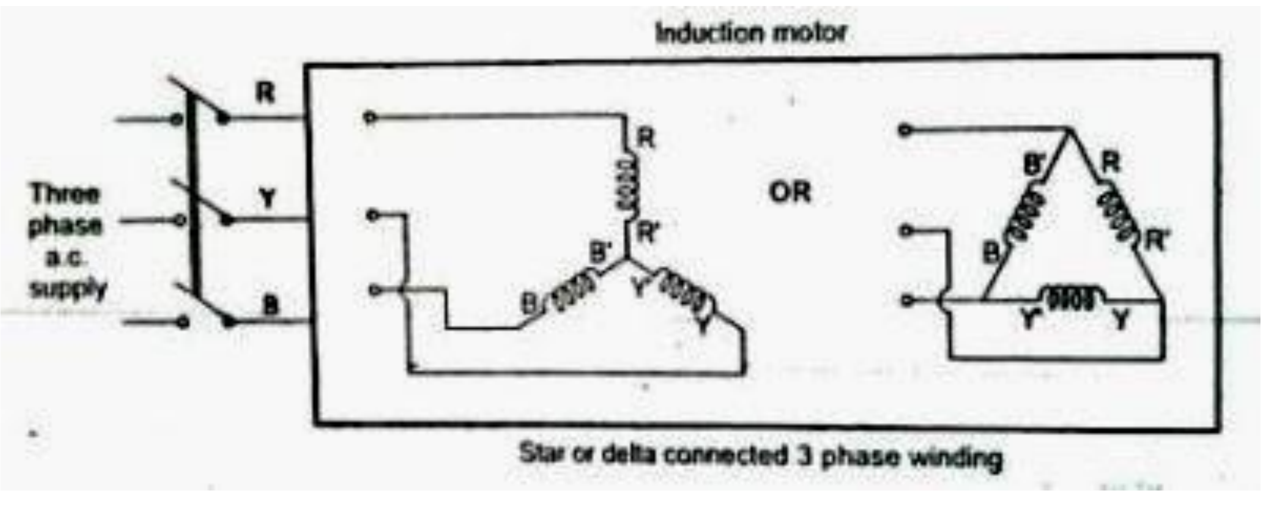
Where,
Ns = Syncronous speed (RPM)
f = Frequency (c/s or Hz)
P = Number of poles

When the stator is stationary, Nr=0; so the slip becomes 1 or 100%. When Nr is at synchronous speed, the slip becomes zero; so the motor never runs at synchronous speed.

2. Production of a Rotating Magnetic Field



The production of Rotating magnetic field in 3 phase supply is very interesting. When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating field. It can be shown that the magnitude of this rotating field is constant and is equal to **1.5** fm where fm is the maximum flux due to any phase. A three-phase induction motor consists of three phases winding as its stationary part called stator. The three-phase stator winding is connected in star or delta. The three-phase windings are displaced from each other by 120°. The windings are supplied by a balanced three phase ac supply.



Star or delta connected 3 phase winding

The three-phase currents flow simultaneously through the windings and are displaced from each other by 120° electrical. Each alternating phase current produces its own flux which is sinusoidal. So all three fluxes are sinusoidal and are separated from each other by 120°. If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes Φ_R, Φ_Y, Φ_B can be written as,

$$\Phi_R = \Phi m \sin(\omega t)$$

$$\Phi_Y = \Phi m \sin(\omega t - 120)$$

$$\Phi_B = \Phi m \sin(\omega t - 240)$$

As windings are identical and supply is balanced, the magnitude of each flux is Φm

Case 1 : ωt = 0

$\Phi_R = \Phi m \sin(0) = 0$

$\Phi_Y = \Phi m \sin(0 - 120) = -0.866\ \Phi m$

$\Phi_B = \Phi m \sin(0 - 240) = +0.866\ \Phi m$

Case 2 : ωt = 60

$\Phi_R = \Phi m \sin(60) = +0.866\ \Phi m$

$\Phi_Y = \Phi m \sin(-60) = -0.866\ \Phi m$

$\Phi_B = \Phi m \sin(-180) = 0$

Case 3 : ωt = 120

$\Phi_R = \Phi m \sin(120) = +0.866\ \Phi m$

$\Phi_Y = \Phi m \sin(0) = 0$

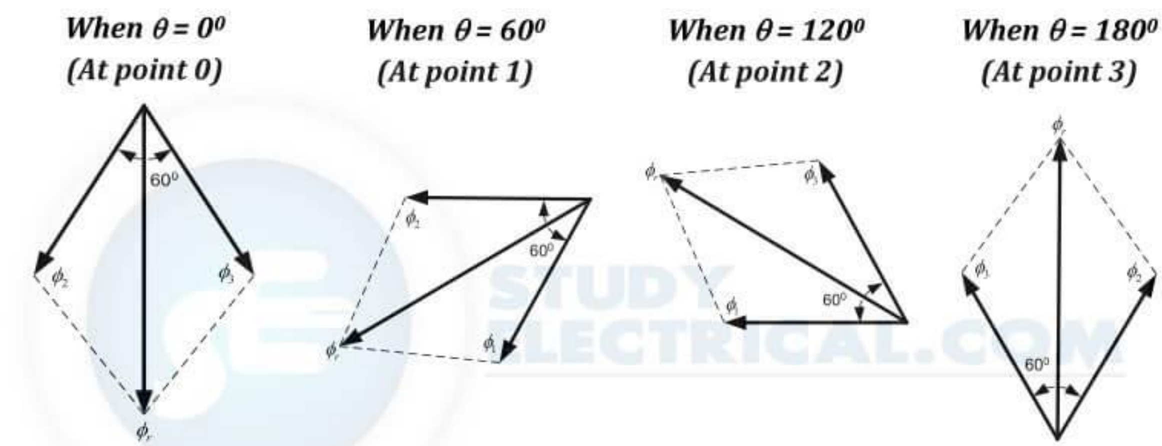
$\Phi_B = \Phi m \sin(-120) = -0.866\ \Phi m$

Case 4 : ωt = 180

$\Phi_R = \Phi m \sin(180) = 0$

$\Phi_Y = \Phi m \sin(60) = +.866\ \Phi m$

$\Phi_B = \Phi m \sin(-60) = -0.866\ \Phi m$



$\emptyset_1 = 0$

$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m \emptyset_3 = 0$

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$\emptyset_1 = 0$

$\emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m \emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$

By comparing the electrical and phasor diagrams we can find the flux rotates one complete 360 degrees on the 180-degree displacement of flux.

3. Effect of Slip on Rotor Parameters

When the supply is given to the induction motor the field winding set-ups a magnetic field rotating at synchronous speed N_s (i.e., N_s = 120f / number of poles), and the field is known as a rotating magnetic field. As the rotor is rotating in this magnetic field, the magnitude of rotor induced currents will be proportional to the relative speed between the stator rotating field and rotor speed and this current always lags with the main field current. Thus it is difficult to maintain synchronism between main field flux speed and rotor rotating speed. Let us assume that the rotor rotates at synchronous speed, so the EMF induced in the rotor conductors would become zero and consequently, there is no torque on the rotor causing the rotor to fails back in speed. Once the rotor falls back in speed, the relative speed increases, and again rotor picks up the speed. But due to the inertia of the rotor, this does not happen in practice and the rotor continues to rotate with a speed slightly less than the synchronous speed of the rotating field. Therefore, an induction motor will always rotate at a speed N less than the speed of synchronous speed N_s (speed of rotating magnetic field).

i.e., $N < N_s$

What is Slip in Induction Motor?

We have seen that there will be a difference in the speed of the rotating magnetic field and rotor rotating speed. This difference in speed expressed by the percentage of synchronous speed N_s is known as slip of the motor. Therefore, The slip's' is defined as the difference between the speed of the main magnetic field (Ns) and the rotor rotating speed (N).

Thus slip,

$$s = \frac{N_s - N}{N_s}$$

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

The actual speed of the motor can be expressed, from the above equation as

$$sN_s = N_s - N$$

$$N = N_s - sN_s$$

$$N = N_s(1 - s)$$

From the equation of slip s, it may be noticed that the relative speed or slip speed (Ns - N) of the rotor and rotating magnetic field is directly proportional to the slip.

- At starting or standstill position of the rotor, N = 0. At this condition the slip s = 1, and this is the maximum value of slip.
- The value of slip cannot be zero because when s = 0, N = N_s, and the torque produced will be zero. This can be understood by the torque-slip characteristics of the induction motor.
- At no-load slip is very low (near to 0) about 1% and at full load, it is about 3-5%. The variation in slip and therefore speed, from no-load to full load is very small. Thus we can say a 3-phase induction motor is also a constant speed motor.

Effect of Slip on Induction Motor Parameters

Rotor Frequency

In an induction motor, the relation between synchronous speed, supply frequency, and the number of stator poles is given by,

$$f = \frac{N_s P}{120} \quad Hz \quad \ldots.(1)$$

When the rotor rotates at a speed 'N' then the rotor conductor cut the rotating magnetic field at the relative speed i.e., N_s - N. The frequency of the rotor induced EMF or current 'f_r' can be expressed as

$$f_r = \frac{(N_s - N)\,P}{120} \quad Hz \quad \ldots.(2)$$

Dividing equation (2) by (1), we get

$$\frac{f_r}{f} = \frac{\frac{(N_s - N)\,P}{120}}{\frac{N_s\,P}{120}}$$

$$= \frac{N_s - N}{N_s} = slip, s$$

$$\therefore \;\; f_r = s\,f$$

Therefore, f_r = s f at the running condition. So rotor frequency in running condition is slip times the supply frequency.

- Suppose, at starting, N = 0 and slip = 1, hence f_r = f.
- Under the normal running condition, the rotor frequency is very small as the slip is very small.

Rotor Induced EMF

When the rotor is stationary or at standstill *(N = 0)* i.e., slip = 1, the *EMF* induced in the rotor is maximum. This is due to the rate of cutting the flux by the rotor is maximum as the relative speed between the *rotors* and rotating magnetic field is maximum. Let E_2 be the rotor induced *EMF* per phase at standstill.

$$E_2 \;=\; N_s \;\ldots.(1)$$

$$(\,as\; N = 0)$$

As the speed of the rotor increases, the relative speed decreases. This reduces the magnitude of induced EMF in the rotor, proportionality. The relative speed is 'N_s - N' rpm when the motor is running at speed 'N' rpm. Let E_{2r} be the rotor induced EMF per phase under running condition.

$$E_{2r} \;=\; (\,N_s - N) \;\;\ldots.(2)$$

Dividing equation (2) by (1), we get

$$\frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s}$$

$$\left(As, s = \frac{N_s - N}{N_s} \right)$$

$$\therefore\ E_{2r} = s\, E_2$$

Therefore, rotor induced EMF under running condition will be slip times the rotor induced EMF at standstill.

Rotor Reactance:

The rotor reactance depends upon the frequency. We know that at slip s, the frequency of the rotor induced EMF is given by $f_s = s\, f$.

At standstill (s = 1) condition the frequency of the rotor is given be $f_r = f$. As the rotor winding comprises inductance, the formula for rotor inductive reactance is given by $X_2 = 2\pi\, f\, L_2$. Where L_2 is the per phase inductance of the rotor. Therefore, under standstill condition, the rotor per phase reactance X_2 is given by,

$$X_2 = 2\pi\, f_r\, L_2$$

$$(\, As\ f_r = f\,)$$

$$X_2 = 2\pi\, f\, L_2$$

Similarly, under running condition ($s \neq 1$) condition the frequency of the rotor is given be $f_r = sf$. Therefore, the per-phase rotor reactance X_{2r} under running condition is given by,

$$X_{2r} = 2\pi\, f_r\, L_2$$

$$(\,As\ f_r = sf\,)$$

$$X_{2r} = 2\pi\, sf\, L_2$$

$$X_{2r} = s\,(\,2\pi\, f\, L_2\,)$$

$$X_{2r} = s\, X_2$$

Therefore, rotor reactance under running condition will be slip times the rotor reactance at standstill.

Rotor Resistance

The resistance of the rotor is independent of frequency and hence rotor resistance remains same as R_2 Ω / phase at standstill as well as in running condition.

Rotor Impedance

The expression for rotor impedance is obtained by combining rotor resistance and rotor reactance. Therefore, the per-phase rotor impedance Z_2 at standstill and under running condition is given by,

At standstill condition,

$$Z_2 = R_2 + jX_2$$

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

Under running condition,

$$Z_{2r} = R_2 + j\, sX_2$$

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

Rotor Current & Power Factor

From the equations of rotor resistance, impedance, and power factor under standstill and running condition. The equivalent circuit of the rotor at standstill can be drawn as shown below. From the equivalent circuit, the standstill rotor current I_2 and power factor cos φ_2 is given as,

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

$$Cos\ \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

Similarly, under the running condition, the equivalent circuit is shown below. From the equivalent circuit, the rotor current I_{2r} and power factor cos φ_{2r} under running condition is given as,

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{s\ E_2}{\sqrt{R_2^2 + sX_2^2}}$$

$$Cos\ \phi_{2r} = \frac{R_{2r}}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + sX_2^2}}$$

Speed of Rotating Magnetic Field

The speed at which the rotating magnetic field revolves is called the **synchronous speed (N_s)**. During this one-quarter cycle, the field has rotated through 90°. At one complete cycle of current from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, for P poles, the rotating field makes one revolution in P/2 cycles of current.

Direction of Rotating Magnetic Field

The phase sequence of the three-phase voltage applied to the stator winding in the first figure is R-Y-B. If this sequence is changed to R-B-Y, it is observed that the direction of rotation of the field is reversed i.e., the field rotates counterclockwise rather than clockwise. However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines. As we shall see, the rotor in an induction motor runs in the same direction as the rotating magnetic field. **Therefore, the direction of rotation of a 3 phase induction motor can be reversed by interchanging any two of the three motor supply lines.**

Power Flow in an Induction Motor

Induction motor converts an electrical power supplies to it into mechanical power. The various stages in this conversion are called power flow in an inductor 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 electrical supplied to the motor can be calculated as

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

This is nothing but the stator input. The part of this power is utilized 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 P_2

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

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. 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 P_m.

$$\therefore \quad \boxed{P_m = P_2 - P_c}$$

Now this power, motor tries to deliver to the load connected to the shaft. But during this mechanical transmission, part of P_m is utilized 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 P_{out}. This is also called shaft power.

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

The rating of the motor is specified in terms of value of P_{out} when load condition is full load condition. The above stages can be shown diagrammatically called power flow diagram of an induction motor. This is shown in the Fig. 6.

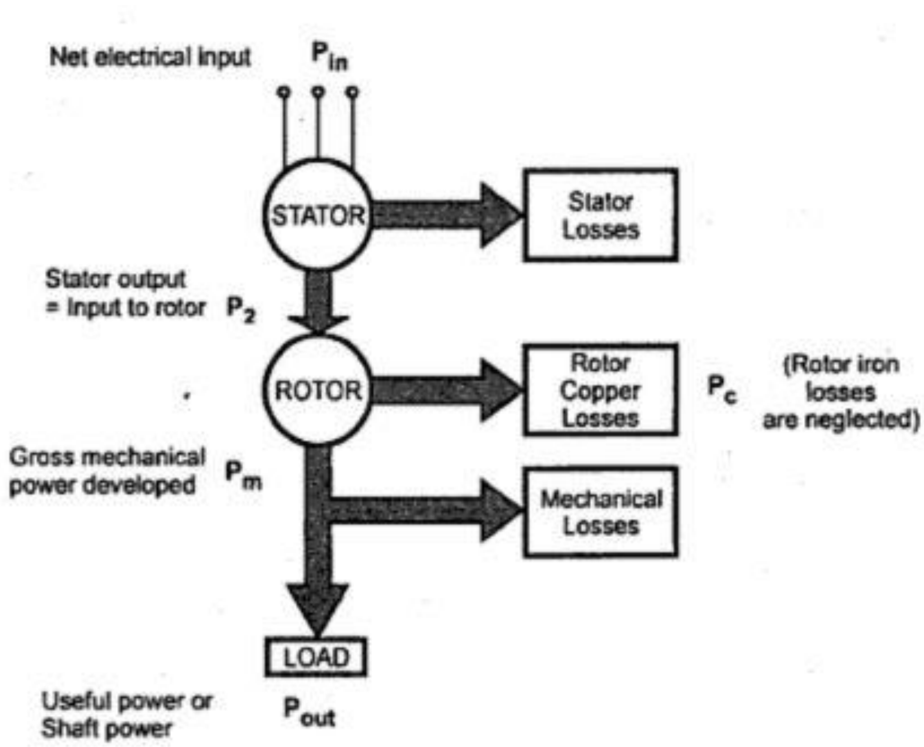

Fig. 6. Power flow in induction motor

$$\boxed{\text{Rotor efficiency} = \frac{\text{rotor output}}{\text{rotor input}} = \frac{\text{gross mechanical power developed}}{\text{rotor input}}}$$

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

Relation between P_2, P_c, P_m

The rotor input P_2, rotor copper loss P_c and gross mechanical power developed P_m are related through slip s. Let us derive the relationship.

T = Gross torque developed by motor (Nm)

$$P = T \times \omega$$

where P = Power & ω = angular speed $\frac{2\pi N}{60}$

Now input to the rotor P_2 is from stator side through RMF which is rotating @ N_s. So the torque developed by the rotor can be expressed interms of P_2 & ω_s.

$$\therefore \quad P_2 = T \times \omega_s \quad \text{where } \omega_s = \frac{2\pi N_s}{60} \ \text{rad/sec}$$

$$P_2 = T \times \frac{2\pi N_s}{60} \quad (\text{when } N_s \text{ in rpm})$$

The rotor tries to deliver this torque to the load. So the rotor output is gross mechanical power developed P_m and torque T. But rotor gives output at speed N_r and Not N_s. so from outputside P_m and T can

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be related through angular speed ω and not ω_s.

$$\therefore \quad P_m = T \times \omega \quad \text{where } \omega = \frac{2\pi N_r}{60}$$

$$P_m = \frac{2\pi N_r}{60} \times T$$

The difference between P_2 and P_m is rotor copper loss P_c.

$$P_c = P_2 - P_m \Rightarrow T \times \frac{2\pi N_s}{60} - T \times \frac{2\pi N_r}{60}$$

$$P_c = T \times \frac{2\pi}{60}(N_s - N_r) = \text{Rotor Copper loss}$$

Dividing P_2 from P_c we'll get

$$\frac{P_c}{P_2} = \frac{T \times \frac{2\pi}{60}(N_s - N_r)}{T \times \frac{2\pi N_s}{60}} = \frac{N_s - N_r}{N_s}$$

$$\therefore \frac{P_c}{P_2} = s \qquad \because \frac{N_s - N_r}{N_s} = s$$

$$\therefore P_2 - P_c = P_m \qquad \therefore P_c = s \cdot P_2$$

$$\therefore P_2 - s P_2 = P_m$$

$$P_2(1-s) = P_m$$

$\therefore$ The relationship $P_2 : P_c : P_m = 1 : s : 1-s$

Equivalent circuit of 3 phase induction motor

The induction motor is equivalent to a rotating transformer. Hence, we can draw the induction motor equivalent circuit with the help of equivalent circuit of the transformer. The basic equivalent circuit of induction motor is shown in Fig. 7, which is very similar to that of a transformer.

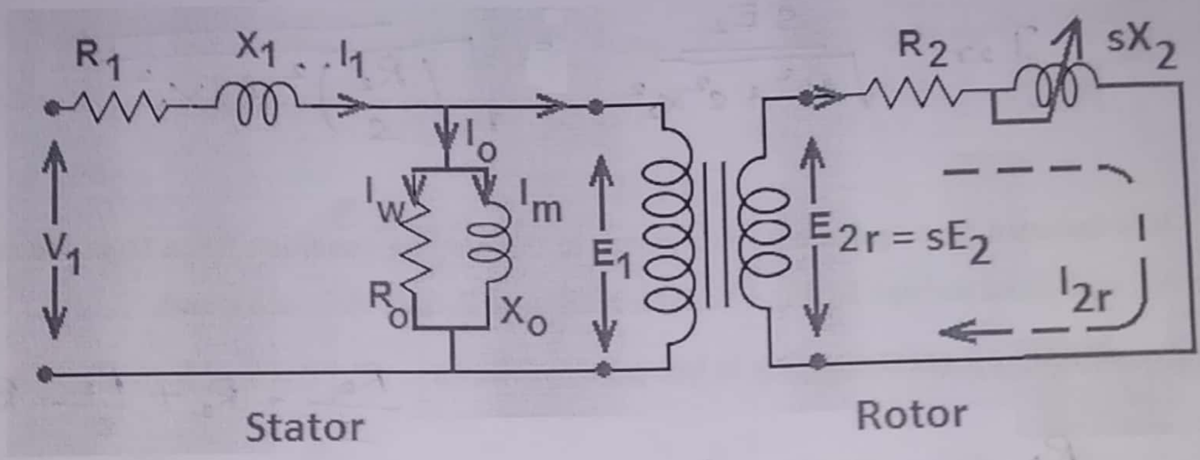


Fig. 7 Basic equivalent circuit of 3 phase induction motor

Here R_1 and X_1 are the per phase values of stator resistance and stator leakage reactance.

E_1 is per phase stator voltage

N_1 the number of stator turns per phase

R_2 rotor resistance per phase

X_2 is rotor reactance per phase in standstill condition

sX_2 is rotor reactance per phase in running condition

s is the slip

R_o is the no-load resistance per phase, that represents the resistance for core losses

X_o represents the no load reactance

I_w is the active component which supplies no load loses

I_m is the magnetizing component which sets the flux in core and airgap

$E_{2r} = sE_2$ is the per phase rotor induced EMF (in running condition)

E_2 = induced EMF in rotor at standstill.

The rotor current I_{2r} is given by

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

Representation of rotor impedance:

$$I_{2r} = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}}$$

It is assumed that equivalent rotor circuit in the running condition has a fixed reactance X_2, with fixed voltage E_2, but a variable resistance R_2/s as indicated above.

We can express resistance R_2/s in two parts as follows $\frac{R_2}{s} = R_2 + \frac{R_2}{s} - R_2$

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

Where, the first part R_2 is the rotor resistance representing the rotor copper losses and the second part R_2 $(1/s - 1)$ is the load resistance R_L.

It is the electrical equivalent of the mechanical load on the motor.

It is the electrical power that is converted into the mechanical power by the motor.

Hence equivalent rotor circuit of the induction motor can be drawn as under Fig. 8.

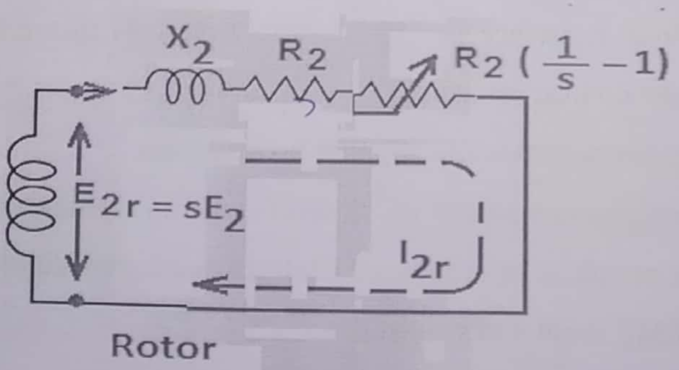


Fig. 8. Rotor equivalent circuit

Equivalent circuit of induction motor referred to stator:

We can draw the equivalent circuit of induction motor referred to stator or rotor side like that of a transformer.

$$K = \frac{E_2}{E_1} = \text{Transformation ratio}$$

$$E_2' = \frac{E_2}{K}$$

The rotor current I_{2r} has its reflected Component on the stator side which is I_{2r}'.

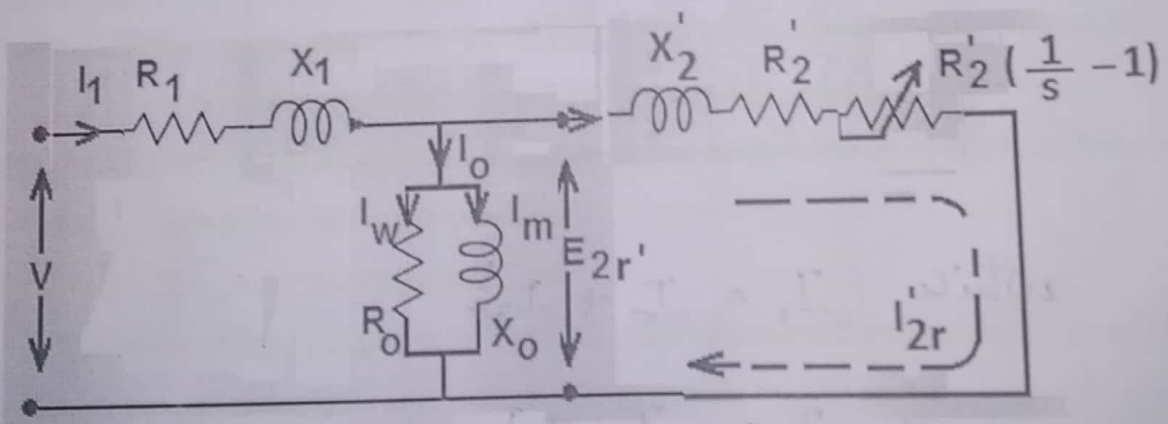
$$I_{2r}' = K I_{2r} = \frac{K s E_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

$$X_2' = \frac{X_2}{K^2} = \text{Reflected rotor reactance}$$

$$R_2' = \frac{R_2}{K^2} = \text{Reflected rotor resistance}$$

$$R_L' = \frac{R_L}{K^2} = \frac{R_2}{K^2}\left[\frac{1-s}{s}\right] = R_2'\left(\frac{1-s}{s}\right)$$

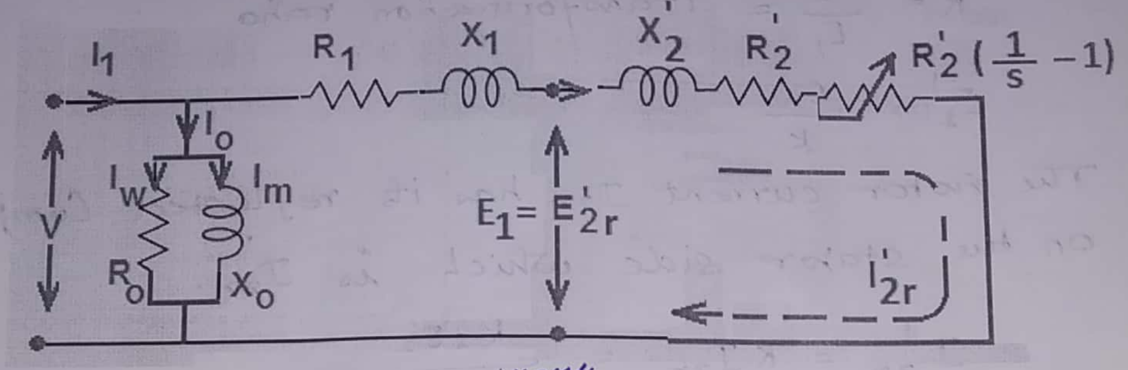
$$= R_2'\left(\frac{1}{s} - 1\right)$$



Equivalent Circuit of I.M. Referred to Stator

Approximate Equivalent circuit:

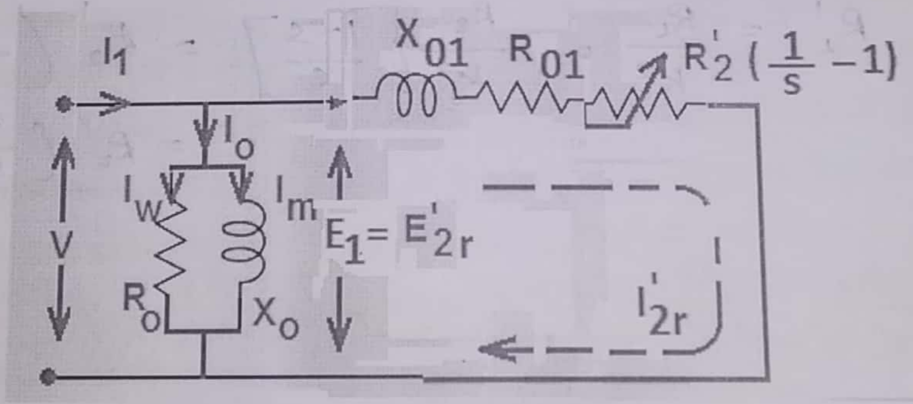
The no-load circuit components R_o and X_o can be shifted to the left of R_1 and X_1 to obtain the approximate equivalent circuit of the induction motor.



R_{01} = Equivalent resistance referred to stator $= R_1 + R_2'$

X_{01} = Equivalent reactance referred to stator $= X_1 + X_2'$

$R_{01} = R_1 + \frac{R_2}{K^2}$ & $X_{01} = X_1 + \frac{X_2}{K^2}$



while $I_1 = I_o + I_{2r}'$

& $I_o = I_w + I_m$

Phasor diagram of 3 phase Induction motor

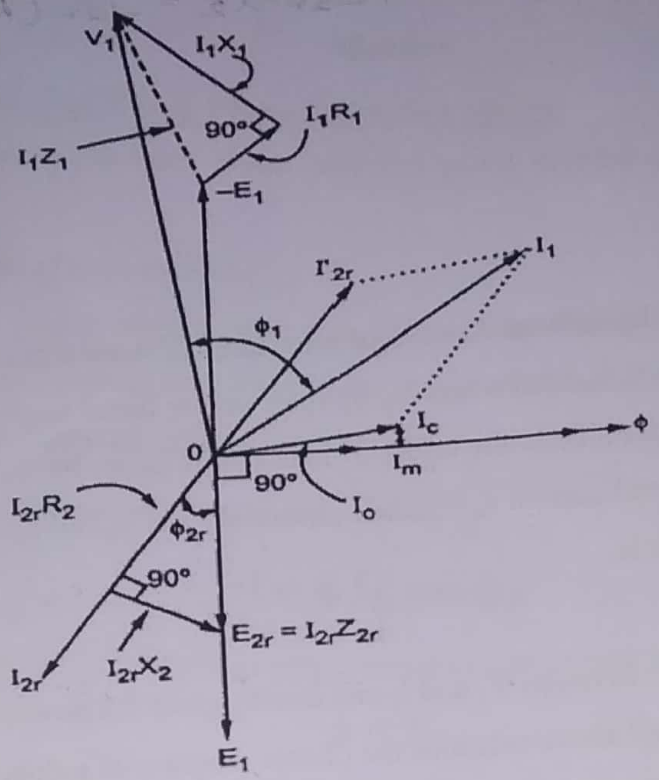


Fig. 9. Phasor diagram of 3 phase induction motor

The phasor diagram of loaded induction motor is similar to the loaded transformer. The only difference is the secondary of induction motor is rotating and short circuited while transformer secondary is stationary and connected to load. The load on induction motor is mechanical while load on transformer is electrical. Still by finding electrical equivalent of mechanical load on the motor, the phasor diagram of induction motor can be developed.

Let Φ = Magnetic flux links with both primary and secondary.

There is self induced EMF E_1 in the stator while a mutually induced EMF E_{2r} in the rotor.

Let R_1 = Stator resistance per phase.

X_1 = Stator reactance per phase

The stator voltage per phase V_1 has to counter balance self induced EMF E_1 and has to supply voltage drops $I_1 R_1$ and $I_1 X_1$. So on stator side we can write,

$$V_1 = -E_1 + I_1R_1 + jI_1X_1 = E_1 + I_1(R_1 + jX_1) = -E_1 + I_1Z_1$$

and

$$E_{2r} = I_{2r}R_2 + jI_{2r}'X_2 = I_{2r}(R_2 + jX_2) = I_{2r} \cdot Z_{2r}$$

The value of E_{2r} depends on the ratio of rotor turns to stator turns. The rotor current in the running condition is I_{2r} which lags E_{2r} by rotor power factor angle Φ_{2r}. The reflected rotor current I_{2r}' on stator side is the effect of load and is given by, $I_{2r}' = K\ I_{2r}$. The induction motor draws no load current I_o which is phasor sum of I_w and I_m. The total stator current drawn from supply is,

$$\bar{I}_1 = \bar{I}_o + \bar{I}_{2r}'$$

The Φ_1 is angle between V_1 and I_1 and cos Φ_1 gives the power factor of the induction motor. Thus using all above relations the phasor diagram of induction motor on load can be obtained. The steps to draw phasor diagram are,

1. Takes Φ as reference phasor.
2. The induced voltage E_1 lags Φ by 90^o.
3. Show - E_1 by reversing voltage phasor
4. The phasor E_{2r} is in phase with E_1. So I_{2r} show lagging E_{2r} i.e. E_1 direction by Φ_{2r}
5. Show I_{2r} R_2 in phase with I_{2r} and I_{2r} X_{2r} leading the resistive drop by 90^o, to get exact location of
6. Reverse I_{2r} to get I_{2r}'
7. I_m is in phase with Φ while I_w is at leading with. Add I_m and I_w to get I_o
8. Add I_o and I_{2r}' to get I_1
9. From tip of - E_1 phasor, add I_1 R_1 in phase with I_1 and I_1X_1 at 90^o leading to I_1 to V_1 get phasor
10. Angle between V_1 and I_1 is Φ_1

Unit 2 Characteristics, Starting and Testing Methods of Induction Motors

Torque Equation of Three Phase Induction Motor

The torque produced by three phase induction motor depends upon the following three factors

1. Magnitude of rotor current (I_{2r})
2. The flux which interact with the rotor of three phase induction motor and is responsible for producing EMF in the rotor part of induction motor (ϕ)
3. The power factor of rotor of the three phase induction motor ($\cos \phi_{2r}$)

Mathematically, the relationship can be expressed as

$$T = \phi I_{2r} \cos \phi_{2r}$$

The flux φ produced by the stator is proportional to stator EMF E_1

$$\phi \propto E_1$$

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

Therefore, $E_2 \propto \phi$

Rotor current I_{2r} is defined as the ratio of rotor induced EMF under running condition (E_{2r} or sE_2) to total impedance Z_{2r} of rotor side

Therefore,

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

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

$$\cos \phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

Using the above equations, the toque equation can be written as

$$T \propto E_2 \cdot \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + s^2 X_2^2} \quad Nm$$

$$T = \frac{K \cdot s \cdot E_2^2 R_2}{R_2^2 + s^2 X_2^2}$$

where K = constant of proportionality

The constant K is proved to be $\frac{3}{2\pi n_s}$ for the three phase induction motor.

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

$$\therefore T = \frac{3}{2\pi n_s} \cdot \frac{S E_2^2 R_2}{R_2^2 + s^2 X_2^2} \quad Nm$$

* starting torque

$s = 1 \quad N_r = 0$

$$T_{st} = \frac{3}{2\pi n_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

From the torque equation, it is clear that the torque depends on slip at which motor is running. The supply voltage to the motor is usually rated and constant and there exists a fixed ratio between E_1 and E_2. Hence E_2 is also constant. Similarly R_2, X_2 and N_s are constant for the induction motor.

Hence while finding the condition for maximum torque, remember that the only parameter which controls the torque is slip s.

mathematically for the maximum torque we can write, $\frac{dT}{ds} = 0$

where $T = \frac{K s E_2^2 R_2}{R_2^2 + s^2 X_2^2}$

apply the rule $\frac{u}{v} = \frac{v \cdot du - u \cdot dv}{v^2}$

$$\frac{dT}{ds} = \frac{(R_2^2 + s^2 X_2^2)\frac{d}{ds}(K s E_2^2 R_2) - (K s E_2^2 R_2)\frac{d}{ds}(R_2^2 + s^2 X_2^2)}{(R_2^2 + s^2 X_2^2)^2}$$

$$(R_2^2 + s^2 X_2^2)(K E_2^2 R_2) - (K s E_2^2 R_2)(2 s X_2^2) = 0$$

$$R_2^2 K E_2^2 R_2 + K s^2 X_2^2 E_2^2 R_2 - 2 s^2 K X_2^2 E_2^2 R_2 = 0$$

$$R_2^2 K E_2^2 R_2 - K s^2 X_2^2 E_2^2 R_2 = 0$$

$$R_2^2 - s^2 X_2^2 = 0$$

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

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

$$\therefore \quad s = \frac{R_2}{X_2}$$ (neglecting negative slip)

$\therefore$ The slip at which maximum torque occurs $S_m = \dfrac{R_2}{X_2}$

magnitude of maximum torque

This can be obtained by substituting $S_m = \frac{R_2}{X_2}$ in the torque equation. It is denoted by T_m.

$$T_m = \frac{K \cdot S_m \cdot E_2^2 R_2}{R_2^2 + S_m^2 X_2^2}$$

$$T_m = \frac{K\left(\frac{R_2}{X_2}\right) E_2^2 R_2}{R_2^2 + \frac{R_2^2}{X_2^2} \cdot X_2^2}$$

$$\boxed{T_m = \frac{K E_2^2}{2 X_2}} \; Nm$$

Torque ratios :-

full load and maximum torque ratio :-

In general $T \propto \frac{S E_2^2 R_2}{R_2^2 + S^2 X_2^2}$

Let S_{fL} = full load slip

hence $T_{FL} \propto \dfrac{S_{FL} E_2^2 R_2}{R_2^2 + S_{FL}^2 X_2^2}$

and S_m = slip at which max. Torque Occurs

hence $T_m \propto \dfrac{S_m E_2^2 R_2}{R_2^2 + S_m^2 X_2^2}$

$$\therefore \frac{T_{FL}}{T_m} = \frac{S_{FL} E_2^2 R_2}{R_2^2 + S_{FL}^2 X_2^2} \times \frac{R_2^2 + S_m^2 X_2^2}{S_m E_2^2 R_2}$$

$$\therefore \frac{T_{FL}}{T_m} = \frac{S_{FL}}{S_m} \times \frac{R_2^2 + S_m^2 X_2^2}{R_2^2 + S_{FL}^2 X_2^2}$$

Dividing both Nm & DM by X_2^2 we get

$$\frac{T_{FL}}{T_m} = \frac{S_{FL}}{S_m} \times \frac{\left[\frac{R_2^2}{X_2^2} + S_m^2\right]}{\left[\frac{R_2^2}{X_2^2} + S_{FL}^2\right]}$$ here $\frac{R_2}{X_2} = S_m$

$$\therefore \frac{T_{FL}}{T_m} = \frac{S_{FL} \times 2 S_m^2}{S_m\left[S_m^2 + S_{FL}^2\right]} = \frac{2 S_{FL} S_m}{S_m^2 + S_{FL}^2}$$

$$\therefore \frac{T_{FL}}{T_m} = \frac{2 S_{FL} \cdot S_m}{S_m^2 + S_{FL}^2}$$

Starting torque & maximum torque ratio

Again starting with torque equation as

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + s^2 x_2^2}$$

Now for T_{st} (starting torque), $s = 1$

hence $T_{st} \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2}$

while for T_m, $s = s_m$ hence,

$$T_m \propto \frac{s_m E_2^2 R_2}{R_2^2 + s_m^2 x_2^2}$$

(or)

$$\left[T_m \propto \frac{E_2^2}{2 X_2} \right]$$

$$\therefore \frac{T_{st}}{T_m} = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{R_2^2 + s_m^2 X_2^2}{s_m E_2^2 R_2}$$

$$\frac{T_{st}}{T_m} = \frac{R_2^2 + s_m^2 x_2^2}{s_m \left[R_2^2 + x_2^2 \right]}$$

Dividing both Numerator & denominator by x_2^2 we will get

$$\frac{T_{st}}{T_m} = \frac{\frac{R_2^2}{x_2^2} + S_m^2}{S_m\left[\frac{R_2^2}{x_2^2} + 1\right]}$$

here $\frac{R_2}{x_2} = S_m$

$$\therefore \frac{T_{st}}{T_m} = \frac{2S_m^2}{S_m(1+S_m^2)} = \frac{2S_m}{1+S_m^2}$$

$$\therefore \boxed{\frac{T_{st}}{T_m} = \frac{2S_m}{1+S_m^2}}$$

Torque - Slip Characteristics

As the induction motor is located from no load to full load, its speed decreases hence slip increases. Due to the increased load, motor has to produce more torque to satisfy load demand. The torque ultimately depends on slip as explained earlier. The behavior of motor can be easily judged by sketching a curve obtained by plotting torque produced against slip of induction motor. The curve obtained by plotting torque against slip from s = 1 (at start) to s = 0 (at synchronous speed) is called torque-slip characteristics of the induction motor. It is very interesting to study the nature of torque-slip characteristics. We have seen that for a constant supply voltage, E2 is also constant. So we can write torque equations as,

$$\boxed{T \propto \frac{s R_2}{R_2^2 + (sX_2)^2}}$$

Now to judge the nature of torque-slip characteristics let us divide the slip range (s = 0 to s = 1) into two parts and analyze them independently.

Low slip region

In low slip region, 's' is very small. Due to this, the term $(s X_2)^2$ is so small as compared to R_2^2 that it can be neglected.

$$\therefore \quad \boxed{T \propto \frac{s R_2}{R_2^2} \propto s} \qquad \text{As } R_2 \text{ is constant.}$$

Hence in low slip region torque is directly proportional to slip. If the load increases, speed decreases increasing the slip. This increases the torque which satisfies the load demand. Hence the graph is straight line in nature. At $N = N_s$, s = 0 hence T = 0. As no torque is generated at $N = N_s$, motor stops if it tries to achieve the synchronous speed. Torque increases linearly in this region, of low slip values.

High slip region

In this region, slip is high i.e. slip value is approaching to 1. Here it can be assumed that the term R_2^2 is very small as compared to $(s\ X_2)^2$. Hence neglecting from the denominator, we get

$$\boxed{T \propto \frac{sR_2}{(sX_2)^2} \propto \frac{1}{s}}$$ where R_2 and X_2 are constants

So in high slip region torque is inversely proportional to the slip. Hence its nature is like rectangular hyperbola. Now when load increases, load demand increases but speed decreases. As speed decreases, slip increases. In high slip region as $T \alpha 1/s$, torque decreases as slip increases. But torque must increases to satisfy the load demand. As torque decreases, due to extra loading effect, speed further decreases and slip further increases. Again torque decreases as $T\ \alpha 1/s$ hence same load acts as an extra load due to reduction in torque produced. Hence speed further drops. Eventually motor comes to standstill condition.

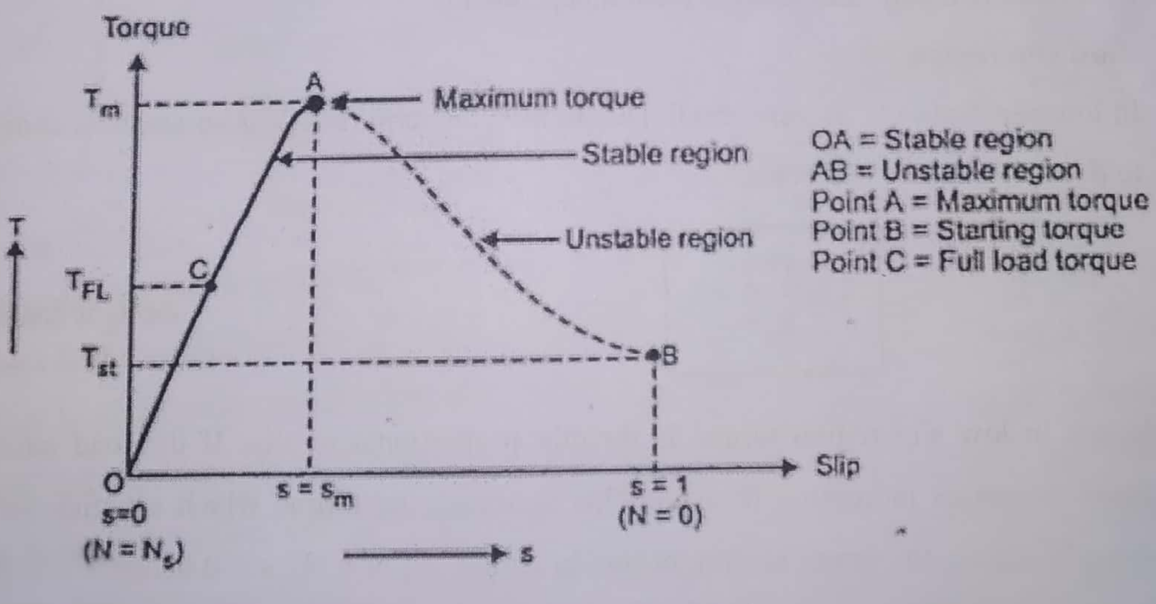


Fig. 1. Torque – Slip Characteristics

The motor cannot continue to rotate at any point in this high slip region. Hence this region is called unstable region of operation.

So torque – slip characteristics has two parts,

1. Straight line called stable region of operation
2. Rectangular hyperbola called unstable region of operation.

In low slip region, as load increases, slip increases and torque also increases linearly. Every motor has its own limit to produce a torque. The maximum torque, the motor can produces as load increases is T_m which occurs at $s = s_m$. So linear behavior continues till $s = s_m$.

Generation and Braking regions (Torque-Slip)

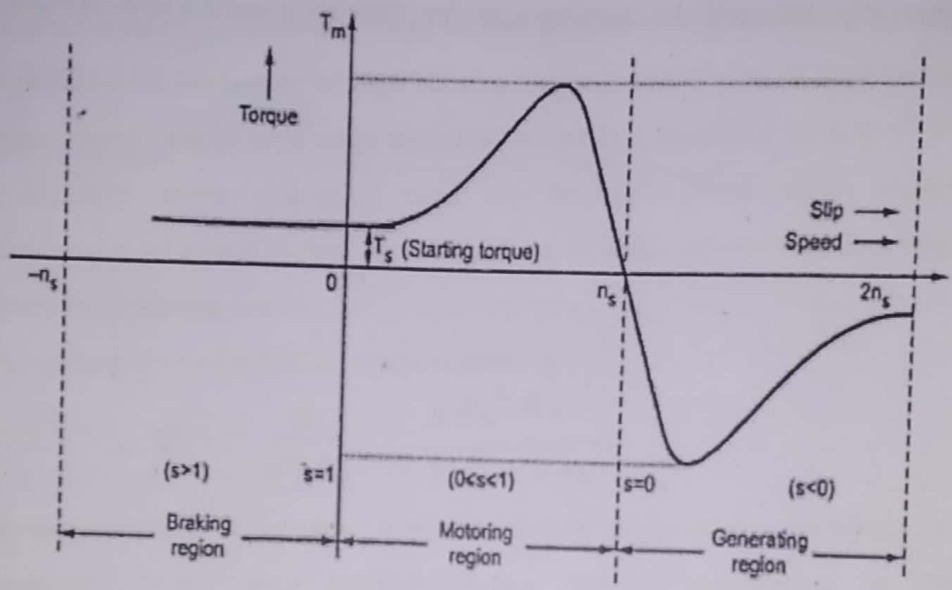


Fig. 2. Regions of Torque slip Characteristics

When the slip lies in the region 0 and 1 i.e. when $0 \leq s \leq 1$, the machine runs as a motor which is the normal operation. The rotation of rotor is in the direction of rotating field which is developed by stator currents. In this region it takes electrical power from supply lines and supplies mechanical power output. The rotor speed and corresponding torque are in same direction. When the **slip is greater than 1**, the machine works in the braking mode. The motor is rotated in opposite direction to that of rotating field. In practice two of the stator terminals are interchanged which changes the phase sequence which in turn reverses the direction of rotation of magnetic field. The motor comes to quick stop under the influence of counter torque which produces braking action. This method by which the motor comes to rest is known as plugging. Only care is taken that the stator must be disconnected from the supply to avoid the rotor to rotate in other direction. To run the induction machine as a generator, its **slip must be less than zero i.e. negative**. The negative slip indicates that the rotor is running at a speed above the synchronous speed. When running as a generator it takes mechanical energy and supplies electrical energy from the stator. Thus the negative slip, generation action takes place and nature of torque – slip characteristics reverses in this generating region. The figure shows the complete torque – slip characteristics showing motoring, generating and the braking region.

Deep Bar Double Cage Rotor

The squirrel cage induction motor lacks in delivering the high starting torque. The application that demands high starting torque can't be started with squirrel cage induction motor. The deep bar double cage induction motor is used for the applications which demands higher starting torque.

The slip ring induction motor can be used for driving the high inertia loads which demand high starting torque. However, the slip ring motor requires more maintenance because it has more parts like slip rings, carbon brushes and the external resistances. One more solution for production of high starting torque is use of double cage squirrel cage induction motor. The double cage induction motor is a modified version of a squirrel cage induction motor and it is used for the applications which demand high starting torque. In a later section we will discuss how the double cage induction motor produces more starting torque

The torque equation of induction motor is given by

$$T = \frac{3}{2\pi n_s} \frac{s E_2^2 R_2}{R_2^2 + s X_2^2}$$

From equation (1), it is clear that the starting torque of the induction motor is proportional to the rotor resistance R_2 and inversely proportional to the rotor reactance(X_2). The rotor resistance of squirrel cage induction motor is kept low to increase the efficiency of the motor by reducing the copper loss. At start the slip of the motor is unity and the rotor supply frequency is

$f_r = sf$ when $s = 1$ @ starting

$f_r = f$

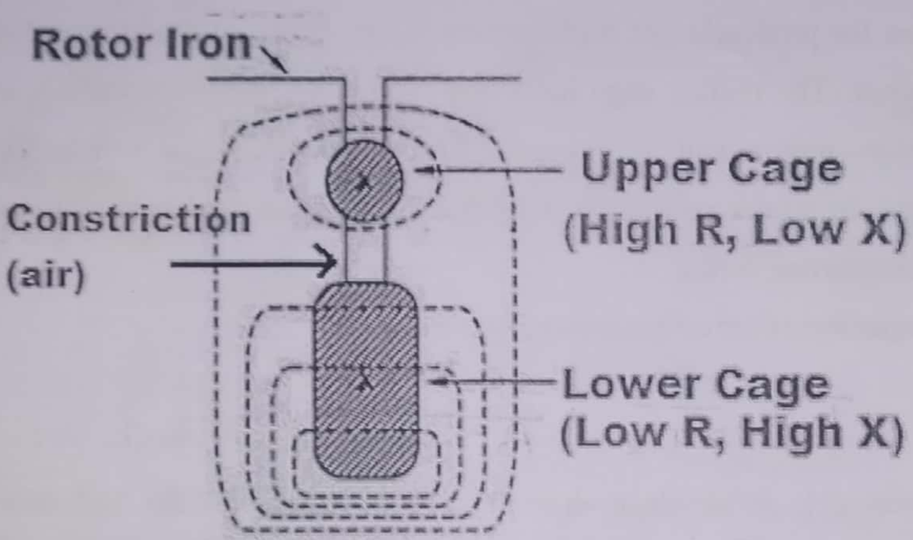
The rotor reactance is slip dependent and at start the rotor reactance is;

$$X_2 = 2\pi s f L_2$$

@ starting, $X_2 = 2\pi f L_2$ $\because s = 1$

reactance will be more @ starting.

At start, the rotor reactance is very high because slip=1. Therefore, the starting torque of the squirrel cage induction motor is low because at start the motor has high rotor reactance. The rotor resistance of the squirrel cage induction motor is low throughout its speed range. Because of these reasons, the squirrel cage induction motor has low starting torque. To increase the starting torque of squirrel cage induction motor, the rotor resistance of a squirrel cage induction is increased by incorporating double bar double cage in the rotor circuit.



Double Cage Rotor Construction

The double cage induction motor has two cages in the rotor circuit used for increasing the starting torque. The rotor of the squirrel cage induction motor has two winding in the rotor. The outer cage has the rotor bars of high resistance and low reactance. The inner cage has rotor bars of low resistance and high reactance. Each rotor bars are short circuited by the end rings. The outer cage bars are made high resistivity materials like aluminum, brass or bronze etc. The cross section area of outer cage bars is less as compared to the cross section area of the inner cage bars. Therefore, the outer cage bars have more resistance than the innner cage bars. The resistance of the outer cage bars is about 5-6 times of the resistance of the inner cage bars. Therefore, the deep bar double cage induction motor produce more starting torque. The leakage flux linking to the outer and inner cage bars depend on the dimension of the air constriction. The air constriction plays a vital role in the flux linking to outer and inner cage bars. In case of air constriction absence, the flux finds its path through the iron part of the rotor and would not reach at the inner cage bars of the motor and the inner cage bars will not contribute in torque production.

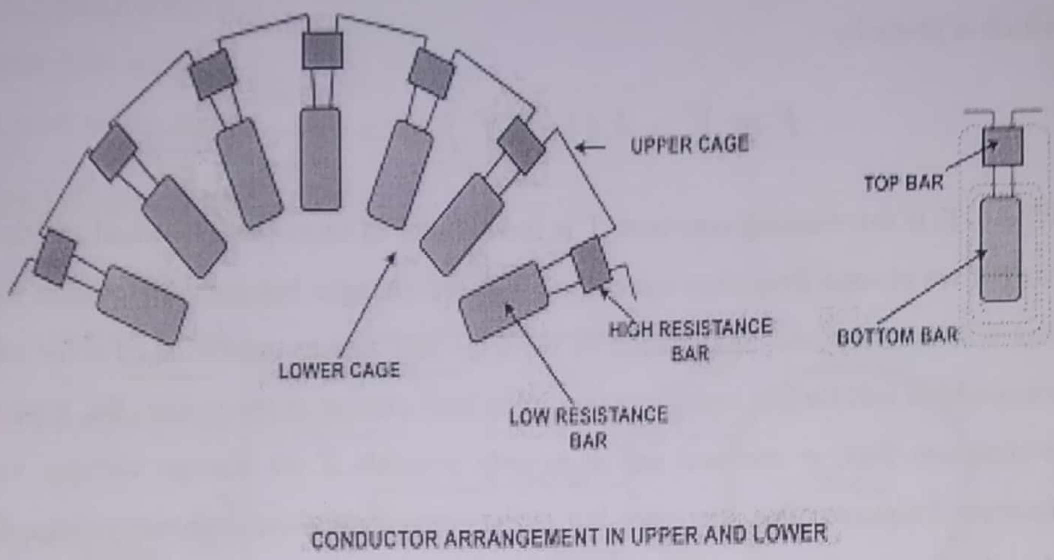


Fig. 3. Conductor arrangements in upper and lower cage

Thus the inner cage impedes the rotor current when the rotor frequency is more. So, most of the current will find its path through the low impedance outer cage bars. The resistance of the outer cage bars are more therefore Deep Bar Double Cage Induction Motor develops high starting torque. The rotor frequency gets decreased with an acceleration of the motor towards its base speed. The frequency of rotor induced voltage and current depend on the slip of the motor. The slip gets decreased with an increase of the motor speed. The slip at start is equal to unity and the slip becomes very less at normal running of the motor. The impedance of the inner cage bars gets reduced when motor attains its full speed. At start the most of the rotor current flows through the outer cage bars. When motor accelerates the current starts shifting from the outer cage bars to the inner cage bars. When the motor attains the full speed, the maximum current flows through the inner cage bars.

Speed Control of 3 Phase Induction Motor by V/F Method

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

$$N_s = \frac{120f}{P}$$

In three phase induction motor EMF is induced by induction similar to that of transformer which is given by

$$E \; or \; V = 4.44\phi K.T.f \; or \; \phi = \frac{V}{4.44KTf}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, it's important to maintain flux, φ constant and it is only possible if we change voltage. i.e. if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ F method. For controlling the speed of three phase induction motor by V/F method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

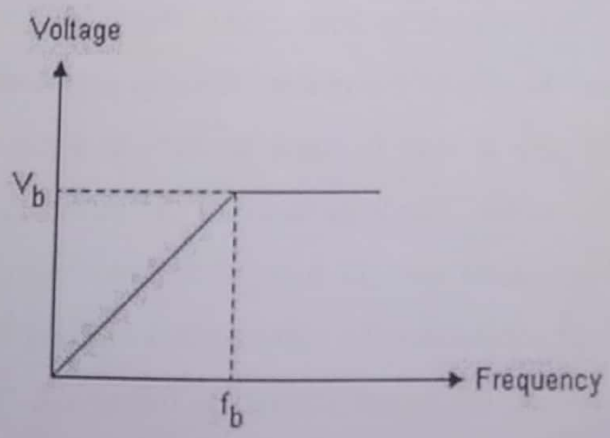


Fig. 4. Constant V/F ratio

Starting Methods of 3 Phase Induction Motors

Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator. These methods are sometimes called as **reduced voltage methods for starting of squirrel cage induction motors**. For this purpose, following methods are used:

1. Stator voltage control
2. Autotransformer starter
3. Star delta starter
4. Direct online starter

Stator voltage control

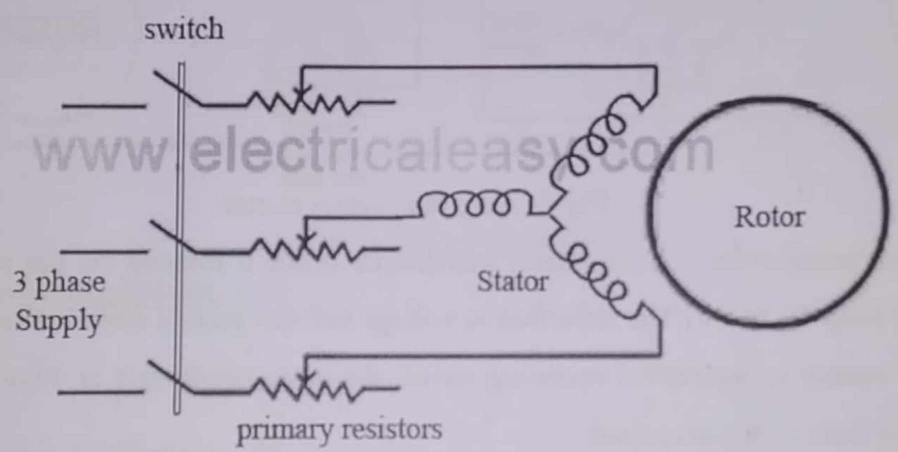


Fig. 5. Stator voltage control

The purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. Then according to the Ohm's law (V=I/Z), the starting current will also be reduced by the same percentage. This method is generally used for a smooth starting of small induction motors. Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

Autotransformer starter

As the name suggests in this method we connect auto transformer in between the three phase power supply and the induction motor as shown in the given diagram.

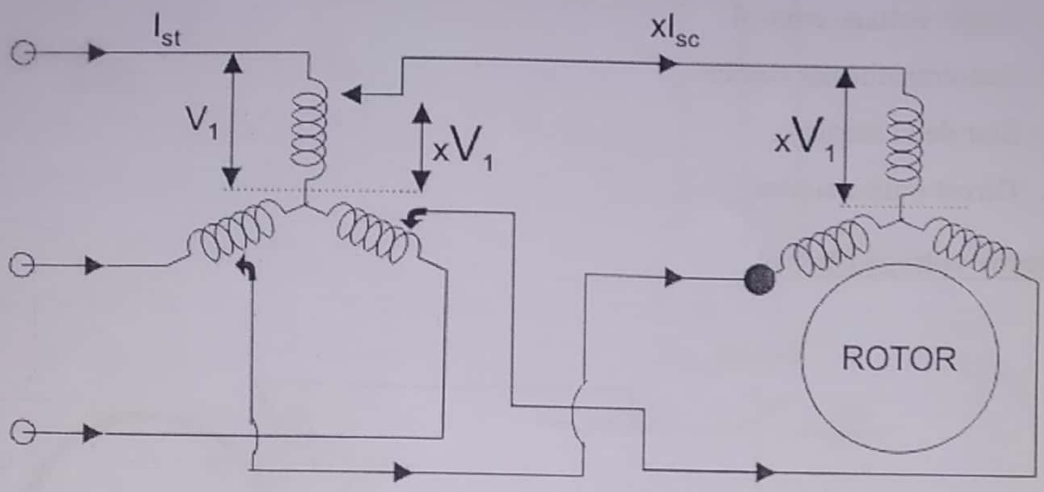


Fig. 6. Autotransformer starter

The auto transformer is a step down transformer hence it reduces the per phase supply voltage from V_1 to xV_1.The reduction in voltage reduces current from I_s to xI_s. After the motor reaches to its normal operating speed, the auto transformer is disconnected and then full line voltage is applied.

Star – Delta Starter

This method is used in the motors, which are designed to run on delta connected stator. A two way switch is used to connect the stator winding in star while starting and in delta while running at normal speed. When the stator winding is star connected, voltage over each phase in motor will be reduced by a factor 1/(sqrt. 3) of that would be for delta connected winding. The starting torque will 1/3 times that it will be for delta connected winding. Hence a star-delta starter is equivalent to an auto-transformer of ratio 1/(sqrt. 3) or 58% reduced voltage.

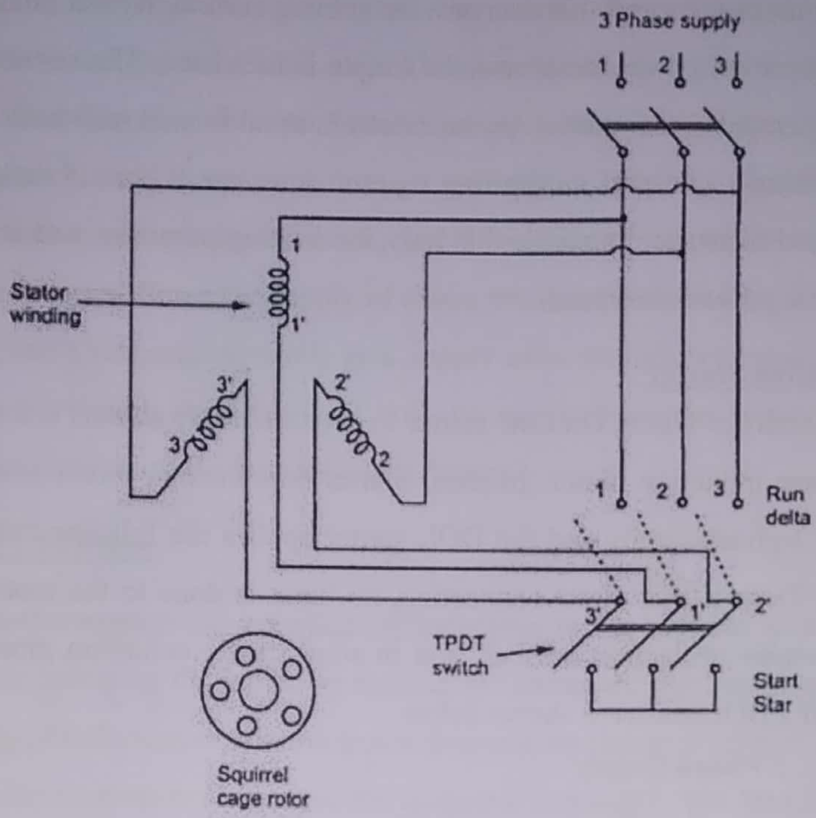


Fig. 7. Star – Delta starter

Rotor Resistance Starter

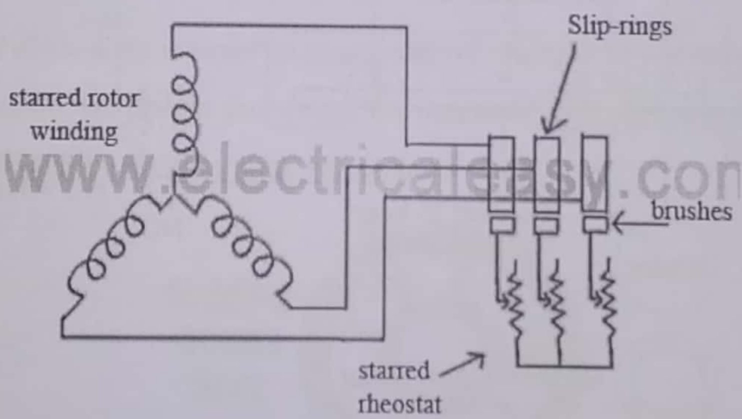


Fig. 8. Rotor resistance starter

Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the above fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand operated or automatic. As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load. The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

Direct Online Starter

A DOL starter (or Direct On Line starter or across the line starter) is a method of starting of a 3 phase induction motor. In DOL Starter an induction motor is connected directly across its 3-phase supply and the DOL starter applies the full line voltage to the motor terminals. Despite this direct connection, no harm is done to the motor. A DOL motor starter contains protection devices, and in some cases, condition monitoring. A wiring diagram of a DOL starter is shown below

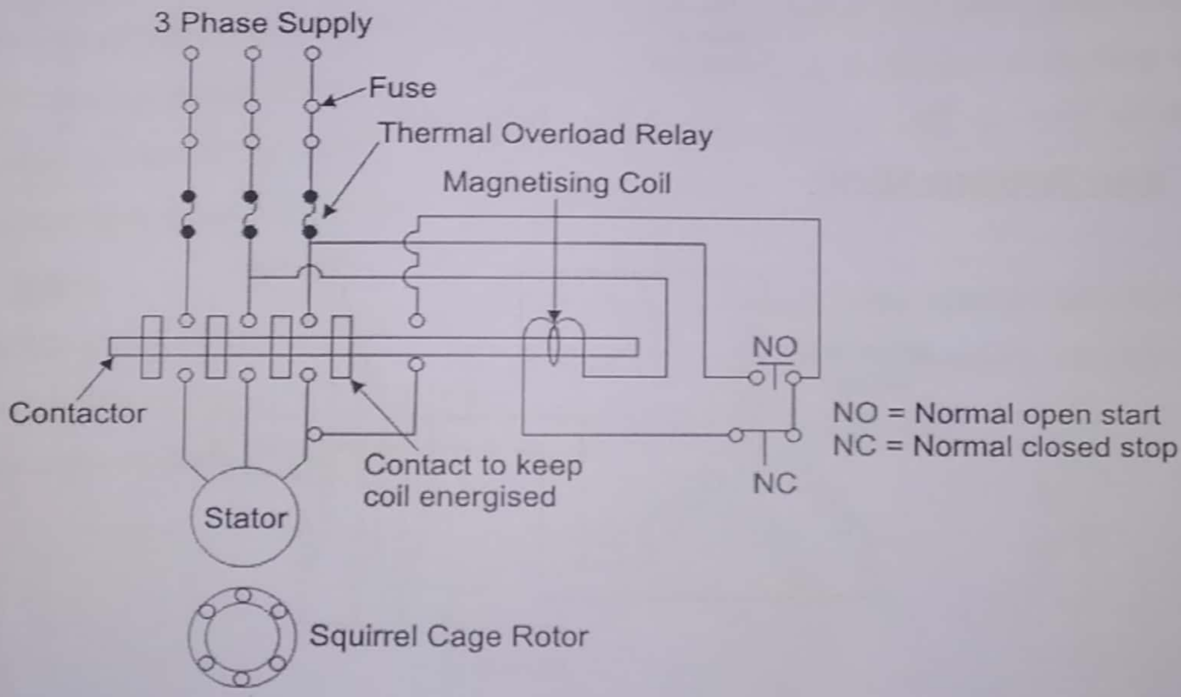


Fig. 9. Star – Delta starter

The working principle of a DOL starter begins with the connection to the 3-phase main with the motor. The control circuit is connected to any two phases and energized from them only. When we press the start button, the current flows through contactor coil (magnetizing coil) and control circuit also. The current energises the contactor coil and leads to close the contacts, and hence 3-phase supply becomes available to the motor. If we press the stop button, the current through the contact becomes discontinued, hence supply to the motor will not be available, and the similar thing will happen when the overload relay operates. Since the supply of motor breaks, the machine will come to rest. The contactor coil (Magnetizing Coil) gets supply even though we release start button because when we release start button, it will get supply from the primary contacts as illustrated in the diagram of the Direct Online Starter.

Cogging and Crawling

The phenomenon cogging and crawling of induction motor happens due to improper motor design or operating the motor by feeding the harmonic rich supply source. In the case of cogging of induction motor, the motor does not accelerate at all and it gets stalled. The cogging phenomenon is also called the magnetic locking. In the case of crawling of induction motor, the motor accelerates up to the speed of 1/7th or 1/13th of the synchronous speed of the motor and it run at slow speed.

Cogging

If the number of stator slots is equal to or an integral multiple of the rotor slots, the motor may refuse to deliver the torque because of the magnetic locking between the stator teeth and rotor teeth caused by the minimum reluctance.

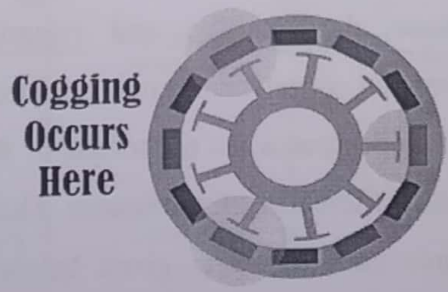


Fig. 10. Cogging effect

The reluctance is minimum when the stator slots are equal to or an integral multiple of the rotor slots. The phenomenon of magnetic locking created between the stator and the rotor teeth is called the cogging. The phenomenon of cogging can be avoided by taking appropriate combination of the stator and the rotor slots while designing the motor. The cogging in induction motor is undesired phenomenon.

There are following ways to eradicate the problem of cogging.

1. The number of stator slots should not be equal to the rotor slots.
2. The rotor slots are skewed. The rotor slots are made not parallel to the axis of the shaft. This arrangement shown in below given picture is called skewing of the rotor.

Crawling

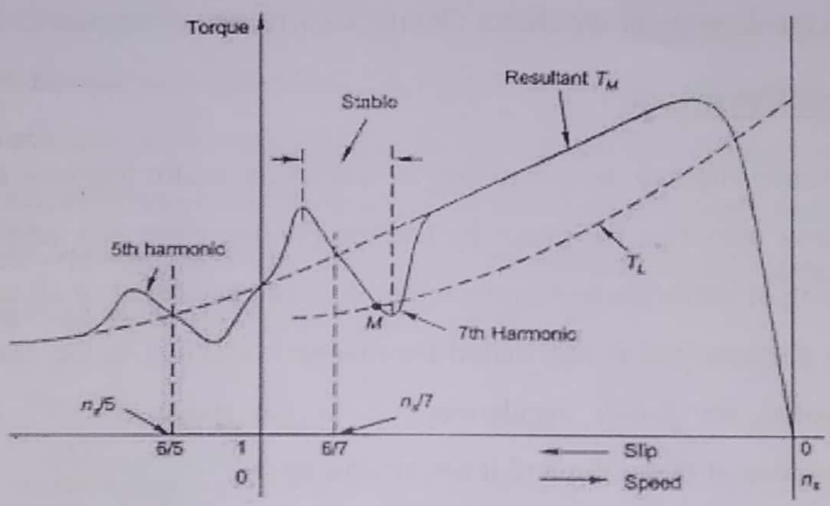


Fig. 11. Crawling effect

When the induction motor is operated with V/F drive, the harmonics of even and odd orders are generated in the motor. The harmonics current produce rotating magnetic field in the stator and the flux gets linked to the rotor. As a result, the current starts flowing in the rotor which produces the positive and negative torque with respect to fundamental. The positive and negative torque produced by the various orders of harmonic current increase or decreases the net torque of the motor. The reduction in the net torque deteriorates the efficiency of the motor. The order of harmonics and the phase sequence of harmonic current are as given below. The phase sequence of the 5^{th} order harmonic is opposite to the phase sequence of the fundamental current. The fundamental current produces the positive torque and the 5^{th} order harmonic current produce the negative torque. The net torque of the motor is always less than the torque produced by the fundamental current if the voltage fed to the stator is distorted. Similarly, 7^{th} order harmonics current produce positive torque and the synchronous speed of the 7^{th} order harmonics is Ns/7. If the torque demand is less, the motor can get a stable point of operation at Ns/7 speed. For example, the motor of 1500 RPM speed can keep operating at the speed 1500/7=214 RPM and the speed of the motor does not increase beyond this point. The phenomenon of running of motor at slow speed is known as the crawling.

Induction Generator

Induction Generator is also known as Asynchronous Generator. An Induction Machine sometimes is used as a generator. Initially, an induction generator or the machine is started as a motor. At the starting, the machine draws the lagging reactive volt-amperes from the supply mains. The speed of the machine is increased above the synchronous speed by an external prime mover. The speed is increased in the same direction as that of the rotating field produced by the stator windings.

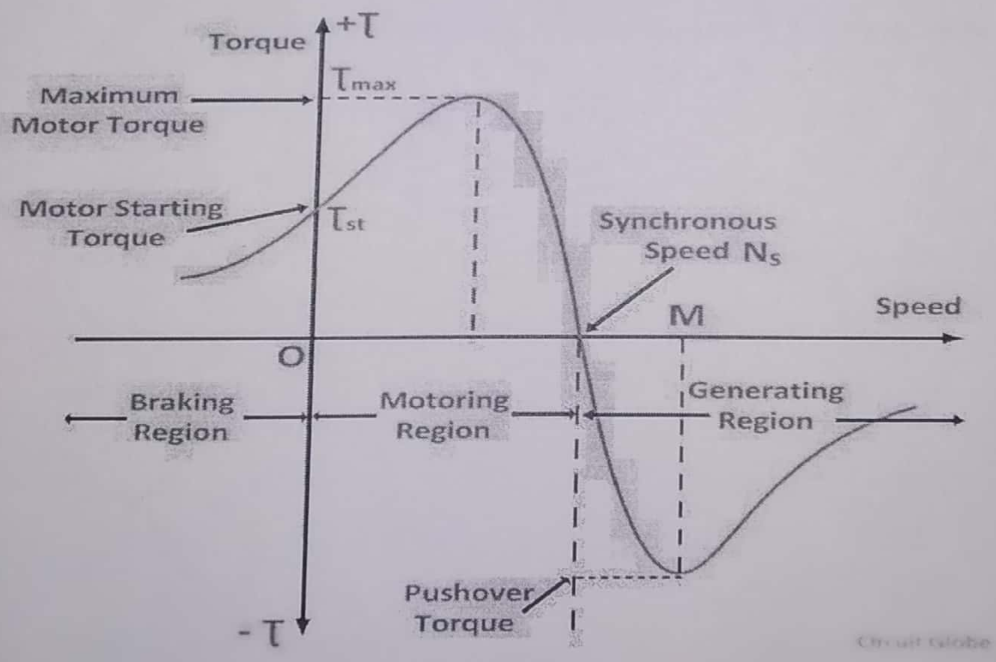


Fig. 12. Regions of Torque slip Characteristics

The induction machine will operate as an induction generator and will start producing a generating torque. This generating torque is opposite to the direction of the rotation of the rotor. At this condition, the slip is negative and the induction generator starts delivering energy to the supply mains. The torque-speed characteristics of a 3 phase induction machine for all ranges of speed are shown above.

The output of the induction generator depends upon the following factors given below.

- ✓ The magnitude of the negative slip.
- ✓ The speed of the rotor or how fast the motor drives above the synchronous speed in the same direction.
- ✓ Rotation of the motor when it operates as an induction motor.

It is clear from the torque-speed characteristic of the induction motor that the maximum possible induced torque occurs in the generating mode. This torque is known as Pushover Torque. If the torque becomes greater than the pushover torque, the generator will over speed. The induction generator is not a self-excited generator. It is necessary to excite the stator with an external polyphase source to produce the rotating magnetic field. This is achieved at the rated voltage and frequency, and the machine is made to operate above the synchronous speed. Since the speed of the induction generator is different from the synchronous speed, it is known as an Asynchronous generator.

known then the rotor induced e.m.f. on standstill can be obtained.

Example 5.8.1 *For a 4 pole, 3 phase, 50 Hz induction motor ratio of stator to rotor turns is 2. On a certain load, its speed is observed to be 1455 r.p.m. when connected to 415 V supply. Calculate,*

i) Frequency of rotor e.m.f. in running condition

ii) Magnitude of induced e.m.f. in the rotor at standstill

iii) Magnitude of induced e.m.f. in the rotor under running condition.

Assume star connected stator.

Solution : The given values are, K = rotor turns/stator turns = 1/2 = 0.5 and

$P = 4$, $f = 50$ Hz, $N = 1455$ r.p.m., $E_{1line} = 415$ V

i)
$$N_s = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

For a given load, N = 1455 r.p.m.

$$\therefore \quad s = \frac{N_s - N}{N_s} = \frac{1500-1455}{1500} = 0.03 \quad \text{i.e.} \quad 3\ \%$$

$$f_r = s\,f = 0.03 \times 50 = \mathbf{1.5\ Hz}$$

ii) At standstill, induction motor acts as a transformer so,

$$\frac{E_{2ph}}{E_{1ph}} = \frac{\text{Rotor turns}}{\text{Stator turns}} = K$$

But ratio of stator to rotor turns is given as 2, i.e.

$$\frac{N_1}{N_2} = 2 \qquad \therefore \quad \frac{N_2}{N_1} = \frac{1}{2} = K$$

and $\quad E_{1\ line} = 415$ V

The given values are always line values unless and until specifically stated as per phase.

$$\therefore \quad E_{1ph} = \frac{E_1}{\sqrt{3}} = \frac{415}{\sqrt{3}} \qquad \text{... As star connection } E_{line} = \sqrt{3}\ E_{ph}$$

$$\therefore \quad E_{1ph} = 239.6 \text{ V}$$

$$\therefore \quad \frac{E_{2ph}}{E_{1ph}} = \frac{1}{2}$$

$$\therefore \quad E_{2ph} = \frac{1}{2} \times 239.6 = \mathbf{119.8\ V} \qquad \text{... Rotor induced e.m.f. on standstill}$$

iii) In running condition,

$$E_{2r} = s\,E_2 = 0.03 \times 119.8 = \mathbf{3.594\ V}$$

The value of rotor induced e.m.f. *in the running condition is also very very small.*

Example 5.8.3 *A 1000 V, 50 Hz, 3 phase slip ring induction motor has star connected stator. The ratio of stator to rotor turns is 3.6. The rotor standstill impedance is 0.01 + j 0.2 Ω. Calculate the external resistance per phase required in rotor circuit to limit starting rotor current to 200 A.*

Solution : The given values are,

$$(E_1)_{line} = 1000 \text{ V}, \quad R_2 = 0.01\ \Omega, \quad X_2 = 0.2\ \Omega, \quad (I_2)_{st} = 200 \text{ A}$$

$$K = \frac{(E_2)_{ph}}{(E_1)_{ph}} = \frac{\text{Rotor turns}}{\text{Stator turns}} = \frac{1}{3.6}$$

Now $$(E_1)_{ph} = \frac{(E_1)_{line}}{\sqrt{3}} = \frac{1000}{\sqrt{3}} = 577.35 \text{ V}$$

$$\frac{E_2}{E_1} = \frac{1}{3.6} = \frac{E_2}{577.35} \quad \text{i.e.} \quad E_2 = \mathbf{160.375\ V}$$

Let at start R_x be the external resistance per phase, introduced in rotor circuit.

$$\therefore \quad R_2' = R_2 + R_x \qquad \text{... At start}$$

$$\therefore \quad (I_2)_{st} = \text{Rotor current at start} = \frac{E_2}{\sqrt{R_2'^2 + X_2^2}}$$

$$\therefore \quad 200 = \frac{160.375}{\sqrt{(R_2')^2 + (0.2)^2}}$$

$$\therefore (R_2')^2 + (0.2)^2 = 0.6429 \quad \text{i.e.} \quad (R_2')^2 = 0.6029$$

$$\therefore \quad R_2' = 0.7765\ \Omega$$

$$\therefore \quad R_x = 0.7765 - 0.01 = \mathbf{0.76665\ \Omega\ per\ phase}$$

Example 5.9.1 *A 3 phase, 400 V, 50 Hz, 4 pole induction motor has star connected stator winding. The rotor resistance and reactance are 0.1 Ω and 1 Ω respectively. The full load speed is 1440 r.p.m. Calculate the torque developed on full load by the motor. Assume stator to rotor ratio as 2 : 1.*

Solution : The given values are,

$P = 4, \; f = 50 \text{ Hz}, \; R_2 = 0.1 \; \Omega, \; X_2 = 1 \; \Omega, \; N = 1440 \text{ r.p.m.}$

$$\frac{\text{Stator turns}}{\text{Rotor turns}} = \frac{2}{1}$$

$$\therefore \quad K = \frac{E_2}{E_1} = \frac{\text{Rotor turns}}{\text{Stator turns}} = \frac{1}{2} = 0.5$$

$$N_s = \frac{120 f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$E_{1 \, line} = 400 \text{ V} \qquad \text{... Stator line voltage given}$$

$$\therefore \quad E_{1ph} = \frac{E_{1 \, line}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94 \text{ V}$$

But $$\frac{E_{2ph}}{E_{1ph}} = 0.5 = K$$

$$\therefore \quad E_{2ph} = 0.5 \times 230.94 = 115.47 \text{ V}$$

$$\text{Full load slip, } s = \frac{N_s - N}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

$$n_s = \text{Synchronous speed in r.p.s.} = \frac{N_s}{60} = \frac{1500}{60} = 25 \text{ r.p.s.}$$

$$T = \frac{3}{2 \pi n_s} \cdot \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} = \frac{3}{2 \pi \times 25} \times \frac{0.04 \times (115.47)^2 \times 0.1}{[(0.1)^2 + (0.04 \times 1)^2]} = \mathbf{87.81 \text{ N-m}}$$

Example 5.10.1 *A 400 V, 4 pole, 3 phase, 50 Hz star connected induction motor has a rotor resistance and reactance per phase equal to 0.01 Ω and 0.1 Ω respectively. Determine i) starting torque ii) slip at which maximum torque will occur iii) speed at which maximum torque will occur iv) maximum torque v) full load torque if full load slip is 4 %. Assume ratio of stator to rotor turns as 4.*

Solution : The given values are,

$P = 4$, $f = 50$ Hz, Stator turns/rotor turns = 4, $R_2 = 0.01\ \Omega$, $X_2 = 0.1\ \Omega$

$$E_{1line} = \text{Stator line voltage} = 400 \text{ V}$$

$$E_{1ph} = \frac{E_{1\,line}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94 \text{ V} \qquad \text{... Star connection}$$

$$K = \frac{E_{2ph}}{E_{1ph}} = \frac{\text{Rotor turns}}{\text{Stator turns}} = \frac{1}{4}$$

$$\therefore \quad E_2 = \frac{1}{4} \times E_{1ph} = \frac{230.94}{4} = 57.735 \text{ V}$$

$$N_s = \frac{120\, f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

i) At start $\quad s = 1$

$$\therefore \quad T_{st} = \frac{k E_2^2 R_2}{R_2^2 + X_2^2} \qquad \text{where } k = \frac{3}{2\pi n_s}$$

$$n_s = \frac{N_s}{60} = \frac{1500}{60} = 25 \text{ r.p.s.}$$

$$\therefore \quad k = \frac{3}{2\pi \times 25} = 0.01909$$

$$\therefore \quad T_{st} = \frac{0.01909 \times (57.735)^2 \times 0.01}{(0.01)^2 + (0.1)^2} = \mathbf{63.031\ N\text{-}m}$$

ii) Slip at which maximum torque occurs is,

$$s_m = \frac{R_2}{X_2} = \frac{0.01}{0.1} = 0.1$$

$$\% \, s_m = 0.1 \times 100 = \mathbf{10\ \%}$$

iii) Speed at which maximum torque occurs is speed corresponding to s_m,

$$N_m = N_s (1 - s_m) = 1500 (1 - 0.1) = \mathbf{1350\ r.p.m.}$$

iv) The maximum torque is,

$$T_m = \frac{k E_2^2}{2 X_2} = \frac{0.01909 \times (57.735)^2}{2 \times 0.1} = \mathbf{318.16\ N\text{-}m}$$

v) Full load slip, $\quad s_f = 0.04 \quad$ as % s_f = 4 %

$$\therefore \quad T_{f.l.} = \frac{k\, s_f\, E_2^2 R_2}{R_2^2 + (s_f X_2)^2} = \frac{0.01909 \times 0.04 \times (57.735)^2 \times 0.01}{(0.01)^2 + (0.04 \times 0.1)^2} = \mathbf{219.52\ N\text{-}m}$$

Example 5.10.2 *A three phase, 50 Hz, 400 V induction motor has 4 poles star connected stator winding. Rotor resistance and reactance per phase are 0.15 Ω and 1 Ω respectively. Full load slip is 5 %. Calculate : a) Total torque developed b) Maximum torque c) Speed at maximum torque. Assume stator to rotor ratio 2:1.*

Solution : The given values are,

$$50 \text{ Hz}, \quad V_L = 400 \text{ V}, \quad P = 4, \quad R_2 = 0.15\ \Omega, \quad X_2 = 1\ \Omega, \quad s = 0.05$$

Now $\quad E_1(\text{line}) = V_L = 400 \text{ V}$

$$\therefore \quad E_{1ph} = \frac{E_1(\text{line})}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94 \text{ V}$$

$$\frac{E_2}{E_1} = \frac{1}{2} \qquad \text{... Given}$$

$$\therefore \quad E_2 = \frac{E_{1ph}}{2} = \frac{230.94}{2} = 115.47 \text{ V}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$n_s = \frac{N_s}{60} = 25 \text{ r.p.s.}$$

i)
$$T = \frac{3}{2\pi n_s} \times \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2} = \frac{3}{2\pi \times 25} \times \frac{0.05 \times (115.47)^2 \times 0.15}{[(0.15)^2 + (0.05 \times 1)^2]} = \mathbf{76.39 \text{ N-m}}$$

ii)
$$T_m = \frac{3}{2\pi n_s} \times \frac{E_2^2}{2X_2} = \frac{3}{2\pi \times 25} \times \frac{(115.47)^2}{2 \times 1} \qquad \text{... As } s = R_2/X_2$$

$$= \mathbf{127.323 \text{ N-m}}$$

iii)
$$s_m = \frac{R_2}{X_2} = \frac{0.15}{1} = 0.15 \quad \text{i.e. } 15\ \%$$

$$\therefore \quad N = (1 - s_m) N_s = (1 - 0.15) \times 1500 = \mathbf{1275 \text{ r.p.m.}}$$

Example 5.12.1 *A 746 kW, 3-phase, 50 Hz, 16-pole induction motor has a rotor impedance of (0.02 + j0.15) Ω at standstill. Full load torque is obtained at 360 r.p.m. Calculate*

1) The ratio of maximum to full-load torque.

2) The speed at maximum torque and

3) The rotor resistance to be added to get maximum starting torque.

4) The ratio of maximum torque to starting torque. **AU : May-14, Marks 12**

Solution : $P = 16$, $f = 50$ Hz, $N_{FL} = 360$ r.p.m., $R_2 = 0.02\ \Omega$, $X_2 = 0.15\ \Omega$

$$N_s = \frac{120\ f}{P} = 375 \text{ r.p.m.} \quad \text{i.e.} \quad s_{fl} = \frac{N_s - N_{FL}}{N_s} = 0.04 = \text{F.L. slip}$$

$$s_m = \frac{R_2}{X_2} = \frac{0.02}{0.15} = 0.1333 \qquad \text{... Slip at } T_{max}$$

1) $$\frac{T_m}{T_{FL}} = \frac{s_m^2 + s_{fl}^2}{2 s_m s_{fl}} = \frac{(0.1333)^2 + (0.04)2}{2 \times 0.1333 \times 0.04} = \mathbf{1.817}$$

2) $$N_m = N_s(1 - s_m) = 375(1 - 0.1333) = \mathbf{325\ r.p.m.}$$

3) To get T_m at start, $s_m = 1$ i.e. $R_2 = X_2$ general

$\therefore$ $$R_{ex} = 0.15 - 0.02 = \mathbf{0.13\ \Omega} \qquad \boxed{R_{ex} = R_2' - R_2} \qquad \text{... External resistance}$$

4) $$\frac{T_m}{T_{st}} = \frac{1 + s_m^2}{2 s_m} = \frac{1 + (0.1333)^2}{2 \times 0.1333} = \mathbf{3.8176}$$

$R_2 - X_2 = 0$
or $X_2 - R_2 = 0$

Example 5.14.1 *A 6 pole, 50 Hz, 3-phase induction motor has a rotor resistance of 0.25 Ω per phase and a maximum torque of 10 N-m at 875 r.p.m. Calculate 1) The torque when the slip is 5 % and 2) The resistance to be added to the rotor circuit to obtain 60 % of the maximum torque at starting. Explain why two values are obtained for this resistance. Which value will be used ? The stator impedance is assumed to be negligible.*

AU : May-08, Marks 12

Solution : $P = 6$, $f = 50$ Hz, $R_2 = 0.25\ \Omega$, $T_{max} = 10$ Nm, $N_m = 875$ r.p.m.

$$N_s = \frac{120f}{P} = \frac{120\times 50}{6} = 1000 \text{ r.p.m.}$$

$$s_m = \frac{N_s - N_m}{N_s} = \frac{1000-875}{1000} = 0.125 \quad \text{i.e.} \quad 1.25\ \%$$

But $\quad s_m = \dfrac{R_2}{X_2} \quad$ i.e. $\quad 0.125 = \dfrac{0.25}{X_2} \quad$ i.e $\quad X_2 = \dfrac{0.25}{0.125} = 2\ \Omega$

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

$$\frac{T_{fl}}{T_m} = \frac{2 s_{fl} s_m}{s_m^2 + s_{fl}^2}$$

$$\therefore \quad \frac{T_1}{T_{max}} = \frac{s_1 E_2^2 R_2}{R_2^2 + (s_1 X_2)^2} \times \frac{R_2^2 + (s_m X_2)^2}{s_m E_2^2 R_2}$$

... $s_1 = 5\ \% = 0.05$

$$\therefore \quad \frac{T_1}{10} = \frac{0.05[(0.25)^2 + (0.125\times 2)^2]}{0.125[(0.25)^2 + (0.05\times 2)^2]}$$

$\therefore \quad T_1 = \mathbf{6.8965\ Nm}$ ... Torque at slip 5 %

2) $$T_{st} = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \quad \text{as } s = 1 \text{ at start}$$

Now R_x is added to the rotor to make its resistance R_2' and T_{st} = 60 % of T_{max}

$$\therefore \quad \frac{T_{st}}{T_{max}} = 0.6 = \frac{E_2^2 R_2'}{(R_2')^2 + (X_2)^2} \times \frac{[R_2^2 + (s_m X_2)^2]}{s_m E_2^2 R_2}$$

$$\therefore \quad 0.6 = \frac{R_2'[(0.25)^2 + (0.125 \times 2)^2]}{0.125[(R_2')^2 + (2)^2] \times 0.25}$$

$\therefore$ 0.01875 $[(R_2')^2 + 4] = 0.125\ R_2'$ i.e. $0.01875\ (R_2')^2 - 0.125\ R_2' + 0.075 = 0$

$\therefore \quad R_2' = 6, \quad 0.6666$

But $\quad R_2' = R_2 + R_x$ i.e. $0.666 = 0.25 + R_x$

$\therefore \quad R_x = \mathbf{0.4166\ \Omega}$

Mathematically there are two values of this resistance, one for motoring action and other for generating action. The higher of the two must be elliminated as it can produce large rotor copper losses and it gives absurd values for the slip at which maximum torque occurs. Hence smaller of the two is to be used.

Example 5.14.2 *An 8 pole, 50 Hz, 3 phase induction motor is running at 4 % slip when delivering full load torque. It has standstill rotor resistance of 0.1 Ω and reactance of 0.6 Ω per phase. Calculate the speed of the motor if an additional resistance of 0.5 Ω per phase is inserted in the rotor circuit. Assume full load torque remains constant.*

AU : Dec.-08, Marks 8

Solution : $P = 8$, $f = 50$ Hz, $s = 4\ \% = 0.04$, $R_2 = 0.1\ \Omega$, $X_2 = 0.6\ \Omega$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ r.p.m.}$$

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

New $R_2' = R_2 + R_{ex} = 0.1 + 0.5 = 0.6\ \Omega$

The corresponding new slip be s'.

$$\therefore \quad \frac{T_1}{T_2} = \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \times \frac{(R_2')^2 + (s' X_2)^2}{s' E_2^2 R_2'} = 1 \qquad \text{...Torque constant}$$

$$\therefore \quad s R_2 \left[(R_2')^2 + (s' X_2)^2\right] = s' R_2' \left[R_2^2 + (s X_2)^2\right]$$

$$\therefore \quad 0.04 \times 0.1 \, [(0.6)^2 + (0.6s')^2] = s' \times 0.6 \, [(0.1)^2 + (0.04 \times 0.6)^2]$$

$$\therefore \quad 0.36(s')^2 - 1.5864 \, s' + 0.36 = 0$$

Solving, $s' = 0.24$ ... Neglecting value greater than 1

Hence the new speed of the motor is,

$$N' = N_s (1 - s') = 750 \, (1 - 0.24) = \mathbf{570 \text{ r.p.m}}$$

Example 5.17.1 *The useful torque of a 3 phase, 50 Hz, 8 pole induction motor is 190 Nm. The rotor frequency is 1.5 Hz. Calculate the rotor copper losses if mechanical losses are 700 watts.*

Solution : $T_{sh} = 190$ Nm, $f_r = 1.5$ Hz, Mechanical loss = 700 W

Now $f_r = sf$ i.e. $1.5 = s \times 50$, i.e. $s = \dfrac{1.5}{50} = 0.03$

Now $P_{out} = T_{sh} \times \omega$ and $N = N_s (1 - s)$

$$N_s = \frac{120\, f}{P} = \frac{120 \times 50}{8} = 750 \text{ r.p.m.} \quad \text{and} \quad N = 750\,(1 - 0.03) = 727.5 \text{ r.p.m.}$$

$$\therefore \quad P_{out} = T_{sh} \times \frac{2\pi N}{60} = 190 \times 2\pi \times \frac{727.5}{60} = 14474.88 \text{ W}$$

From power flow diagram,

$$P_m - \text{Mechanical losses} = P_{out} \quad \text{i.e.} \quad P_m - 700 = 14474.88$$

$$\therefore \quad P_m = 700 + 14474.88 = 15174.88 \text{ W}$$

From $P_2 : P_c : P_m$ is $1 : s : 1-s$ i.e. $\frac{P_c}{P_m} = \frac{s}{1-s}$

$$P_c = P_m \times \frac{s}{1-s} = 15174.88 \times \frac{0.03}{(1-0.03)} = \mathbf{469.326 \text{ W}}$$

Example 5.17.2 *A 415 V, 3 phase, 50 Hz, 4 pole, star connected induction motor runs at 24 rev/s on full load. The rotor resistance and reactance per phase are 0.35 ohm and 3.5 ohm respectively and the effective rotor-stator turns ratio is 0.85 : 1. Calculate :*

1) Slip 2) The full load torque

3) The power output if the mechanical losses amount to 770 W

4) The maximum torque

5) The speed at which the maximum torque occurs and

6) The starting torque.

AU : Dec.-08, Marks 8

Solution : $V_L = 415$ V, $f = 50$ Hz, $P = 4$, $N_{FL} = 24$ r.p.s., $R_2 = 0.35\ \Omega$, $X_2 = 3.5\ \Omega$

$$K = \text{Rotor turns/Stator turns} = 0.85$$

$$N_{FL} = 24 \times 60 = 1440 \text{ r.p.m.}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

1) $$\text{Slip } s = \frac{N_s - N}{N_s} \times 100 = \frac{1500 - 1440}{1500} \times 100 = \mathbf{4\ \%}$$

2) $$E_{1line} = V_L = 415 \text{ V} \quad \text{i.e.} \quad E_{1ph} = \frac{415}{\sqrt{3}} \quad \text{... Star connection}$$

$$\therefore \quad \frac{E_{2ph}}{E_{1ph}} = K = 0.85 \quad \text{i.e.} \quad E_{2ph} = \frac{0.85 \times 415}{\sqrt{3}} = 203.6603 \text{ V}$$

$$T = \frac{3}{2\pi n_s} \times \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2} \quad \text{... } n_s = \frac{N_s}{60} = 25 \text{ r.p.s.}$$

$$= \frac{3}{2\pi \times 25} \times \frac{0.04 \times (203.6603)^2 \times 0.35}{\left[(0.35)^2 + (0.04 \times 3.5)^2\right]} = \mathbf{78.0455 \text{ Nm}}$$

$$P_m = T \times \omega = 78.0455 \times \frac{2\pi \times 1440}{60} = 11768.9902 \text{ W}$$

3) $$P_{out} = P_m - \begin{bmatrix}\text{Mechanical} \\ \text{losses}\end{bmatrix} = 11768.9902 - 770 = \mathbf{10998.99 \text{ W}}$$

4) $$T_m = \frac{3}{2\pi n_s} \times \frac{E_2^2}{2X_2} = \frac{3}{2\pi \times 25} \times \frac{(203.6603)^2}{2 \times 3.5} = \mathbf{113.166 \text{ Nm}}$$

5) $$s_m = \frac{R_2}{X_2} = \frac{0.35}{3.5} = 0.1 \quad \text{i.e.} \quad 10\ \%$$

$$N_m = N_s(1 - s_m) = 1500\,(1 - 0.1) = \mathbf{1350 \text{ r.p.m.}}$$

6) $$T_{st} = \frac{3}{2\pi n_s} \times \frac{E_2^2 R_2}{R_2^2 + X_2^2} = \frac{3}{2\pi \times 25} \times \frac{(203.6603)^2 \times 0.35}{\left[(0.35)^2 + (3.5)^2\right]} = \mathbf{22.3965 \text{ Nm}}$$

Example 5.17.3 *A 100 kW (output), 3300 V, 3 phase, star connected induction motor has a synchronous speed of 500 r.p.m. The full load slip is 1.8 % and full load power factor 0.85. Stator copper loss = 2440 W. Iron loss = 3500 W. Rotational losses = 1200 W. Calculate 1) The rotor copper loss 2) The line current 3) The full load efficiency.*

AU : Dec.-07, Marks 8

Solution : $P_{out} = 100$ kW, $V_L = 3300$ V, Star, $N_s = 500$ r.p.m., $s = 1.8\ \%$

$\cos\phi = 0.85$, Stator copper loss = 2440 W, Iron loss = 3500 W

$$P_m = P_{out} + \text{Rotational losses} = 100 \times 10^3 + 1200 = 101.2 \text{ kW}$$

1) $P_2 : P_c : P_m$ is $1 : s : 1 - s$

$$\therefore \quad \frac{P_c}{P_m} = \frac{s}{1-s} \quad \text{i.e. } P_c = \frac{0.018}{1-0.018} \times 101.2 = \mathbf{1.855 \text{ kW}}$$

2) $$P_2 = \frac{P_c}{s} = \frac{1.855}{0.018} = 103.0555 \text{ kW}$$

$$\therefore \quad P_{in} = P_2 + [\text{Stator copper loss}] + [\text{Iron loss}] = 103.0555 + 2.44 + 3.5$$

$$= 109 \text{ kW}$$

$$P_{in} = \sqrt{3}\, V_L I_L \cos\phi \quad \text{i.e.} \quad I_L = \frac{109 \times 10^3}{\sqrt{3} \times 3300 \times 0.85} = \mathbf{22.4353 \text{ A}}$$

3) $$\%\ \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{100}{109} \times 100 = \mathbf{91.743\ \%}$$

$\therefore \quad T_{max} = 8701.6697$ syn. watts

Example 5.17.5 *An 18.65 kW, 4 pole, 50 Hz, 3 phase induction motor has friction and windage losses of 2.5 percent of the output. Full load slip is 4 %. Find for full load 1) Rotor copper loss 2) Rotor input 3) Shaft torque 4) the gross electromagnetic torque.*

AU : Dec.-06, 10, Marks 8

Solution : $P_{out} = 18.65$ kW, $P = 4$, $f = 50$ Hz, Friction loss $= 2.5\ \%$ of P_{out}, $s = 4\ \% = 0.04$

$$\therefore \quad P_m = P_{out} + \text{Frictional losses} = 18.65\times10^3 + \frac{2.5}{100}\times18.65\times10^3 = 19116.25\ \text{W}$$

Now, $P_2 : P_c : P_m$ is $1 : s : 1-s$ i.e. $\frac{P_c}{P_m} = \frac{s}{1-s}$

$$\therefore \quad P_c = P_m\left[\frac{s}{1-s}\right] = 19116.25\left[\frac{0.04}{1-0.04}\right] = \mathbf{796.51\ W} \quad \text{... Rotor cu loss}$$

$$\therefore \quad P_2 = P_m + P_c = 19116.25 + 796.51 = \mathbf{19912.76\ W} \quad \text{... Rotor input}$$

$$N_s = \frac{120 f}{P} = \frac{120\times50}{4} = 1500\ \text{r.p.m.}$$

$$N_{fl} = N_s(1-s) = 1500\,(1-0.04) = 1440\ \text{r.p.m.}$$

$$\therefore \quad T_{sh} = \frac{P_{out}}{\omega} = \frac{P_{out}}{\frac{2\pi N}{60}} = \frac{18.65\times10^3}{\frac{2\pi\times1440}{60}} = \mathbf{123.6766\ Nm} \quad \text{... Shaft torque}$$

$$T_{lost} = \frac{\text{Frictional losses}}{\frac{2\pi N}{60}} = \frac{\frac{2.5}{100}\times18.65\times10^3}{\frac{2\pi\times1440}{60}} = 3.0919\ \text{Nm}$$

$$\therefore \quad T_{gross} = T_{sh} + T_{lost} = \mathbf{126.7685\ Nm} \quad \text{... Gross torque}$$

Example 5.17.6 *The real 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 the line current, slip, rotor copper loss, mechanical power output and efficiency.* **AU : May-13, Marks 8**

Solution : $V_L = 415$ V, $P = 6$, $f = 50$ Hz, $N = 970$ r.p.m., $P_{in} = 41$ kW

$$N_s = \frac{120 f}{P} = 1000 \text{ r.p.m.}, \quad s = \frac{N_s - N}{N_s} = \mathbf{0.03} \quad \text{i.e.} \quad \mathbf{3\ \%}$$

$$\therefore \quad P_{in} = \sqrt{3}\, V_L\, I_L \cos\phi \qquad \text{i.e.} \quad I_L = \frac{41\times10^3}{\sqrt{3}\times415\times0.9} = \mathbf{63.3771\ A}$$

$$P_2 = P_{in} - \text{Stator losses} = 41 - 1.1 = 39.9 \text{ kW}$$

$P_2 : P_c : P_m$ is $1 : s : 1 - s$ i.e. $\frac{P_2}{P_c} = \frac{1}{s}$

$$\therefore \quad P_c = sP_2 = 0.03 \times 39.9 = \mathbf{1.197\ kW} \qquad \text{... Rotor copper loss}$$

$$P_m = P_2 - P_c = 39.9 - 1.197 = \mathbf{38.703\ kW} \qquad \text{... Mechanical power}$$

$$P_{out} = P_m - \text{Mechanical loss} = 38.703 - 1.2 = \mathbf{37.503\ kW} \qquad \text{... Output}$$

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

Example 5.17.7 *An eight pole, 3-phase induction motor running with the slip of 4 % takest 20 kW from a 50 Hz supply. Stator losses amount to 0.5 kW. If the mechanical torque lost in friction is 16.2 Nm. Find the power output and efficiency.* **AU : May-12, Marks 8**

Solution : $P = 8$, $s = 0.04$, $P_{in} = 20$ kW, $f = 50$ Hz

Stator losses = 0.5 kW, $T_{lost} = 16.2$ Nm

$$N_s = \frac{120\,f}{P} = 750 \text{ r.p.m.},\ N = (1-s)\,N_s = 720 \text{ r.p.m.}$$

$$\text{Firctional loss} = T_{lost}\times\omega = T_{lost}\times\frac{2\pi N}{60} = 1221.4512 \text{ W}$$

$$P_2 = P_{in} - \text{Stator losses} = 20 - 0.5 = 19.5 \text{ kW}$$

$$P_2 : P_c : P_m \text{ is } 1 : s : 1-s \text{ hence } \frac{P_2}{P_m} = \frac{1}{1-s}$$

$$\therefore \quad P_m = P_2\,(1-s) = 19.5\,(1-0.04) = 18.72 \text{ kW}$$

$$\therefore \quad P_{out} = P_m - \text{Friction loss} = 18.72 - 1.2214 = \mathbf{17.4985\ kW}$$

$$\%\,\eta = \frac{P_{out}}{P_{in}}\times 100 = \frac{17.4985}{20}\times 100 = \mathbf{87.49\ \%}$$

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Vishnupur, BHIMAVARAM – 534 202

ELECTRICAL & ELECTRONICS ENGINEERING

II B. Tech. II Semester EEE R20

Electrical Machines – II

Material for Unit III

Single Phase Motors: Single phase induction motors – constructional features – problem of starting–double revolving field theory–starting methods – equivalent circuit – AC series motor.

Unit III Single Phase Motors

About Single Phase Induction Motor

We use the single phase power system more widely than three phase system for domestic purposes, commercial purposes and some extent in industrial uses. Because, the single-phase system is more economical than a three-phase system and the power requirement in most of the houses, shops, offices are small, which can be easily met by a single phase system. The single phase motors are simple in construction, cheap in cost, reliable and easy to repair and maintain. Due to all these advantages, the single phase motor finds its application in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, washing machines, etc.

Construction of Single Phase Induction Motor

Like any other electrical motor asynchronous motor also have two main parts namely rotor and stator

Stator

As its name indicates stator is a stationary part of induction motor. A single phase AC supply is given to the stator of single phase induction motor.

Rotor

The rotor is a rotating part of an induction motor. The rotor connects the mechanical load through the shaft. The rotor in the single-phase induction motor is of squirrel cage rotor type.

The construction of single phase induction motor is almost similar to the squirrel cage three-phase induction motor. But in case of a single phase induction motor, the stator has two windings instead of one three-phase winding in three phase induction motor.

Stator of Single Phase Induction Motor

The stator of the single-phase induction motor has laminated stamping to reduce eddy current losses on its periphery. The slots are provided on its stamping to carry stator or main winding. Stampings are made up of silicon steel to reduce the hysteresis losses. When we apply a single phase AC supply to the stator winding, the magnetic field gets produced, and the motor rotates at speed slightly less than the synchronous speed N_s. Synchronous speed N_s is given by

$$N_s = \frac{120f}{P}$$

Where,

f = supply voltage frequency,

P = No. of poles of the motor.

The construction of the stator of the single-phase induction motor is similar to that of three phase induction motor except there are two dissimilarities in the winding part of the single phase induction motor.

1. Firstly, the single-phase induction motors are mostly provided with concentric coils. We can easily adjust the number of turns per coil can with the help of concentric coils. The MMF distribution is almost sinusoidal.
2. Except for shaded pole motor, the asynchronous motor has two stator windings namely the main winding and the auxiliary winding. These two windings are placed in space quadrature to each other.

Rotor of Single Phase Induction Motor

The construction of the rotor of the single-phase induction motor is similar to the squirrel cage three-phase induction motor. The rotor is cylindrical and has slots all over its periphery. The slots are not made parallel to each other but are a little bit skewed as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of induction motor more smooth and quieter (i.e. less noisy).

The squirrel cage rotor consists of aluminum, brass or copper bars. These aluminum or copper bars are called rotor conductors and placed in the slots on the periphery of the rotor. The copper or aluminum rings permanently short the rotor conductors called the end rings.

To provide mechanical strength, these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling a cage and hence got its name as squirrel cage induction motor. As end rings permanently short the bars, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars get permanently shorted. The absence of slip ring and brushes make the construction of single phase induction motor very simple and robust.

Working Principle of Single Phase Induction Motor

When we apply a single phase AC supply to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors.

According to the Faraday’s law of electromagnetic induction, EMF gets induced in the rotor. As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its flux called rotor flux. Since this flux is produced due to the induction principle so, the motor working on this principle got its name as an induction motor. Now there are two fluxes one is main flux, and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

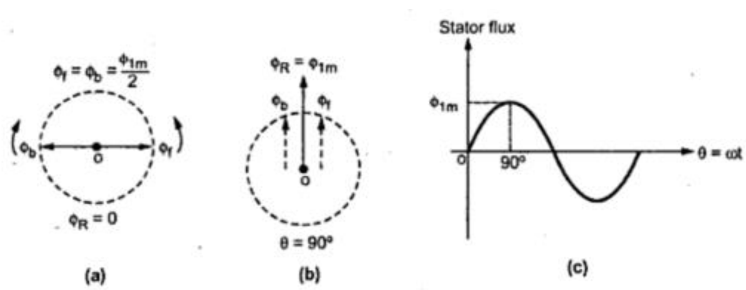
Why single phase induction motor not self starts?

Because of single phase supply, at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero. **So, the single phase induction motors are not self-starting motors.**

Double Revolving Field Theory

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating quantity. In case of single phase induction motors, the stator winding produces an alternating magnetic field having maximum magnitude of $\mathbf{\Phi_{1m}}$. According to double revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e. ($\mathbf{\Phi_{1m}/2}$). Both these components are rotating in opposite directions at the synchronous speed N_s which are dependent on frequency and stator poles.

Let $\mathbf{\Phi_f}$ is forward component rotating in anticlockwise direction while $\mathbf{\Phi_b}$ is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at the instant. So resultant of these two is the original stator flux.



Stator flux and its two components

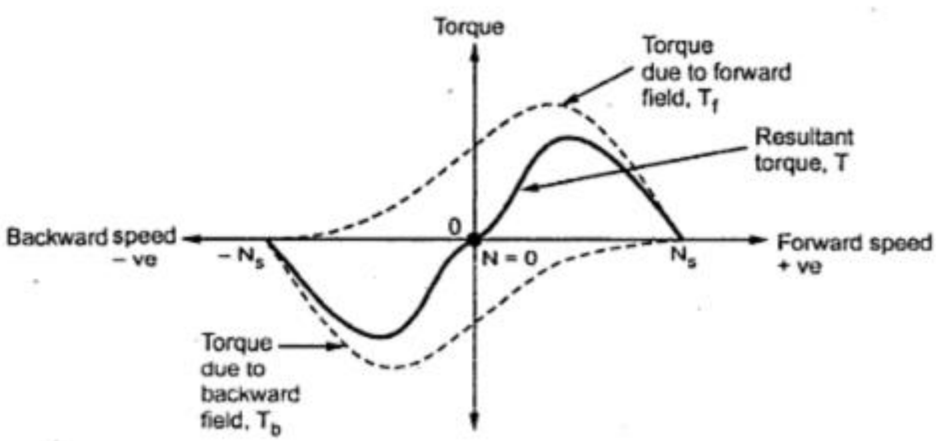
The above Fig shows the stator flux and its two components $\mathbf{\Phi_f}$ and $\mathbf{\Phi_b}$. At start both the components are shown opposite to each other in the Fig. (a). Thus the resultant $\mathbf{\Phi_R = 0}$. This is nothing but the instantaneous value of the stator flux at start. After 90^o, as shown in the Fig. (b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant Φ_R is the algebraic sum of the magnitudes of the two components. So $\mathbf{\Phi_R = (\Phi_{1m}/2) + (\Phi_{1m}/2) = \Phi_{1m}}$. This is nothing but the instantaneous value of the stator flux at $\mathbf{\theta = 90^o}$ as shown in the Fig (c). Thus continuous rotation of the two components gives the original alternating stator flux.

Both the components are rotating and hence get cut by the motor conductors. Due to cutting of flux, EMF gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component $\mathbf{\Phi_f}$ to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component $\mathbf{\Phi_b}$ to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative.

At start these two torques are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at start. And hence the single phase induction motors are not self starting. The resultant torque is shown below

Torque speed characteristics

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



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

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

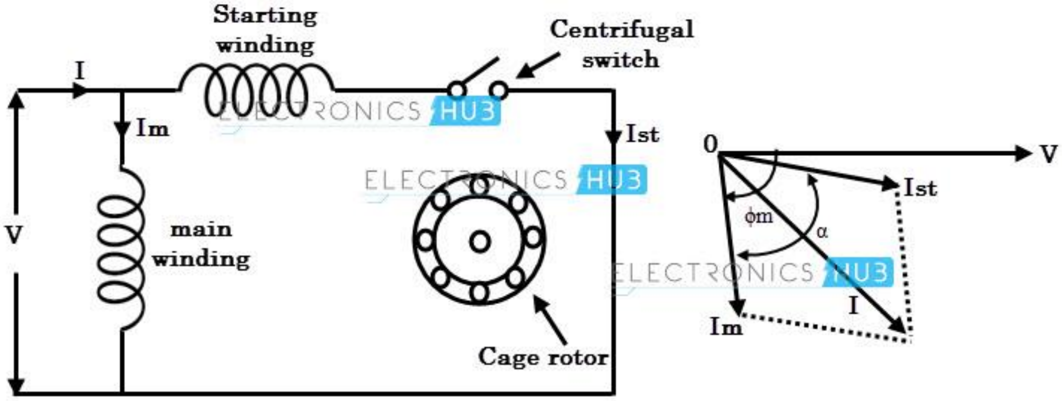
Starting Methods of Single-Phase Induction Motors

A single-phase induction motor with main stator winding has no inherent starting torque, since main winding introduces only stationary, pulsating air-gap flux wave. For the development of starting torque, rotating air-gap field at starting must be introduced. Several methods which have been developed for the starting of single-phase induction motors, may be classified as follows

1. Split-phase motor
2. Capacitor start motor
3. Permanent capacitor run motor
4. Capacitor start capacitor run motor
5. Shaded pole motor

This is one of the most widely used types of single phase induction motors. The essential parts of the split phase motor include main winding, auxiliary winding and a centrifugal switch.

This is the simplest arrangement to set up a rotating magnetic field by providing two winding on the same stator core as shown in figure.



Circuit diagram of split phase motor

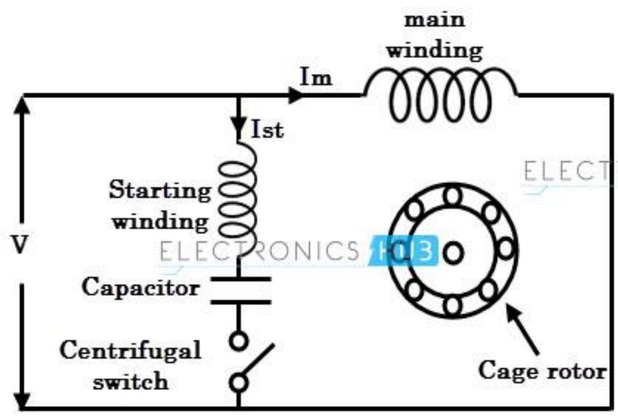
Phasor diagram

The auxiliary or starting winding carries a series resistance such that its impedance becomes highly resistive in nature. It is not wound identical to the main winding but contains fewer turns of much smaller diameter as compared to main winding. This will reduce the amount of start current lags the voltage. The main winding is inductive in nature in such that current lags the voltage by some angle. This winding is designed for the operation of 75 % of synchronous speed and above. These two windings are connected in parallel across the supply. Due to the inductive nature, current through main winding lags the supply voltage by a large angle while the current through starting winding is almost in phase with voltage due to resistive nature. Hence there exists a phase difference between these currents and thereby phase difference between the fluxes produced by these currents. The resultant of these two fluxes produce rotating magnetic field and hence the starting torque. The centrifugal switch is connected in series with the starting winding. When the motor reaches 75 to 80 percent of synchronous speed, the centrifugal switch is opened mechanically and thereby auxiliary winding is out of the circuit. Therefore, the motor runs only with main winding. Split phase motors give poor starting torque due to small phase difference between main and auxiliary currents. Also, the power factor of these motors is poor. These are mainly used for easily started loads such as blowers, fans, washing machines, grinders, etc.

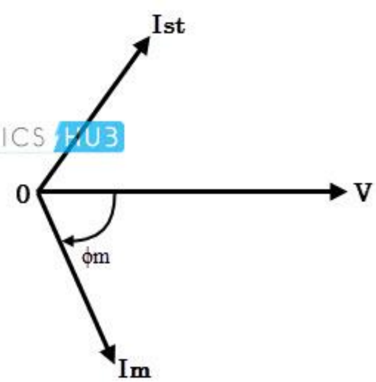
Capacitor Start Induction Motor

This motor is similar to the split phase motor, but in addition a capacitor is connected in series to auxiliary winding. This is a modified version of split phase motor.

Since the capacitor draws a leading current, the use of a capacitor increases the phase angle between the two currents (main and auxiliary) and hence the starting torque. This is the main reason for using a capacitor in single phase induction motors.



Circuit diagram of capacitor start motor



Phasor diagram

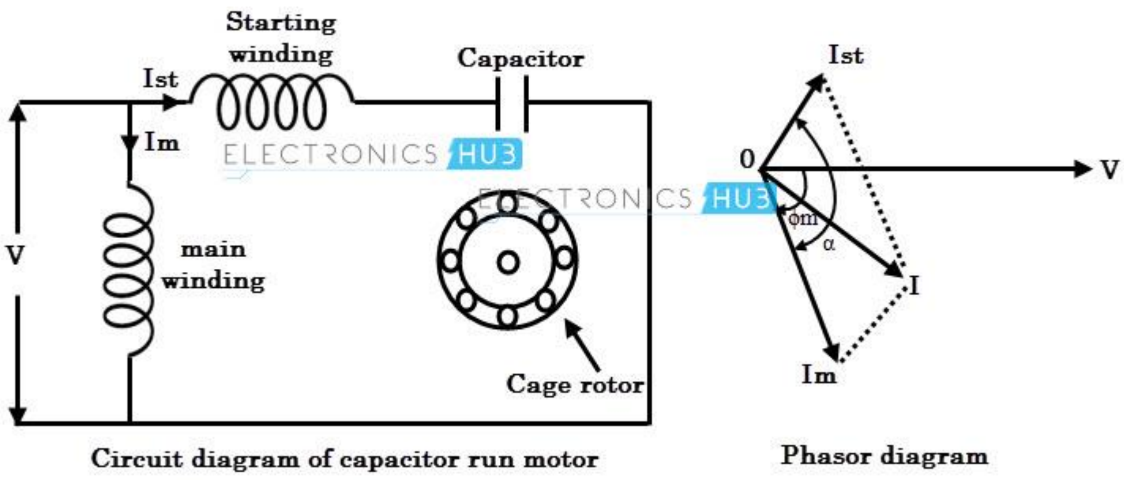
Here the capacitor is of dry-type electrolytic one which is designed only for alternating current use. Due to the inexpensive type of capacitors, these motors become more popular in wide applications.

These capacitors are designed for definite duty cycle, but not for continuous use. The schematic diagram of capacitor start motor is shown in figure above. The operation of this motor is similar to the split phase motor where the starting torque is provided by additional winding. Once the speed is picked up, the additional winding along with capacitor is removed from the circuit with the help of centrifugal switch. But, the difference is that the torque produced by this motor is higher than split phase motor due to the use of capacitor. Due to the presence of a capacitor, the current through auxiliary winding will leads the applied voltage by some angle which is more than that of split case type. Thus, the phase difference between main and auxiliary currents is increased and thereby starting torque.

The performance of this motor is identical to the split phase motor when it runs near full load RPM. Due to the capacitor, the inrush currents are reduced in this motor. These motors have very high starting torque up to 300% full load torque. However the power factor is low at rated load and rated speed. Owing to the high starting torque, these motors are used in domestic as well as industrial applications such as water pumps, grinders, lathe machines, compressors, drilling machines, etc.

Capacitor Run Induction Motor

In this capacitor, a low capacitor is connected in series with the starting winding and is not removed from the circuit even in running condition. Due to this arrangement, centrifugal switch is not required. Here the capacitor is capable of running continuously.

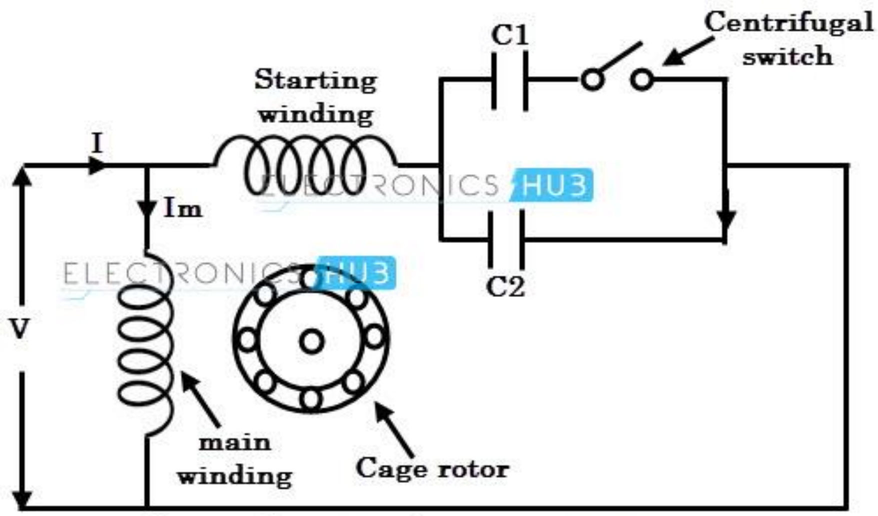


The low value capacitor produces more leading phase shift bur less total starting current as shown in phasor diagram. Hence, the starting torque produced by these motors will be considerably lower than that of capacitor start motor. The schematic circuit of this motor is shown in figure above. In this, the auxiliary winding and capacitor remains in circuit permanently and produce an approximate two phase operation at rated load point. This is the key strength of these motors. This will result better power factor and efficiency. However, the starting torque is much lower in these motors, typically about 80 percent of full load torque. Due to the continuous duty of auxiliary winding and capacitor, the rating of these components should withstand running conditions and hence permanent capacitor motor is more than equivalent split phase or capacitor start motors. These motors are used in exhaust and intake fans, unit heaters, blowers, etc.

Capacitor Start and Capacitor Run Induction Motor

These motors are also called as two-value capacitor motors. It combines the advantages of capacitor start type and permanent capacitor type induction motors.

This motor consists of two capacitors of different value of capacitance for starting and running. A high value capacitor is used for starting conditions while a low value is used for running conditions. It is to be noted that this motor uses same winding arrangement as capacitor-start motor during startup and permanent capacitor motor during running conditions. The schematic arrangement of this motor is shown in figure below.



Circuit diagram of capacitor start capacitor run motor

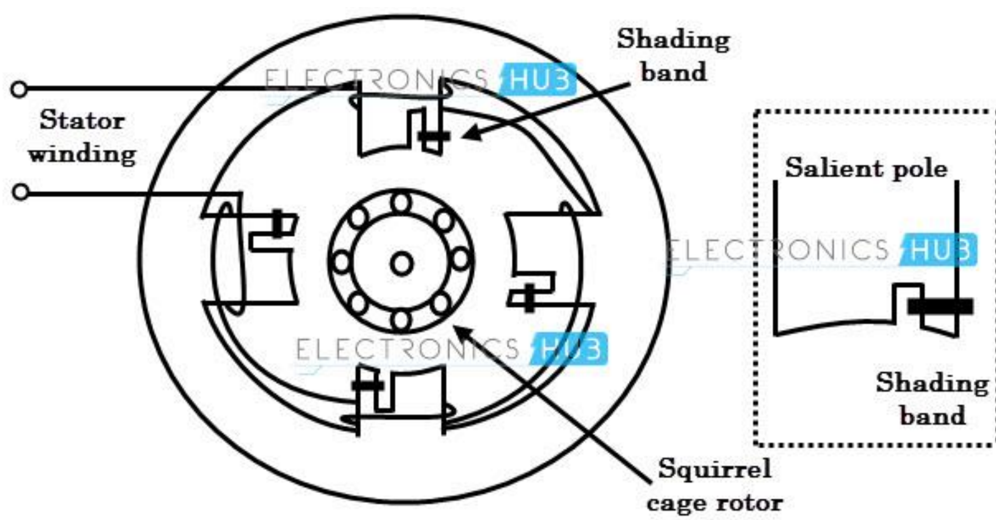
At starting, both starting and running capacitors are connected in series with the auxiliary winding. Thus the motor starting torque is more compared with other types of motors.

Once the motor reaches some speed, the centrifugal switch disconnects the starting capacitor and leaves the running capacitor in series with auxiliary winding.

Thus, both running and auxiliary windings remain during running condition, thereby improved power factor and efficiency of the motor. These are the most commonly used single phase motors due to high starting torque and better power factor. These are used in compressors, refrigerators, air conditioners, conveyors, ceiling fans, air circulators, etc

Shaded Pole Induction Motor

This motor uses entirely different technique to start the motor as compared with other motors so far we have discussed now. This motor doesn't use any auxiliary winding or even it doesn't have a rotating field, but a field that sweeps across the pole faces is enough to drive the motor. So the field moves from one side of the pole to another side of the pole. Although these motors are of small ratings, inefficient and have low starting torque, these are used in a variety of applications due to its outstanding features like ruggedness, low initial cost, small size and simple construction. A shaded pole motor consists of a stator having salient poles (or projected poles), and a rotor of squirrel cage type. In this, stator is constructed in a special way to produce moving magnetic field. Stator poles are excited with its own exciting coils by taking the supply from a single phase supply. A 4-pole shaded pole motor construction is given in below figure.

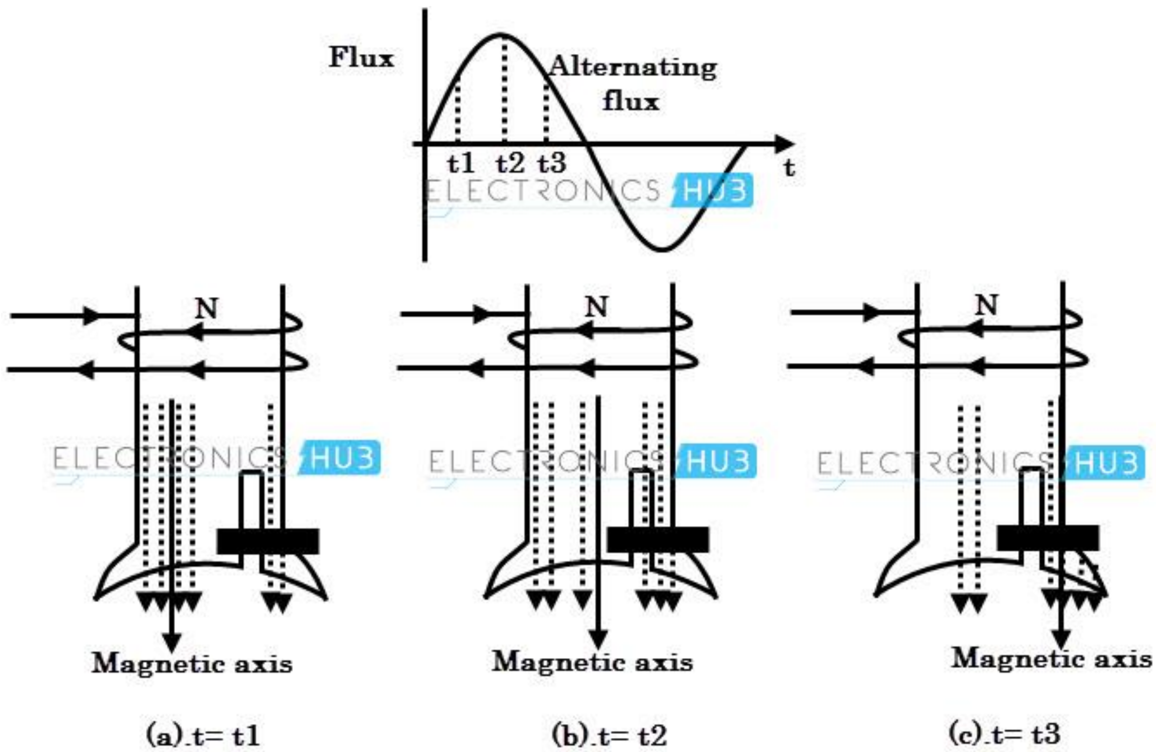


4-Pole Shaded pole motor construction

Each salient pole is divided into two parts; shaded and un-shaded. A shading portion is a slot cut across the laminations at about one third distance from one edge, and around this a heavy copper ring (also called as shading coil or copper shading band) is placed. This part where shading coil is placed is generally termed as shaded part of the pole and remaining portion is called as un-shaded part as shown in figure. Let us discuss how the sweeping action of the field takes place.

When an alternating supply is given to the stator coils, an alternating flux will be produced. The distribution of flux in the pole face area is influenced by the presence of copper shading band.

Let us consider the three instants, t1, t2, and t3 of alternating flux for an half cycle of the flux as shown in figure.



1. At instant t= t1, the rate of change of flux (rising) is very high. Due to this flux, an EMF is induced in the copper shading band and as the copper shading band is shorted, current circulates through it. This causes current to create its own field. According to Lenz's law, the current through copper shading band opposes the cause, i.e., rise of supply current (and hence rise of main flux). Therefore the flux produced by shading ring opposes the main flux. So there is weakening of flux in the shaded part while crowding of flux in un-shaded part. So the axis of overall flux shifts to non-shaded part of the pole as shown in the figure.

2. At instant t=t2, the rate of rise of flux is almost zero, and hence very little EMF is induced in the shaded band. It results negligible shaded ring flux and hence there is no much affect on distribution of main flux. Therefore, the distribution of flux is uniform and the overall flux axis lies at the center of the pole as shown in figure.
3. At instant t=t3, the rate of change of flux (decreasing) is very high, and induces EMF in copper shading band. The flux produced by the shading ring is now opposes the cause according to Lenz's law. Here, the cause is decreasing flux, and opposing means its direction is same as that of main flux. Hence, this flux strengthens the main flux. So there will be crowding of flux in the shaded part compared to the non shaded part. Due to this overall flux axis shifts to the middle of shaded part. This sequence will repeat for negative cycle too and consequently it produce moving magnetic field for every cycle from non shaded part of the pole to shaded part of the pole. Due to this field, motor produces the starting torque. This starting torque is low about 40 to 50 percent of full load torque. Therefore, these motors are used in low starting torque applications such as fans, toy motors, blowers, hair dryers, photocopy machines, film projectors, advertising displays, etc.

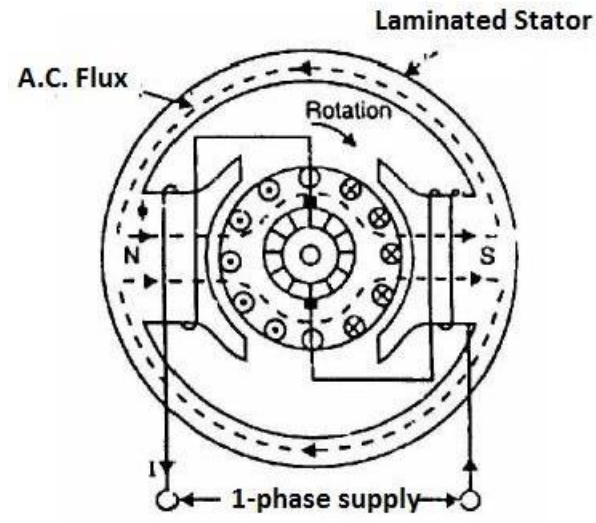
A.C. Series Motor

A DC series motor will rotate in the same direction regardless of the polarity of the supply. One can expect that a DC series motor would also operate on a single-phase supply. It is then called an AC series motor. However, some changes must be made in a DC motor that is to operate satisfactorily on AC supply. The changes effected are:

- ✓ The entire magnetic circuit is laminated in order to reduce the eddy current loss. Hence an AC series motor requires a more expensive construction than a DC series motor.
- ✓ The series field winding uses as few turns as possible to reduce the reactance of the field winding to a minimum. This reduces the voltage drop across the field winding.
- ✓ A high field flux is obtained by using a low-reluctance magnetic circuit.
- ✓ There is considerable sparking between the brushes and the commutator when the motor is used on AC supply. It is because the alternating flux establishes high currents in the coils short-circuited by the brushes. When the short-circuited coils break contact from the commutator, excessive sparking is produced. This can be eliminated by using high- resistance leads to connect the coils to the commutator segments.

Construction

The construction of an AC series motor is very similar to a DC series motor except that above modifications are incorporated. Such a motor can be operated either on AC or DC supply and the resulting torque-speed curve is about the same in each case. For this reason, it is sometimes called a universal motor.



Operation

When the motor is connected to an AC supply, the same alternating current flows through the field and armature windings. The field winding produces an alternating flux that reacts with the current flowing in the armature to produce a torque. Since both armature current and flux reverse simultaneously, the torque always acts in the same direction. It may be noted that no rotating flux is produced in this type of machines; the principle of operation is the same as that of a DC series motor.

Characteristics

The operating characteristics of an AC series motor are similar to those of a DC series motor.

- ✓ The speed increases to a high value with a decrease in load. In very small series motors, the losses are usually large enough at no load that limits the speed to a definite value (1500 - 15,000 RPM).
- ✓ The motor torque is high for large armature currents, thus giving a high starting torque.
- ✓ At full-load, the power factor is about 90%. However, at starting or when

carrying an overload, the power factor is lower.

Applications

The fractional horsepower AC series motors have high speed (and corresponding small size) and large starting torque. They can, therefore, be used to drive

- ✓ High-speed vacuum cleaners
- ✓ Sewing machines
- ✓ Electric shavers
- ✓ Drills
- ✓ Machine tools etc.

Equivalent circuit of single phase induction motor :-

The double revolving field theory can be effectively used to obtain the equivalent circuit of a single phase induction motor. The method consist of determining the values of both the field clock-wise and anticlockwise at any given slip. When the two fields are known, the torque produced by each can be obtained. The difference between these two torque is the net torque acting on the rotor.

Imagine that the single phase IM is made up of one stator winding and two imaginary rotor windings. One rotor is rotating in forward direction i.e in the direction of RMF with slip s while other is rotating backward i.e, in the direction of oppositely directed RMF with slip 2 - s.

To develop equivalent circuit with & without core loss

1) without core loss :-

Let the stator impedance be Z Ω

$$Z = R_1 + jX_1$$

where R_1 - stator resistance

X_1 - Stator reactance

X_2 - Rotor reactance referred to stator

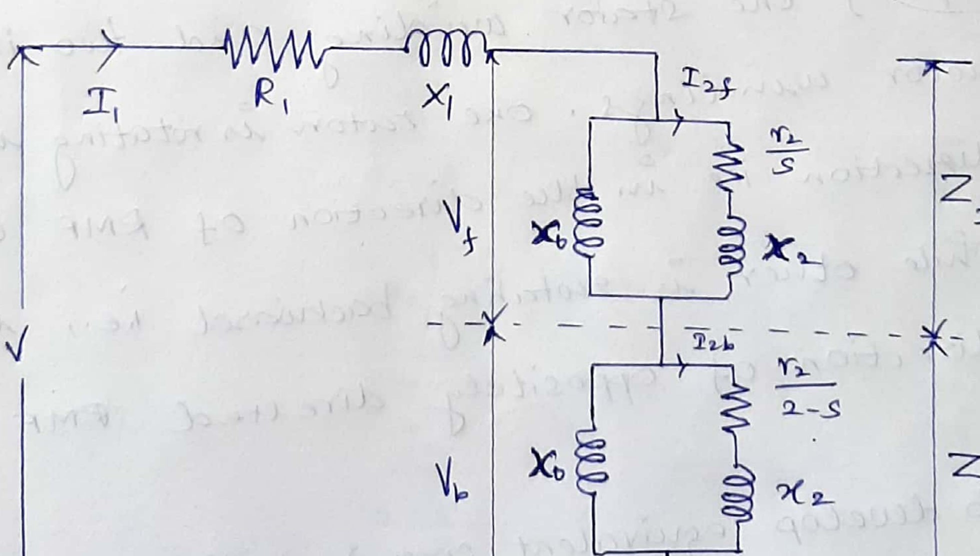
R_2 - Rotor resistance " " "

hence the impedance of each rotor is

$r_2 + jx_2$ where

$$x_2 = \frac{X_2}{2}$$

The resistance of forward field rotor is $\frac{r_2}{s}$ while the resistance of backward field rotor is $\frac{r_2}{2-s}$. The r_2 value is half of the actual



Equivalent ckt without core loss

rotor resistance referred to stator. As the core loss is neglected, R_0 is not existing in the

(2)

(PTO)

equivalent circuit. The x_0 is half of the actual magnetising reactance of the motor. So the equivalent circuit referred to stator is shown in the figure above.

Now the impedance of the forward field rotor is Z_f which is parallel combination of $(0 + jx_0)$ and $\left(\frac{r_2}{s}\right) + jx_2$.

$$Z_f = \frac{jx_0\left[\left(\frac{r_2}{s}\right) + jx_2\right]}{\frac{r_2}{s} + j(x_0 + x_2)}$$

while the impedance of the backward field rotor is Z_b which is parallel combination of $(0 + jx_0)$ and $\left(\frac{r_2}{2-s}\right) + jx_2$.

$$Z_b = \frac{jx_0\left[\left(\frac{r_2}{2-s}\right) + jx_2\right]}{\frac{r_2}{2-s} + j(x_0 + x_2)}$$

under the standstill condition, $s = 1$ & $2 - s = 1$

hence $\boxed{Z_f = Z_b}$ & hence $V_f = V_b$. But in the running Condition, V_f becomes almost 90 to 95 %. Of the applied voltage.

$$Z_{eq} = Z_1 + Z_f + Z_b \Rightarrow \text{Equivalent Impedance}$$

let I_{2f} = current through forward rotor referred to stator

I_{2b} = current through backward rotor referred to stator

$$I_{2f} = \frac{V_f}{\left[\frac{r_2}{s} + jx_2\right]} \quad \text{where } V_f = I_1 \times Z_f$$

and

$$I_{2b} = \frac{V_b}{\left[\frac{r_2}{2-s} + jx_2\right]} \quad \text{where } V_b = I_1 \times Z_b$$

$P_f \Rightarrow$ Power input to forward field rotor

$\Rightarrow (I_{2f})^2 \left(\frac{r_2}{s}\right)$ watts

$P_b \Rightarrow$ Power input to backward field rotor

$\Rightarrow (I_{2b})^2 \left(\frac{r_2}{2-s}\right)$ watts

$P_m = (1-s)$ [Net power i/p] $\Rightarrow (1-s)(P_f - P_b)$ watts

$P_{out} = P_m$ - Mechanical loss - Core loss

T_f = forward torque = $\dfrac{P_f}{\left(\dfrac{2\pi N}{60}\right)}$ N-m

T_b = Backward torque = $\dfrac{P_b}{\left(\dfrac{2\pi N}{60}\right)}$ N-m

T = Net torque = $T_f - T_b$

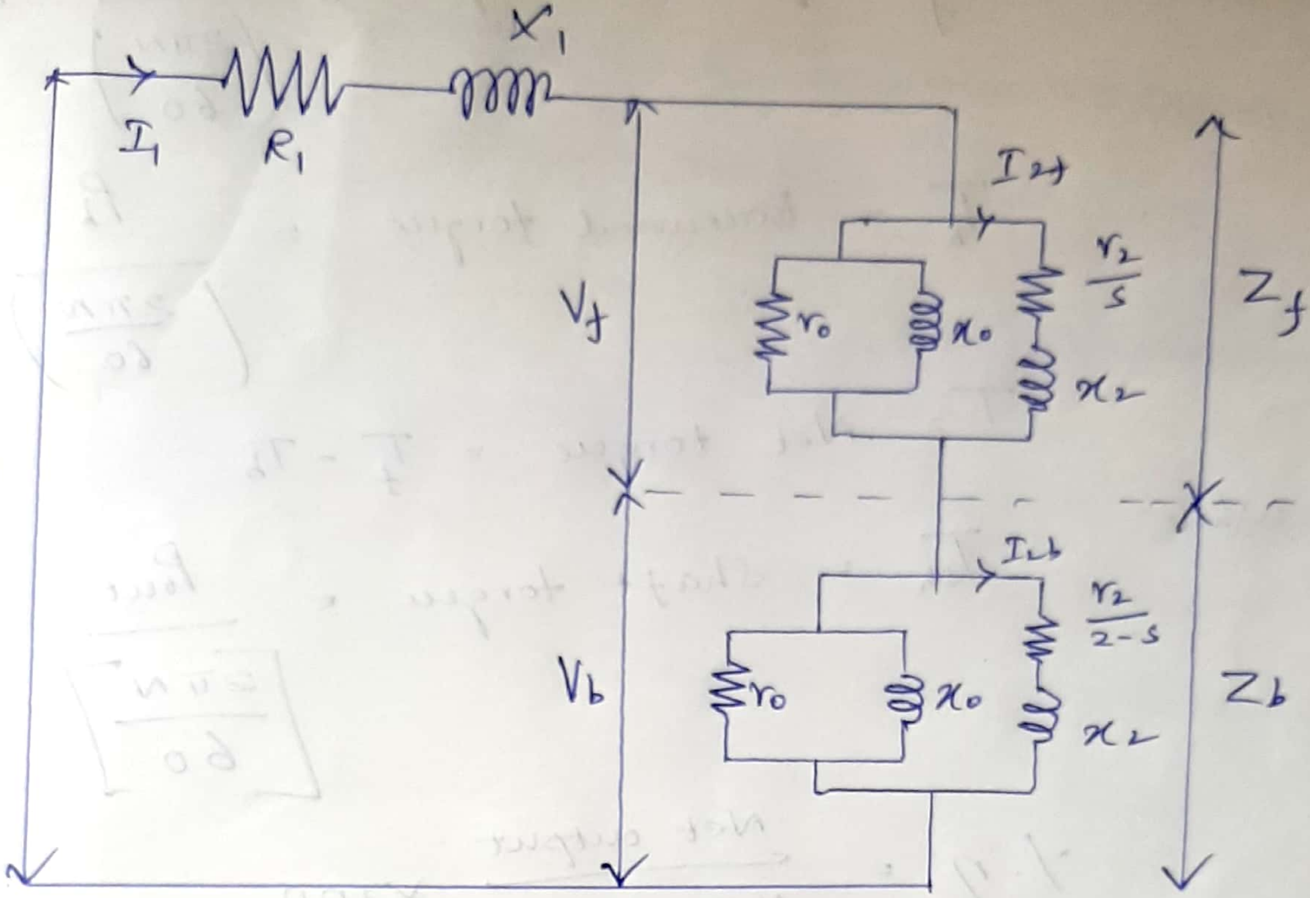
while T_{sh} = Shaft torque = $\dfrac{P_{out}}{\left[\dfrac{2\pi N}{60}\right]}$ Nm

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

with Core loss :-

If the core loss is to be considered then it is necessary to connect a resistance r_0 in parallel with x_0, in an exciting branch of each rotor. r_0 is half the value of actual core loss resistance. Thus the equivalent circuit with core loss can be shown as in the fig.

(P.T.O)



equivalent Circuit with Core loss

Let Z_{0f} ⇒ equivalent impedance of exciting branch in forward rotor ⇒ $r_0 \parallel (j x_0)$

& Z_{0b} ⇒ " " " in backward rotor

⇒ $r_0 \parallel (j x_0)$

$$Z_f = Z_{0f} \parallel \left[\frac{r_2}{s} + j x_2 \right]$$

all other expressions remains same as stated earlier in case of without core loss.

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Vishnupur, BHIMAVARAM – 534 202

ELECTRICAL & ELECTRONICS ENGINEERING

II B. Tech. II Semester EEE R20

Electrical Machines – II

Material for Unit IV

3-Phase Synchronous Generator: Constructional features of non–salient and salient pole rotor – armature windings – distributed and concentrated windings – distribution, pitch and winding factors – EMF equation – armature reaction–voltage regulation by synchronous impedance, MMF and Potier triangle methods – phasor diagrams – parallel operation with infinite bus bar and other alternators – synchronizing power – load sharing – numerical problems.

Unit IV 3-Phase Synchronous Generator

Construction of 3 Phase Alternator or Synchronous Generator

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.

Stator Construction

The stationary part of the machine is called Stator. It includes various parts like stator frame, stator core, stator windings and cooling arrangement. They are explained below in detail.

Stator Frame

It is the outer body of the machine made of cast iron, and it protects the inner parts of the machine.

Stator Core

The stator core is made of silicon steel material. It is made from a number of stamps which are insulated from each other. Its function is to provide an easy path for the magnetic lines of force and accommodate the stator winding.

Stator Winding

Slots are cut on the inner periphery of the stator core in which 3 phase or 1 phase winding is placed. Enameled copper is used as winding material. The winding is star connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF.

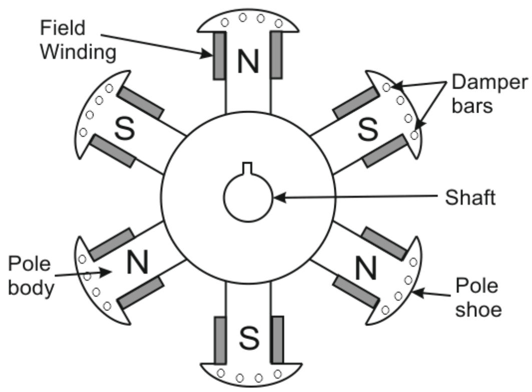
Rotor Construction

The rotating part of the machine is called Rotor. There are two types of rotor construction, namely the salient pole type and the cylindrical rotor type.

Salient Pole (Non cylindrical) Rotor

The term salient means projecting. Thus, a salient pole rotor consists of poles projecting out from the surface of the rotor core. Construction of a salient pole rotor is as shown in the figure. The projected poles are made up from laminations of steel.

- ✓ Salient pole rotors have large diameter and shorter axial length.
- ✓ They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.

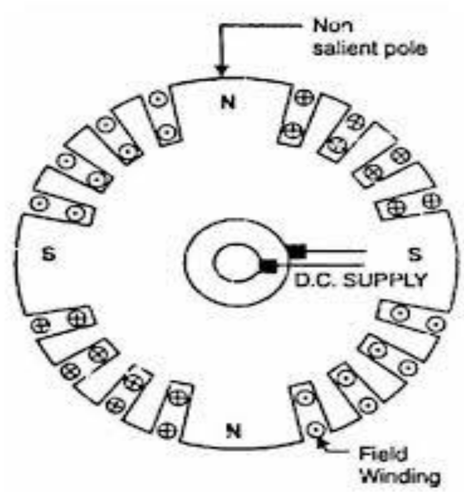


Six pole salient pole rotor

- ✓ Flux distribution is relatively poor than non-salient pole rotor, hence the generated EMF waveform is not as good as cylindrical rotor.
- ✓ Salient pole rotors generally need damper windings to prevent rotor oscillations during operation.
- ✓ Salient pole synchronous generators are mostly used in hydro power plants.

Non-salient pole (cylindrical) rotor

Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings. It is made up of solid steel. The construction of non-salient pole rotor (cylindrical rotor) is as shown in figure below. Sometimes, they are also called as drum rotor.



- ✓ They are smaller in diameter but having longer axial length.
- ✓ Cylindrical rotors are used in high speed electrical machines, usually 1500 RPM to 3000 RPM.
- ✓ Windage loss as well as noise is less as compared to salient pole rotors.

- ✓ Their construction is robust as compared to salient pole rotors.
- ✓ Number of poles is usually 2 or 4.
- ✓ Damper windings are not needed in non-salient pole rotors.
- ✓ Flux distribution is sinusoidal and hence gives better EMF waveform.
- ✓ Non-salient pole rotors are used in nuclear, gas and thermal power plants.

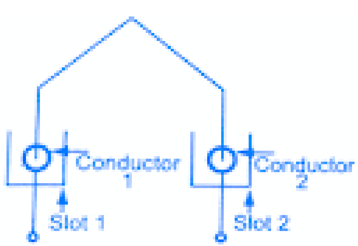
Armature Winding

Armature windings of alternators are different from that of DC machines. Basically, three phase alternators carry three sets of windings arranged in the slots in such a way that there exists a phase difference of 120° between the induced EMF in them. In a DC machine, winding is closed while in alternators winding is open i.e., two ends of each set of the winding are brought out.

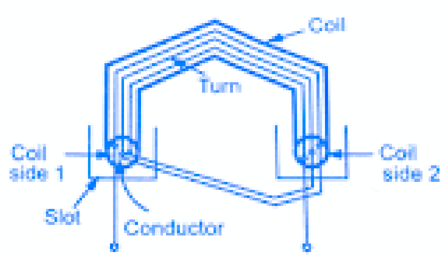
In three phase alternators, the six terminals are brought out which are finally connected in star or delta and then the three terminals are brought out. Each set of windings represents winding per phase and induced EMF in each set is called induced EMF per phase denoted as $\mathbf{E_{ph}}$. All the coils used for one phase must be connected in such a way that their EMF helps each other. And overall design should be in such a way that the waveform of an induced EMF is almost sinusoidal in nature.

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 constitute a turn. This is shown in the below figure (a).



(a)Turn



(b)Multiturn coil

3) **Coil:** As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multi-turn coil. A coil may consist of single turn called single turn coil. Figure (b) shows a multi-turn coil.

4) **Coil Side:** Coil consists of many turns. Part of the coil in each slot is called coil side of a coil as shown in the above figure (b).

5) **Pole Pitch:** It is centre to centre distance between the two adjacent poles. We have seen that for one rotation of the conductors, 2 poles are responsible for 360° electrical of EMF, 4 poles are responsible for 720° electrical of EMF and so on. So 1 pole is responsible for 180° electrical of induced EMF

Key Point: **So 180° electrical is also called one pole pitch.**

Practically how many slots are under one pole which is responsible for 180° electrical, are measured to specify the pole pitch.

For example let us consider 2 poles, 18 slots armature of an alternator. Then under 1 pole, there are 18/2 i.e. 9 slots. So pole pitch is 9 slots or 180° electrical. This means 9 slots are responsible for producing a phase difference of 180° between the EMFS induced in different conductors.

This number of **slots/pole** is denoted as **'n'**.

Pole pitch = 180° electrical = slots per pole (no. of slots/P) = **n**

6) **Slot angle (β)**: The phase difference contributed by one slot in degrees electrical is called slot angle As slots per pole contributes 180° electrical which is denoted as 'n', we can write,

$$1 \text{ slot angle} = 180°/n$$

$$\beta = 180°/n$$

In the above example,

$$n = 18/2 = 9, \qquad \text{while } \beta = 180°/n = 20°$$

Note: This means that if we consider an induced EMF in the conductors which are placed in the slots which are adjacent to each other, there will exist a phase difference of in between them. While if EMF induced in the conductors which are placed in slots which are 'n' slots distance away, there will exist a phase difference of 180° in between them.

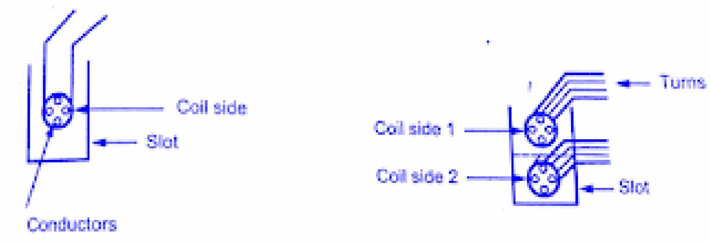
Types of Armature Windings in Alternator

The different types of armature windings in alternators are,

1) Single layer and double layer winding
2) Full pitch and short pitch winding
3) Concentrated and distributed winding

Single Layer and Double Layer Winding:

If a slot consists of only one coil side, winding is said to be a single layer. This is shown in figure (a). While there are two coil sides per slot, one, at the bottom and one at the top the winding is called double layer as shown in figure (b).A lot of space gets wasted in single layer hence in practice generally double layer winding is preferred.



(a) Single layer (b) Double layer

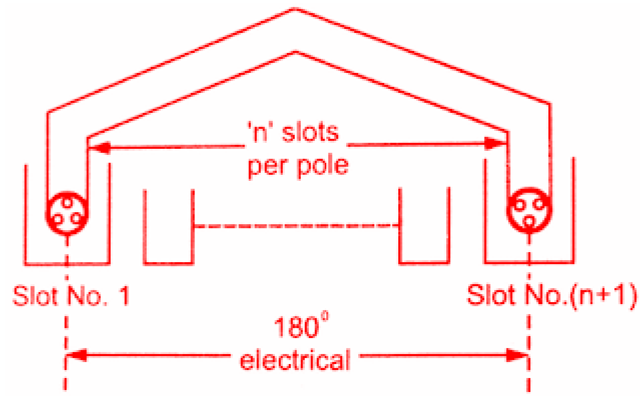
Full Pitch and Short Pitch Winding:

As seen earlier, one pole pitch is 180° electrical. The value of **'n'**, slots per pole indicates how many slots are contributing 180° electrical phase difference. So if coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot, the winding is said to be full pitch winding and coil is called full pitch coil. For example, in 2 poles, 18 slots alternator, the pole pitch is **n = 18/2 = 9 slots**. So if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, **the coil is called full pitch coil**. Here we can define one more term related to a coil called coil span.

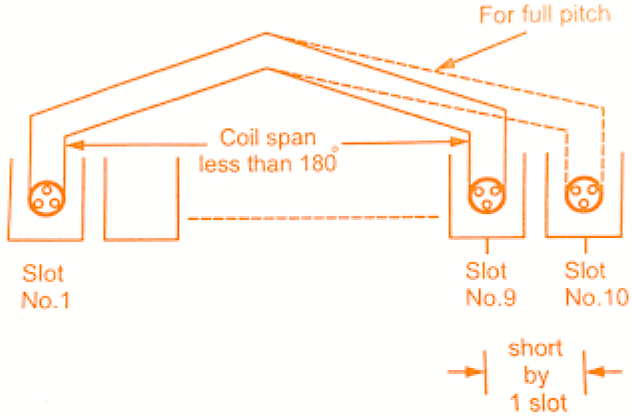
Coil Span:

It is the distance on the periphery of the armature, between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is **'n' slots or 180°** electrical the coil is called **180° full pitch coil**. This is shown in the figure to left. As against this if coils are used in such a way that coil span is slightly less than a pole pitch i.e. less than 180°

electrical, the coils are called, **short pitched coils or fractional pitched coils**. Generally, coils are shorted by one or two slots.



So in 18 slots, 2 pole alternator instead of connecting a coil side in slot No 1 to slot No.10, it is connected to a coil side in slot No.9 or slot No. 8, the coil is said to be short pitched coil and winding are called **short pitch winding**. This is shown in the below figure.



Advantages of Short Pitch Coils:

In actual practice, short pitch coils are used as it has following advantages,

- ✓ The length required for the end connections of coils is less i.e. the inactive length of winding is less and so less copper is required. Hence economical
- ✓ Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of EMF Hence waveform of an induced EMF is more sinusoidal due to short pitching.
- ✓ As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimized. This increases the efficiency

Concentrated and distributed winding:

In three phase alternators, we have seen that there are three different sets of windings, each for a phase. So depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as 'm'.

m = Slots per pole per phase = n/number of phases

= n/3 (generally no. of phases is 3)

For example in 18 slots, 2 pole alternator we have,

n = 18/2 = 9

Therefore m = 9/3

So we have 3 slots per pole per phase available. Now let 'x' number of conductors per phase are to be placed under one pole. And we have 3 slots per pole per phase available. But if all 'x' conductors per phase are placed in one slot keeping remaining 2 slots per pole per phase empty then the winding is called concentrated winding.

Key Point: So in a concentrated winding, all conductors or coils belonging to a phase are placed in one slot under every pole.

But in practice, an attempt is always made to use all the 'm' slots per pole per phase available for distribution of the winding. So if 'x' conductors per phase are distributed amongst the 3 slots per phase available under every pole, the winding is called distributed winding. So in distributed type of winding all the coils belonging to a phase are well distributed over the 'm' slots per phase, under every pole. Distributed winding makes the waveform of the induced EMF more sinusoidal in nature. Also in concentrated winding due to a large number of conductors per slot, heat dissipation is poor.

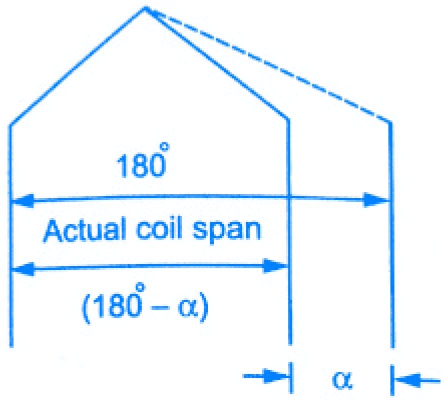
Key Point: So in practice, double layer, short pitched and distributed type of armature winding is preferred for the alternators.

Pitch Factor or Coil Span Factor (K_c):

In practice, short pitch coils are preferred. So coil is formed by connecting one coil side to another which is less than one pole pitch away. So actual coil span is less than 180°. The coil is generally shorted by one or two slots.

Key Point: *The angle by which coils are short pitched is called angle of short pitch denoted as 'α'.*

α = Angle by which coils are short pitched.



Angle of short pitch

As coils are shorted in terms of the number of slots i.e. either by one slot, two slots and so on and slot angle is β then the angle of short pitch is always a multiple of the slot angle β.

α = β x Number of slots by which coils are short pitched

(or)

α = (180° - Actual coil span of the coils)

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

$$K_c = \frac{E_R \text{ when coil is short pitched}}{E_R \text{ when coil is full pitched}} = \frac{2E\cos\left(\frac{\alpha}{2}\right)}{2E}$$

$$\boxed{K_c = \cos\left(\frac{\alpha}{2}\right)}$$

Where α = Angle of short pitch

Distribution Factor (K_d):

Similar to full pitch coils, concentrated winding is also rare in practice. Attempt made to use all the slots available under a pole for the winding which makes the nature of the induced EMF more sinusoidal. Such a winding is called distributed winding.

Consider 18 slots 2 pole alternator. So slots per pole i.e. n = 9.

m = Slots per pole per phase = 3

β = 180°/9 = 20°

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.

$$K_d = \frac{E_R \text{ when coils are distributed}}{E_R \text{ when coils are concentrated}} = \frac{2R\sin\left(\frac{m\beta}{2}\right)}{2mR\sin\left(\frac{\beta}{2}\right)}$$

$$\boxed{K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)}}$$

Where m = Slots per pole per phase

β = Slot angle = $180°/n$

n = Slots per pole

EMF Equation of Alternator

We know that Synchronous Generator or Alternator will generate an EMF. The following is the derivation of EMF equation of Synchronous Generator or Alternator.

Let Φ = Flux per pole, in Wb

P = Number of poles

N = Synchronous speed in RPM

f = Frequency of induced EMF in Hz

Z = Total number of conductors

Z_{ph} = Conductors per phase connected in series

$Z_{ph} = Z/3$ as number of phases = 3

Consider a single conductor placed in a slot.

The average value of EMF induced in a conductor = $d\Phi/dt$

For one revolution of a conductor,

E_{Avg} per conductor = (Flux cut in one revolution/Time taken for one revolution)

Total flux cut in one revolution is Φ x P.

Time taken for one revolution is $60/N_s$ seconds.

$\therefore$ E_{Avg} per conductor = $\Phi P / (60/N_s)$ …… (1)

$= \Phi P N_s/60$

But $f = PN_s/120$

Therefore $PN_s/60 = 2f$

Substation in (1),

E_{Avg} per conductor = $2 f \Phi$ volts

Assume full pitch winding for simplicity i.e. this conductor is connected to a conductor which is 180^o electrical apart. So there two EMFs will try to set up a current in the same direction i.e.

the two EMF are helping each other and hence resultant EMF per turn will be twice the EMF induced in a conductor.

$\therefore$ EMF per turn = 2 x (EMF per conductor)

$= 2 \times (2 f \Phi)$

$= 4 f \Phi$ volts

Let T_{ph} be the total number of turns per phase connected in series. Assuming concentrated winding, we can say that a are placed in single slot per pole per phase (So induced EMF's in all turns will be in phase as placed in a single slot. Hence net EMF per phase will be algebraic sum of the EMF'S per turn.

Average $E_{ph} = T_{ph}$ x (Average EMF per turn)

Average $E_{ph} = T_{ph} \times 4 f \Phi$

But in AC circuits RMS value of an alternating quantity is used for the analysis. The form factor is 1.11 of sinusoidal EMF

Form Factor, K_f = (R.M.S.)/Average = 1.11 .... for sinusoidal

$\therefore$ R.M.S. value of $E_{ph} = K_f$ x Average value

Therefore, the EMF equation of alternator is given by

$E = 4.44 \times f\, \Phi\, T_{ph}$ volts .... (2)

Note: This is the basic EMF equation for an induced EMF per phase for full pitch, concentrated type of winding.

Where T_{ph} = Number of turns per phase

$T_{ph} = Z_{ph}/2$ .... as 2 conductors constitute 1 turn

But as mentioned earlier, the winding used for the alternators is distributed and short pitch hence EMF induced slightly gets affected. Let us see now the effect of distributed and short pitch type of winding on the EMF equation.

So generalized expression for the derivation of EMF equation of Synchronous generator or Alternator can be written as

$$E_{ph} = 4.44 f\, \Phi T_{ph} K_c K_d \text{ volts}$$

But For full pitch coil, $K_c = 1$ and For concentrated winding $K_d = 1$

Armature Reaction in Synchronous Generator

When the load is connected to the alternator, the armature winding of the alternator carries a current. Every current carrying conductor produces its own flux so armature of the alternator also produces its own flux, when carrying a current. So there are two fluxes present in the air gap, one due to armature current while second is produced by the filed winding called main flux. The flux produced by the armature is called armature flux.

Note: So effect of the armature flux on the main flux affecting its value and the distribution is called armature reaction.

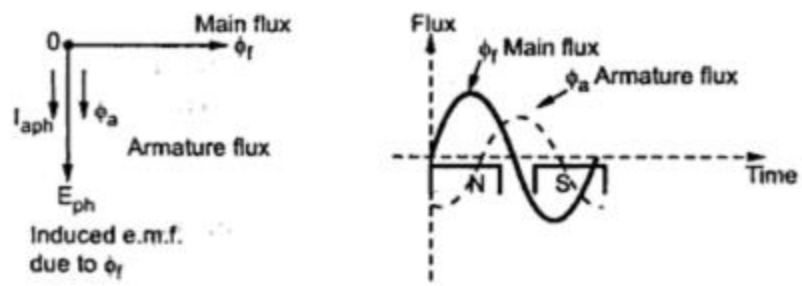
The effect of the armature flux not only depends on the magnitude of the current flowing through the armature winding but also depends on the nature of the power factor of the load connected to the alternator. Now we will study the effect of nature of the load power factor on the armature reaction.

Unity Power Factor Load

Consider a purely resistive load connected to the alternator, having unity power factor. As induced EMF. E_{ph} drives a current of I_{aph} and load power factor is unity, E_{ph} and I_{ph} are in phase with each other.

If Φ_f is the main flux produced by the field winding responsible for producing E_{ph} then E_{ph} lags Φ_f by 90^o. Now current through armature I_a, produces the armature flux say Φ_a. So flux Φ_a and I_a are always in the same direction.

This relation between Φ_f , Φ_a, E_{ph} and I_{aph} can be shown in the phasor diagram. (See Fig.)



It can be seen from the phasor diagram that there exists a phase difference of 90^o between the armature flux and the main flux. The waveforms for the two fluxes are also shown in the above Fig. From the waveforms it can be seen that the two fluxes oppose each other on the left half of each pole while assist each other on the right half of each pole. Hence average flux in the air gap remains constant but its distribution gets distorted.

Note : Hence such distorting effect of armature reaction under unity p.f. condition of the load is called cross magnetizing effect of armature reaction.

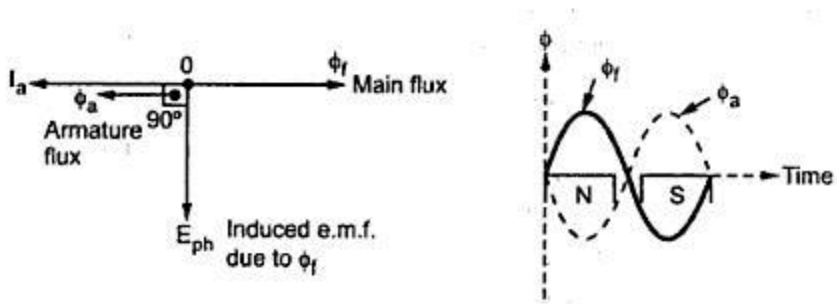
Due to such distortion of the flux, there is small drop in the terminal voltage of the alternator.

Zero Lagging Power Factor Load

Consider a purely inductive load connected to the alternator having zero lagging power factor. This indicates that I_{aph} driven by E_{ph} lags E_{ph} by 90^o which is the power factor angle Φ. Induced EMF E_{ph} lags main flux Φ_f by 90^o while Φ_a is in the same direction as that of I_a. So the phasor diagram and the waveforms are shown in the below Fig. It can be seen from the phasor diagram that the armature flux and the main flux are exactly in opposite direction to each other.

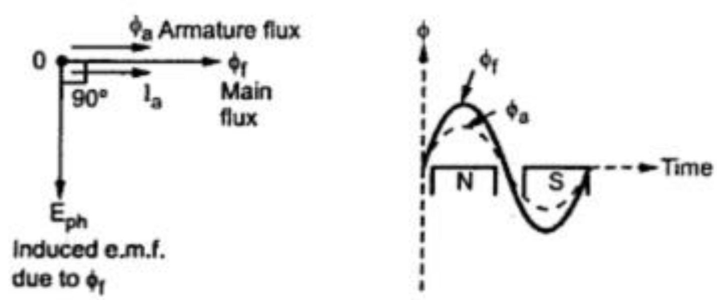
Note: So armature flux tries to cancel the main flux. Such an effect of armature reaction is called demagnetizing effect of the armature reaction.

As this effect causes reduction in the main flux, the terminal voltage drops. This drop in the terminal voltage is more than the drop corresponding to the unity p.f. load.



Zero Leading Power Factor Load

Consider a purely capacitive load connected to the alternator having zero leading power factor. This means that armature current I_{aph} driven by E_{ph}, leads E_{ph} by 90^o, which is the power factor angle Φ. Induced EMG=F E_{ph} lags Φ_f by 90^o while I_{aph} and Φ_a are always in the same direction. The phasor diagram and the waveforms are shown in the below Fig.



It can be seen from the phasor diagram and waveforms shown in the above Fig, the armature flux and the main field flux are in the same direction i.e. they are helping each other. This results into the addition in main flux.

Note : Such an effect of armature reaction due to which armature flux assists field flux is called magnetizing effect of the armature reaction.

As this effect adds the flux to the main flux, greater EMF gets induced in the armature. Hence there is increase in the terminal voltage for leading power factor loads.

For intermediate power factor loads i.e. between zero lagging and zero leading the armature reaction is partly cross magnetizing and partly demagnetising for lagging power factor loads or partly magnetizing for leading power factor loads.

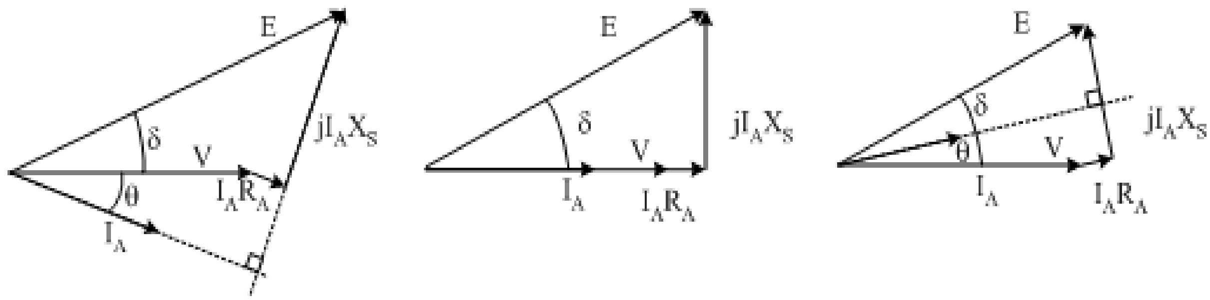
Armature Reaction Reactance (X_{ar})

In all the conditions of the load power factors, there is change in the terminal voltage due to the armature reaction. Mainly the practical loads are inductive in nature, due to demagnetizing effect of armature reaction; there is reduction in the terminal voltage. Now this drop in the voltage due to the interaction of armature and main flux. This drop is not across any physical element. But to quantify the voltage drop due to the armature reaction, armature winding is assumed to have a fictitious reactance. This fictitious reactance of the armature is called armature reaction reactance denoted as X_{ar} Ω/ph. And the drop due to armature reaction can be accounted as the voltage drop across this reactance as $I_{ar} X_{ar}$.

Note: The value of this reactance changes as the load power factor changes, as armature reaction depends on the load power factor.

Phasor Diagram of Synchronous Generator

The phasor diagram is a very significant factor of the power system analysis. As the output of the synchronous generator is alternating current, so it can easily be explained by the phasor diagrams. If we draw the output voltage and current in such a geometrically way that they show some relation among them, the resultant diagram called a phasor diagram.



Lagging Power Factor Phasor Diagram | Unity Power Factor Phasor Diagram | Leading Power Factor Phasor Diagram

In the electrical power system, there are three main types of load first one is resistive, the second one is capacitive and the third one is inductive. We will connect all these three loads with the synchronous generator and will see their effect and will draw their phasor diagram.

The given diagram shows the relation among the parameter like phase voltage (V), internal generated voltage (E), armature current (I_A), synchronous reactance (X_S) and some other factors by phasor diagram when the generator is working with the resistive load and have unity power factor (**Fig. 2**).

$$V = E - jX_sI_A - R_AI_A$$

We can observe from the above-given equation that internal generated voltage (E_A) are will be equal to the phase or terminal voltage of the generator if we deduct the voltage loss due to armature resistance and the synchronous reactance from it.

All these parameters and their facts are shown in an above-given diagram.

In a given diagram (**Fig. 1**), we have construed the phasor diagram of the synchronous generator when it relates to the inductive load, in this case, the power factor will be lagging. There is also a phasor diagram of the synchronous generator when it connected with the capacitive load, in this case, the power factor will be leading (**Fig. 3**).

If we compare the lagging and leading load phasor diagrams of the synchronous generator we can conclude that to get a specific value of the phase or terminal voltage and armature current we will require larger amount of internal generated voltage E for the inductive load (lagging) than the capacitive load (leading). So, we will have to provide a larger field current at the rotor in case of inductive load (lagging load) than the leading load to generates the same amount of the terminal voltage.

Need for Parallel Operation of Alternators

When the load on a system exceeds the amount of power that a single or existing number of generators can deliver, an additional generator is connected to the system to deliver required power. This method of adding an alternator in the existing system is called **parallel operation of alternators.**

It is essential to know that the incoming alternator must be paralleled such that each machine is supplying a proportionate amount of active and reactive power to the common load.

Reasons of Parallel Operation

- ✓ Several alternators can supply a bigger load than a single alternator.
- ✓ One or more alternators may shut down during the period of light loads. Thus, the remaining alternator operates at near or full load with greater efficiency.
- ✓ When one machine is taken out of service for its scheduled maintenance and inspection, the remaining machines maintain the continuity of the supply.
- ✓ If there is a breakdown of the generator, there is no interruption of the power supply.
- ✓ Number of machines can be added with disturbing the initial installation according to the requirement to fulfill the increasing future demand of the load.
- ✓ Parallel operation of the alternator, reduces the operating cost and the cost of energy generation.
- ✓ It ensures the greater security of supply and enables overall economic generation.

Necessary Conditions for Parallel Operation of the Alternator

Most synchronous machines will operate in parallel with other synchronous machines. The process of connecting one machine in parallel with another machine or with an Infinite Busbar system is known as **Synchronizing**. The machine carrying load is known as **Running Machines** while the alternator which is to be connected in parallel with the system is known as the **Incoming machine.**

The following condition should be satisfied for parallel operations are as follows:-

- ✓ The phase sequence of the Busbar voltages and the incoming machine voltage must be the same.
- ✓ The Busbar voltages and the incoming machine terminal voltage must be in phase.
- ✓ The terminal voltage of the incoming machine and the alternator which is to be connected in parallel or with the Busbar voltage should be equal.

- ✓ The frequency of the generated voltage of the incoming machine and the frequency of the voltage of the Busbar should be equal.

Synchronizing Methods

Synchronization is done generally by lamp methods. It can be done by two ways.

a) Lamp dark method b) Lamps bright Method

Lamps Dark Method

In this method the lamps are arranged as shown in Fig. The alternator to be synchronized (which is also called incoming alternator) consists of two lamps connected across the switch terminals of the same phase.

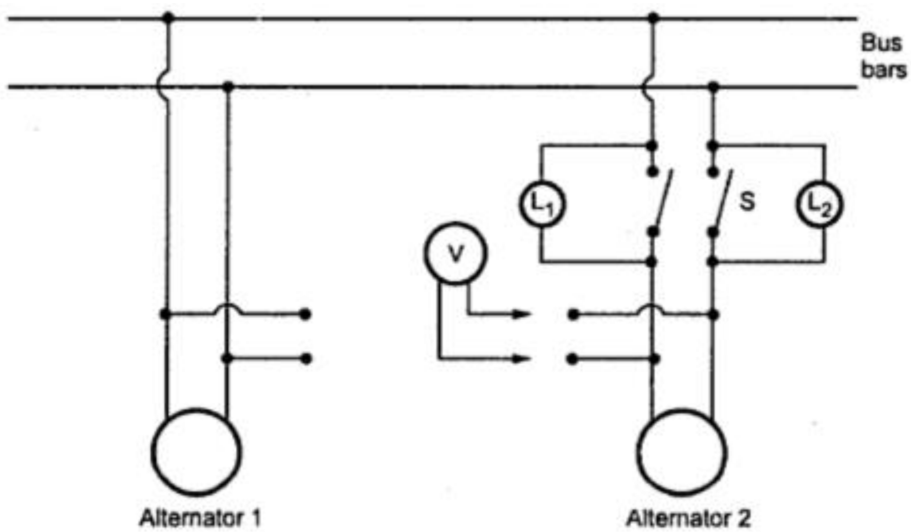
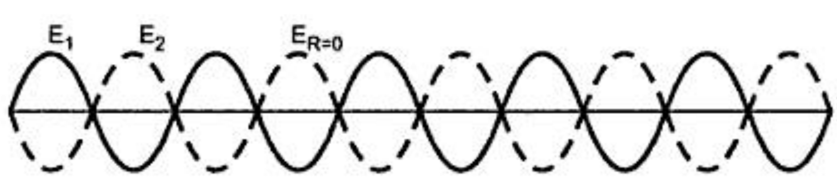


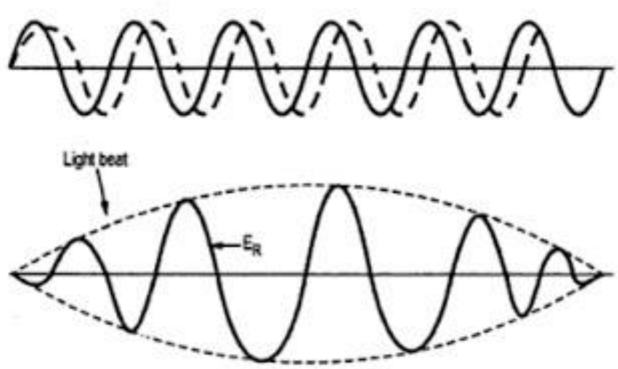
Fig. Dark Lamp Method

The voltage for the two alternators is measured with the help of a voltmeter. The lamps are connected in such a way that the polarity and the frequency for the two machines can be checked. No resultant voltage will appear across the switch terminals if the frequency of the two alternators is exactly same as their voltages are in exact phase opposition. Thus under this case lamps will not glow. The voltages for both the machines are having same maximum and RMS values and are in exact phase opposition thus resultant voltage is zero in local circuit. This is represented in the Fig. below.



It can be seen that with unequal frequencies of the two alternators, the two lamps will become alternately bright and dark. The light beat will be produced whose number is equal to the difference in frequencies for the two machines.

The resultant voltage appearing across the lamp will be difference of the two voltages at any instant resulting in a waveform shown in the Fig below. Since number of cycle completed by two machines in any given time are not same the light beat is produced which is shown in the Figure clearly.



Whenever the two voltage are in exact phase opposition (i.e. angle between them is 180°) then resultant voltage E_R is zero. If the switch is not closed at this instant the voltage across lamp will go on rising and synchronization will not appear proper.

The alternate darkness and brightness of the lamp will not indicate whether the incoming alternator is running fast or slow. For the exact synchronization the speed of incoming alternator is adjusted in such a way that the light beats are produced at a very slow speed and the alternators are synchronized during the middle of the dark period where resultant voltage E_R will be zero. The word middle is used as the lamp will not glow even though there is sufficient voltage across it. So it becomes difficult to know the correct instant of zero voltage.

Lamps Bright Method

Since it is very difficult to judge the correct instant of zero voltage in Lamps dark method, this method is introduced which is shown in the Fig. 4. The lamps remain maximum bright when there is no difference in voltages for the two machines. This is more sharp and accurate method of synchronization because the lamps are much more sensitive to changes in voltage at their maximum brightness than when they are dark.

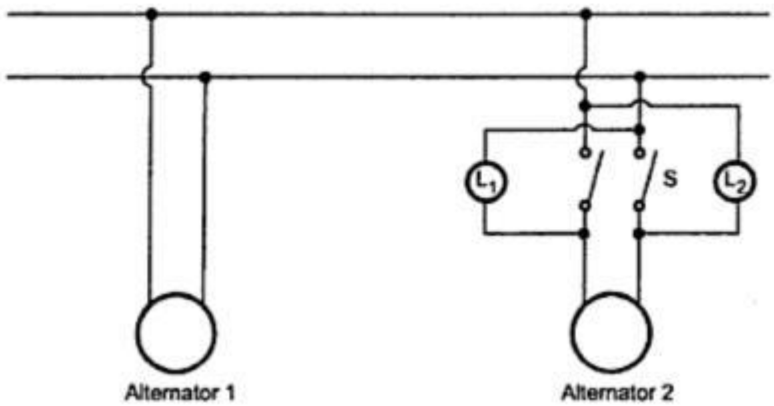
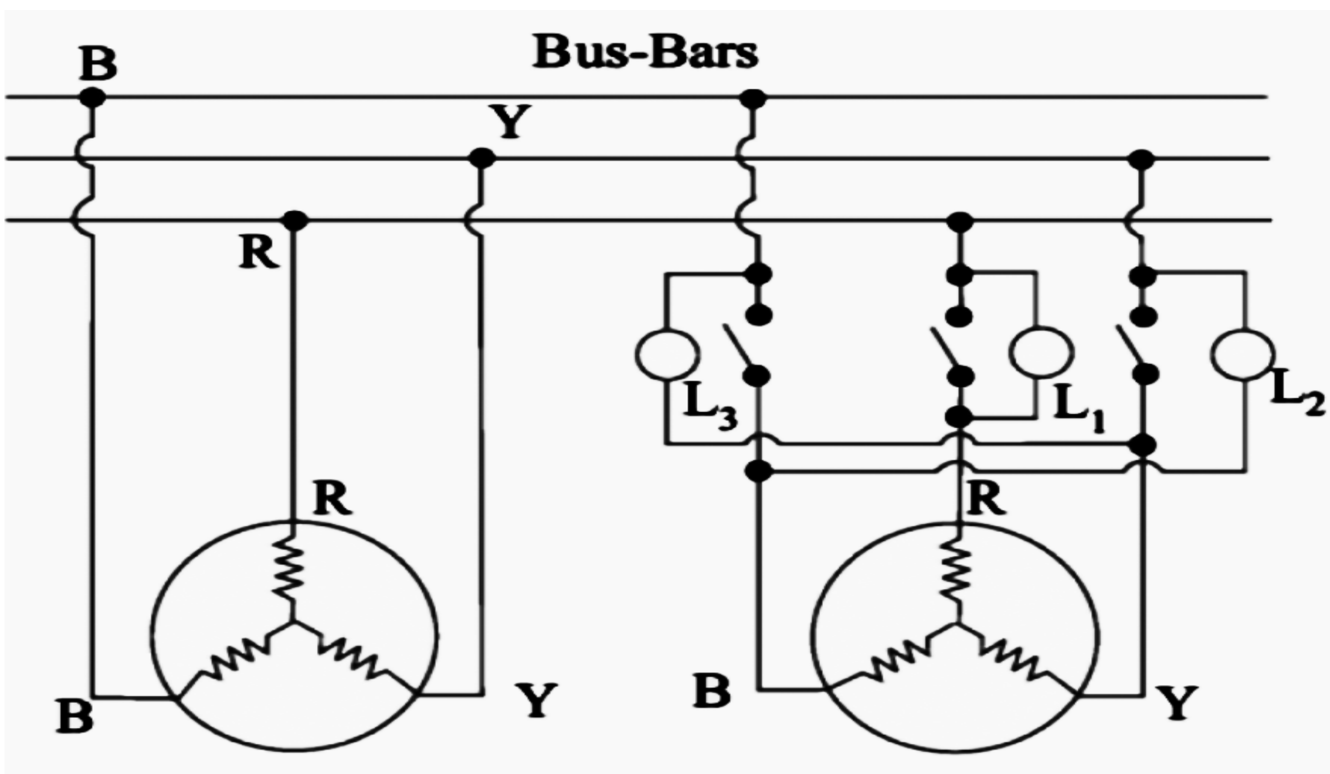


Fig. Bright lamp method

<u>**Three Phase Bright and Dark Lamp Representation**</u>



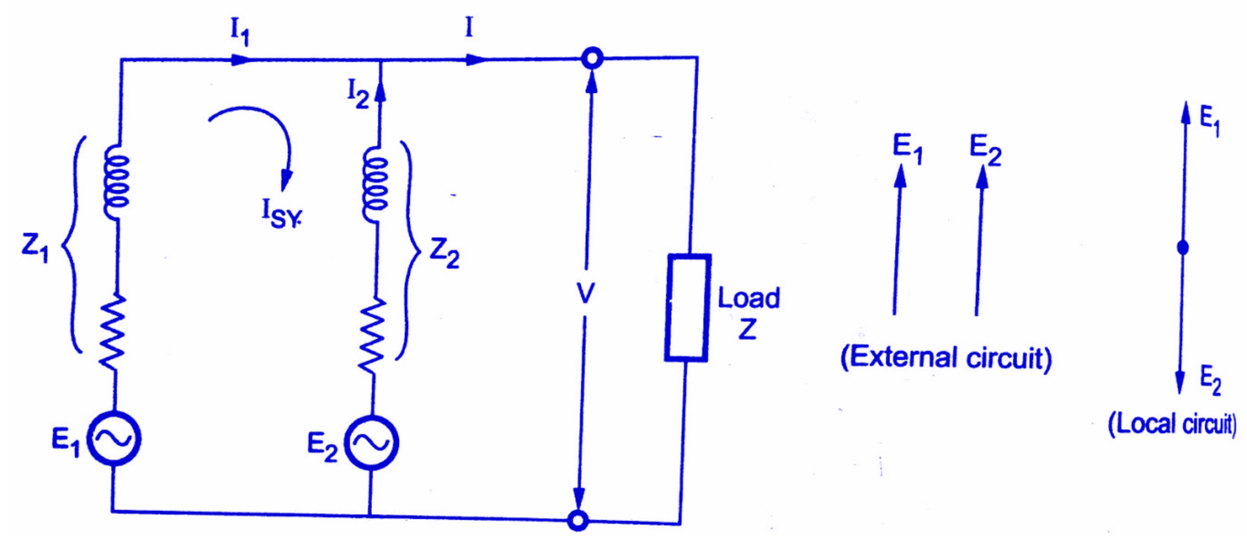
(Concept is same for both single and three phase)

<u>**Load Sharing Between Two Alternators**</u>

It has already been seen that in the case of interconnected systems at power stations the parallel operation of two alternators. In fact, the electricity demand of a country is fed by many alternators operating in parallel. There are various advantages of Parallel Operation of Two Alternators or Synchronous Generators. Some of them are listed below.

For a given capacity of a generating station, either a single large unit or many small units may be installed. If there are many small units operating in parallel instead of the single large unit then a number of alternators operating at a time can be changed depending upon electricity requirements or load demands. This will in operating the alternator near its hill load capacity so that efficiency will also be better. Therefore operating cost will be significantly reduced compared to the single large unit.

Consider two identical alternators in parallel operation as shown in below figure.



Here cylindrical rotor alternators are assumed for simplicity, but the results obtained are equally applicable to both salient and non-salient machines.

E_1	- Induced EMF in alternator 1	I_1	- Current from alternator 1
E_2	- Induced EMF in alternator 2	I_2	- Current from alternator 2
Z_1	- Impedance of alternator 1	I	- Total load current
Z_2	- Impedance of alternator 2	Z	- Load impedance
V	- Terminal voltage across the load	I_{SY}	- Circulating current

The terminal voltage V is given by,

$$\bar{V} = \bar{E}_1 - \bar{I}_1 \bar{Z}_1 = \bar{E}_2 - \bar{I}_2 \bar{Z}_2$$

Terminal voltage, $\bar{V} = \bar{I}\,\bar{Z}$

Load current $\bar{I} = \bar{I}_1 + \bar{I}_2$

From the above expression,

$$\bar{E}_1 = \bar{V} + \bar{I}_1 \bar{Z}_1$$

$$\therefore \quad \bar{E}_1 = \bar{I}\,\bar{Z} + \bar{I}_1 \bar{Z}_1 = (\bar{I}_1 + \bar{I}_2)\,\bar{Z} + \bar{I}_1 \bar{Z}_1 = \bar{I}_1 (\bar{Z} + \bar{Z}_1) + \bar{I}_2 \bar{Z}$$

Also, $$E_2 = \bar{I}\,\bar{Z} + \bar{I}_2 \bar{Z}_2 = (\bar{I}_1 + \bar{I}_2)\,\bar{Z} + \bar{I}_2 \bar{Z}_2 = \bar{I}_2 (\bar{Z} + \bar{Z}_2) + \bar{I}_1 \bar{Z}$$

Solving above two equations,

$$\bar{I}_1 = \frac{(\bar{E}_1 - \bar{E}_2)\,\bar{Z} + \bar{E}_1 \bar{Z}_2}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

$$\bar{I}_2 = \frac{(\bar{E}_2 - \bar{E}_1)\,\bar{Z} + \bar{E}_2 \bar{Z}_1}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

$$\bar{I} = \bar{I}_1 + \bar{I}_2 = \frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

$$= \frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{\bar{Z}\left[(\bar{Z}_1 + \bar{Z}_2) + \dfrac{\bar{Z}_1 \bar{Z}_2}{\bar{Z}}\right]}$$

$$\bar{V} = \bar{I}\,\bar{Z} = \bar{Z}\,.\,\frac{\bar{E}_1\,\bar{Z}_2 + \bar{E}_2\,\bar{Z}_1}{\bar{Z}\left[(\bar{Z}_1 + \bar{Z}_2) + \dfrac{\bar{Z}_1\,\bar{Z}_2}{\bar{Z}}\right]}$$

$$= \frac{\bar{E}_1\,\bar{Z}_2 + \bar{E}_2\,\bar{Z}_1}{(\bar{Z}_1 + \bar{Z}_2) + \dfrac{\bar{Z}_1\,\bar{Z}_2}{\bar{Z}}}$$

If no load is connected to the alternators only circulating current I_{SY} will flow in the circuit. The current is given by

$$\bar{I}_{SY} = \frac{\bar{E}_1 - \bar{E}_2}{\bar{Z}_1 + \bar{Z}_2}$$

<u>Determination of Voltage Regulation of Alternators</u>

1. **EMF or Synchronous Impedence or Pessimistic method**
2. **MMF or Ampere turns or Optimistic method**
3. **ZPF or Potier triangle method**

FOR THE ABOVE TOPIC (EMF, MMF, ZPF) REFER CLASS NOTES

1) An armature of a three phase alternators has 120 slots. The armature has 8 poles. calculate the distribution factor.

Given:- No. of. slots, $S = 120$

No. of. poles, $P = 8$

To find:-

Distribution factor, $k_d = ?$

$$k_d = \frac{\sin\left[\frac{m\beta}{2}\right]}{m \sin\left[\frac{\beta}{2}\right]} = ?$$

Solution:-

$$n = \frac{\text{Slot}}{\text{pole}} = \frac{120}{8} = 15$$

$$m = \frac{\text{Slot}}{\text{pole}} \Big/ \text{phase} = \frac{15}{3} = 5$$

($\because$ No. of phases is 3, as given)

$$\text{Slot angle, } \beta = \frac{180^\circ}{n} = \frac{180^\circ}{15} = 12^\circ$$

$$\beta = 12^\circ$$

$$\therefore K_d = \frac{\sin\left[\frac{5 \times 12}{2}\right]}{5 \times \sin\left[\frac{12}{2}\right]}$$

$\therefore$ Distribution factor, $\boxed{K_d = 0.957}$

---

(2) In a 4 pole, 3 ϕ alternator, armature has 36 slots. It is using an armature winding which is short pitched by one slot. calculate its coil span factor.

Given:- No. of poles = 4

No. of slots = 36

No. of phases = 3

The coil is short pitched by 1 slot.

To find :- Coil span factor (or) pitch factor (K_c)

$$K_c = \cos\frac{\alpha}{2} = ?$$

Solution:-

$$n = \frac{\text{slot}}{\text{pole}} = \frac{36}{4} = 9$$

$$\beta = \frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$$

given that the coil is short pitched by one slot i.e by 20° to full pitch distance.

$$\therefore K_c = \cos\frac{\alpha}{2} = \cos\frac{20}{2} = \cos 10$$

$\boxed{K_c = 0.9848}$ Coil span factor

---

③ An alternator runs at 250 rpm and generates an EMF at 50 Hz. There are 216 slots each containing 5 conductors. The winding is distributed and full pitch. All the conductors of each phase are in series and flux/pole is 30 mWb which is sinusoidally distributed. If the winding is star connected, determine the value of induced EMF available across the terminals.

Given :- Speed N_s = 250 rpm

frequency f = 50Hz

No. of slots = 216

Total no. of conductors = $216 \times 5 = 1080$

flux/pole = 30×10^{-3} wb

The winding is distributed & full pitched

for full pitched coil, $\boxed{K_c = 1}$

To find :- Induced EMF = ?

$$E_{ph} = 4.44 f \phi T_{ph} \cdot K_c \cdot K_d.$$

Solution :-

To find no. of poles, P.

$$\therefore \quad N_s = \frac{120 f}{P} \quad \therefore \quad P = \frac{120 f}{N_s}$$

$$\therefore \quad P = \frac{120 \times 50}{250} = 24$$

$$\boxed{P = 24 \text{ poles}}$$

$$n = \frac{\text{Slot}}{\text{pole}} = \frac{216}{24} = 9$$

$$m = \frac{n}{3} = \frac{9}{3} = 3$$

$$\text{Slot angle, } \beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$

$$\therefore \quad K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \beta/2} = \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3 \times \sin\left(\frac{20}{2}\right)}$$

$\therefore \; K_d = 0.9597$

& $K_c = 1$ ($\because$ full pitch Coil)

Total no. of Conductors, $Z = 216 \times 5 = 1080$

$\therefore \; Z_{ph} = \frac{Z}{3} = \frac{1080}{3} = 360$

$\therefore \; T_{ph} = \frac{Z_{ph}}{2} = \frac{360}{2} = 180$

$E_{ph} = 4.44 f \phi T_{ph} \, K_c . K_d$

$\Rightarrow 4.44 \times 50 \times 30 \times 10^{-3} \times 180 \times 1 \times 0.9597$

$\boxed{E_{ph} \Rightarrow 1150.48 \text{ V}}$

$E_{line} = \sqrt{3} \, E_{ph}$

$E_{line} = \sqrt{3} \times 1150.48 \rightarrow 1992.79 V$

$\therefore \; \boxed{E_{line} = 1992.79 \text{ V}}$

---

(4) A 3 phase, 16 pole, star connected alternator has 144 slots on the armature periphery. Each slot contains 10 conductors. It is driven at 375 rpm. The line value

of EMF available across the terminals is observed to be 2.657 KV. find the frequency of the induced EMF & flux/pole

Given :- 3ϕ, 16 pole, 144 slots

No. of conductors $= 144 \times 10 = 1440$

Speed $= 375$ rpm

$E_{line} = 2.657$ KV.

To find :-

frequency & flux / pole.

Solution :-

$$N_s = \frac{120 f}{P} \quad \therefore \quad f = \frac{N_s \times P}{120}$$

$$\therefore f = \frac{375 \times 16}{120} = 50 \text{ Hz}$$

$$\boxed{\text{frequency, } F = 50 \text{ Hz}}$$

$$n = \frac{\text{slot}}{\text{pole}} = \frac{144}{16} = 9$$

$$m = \frac{n}{3} = \frac{9}{3} = 3$$

$$\beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$

Assume full pitch coil, $\therefore \boxed{K_c = 1}$

$$\therefore K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin\left(\frac{3\times 20}{2}\right)}{3\sin\left(\frac{20}{2}\right)}$$

$$\boxed{K_d = 0.9597}$$

Total no. of Conductors, $Z = 144 \times 10$

$$Z = 1440$$

$$\therefore Z_{ph} = \frac{1440}{3} = 480$$

$$T_{ph} = \frac{480}{2} = 240$$

$$E_{ph} = \frac{E_{line}}{\sqrt{3}} = \frac{2.657}{1.732}$$

$$\boxed{E_{ph} = 1.534\ KV}$$

$$\therefore E_{ph} = 4.44\, f\, \phi\, T_{ph}\, K_c \cdot K_d$$

$$1.534 \times 10^3 = 4.44 \times 50 \times \phi \times 240 \times 1 \times 0.9597$$

$$\therefore \boxed{\phi = 0.03\ wb}$$

$$= 30\ mwb.$$

(5) A 3 phase, 50 Hz, 16 pole, star Connected alternator has a stator winding with 144 Slots with 10 Conductors/slot. The magnetic flux/pole is 0.03 webers, and is sinusoidally distributed in space. The Coil pitch of the winding is 8 slots. Estimate the EMF induced between the lines of the alternator.

Given :-

No. of poles = 16

frequency = 50 Hz

No. of slots = 144

No. of Conductors = $144 \times 10 = 1440$

$\phi = 0.03$ wb

Coil pitch = 8 slots

To find :- $E_{Line} = ?$

Solution :-

$$n = \frac{\text{slots}}{\text{pole}} = \frac{144}{16} = 9$$

$$m = \frac{\text{Slots/pole}}{\text{phase}} = \frac{n}{3} = \frac{9}{3} = 3$$

$$\beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$

for full pitch, the coil pitch is $(n = 9)$ slots

but the actual coil pitch is 8 slots.

$\therefore$ The coils are shorted by 1 slot.

$\therefore$ we know $\beta = 20^\circ$

$\therefore$ Short pitch angle (or) angle by which coils are short pitched $= \alpha$

$$\therefore \alpha = 1 \times \beta = 1 \times 20^\circ = 20^\circ$$

$$\therefore \boxed{\alpha = 20^\circ}$$

$$\therefore K_c = \cos\frac{\alpha}{2} \Rightarrow \cos\frac{20}{2} \Rightarrow \cos 10^\circ$$

$$\boxed{K_c = 0.9848}$$

$$\therefore K_d = \frac{\sin\frac{m\beta}{2}}{m \sin \beta/2} = \frac{\sin\left(\frac{3\times 20}{2}\right)}{3 \sin\left(\frac{20}{2}\right)} = 0.9597$$

$$\therefore K_d = 0.9597$$

No. of Conductors, $Z = 1440$

$$\therefore Z_{ph} = \frac{1440}{3} = 480$$

$$\therefore T_{ph} = \frac{Z_{ph}}{2} = 240$$

$$\therefore E_{ph} = 4.44\, f \phi T_{ph} K_c . K_d$$

$$E_{ph} = 4.44 \times 50 \times 0.03 \times 240 \times 0.9848 \times 0.9597$$

$$\boxed{E_{ph} = 1510.66\ V}$$

$$E_{line} = \sqrt{3}\, E_{ph} = 2616.5535\ V$$

$$\boxed{E_{line} = 2616.55\ V}$$

---

(6) A 3-phase, 16 pole alternator has star connected winding with 144 slots and 10 conductors/slot. The flux per pole is 0.04 wb and is distributed sinusoidal. The speed is 375 rpm. find the frequency, phase EMF. The coil span is 120° electrical

given :- poles = 16 , $\phi = 0.04$ wb

$N_s = 375$ rpm, Coil span = 120°

To find :-

frequency & phase EMF & line EMF.

Solutions :-

$$N_s = \frac{120 f}{P} \quad \therefore f = \frac{375 \times 16}{120} = 50 Hz$$

$$n = \frac{Slots}{pole} = \frac{144}{6} = 9$$

$$m = \frac{n}{3} = 3$$

$$\therefore \text{Slot angle, } \beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$

given that the Coil span is 120° electrical.

$\therefore$ Total Coil span is 180° electrical

$$\therefore \alpha = 180^\circ - 120^\circ = 60^\circ$$

$$\therefore K_c = \cos\frac{\alpha}{2} = 0.866$$

$$K_d = \frac{\sin\frac{m\beta}{2}}{m \sin\beta/2}$$

$$K_d = 0.9597$$

$$Z = slots \times \frac{Conductors}{slot} = 1440$$

$$Z_{ph} = \frac{Z}{3} = \frac{1440}{3} = 480$$

$$T_{ph} = \frac{Z_{ph}}{2} = 240$$

$$\therefore E_{ph} = 4.44 f \phi T_{ph} K_c \cdot K_d$$

$$E_{ph} = 4.44 \times 50 \times 0.04 \times 240 \times 0.866 \times 0.9597$$

$E_{ph} = 1771.24\ V$

$E_{line} = \sqrt{3}\ E_{ph} = 3067.87\ V$

---

(7) find the no load phase and line voltag of a Star Connected 3 phase, 6 pole alternator which runs @ 1200 rpm, having a flux per pole of 0.1 wb Sinusoidally distributed. Its Stator has 54 slots having double layer winding. Each Coil has 8 turns and the coil is chorded by 1 slot.

given :- poles = 6, Speed = 1200 rpm

$\phi = 0.1 wb$, 54 slots 8 turns/coil.

To find :- E_{ph} & E_{line} = ?

Solution :- $N_s = \frac{120 f}{P}$ ie $f = \frac{N_s P}{120}$

$\therefore f = \frac{1200 \times 6}{120} = 60\ Hz$

$n = \frac{slots}{pole} = \frac{54}{6} = 9$

$m = n/3 = 3$

$$\beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$

The coil is chorded by 1 slot ie by 20°

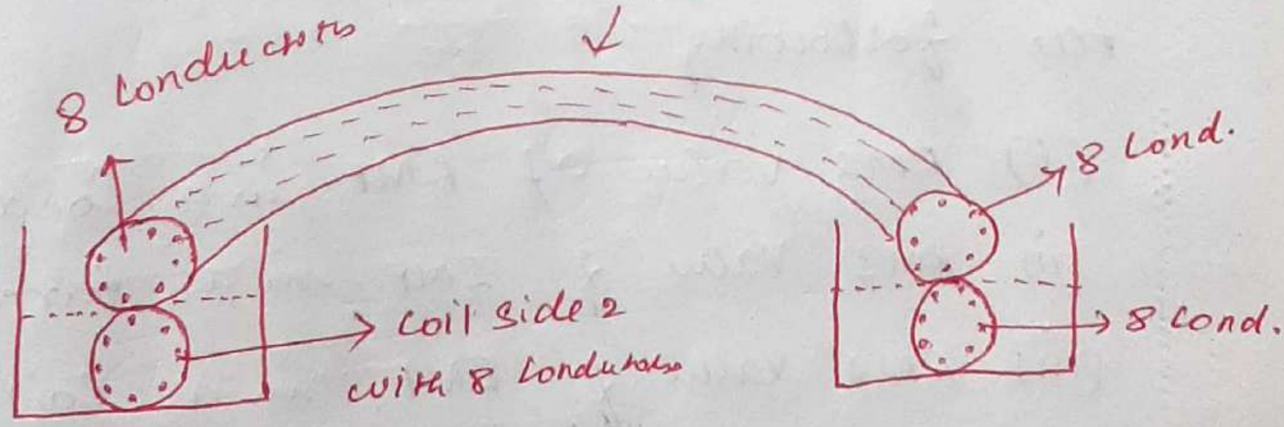
$\therefore \alpha = 20^\circ$

$$\therefore K_c = \cos\frac{\alpha}{2} = \cos 10 = 0.9848$$

$$K_d = \frac{\sin m\beta/2}{m \sin \beta/2} = \frac{\sin\left(\frac{3\times 20}{2}\right)}{3\sin\left(\frac{20}{2}\right)}$$

$K_d = 0.9598$.

given that the winding is double layer which means 2 coil side/slot and each coil has 8 turns. Thus each coil side has 8 conductors as shown below



$\therefore$ Conductors/slot $= 8 + 8 = 16$ conductors

$\therefore$ Total conductors (Z) $= 54 \times 16 = 864$

$$\therefore Z_{ph} = \frac{Z}{3} = \frac{864}{3} = 288$$

$$T_{ph} = \frac{Z_{ph}}{2} = 144$$

$$\therefore E_{ph} = 4.44 f \phi T_{ph} K_c . K_d$$

$$\therefore E_{ph} = 4.44 \times 60 \times 0.1 \times 144 \times 0.9848 \times 0.9598$$

$$\therefore \boxed{E_{ph} = 3625.9807 \text{ V}}$$

$$\therefore E_{line} = \sqrt{3} E_{ph} = 6.2803 \text{ KV}$$

---

(8) A 12 pole, 3 phase, 600 rpm Star Connected has 180 slots. These are 2 coil sides per slot and total 10 Conductors/slot. If the flux/pole is 0.05 wb. Determine the following

(i) RMS value of EMF in a Conductor

(ii) RMS value of EMF in a turn

(iii) RMS value of EMF in a Coil

(iv) Per phase induced EMF.

Assume full pitch Coil,

given :- poles = 12, speed = 600 rpm,

Slots = 180, 2 coil side/slot, 10 C/slot

$\phi = 0.05$ wb.

Solution :-

$$f = \frac{PN_s}{120} = \frac{12 \times 600}{120} = 60 \text{ Hz}$$

(i) Average value of EMF in a conductor is $= 2f\phi$

$\therefore$ RMS value of EMF in a conductor is

$\Rightarrow 1.11 \times 2f\phi$

$\Rightarrow 1.11 \times 2 \times 60 \times 0.05$

$\Rightarrow 6.66$ V

(ii) Average value of EMF in a turn is

$\Rightarrow 4f\phi$

RMS value of EMF in a turn is

$\Rightarrow 1.11 \times 4f\phi \Rightarrow 1.11 \times 4 \times 60 \times 0.05$

$\Rightarrow 13.32$ V

(iii) Each slot has 10 conductors & there are 2 coil sides. $\therefore$ Conductor / coil side is 5 & $\therefore$ 5 turns respectively.

∴ In a coil side there are 5 turns.

∴ RMS value of EMF in a coil $\Big\} = 13.32 \times 5$

$\Rightarrow 66.6\,V$

iv) Now total conductors

$$Z = 180 \times 10 = 1800$$

$$\therefore Z_{ph} = \frac{1800}{3} = 600$$

$$T_{ph} = \frac{600}{2} = 300$$

$$\therefore n = \frac{\text{slot}}{\text{pole}} = \frac{180}{12} = 15$$

$$\therefore m = \frac{n}{3} = 5$$

$$\therefore \beta = \frac{180^\circ}{n} = \frac{180^\circ}{15} = 12^\circ$$

∴ full pitch coil, ∴ $\boxed{K_c = 1}$

$$\therefore K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \beta/2} = \frac{\sin \frac{5 \times 12}{2}}{5 \sin \frac{12}{2}}$$

$$\boxed{K_d = 0.9566}$$

$\therefore E_{ph} \Rightarrow 4.44 f \phi T_{ph} K_c \cdot K_d$

$E_{ph} = 4.44 \times 60 \times 0.05 \times 300 \times 1 \times 0.9566$

$$\boxed{E_{ph} = 3822.88 \, V}$$

---

(9) A single phase 1500 rpm, 4 pole alternator has 8 conductors per slot with total of 24 slot. The winding is short pitched by $1/6^{th}$ of full pitch. Assume distributed winding with flux per pole as 0.05 wb. calculate the induced EMF.

given :- $N_s = 1500$ rpm

poles $= 4$

slots $= 24$

conductor / slot $= 8$

To find :- Induced EMF.

Solution :- $f = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50 \, Hz$

$n = \frac{slot}{pole} = \frac{24}{4} = 6$

$m = \frac{n}{1} = 6$ ($\because$ only one phase)

$\therefore \beta = \frac{180^\circ}{n} = \frac{180^\circ}{6} = 30^\circ$

$\therefore K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin\left(\frac{6 \times 30}{2}\right)}{6 \sin\left(\frac{30}{2}\right)}$

$\therefore \boxed{K_d = 0.6439}$

full pitch $= n = 6$ slots &

Coil is short pitched by $\frac{1}{6}^{th}$ of full pitch

$\therefore \frac{1}{6} \times 6 = 1$ slot

here one slot angle, $\beta = 30^\circ$ & $\therefore \alpha = 30^\circ$

(or)

full pitch $= 180^\circ$ Electrical

for $\frac{1}{6}^{th} = 180^\circ \times 1/6 = 30^\circ$

$\therefore \boxed{\alpha = 30^\circ}$

$\therefore K_c = \cos \frac{\alpha}{2} = \cos 15 = 0.9659$

Total conductors, $Z = 8 \times 24 = 192$

$$Z_{ph} = \frac{Z}{1} = 192 \quad \left(\because \text{single phase alternator} \right)$$

$$T_{ph} = \frac{Z_{ph}}{2} = 96$$

$$\therefore E_{ph} = 4.44 f \phi T_{ph} K_c \cdot K_d$$

$$\therefore E_{ph} = 4.44 \times 50 \times 0.05 \times 96 \times 0.9659 \times 0.6439$$

$$\therefore \boxed{E_{ph} = 662.74\ V}$$

EMF, MMF

VOLTAGE REGULATION

Methods of determining the Voltage regulation in alternator

1) EMF (or) Synchronous Impedance method
2) MMF (or) Ampere turns method
3) ZPF (or) Potier triangle method.

P1 The open circuit and short circuit test is conducted on a 3 phase Y connected 866 V, 100 KVA alternator.

I_f (A)	1	2	3	4	5	6
V_{oc} (line)	173	310	485	605	728	790
V_{oc} (ph)	$\frac{173}{\sqrt{3}}$	$\frac{310}{\sqrt{3}}$	$\frac{485}{\sqrt{3}}$	$\frac{605}{\sqrt{3}}$	$\frac{728}{\sqrt{3}}$	$\frac{790}{\sqrt{3}}$

The field current of 1 A produces a short circuit current of 25 A. The armature Resistance per phase is $0.15\,\Omega$. Calculate its full load regulation at 0.8 lagging P.F

Solution :-

$V_L = 866\ V$ & $KVA = 100$

$\therefore\ KVA = \sqrt{3}\, V_L I_L \times 10^{-3}$

$\therefore\ I_L = KVA / \sqrt{3}\, V_L \times 10^{-3}$

$\therefore\ \boxed{I_L = 66.67\ A}$

here $I_{aph} = I_L = 66.67\ A$

(∵ it is star connected)

$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{866}{\sqrt{3}} = 500\ V$ (star connected)

for the calculation of Z_s, it is required to plot OCC & SCC to the scale.

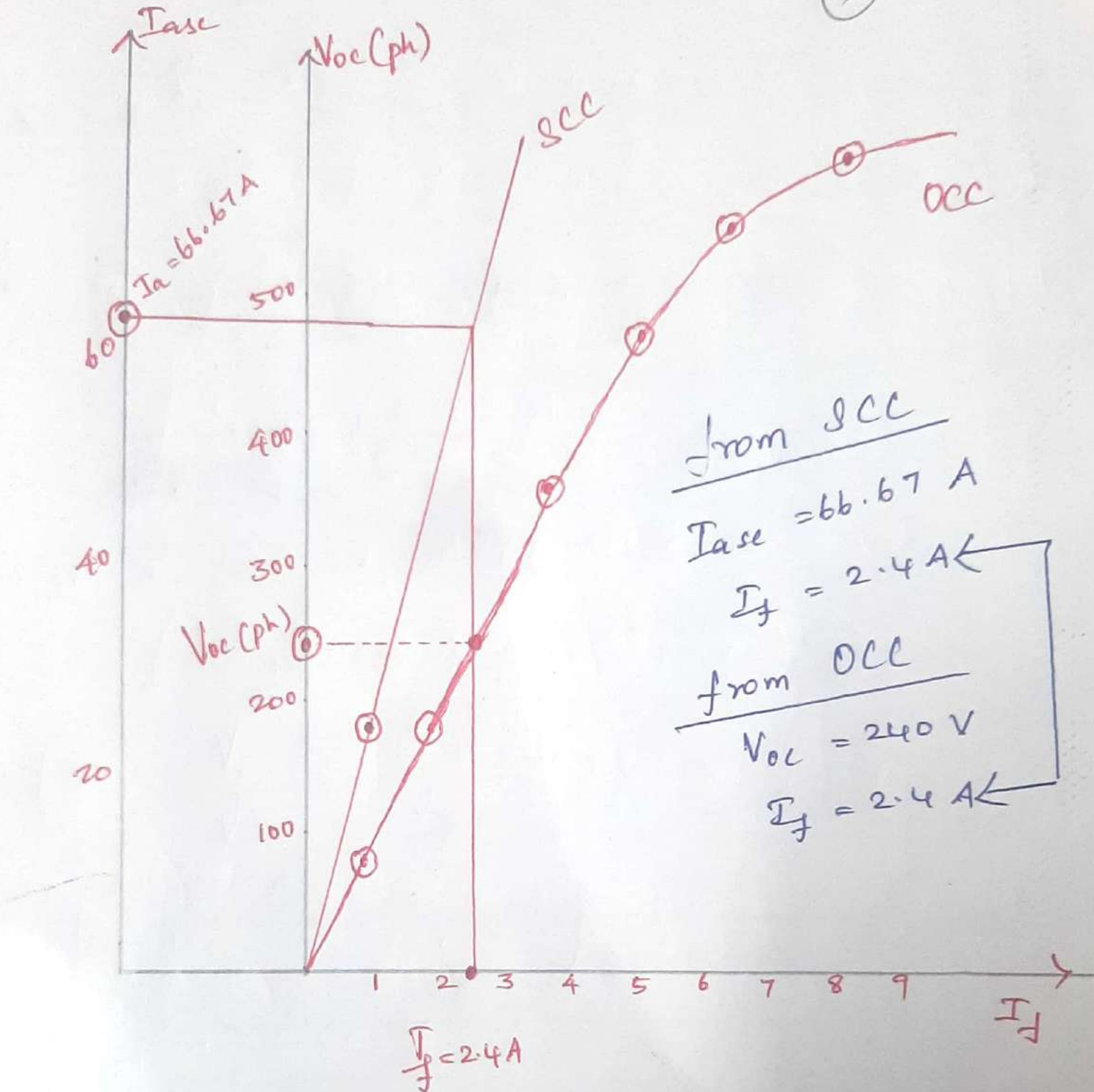
from the below graph

Synchronous impedance $Z_s = \left. \frac{V_{oc}\,(ph)}{I_{asc}\,(ph)} \right|_{I_f = \text{same}}$

$\therefore\ Z_s \Rightarrow \left. \frac{240}{66.67} \right|_{I_f = 2.4\ A}$

Z_s

$\therefore\ \boxed{Z_s = 3.6\ \Omega / ph}$



from SCC

$I_{asc} = 66.67$ A

$I_f = 2.4$ A

from OCC

$V_{oc} = 240$ V

$I_f = 2.4$ A

given, $R_a = 0.15\,\Omega/ph$

$\therefore$ Syn. reactance, $X_s = \sqrt{Z_s^2 - R_a^2}$

$X_s = \sqrt{3.6^2 - 0.15^2} \Rightarrow 3.597\,\Omega/ph.$

$V_{ph} = 500V$, $\cos\phi = 0.8$ & $\sin\phi = 0.6$

To find $E_{ph} = ?$ (4)

$$E_{ph}^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2$$

$$\therefore E_{ph}^2 \Rightarrow (500 \times 0.8 + 66.67 \times 0.15)^2 + (500 \times 0.6 + 66.67 \times 3.597)^2$$

$$\therefore \boxed{E_{ph} = 677.86\ V}$$

$$\therefore \%\ \text{Regulation} \Rightarrow \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$\Rightarrow \frac{677.86 - 500}{500} \times 100$$

$$\boxed{\%\ \text{Reg.} \Rightarrow +35.57\%}$$

(P2) calculate from the observations taken on 125 KVA, 400 V, 3 phase alternator, the % regulation for the half load condition at 0.8 P.F leading. while the full load current is obtained on the short circuit condition at a field current of 8A. Assume Y & $R_a = 0.1\ \Omega/ph$.

I_f	0	2	4	6	8	10
V_{oc} (lin)	0	80	140	200	250	300
V_{oc}(ph)	0	$\frac{80}{\sqrt{3}}$	$\frac{140}{\sqrt{3}}$	$\frac{200}{\sqrt{3}}$	$\frac{250}{\sqrt{3}}$	$\frac{300}{\sqrt{3}}$

Solution:- $V_L = 400\,V$ & $KVA = 125$

$$KVA = \sqrt{3}\, V_L I_L \times 10^{-3}$$

$$\therefore\ I_L = 125 / \sqrt{3} \times 400 \times 10^{-3}$$

$$\therefore\ \boxed{I_L = 180.42\ A}$$

Now @ the field current of 8A (produces) full load current is obtained & it has a linear variation.

$\therefore$ for half load, $I_f = \frac{8}{2} = 4A$

for half load, $I_{asc} = \frac{180.42}{2}$

$= 90.21\ A$

for half load, $V_{oc\,(ph)} = \frac{140}{\sqrt{3}}$

$= 80.829\ V$

$\therefore$ $\left.\begin{array}{l} Z_s \text{ for half} \\ \text{load} \end{array}\right\} = \dfrac{V_{oc}(ph)}{I_{asc}(ph)} \Big|_{I_f = \text{same}}$

$Z_s \Rightarrow \dfrac{80.829}{90.21} \Rightarrow 0.896\,\Omega/ph$

$\therefore$ $X_s = \sqrt{Z_s^2 - R_a^2} \Rightarrow \sqrt{(0.896)^2 - (0.1)^2}$

$\boxed{X_s = 0.895\,\Omega/ph}$

hence to calculate E_{ph} & % R (leading)

$\therefore$ $V_{ph} = \dfrac{V_L}{\sqrt{3}}, \dfrac{400}{\sqrt{3}} = 230.94\,V$

$\cos\phi = 0.8$ & $\sin\phi = 0.6$

$\therefore$ $E_{ph}^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi - I_a X_s)^2$

$\boxed{E_{ph} = 202.347\,V}$

$\therefore$ % Regulation $= \dfrac{E_{ph} - V_{ph}}{V_{ph}} \times 100$

$= \dfrac{202.34 - 230.94}{230.94} \times 100$

Regulation

$\boxed{\% \text{ Reg} = -12.38\,\%}$

(P3) A 3 phase, Y connected, 1000 KVA, 11000 V alternator has a rated current of 52.5 A. The ac resistance of the winding per phase is 0.45 Ω. The test results are given below.

OC Test: $I_f = 12.5\,A$ & Voltage b/w line = 422 V

SC Test: $I_f = 12.5\,A$ & line current = 52.5 A

Determine the full load regulation of alternator. 0.8 lagging & leading.

Solution :- $V_L = 11{,}000\,V$ & 1000 KVA

$I_L = 52.5\,A$ (given)

$R_a = 0.45\,\Omega/ph.$

Y Connection, $I_L = I_{aph} = 52.5\,A$

" $V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{11{,}000}{\sqrt{3}} = 6350.85\,V$

$$\therefore Z_s = \left.\frac{V_{oc}(ph)}{I_{asc}(ph)}\right| I_f \text{ (same)} \Rightarrow \frac{\left(\frac{422}{\sqrt{3}}\right)}{52.5}$$

$$\Rightarrow 4.64\,\Omega$$

(8)

$$\therefore X_s = \sqrt{Z_s^2 - R_a^2} \Rightarrow \sqrt{4.64^2 - 0.45^2}$$

$$\boxed{X_s = 4.6189\ \Omega}$$

(i) $\cos\phi = 0.8$ lagging, $V_{ph} = 6350.85$

$$\therefore E_{ph}^2 \Rightarrow (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2$$

$$\boxed{E_{ph} = 6517.729\text{V}}$$ E_{ph} (lagging)

$$\%R = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100 \Rightarrow \frac{6517.72 - 6350.85}{6350.85} \times 100$$

$$\boxed{\%R = +2.627\%}$$ (+)

(ii) $\cos\phi = 0.8$ leading, $V_{ph} = 6350.85$ V

$$E_{ph}^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi - I_a X_s)^2$$

$$\therefore E_{ph} = 6227.75\text{ V}$$

$$\therefore \%R = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100 = -1.938\%$$

$$\boxed{\%R = -1.938\%}$$ (−)

(9)

(P4) The open circuit and short circuit test readings for a 3 phase Y connected, 1000 KVA, 2000 V, 50 Hz synchronous generator are

I_f	10	20	25	30	40	50
I_{sc}	—	200	250	300	—	—
V_{oc}(line)	800	1500	1760	2000	2350	2600
V_{oc}(ph)	$\frac{800}{\sqrt{3}}$	$\frac{1500}{\sqrt{3}}$	$\frac{1760}{\sqrt{3}}$	$\frac{2000}{\sqrt{3}}$	$\frac{2350}{\sqrt{3}}$	$\frac{2600}{\sqrt{3}}$

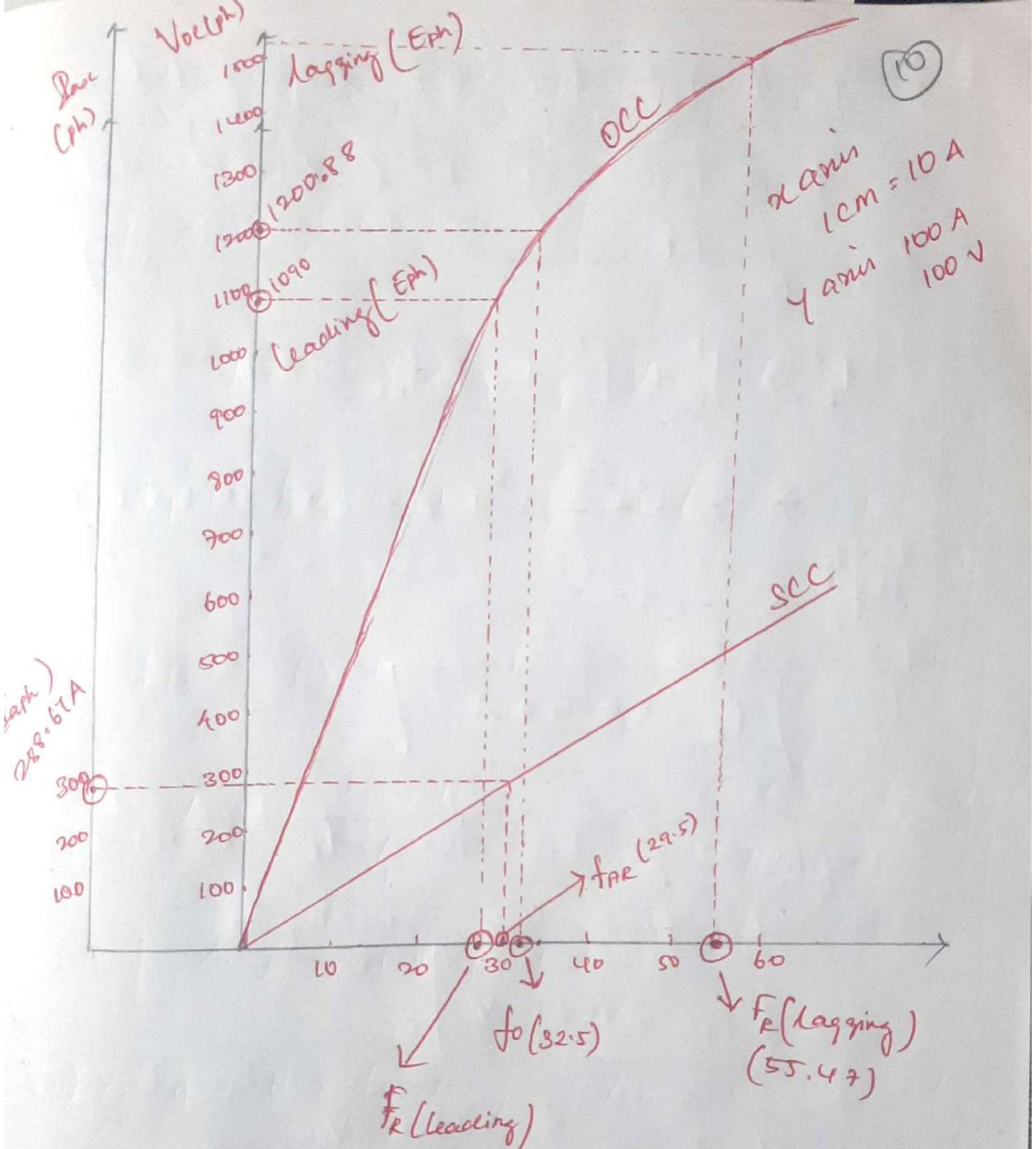
The armature effective resistance is $0.2\ \Omega/ph$.
Draw the characteristics curves and estimate the full load percentage regulation

a) 0.8 P.F lagging

b) 0.8 PF Leading by mmf method.

Solution:-

Draw the OCC & SCC characteristics in the graph.



$V_L = 2000\,V$

$\therefore \quad V_{ph} = \dfrac{2000}{\sqrt{3}} = 1154.70\,V$ (Y Connected)

$R_a = 0.2\,\Omega$, $\cos\phi = 0.8$, $\sin\phi = 0.6$

f_o is the field current required to obtain the Voltage equal to $V_{ph} + I_{aph} R_a \cos\phi$

I_{aph} - full load armature current.

(11)

$KVA = \sqrt{3} V_L I_L \times 10^{-3}$

$\therefore I_L = 288.67 A$

$\therefore I_L = I_{aph} = 288.67 A \quad (\because Y \text{ conn})$

$\therefore V_{ph} + I_{aph} R_a \cos\phi \Rightarrow 1154.70 + (288.67)(0.2)(0.8)$

$\therefore \Rightarrow 1200.8872 \text{ Volts}$

f_o corresponding to the Voltage is obtained from the above graph

1200.88V

$\boxed{f_o = 32.5 A}$

f_{AR} is the field current required to circulate full load short circuit current of 288.67. (obtained from scc)

288.67A

$\boxed{f_{AR} = 29.5 A}$

∴ find E_{ph} for 0.8 lagging P.F

To find resultant field current for lagging P.F

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$$f_R^2 \Rightarrow f_o^2 + f_{AR}^2 + 2 f_o f_{AR} \sin\phi$$

$$\Rightarrow 32.5^2 + 29.5^2 + 2 \times 32.5 \times 29.5 \times 0.6$$

$$f_R^2 \Rightarrow 3077$$

$$\therefore \boxed{f_R = 55.47\ A}$$

Corresponding E_{ph} for $f_R = 55.47\ A$ is obtained from the graph, as

$$\boxed{E_{ph} = 1560\ V}$$

$$\therefore \%\ \text{Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$\therefore \%\ R = \frac{1560 - 1154.70}{1154.70} \times 100$$

lagging p.f

$$\boxed{\therefore \%\ R = +35.10\%}$$

(+)

∴ find E_{ph} for 0.8 leading p.f

To find the resultant field current for leading p.f (13)

$$F_R^2 = f_0^2 + f_{AR}^2 - 2 f_0 f_{AR} \sin\phi$$

$$F_R^2 = (32.5)^2 + (29.5)^2 - 2(32.5)(29.5)(0.6)$$

∴ $\boxed{F_R = 27.86\ A}$

Corresponding E_{ph} for $F_R = 27.86A$ is obtained from the graph as

$$\boxed{E_{ph} = 1090\ V}$$

$$\therefore \%\ \text{Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$\therefore \%\ R = \frac{1090 - 1154.70}{1154.70} \times 100$$

leading $\boxed{\%\ R = -5.6031\ \%}$ (−)

(P5) A 1.1 MVA, 2.2 KV, 3 phase, Y Connected alternator gave the following test result during OC and SC Tests: (14)

I_f	10	20	30	40	50
I_{sc}	200	400	—	—	—
V_{oc} (line) (KV)	0.88	1.65	2.20	2.585	2.86
V_{oc} (ph) (KV)	$\frac{0.88}{\sqrt{3}}$	$\frac{1.65}{\sqrt{3}}$	$\frac{2.20}{\sqrt{3}}$	$\frac{2.585}{\sqrt{3}}$	$\frac{2.86}{\sqrt{3}}$

Solution:- $R_a = 0.22\ \Omega/ph$, $\cos\phi = 0.8$ lag,

$V_L = 2.2$ KV.

$$MVA = \sqrt{3}\, V_L I_L \times 10^{-6}$$

$$\therefore I_L = \frac{1.1 \times 10^6}{\sqrt{3} \times 2.2 \times 10^3} = 288.67\,A$$

$= I_{aph}$.

Since Y Connected.

Draw the OCC & SCC characteristics.

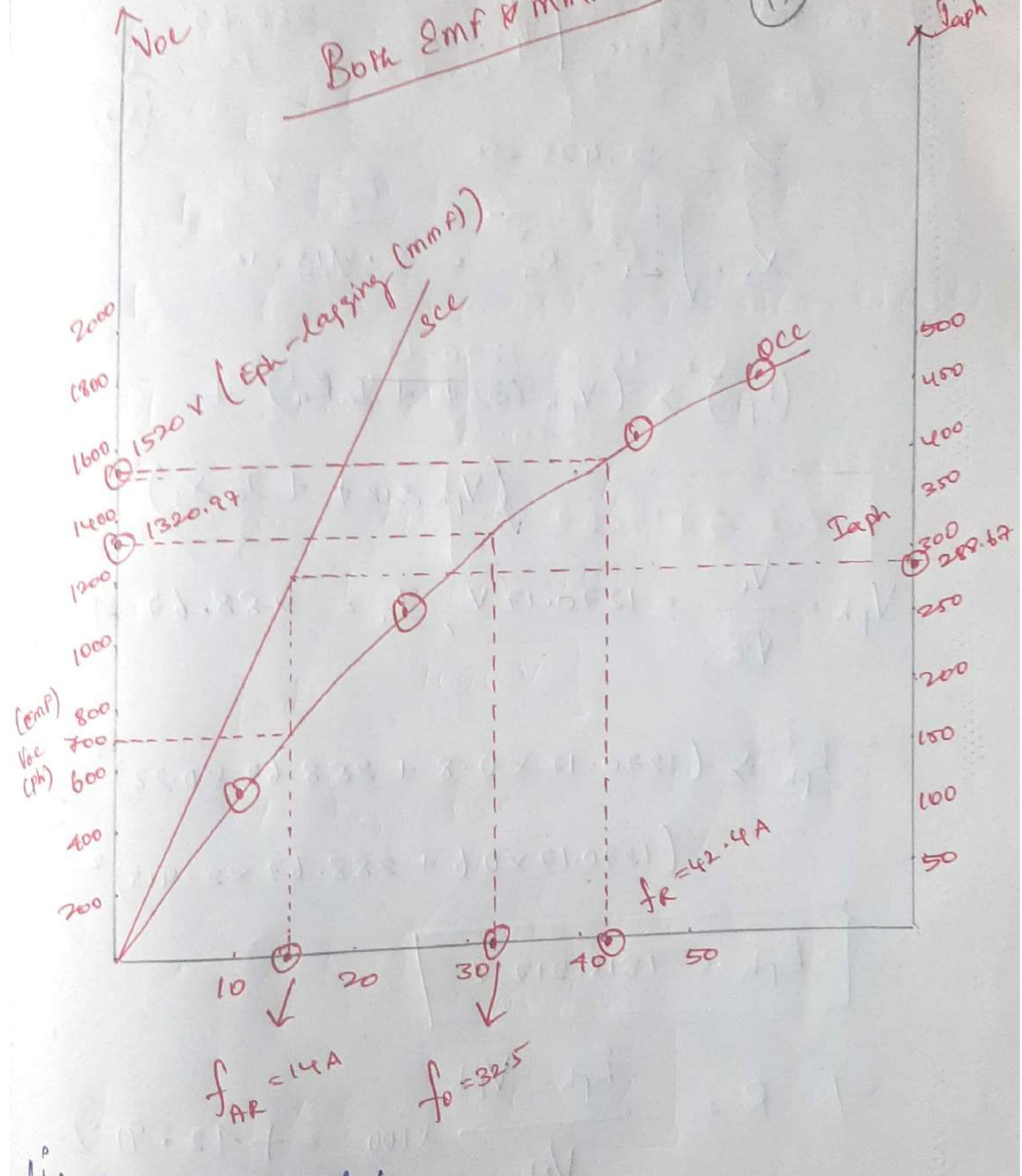
Question

The effective resistance of 3ϕ winding $0.22\Omega/ph$. Estimate the load regulation @ .8 PF lagging

i) EMF ii) MMF methods.

(15)

Both Emf & mmf



(i) EMF method :-

$I_{aph} = I_{asc} = 288.67A$, $I_f = 14A$ from graph.

$V_{oc(ph)} = 700V$, for $I_f = 14A$ from graph.

$$Z_s = \frac{V_{oc}}{I_{osc}}\Big|_{I_f = \text{same}} = \frac{700}{288.67}$$

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$$Z_s = 2.425\ \Omega$$

$$\therefore X_s = \sqrt{Z_s^2 - R_a^2} = 2.415\ \Omega$$

$$\therefore (E_{ph})^2 \Rightarrow (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = 1270.17\ V, \quad I_a = 288.67\ A$$

$$\therefore E_{ph}^2 \Rightarrow (1270.17 \times 0.8 + 288.67 \times 0.22)^2 + (1270.17 \times 0.6 + 288.67 \times 2.415)^2$$

$$\boxed{E_{ph} = 1815.217\ V}$$

$$\%\ R = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100 = +42.91\ \%$$

$$\boxed{\%\ R = +42.91\ \%}$$

(ii) MMF Method :-

(17)

f_o is the field current required to obtain the voltage equal to $V_{ph} + I_{aph} R_a \cos\phi$

$V_{ph} + I_a R_a \cos\phi = 1270.17 + 288.67 \times 0.22 \times 0.8$

$\Rightarrow 1320.97\ V$

from OCC, I_f corresponding to $1320.97\ V$

is $\boxed{f_o = 32.5A}$

f_{AR} is the current required to circulate full load short circuit of $288.67\ A$

i.e $\boxed{f_{AR} = 14A}$

$\therefore$ To find resultant field current for the calculation of E_{ph}. (lagging)

$$f_R^2 = f_o^2 + f_{AR}^2 + 2 f_o f_{AR} \sin\phi$$

$\boxed{f_R = 42.4A}$

from occ in the graph, E_{ph} corresponding to $f_R = I_f = 42.4A$ is $1520\,V$.

$\therefore$ % Regulation $= \dfrac{E_{ph} - V_{ph}}{V_{ph}} \times 100$

$$\Rightarrow \frac{1520 - 1270.17}{1270.17} \times 100$$

$$\boxed{\%R \Rightarrow +19.67\,\%}$$

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VISHNU INSTITUTE OF TECHNOLOGY

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Vishnupur, BHIMAVARAM – 534 202

ELECTRICAL & ELECTRONICS ENGINEERING

II B. Tech. II Semester EEE R20

Electrical Machines – II

Material for Unit V

Synchronous motor operation, starting and performance: Principle of operation – Phasor diagram – Methods of starting, variation of current and power factor with excitation (V curves) –synchronous condenser – mathematical analysis for power developed – synchronizing torque –hunting and its suppression– applications.

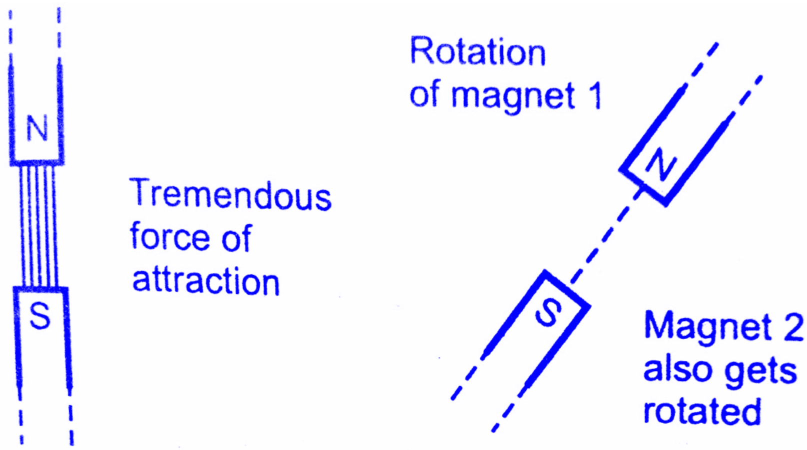
Unit V Synchronous motor operation, starting and performance

Construction of synchronous motor

Construction of synchronous motor and synchronous generator are same. Therefore for construction refer Unit 4.

Principle operation of synchronous motor

Synchronous motor works on the principle of the magnetic locking. When two, unlike poles, are brought near each other, if the magnets are strong, there exists a tremendous force of attraction between those two poles. In such condition, the two magnets are said to be magnetically locked. If now one of the two magnets is rotated, the other also rotates in the same direction with the same speed due to the force of attraction i.e. due to magnetic locking condition. The principle is shown schematically in the below figure.



So to have the magnetic locking condition, there must exist two unlike poles and magnetic axes of two must be brought very close to each other. Let us see the application of this **principle of synchronous motor**. Consider a three-phase synchronous motor, whose stator is wound for 2 poles. The two magnetic fields are produced in the synchronous motor by exciting both the windings stator and rotor with three-phase a.c. supply and d.c. supply respectively. When the three-phase winding is excited by a three-phase a.c. supply then the flux produced by the three-phase winding is always of rotating type. Such a magnetic flux rotates in space at a speed called **synchronous speed**. This magnetic is called a ***rotating magnetic field***.

The rotating magnetic field creates an effect similar to the physical rotation of magnets in space with synchronous speed. So stator of the synchronous motor produces one magnet which is as good as rotating in space with the synchronous speed. The synchronous speed of a stator rotating magnetic field depends on supply frequency and the number of poles for which stator winding is wound. If the frequency of the a.c supply is f Hz and stator is wound for P number of poles, then the speed of the **rotating magnetic field** is synchronous given by,

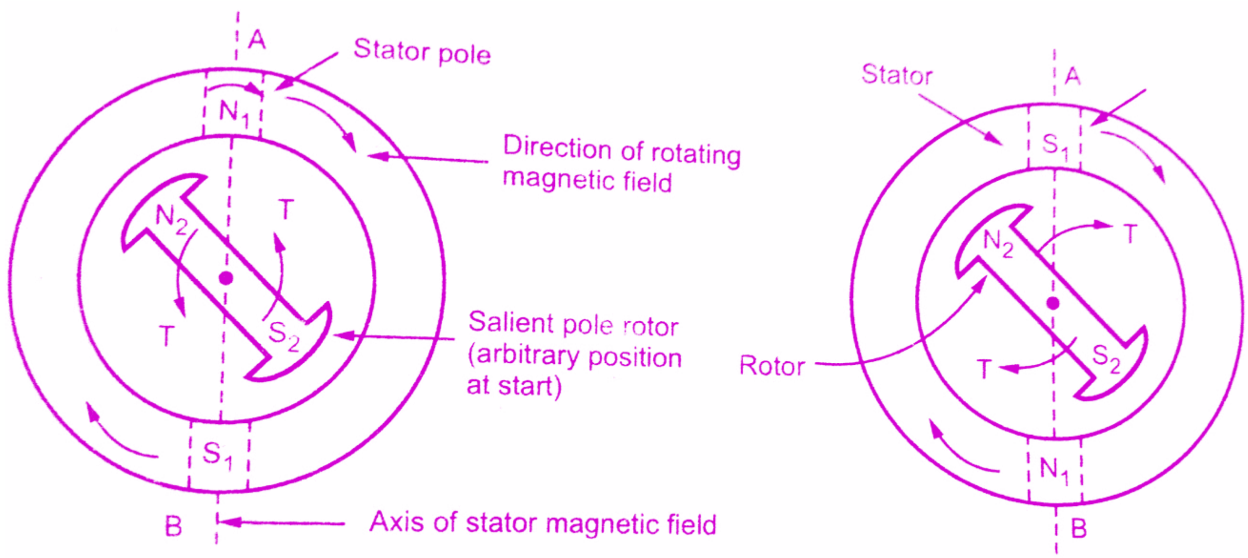
$$N_s = 120f/p \quad \text{RPM}$$

In this case, as the stator is wound for say 2 poles, with 50 Hz supply, the speed of the rotating magnetic field will be 3000 RPM. This effect is similar to the physical rotation of two poles with a speed of Ns RPM. For simplicity of understanding let us assume that the stator poles are N1 and S1 which are rotating at a speed of Ns. The direction of rotation of the rotating magnetic field says clockwise. When the field winding on the rotor is excited by a d.c supply, it also produces two poles, assuming rotor construction to be two poles, salient type. Let these poles be N2 and S2. Now one magnet is rotating at Ns having poles N1 and S1 while at start rotor is stationary i.e. second magnet is stationary having poles N2 and S2. If somehow the unlike poles N1 and S2 or S1 and N2 are brought near each other, the magnetic locking may get established between stator and rotor poles.

As stator poles are rotating, due to magnetic rotor will also rotate in the same direction as that of stator poles i.e. in the direction of **rotating magnetic field**, with the same speed i.e. Ns. Hence synchronous motor rotates at one and only one speed i.e. **synchronous speed**. But this all depends on the existence of magnetic locking between stator and rotor poles. Practically it is not possible for stator poles to pull the rotor poles from their stationary position into magnetic locking condition. Hence synchronous motors are not self-starting. Let us see the reason behind this in detail.

WHY Synchronous Motor is not self-starting?

Consider the rotating magnetic field is equivalent to the physical rotation of two stator poles N1 and S1.Consider an instant when two poles are at such a position where the stator magnetic axis is vertical, along A-B as shown in the below figure(a). At this instant, rotor poles are arbitrarily positioned as shown in the below figure. At this instant, the rotor is stationary and unlike poles will try to attract each other. Due to this rotor will be subjected to an instantaneous torque in the anti-clockwise direction as in figure (a).



Now stator poles are rotating very fast i.e. at a speed Ns RPM. Due to inertia, before rotor hardly rotates in the direction of anticlockwise torque, to which it is subjected, the stator poles change their positions. Consider an instant half a period latter where stator poles are exactly reversed but due to inertia rotor is unable to rotate from its initial position. This is shown in figure(b).

At this instant, due to the unlike poles trying to attract each other, the rotor will be subjected to torque in the clockwise direction. This will tend to rotate the rotor in the direction **rotating magnetic field**. But before this happens, stator poles again change their positions reversing the direction of the torque exerted on the rotor.

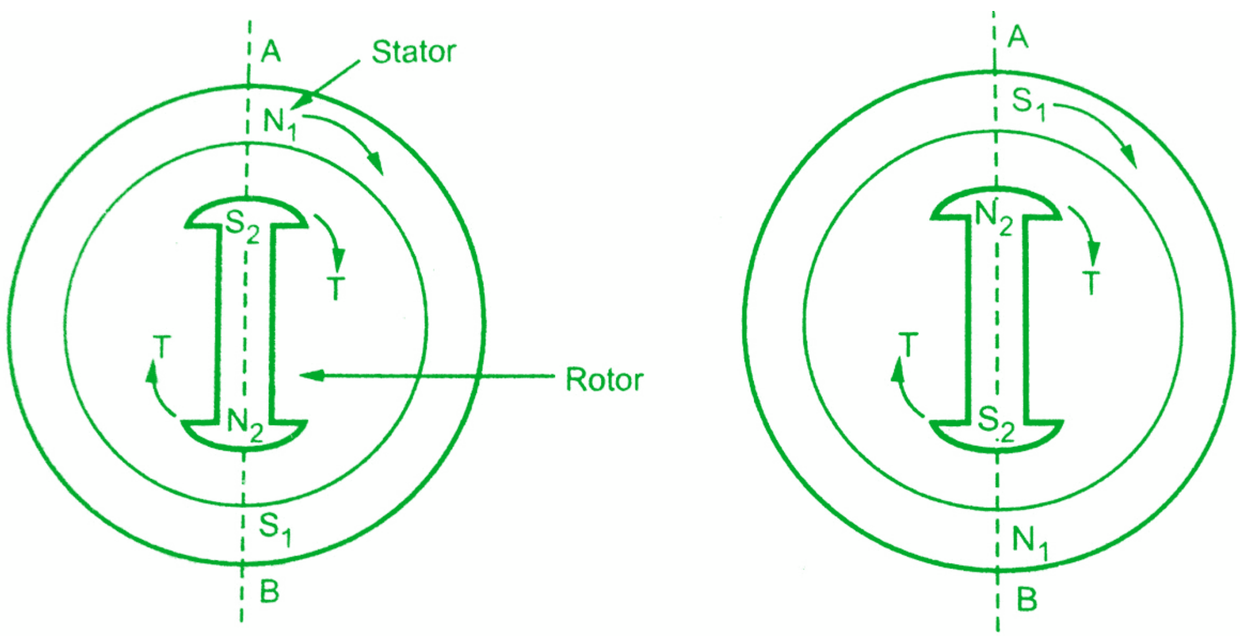
Note: The question is obvious that what will happen if by chance the rotor position is in such a way that the unlike rotor and stator poles are facing each other? But owing to the large inertia of the rotor, the rotor fails to rotate along with the stator poles. Hence again the difference of position of magnetic axes gets created and rotor gets subjected to reversing torque.

This is because the speed with which rotating magnetic field is rotating is so high that it is unable to rotate the rotor from its initial position, due to the inertia of the rotor. So under any case, whatever may be the starting position of the rotor, the synchronous motor is not self-starting.

Procedure to start a Synchronous Motor:

Now suppose the rotor is rotated by some external means at a speed almost equal to **synchronous speed**. And then the rotor is excited to produce its poles. At a certain instant now, the stator and rotor, unlike poles, will face each other such that their magnetic axes near each other. Then the force of attraction between the two pulls both of them into magnetic locking condition. Once magnetic locking is established, the rotor and stator poles continue to occupy the same relative positions. Due to this, the rotor continuously experiences a unidirectional torque in the direction of the rotating magnetic field. Hence rotor rotates at synchronous speed said to be in synchronism with the **rotating Magnetic field**.

The external device used to rotate rotor near synchronous speed can be removed once synchronism is established. Then continues its rotation at Ns due to magnetic locking. This is the reason why synchronous motor runs only at synchronous speed and does not rotate at any speed other than the synchronous. This operation is shown in the below figures (a) and (b).



It is necessary to keep field winding i.e. rotor excited from d.c supply to maintain the magnetic locking, as long as the motor is operating.

Starting methods of synchronous motors or Methods of starting Synchronous Motor:

We have to think about an alternative to rotate the rotor at a speed almost equal that of synchronous speed. So this can be possible by employing various methods to start the synchronous motor. The following are the different methods to start a synchronous motor.

1. Using Pony Motors

2. Using Damper Winding

3. As a slip ring Induction motor

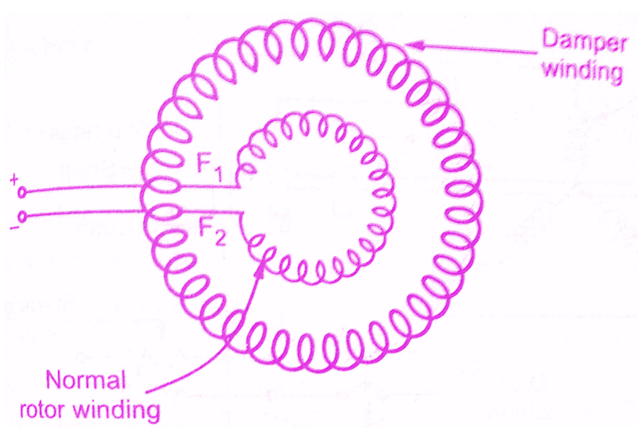
4. Using Small dc machine coupled to it

1. Using pony Motors

In this method, some external devices like small induction motor used to bring rotor near to synchronous motor. his external device is called Pony motor. When the rotor attains synchronous speed, dc excitation to the rotor is switched on. After some time synchronism is developed and then pony motor is decoupled. Due to synchronism promoter continues to rotate as a synchronous motor.

2. Using damper winding

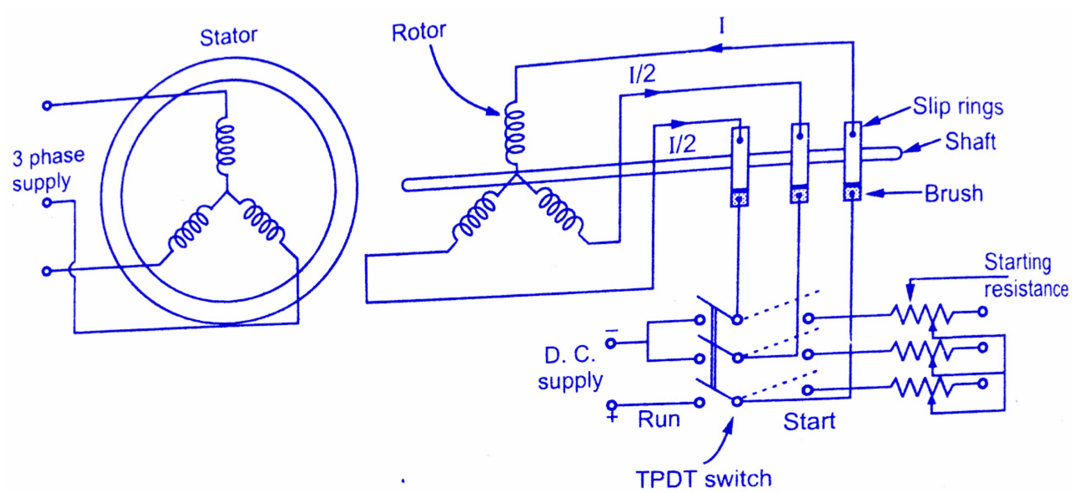
In a synchronous motor, we have normal field winding and in addition to this additional winding consisting of copper bars is placed in the slots in the pole faces. These bars short-circuited with the help of end rings. This additional winding on the rotor is called damper winding. This winding as it is short-circuited, it acts like squirrel cage rotor winding of an induction motor. The schematic diagram of this damper winding is shown in the below figure.



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

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 the 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.

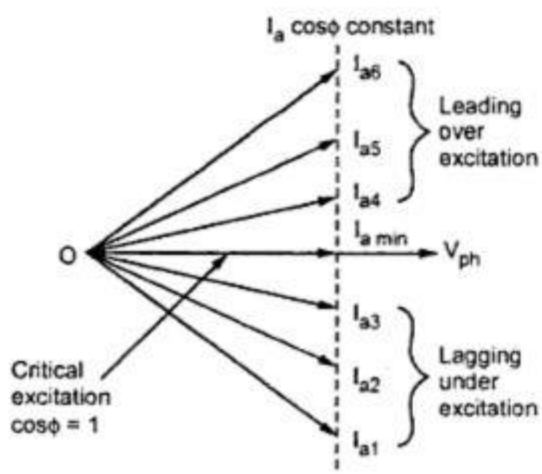
The synchronous motor started by this method is called a slip ring induction motor is shown in the below figure. It can be observed from the above figure that the same three phase rotor winding acts as a normal rotor winding by shorting two of the phases. From the positive terminal, current 'I' flows in one of the phases, which divides into two other phases at start point as 1/2 through each, when the switch is thrown on d.c. supply side.

4. Using Small D.C. Machine:

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

V Curves and Inverted V Curves of Synchronous Motor

It is clear that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current I_a decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the Fig. 1.

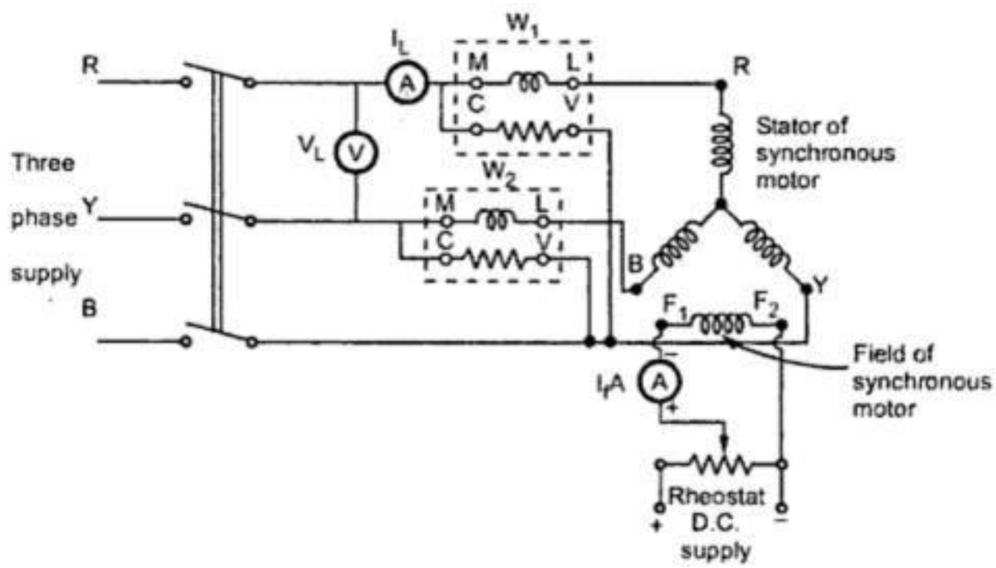


Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (I_a) against field current (I_f) is plotted, then its shape looks like an English alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V-curves of synchronous motor. These are shown in the Fig.

As against this, if the power factor (cos Φ) is plotted against field current (I_f), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against I_f, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the Fig.

Experimental Setup to Obtain V-Curves

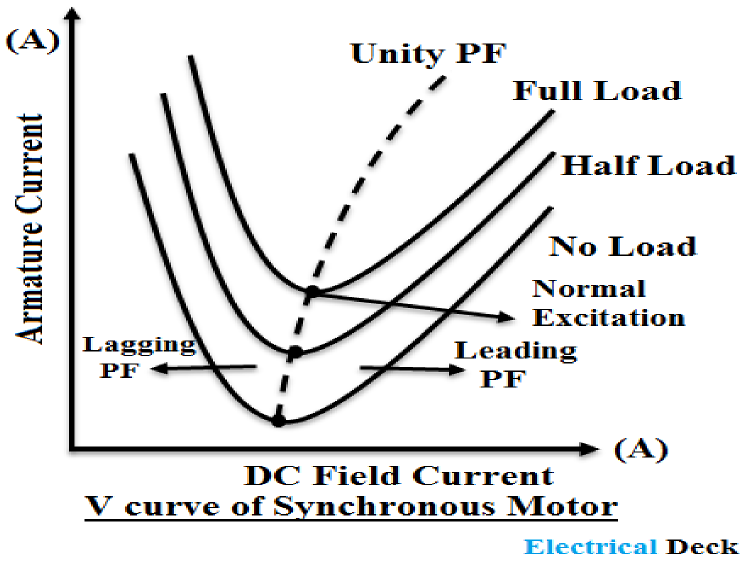
Stator is connected top three phase supply through wattmeter's and ammeter. The two wattmeter method is used to measure input power of motor. The ammeter is reading line current which is same as armature (stator) current. Voltmeter is reading line voltage.



A rheostat in a potential divider arrangement is used in the field circuit. By controlling the voltage by rheostat, the field current can be changed. Hence motor can be subjected to variable excitation condition to note down the readings.

V-Curves of Synchronous Motor:

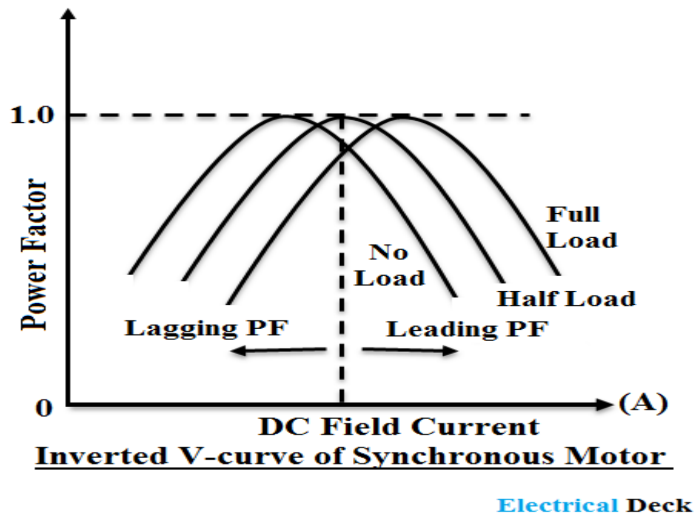
If the armature current I_a is plotted against excitation or field current for various load conditions, we obtain a set of curves known as 'V-Curves' clue to their shape similar to english letter V. In the below figure V-Curve of a synchronous motor shows how armature current I_a changes with excitation for the same input, at no-load, half full-load, and full-load.



From V-Curves it is observed that the armature current has large values both for low and high values of excitation (though it is lagging for low excitation and leading for higher excitation). In between, it has a minimum value corresponding to the unity power factor (normal excitation).

Inverted V-Curves of Synchronous Motor:

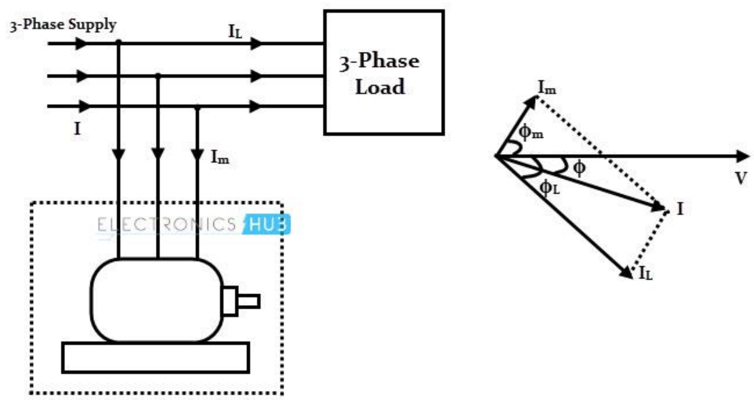
If the power factor is plotted against excitation for various load conditions, we obtain a set of curves known as 'Inverted V-Curves'.



The inverted V-Curves of synchronous motor show how the power factor varies with excitation. From inverted V-curves, it is observed that the power factor is lagging when the motor is under excited and leading when it is over-excited. In between, the power factor is unity.

Synchronous condenser

Like capacitor bank, we can use an overexcited synchronous motor to improve the poor power factor of a power system. The main advantage of using synchronous motor is that the improvement of power factor is smooth. When a synchronous motor runs with over-excitation, it draws leading current from the source. We use this property of a synchronous motor for the purpose. Here, in a three-phase system, we connect one three-phase synchronous motor and run it at no load.

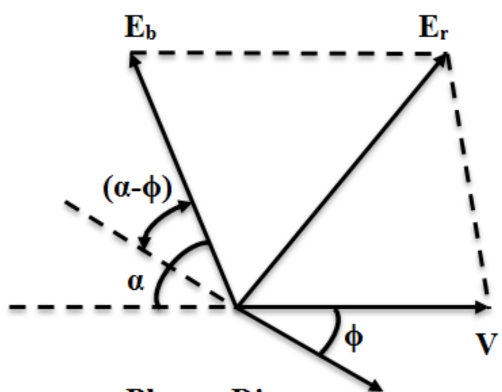


Suppose due to a reactive load of the power system the system draws a current I_L from the source at a lagging angle θ_L in respect of voltage. Now the motor draws a I_M from the same source at a leading angle θ_M. Now the total current drawn from the source is the vector sum of the load current I_L and motor current I_M. The resultant current I drawn from the source has an angle θ in respect of voltage. The angle θ is less than angle θ_L. Hence power factor of the system cos θ is now more than the power factor cos θ_L of the system before we connect the synchronous condenser to the system. The synchronous condenser is the more advanced technique of improving power factor than a static capacitor bank, but power factor improvement by synchronous condenser below 500 kVAR is not economical than that by a static capacitor bank. For major power network we use synchronous condensers for the purpose, but for comparatively lower rated systems we usually employ capacitor bank. The advantages of a synchronous condenser are that we can control the power factor of system smoothly without stepping as per requirement. In case of a static capacitor bank, these fine adjustments of power factor cannot be possible rather a capacitor bank improves the power factor stepwise. The short circuit withstand-limit of the armature winding of a synchronous motor is high. Although, synchronous condenser system has some disadvantages. The system is not silent since the synchronous motor has to rotate continuously. An ideal load less synchronous motor draws leading current at 90^o (electrical).

Power Developed in Synchronous Motor

The phasor diagram of a synchronous motor is shown below. From the phasor diagram, let,

- V = Supply voltage / phase
- I_a = Armature current / phase
- R_a = Armature resistance / phase
- α = Load angle
- φ = Power factor angle



Phsaor Diagram

Electrical Deck

Input Power to Motor:

Motor input power per phase is V I_a Cos φ. Now, the total input power for 3-φ star-connected motor is,

$$P = \sqrt{3}\, V_L I_L \cos \varphi$$
$$= 3\, V_{ph} I_{ph} \cos \varphi$$

Where,

- V_L and I_L are line values.
- V_{ph} and I_{ph} are phase values.

Power Developed by Motor:

The mechanical power developed / phase is,

P_m = Back EMF * Armature current * Cosine of the angle between E_b and I_a

$$P_m = E_b I_a \cos(\alpha - \varphi) \text{ for lagging p.f}$$

$$P_m = E_b I_a \, Cos\,(\alpha + \varphi) \text{ for leading p.f}$$

The copper loss in a synchronous motor takes place in the armature windings. Therefore,

Armature copper loss / phase = $I_a^2 R_a$

Total copper loss = $3 I_a^2 R_a$

By subtracting the copper loss from the power input, we obtain the mechanical power developed by a synchronous motor as

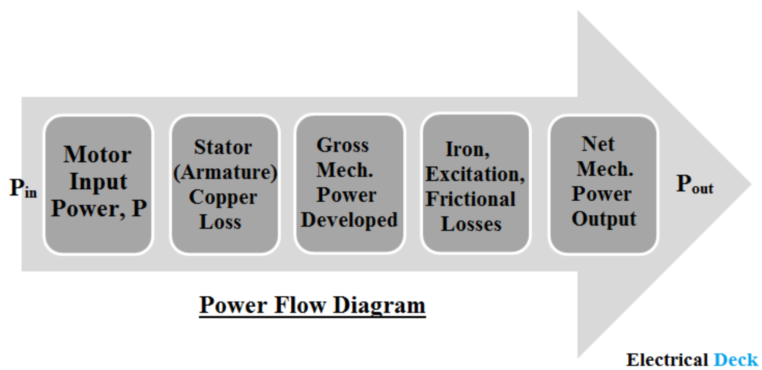
$$P_m = P - P_{cu}$$

For three-phase,

$$P_m = \sqrt{3}\, I_L I_L \,Cos\,\varphi - 3 I_a^2 R_a$$

Power Output of the Motor:

To obtain the power output we subtract the iron, friction, and excitation losses from the power developed. Therefore, Net output power, $P_{out} = P_m$ - iron, friction, and excitation losses. The above two stages can be shown diagrammatically called as Power Flow Diagram of a Synchronous Motor



Power Flow Diagram

The power developed in a synchronous motor as follows. Motor Input Power, P

- Stator (Armature) copper loss P_{cu}
- Mechanical power developed, P_m
- Iron, friction, and excitation losses
- Output power, P_{out}

Net Power Developed by a Synchronous Motor:

The expression for power developed by the synchronous motor in terms of α, θ, V, E_b, and Z_s are as follows

Let

- V = Supply voltage
- E_b = Back EMF / phase
- α = Load angle
- θ = Internal or Impedance angle = Tan^{-1} (X_r / Z_s)
- I_a = Armature current / phase = E_r / Z_s
- $Z_s = R_a + J\, X_s$ = Synchronous impedance

Mechanical power developed / phase,

$$P_m = \frac{E_b\, V}{Z_s}\cos(\theta - \alpha) - \frac{E_b^2}{Z_s}\cos\theta$$

The armature resistance is neglected

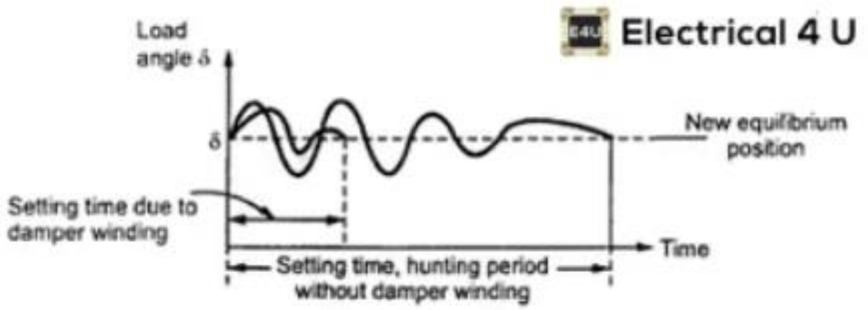
If R_a is neglected, then $Z_s \approx X_s$ and $\theta = 90°$. Substituting these values in the above equation.

$$P_m = \frac{E_b\, V}{X_s}\cos(90 - \alpha) - \frac{E_b^2}{X_s}\cos 90^0$$

$$P_m = \frac{E_b\, V}{X_s}\sin\alpha$$

Hunting and its suppression

The word hunting is used because after the sudden application of load the rotor has to search or 'hunt' for its new equilibrium position. That phenomenon is referred to as hunting in a synchronous motor**.** Now let us know what is the condition of equilibrium in synchronous motor. A steady state operation of synchronous motor is a condition of equilibrium in which the electromagnetic torque is equal and opposite to load torque. In steady state, rotor runs at synchronous speed thereby maintaining a constant value of torque angle (δ). If there is a sudden change in load torque, the equilibrium is disturbed and there is resulting torque which changes the speed of the motor.



What is hunting?

Unloaded synchronous machine has zero degree load angle. On increasing the shaft load gradually load angle will increase. Let us consider that load P_1 is applied suddenly to unloaded machine shaft so machine will slow down momentarily. Also load angle (δ) increases from zero degree and becomes δ_1. During the first swing electrical power developed is equal to mechanical load P_1. Equilibrium is not established so rotor swings further. Load angle exceeds δ_1 and becomes δ_2. Now electrical power generated is greater than the previous one. Rotor attains synchronous speed. But it does not stay in synchronous speed and it will continue to increase beyond synchronous speed. As a result of rotor acceleration above synchronous speed the load angle decreases. So once again no equilibrium is attained. Thus rotor swings or oscillates about new equilibrium position. This phenomenon is known as hunting or phase swinging. Hunting occurs not only in synchronous motors but also in synchronous generators upon abrupt change in load.

Causes of Hunting in Synchronous Motor

1. Sudden change in load.
2. Sudden change in field current.
3. A load containing harmonic torque.
4. Fault in supply system.

Effects of Hunting in Synchronous Motor

1. It may lead to loss of synchronism.
2. Produces mechanical stresses in the rotor shaft.
3. Increases machine losses and cause temperature rise.
4. Cause greater surges in current and power flow.
5. It increases possibility of resonance.

How to overcome hunting? Or Reduction of Hunting

Two techniques should be used to reduce hunting. These are

- Use of Damper Winding: It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. Damper winding damps out hunting by producing torque opposite to slip of rotor. The magnitude of damping torque is proportional to the slip speed.
- Use of Flywheels: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.
- Designing synchronous machine with suitable synchronizing power coefficients.