UNIT-I

POLY-PHASE INDUCTION MACHINES

Induction Motor or machines are also called as Asynchronous Machine. The word Asynchronous means that the machine never runs at synchronous speed. Induction motors are mainly of two types. It can besingle-phase or three-phase induction motors.

A Single-phase induction motor is usually built-in small size (up to 3 H.P). The three-phase induction motorsare the most commonly used AC motors in the industry. They are simple in construction, reliable. It has lowcost, high efficiency, reasonably good power factor, reliable, self-starting torque, and low maintenance. Almost more than 90% of the mechanical energy used in the industry is provided by three-phase induction motors.

Three-phase induction motors are mainly used in the industry for power conversion, i.e., electrical to mechanical power conversion in bulk or a large quantity. But for small power conversion single-phase induction motors are used. The induction motors perform a variety of services in the home, office, business, factories, etc.

In all the domestic appliances such as refrigerators, fans, washing machines, hair dryers, mixer grinder, etc., single-phase induction motor are used.

Construction of Induction Motor:

The three-phase induction motor is a preferable type of motor. It is mostly used in industrial drives because it is very reasonable and vigorous, economical and reliable. It is also called asynchronous motor because it does not run at a synchronous speed. The induction motor requires very little maintenance and alsoit has high overloading capacity.

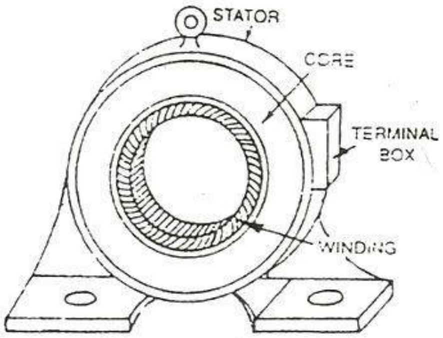
A three-phase Induction motor mainly consists of two parts called the Stator and the Rotor. The stator is the stationary part of the induction motor, and the rotor is the rotating part. The construction of the stator is similarto the three-phase synchronous motor, and the construction of the rotor is different for the different machines.The construction of the induction motor is explained below in detail.

Construction of Stator:

The stator is built up of high-grade alloy steel laminations to reduce eddy current losses. It has three main parts, namely the outer frame, the stator core, and a stator winding.

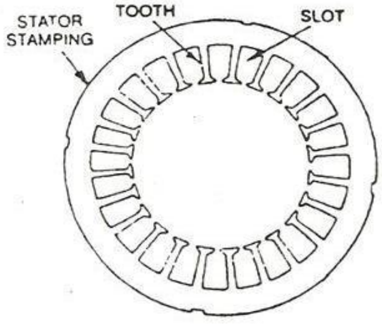
Outer frame:

It is the outer body of the motor. Its main function is to support the stator core and to protect the innerparts of the machine. For small machines, the outer frame is casted, but for the large machine, it is fabricated.The figure below shows the stator construction.



Stator Core:

The stator core is built of high-grade silicon steel stampings. Its main function is to carry the alternating magnetic field which produces hysteresis and eddy current losses. The stampings are fixed to the stator frame. Each stamping is insulated from the other with a thin varnish layer. The thickness of the stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner side of the stampings as shown in the figure below:



Stator windings:

The core of the stator carries three-phase windings which are usually supplied from a three-phase supply system. The six terminals of the windings (two of each phase) are connected in the terminal box of the machine. The stator of the motor is wound for a definite number of poles, depending on the speed of the motor. If the number of poles is greater, the speed of the motor will be less and if the number of poles is less than the speed will be high.

As the relationship between the speed and the pole of the motor is given as:

$$N_S \propto \frac{1}{P} \quad \text{or} \quad N_S = \frac{120f}{P}$$

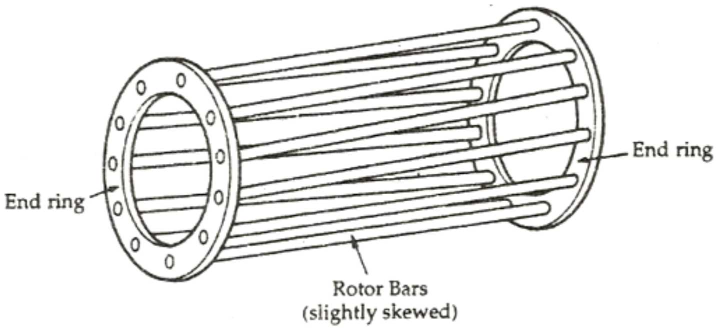
The windings may be connected in star and delta.

Construction of Rotor:

The rotor is also built of thin laminations of the same material as the stator. The laminated cylindrical core is mounted directly on the shaft. These laminations are slotted on the outer side to receive the conductors. There are two types of rotors.

Squirrel Cage Rotor:

A squirrel cage rotor consists of a laminated cylindrical core. The circular slots at the outer periphery are semi-closed. Each slot contains an uninsulated bar conductor of aluminium or copper. At the end of the rotor the conductors are short-circuited by a heavy ring of copper or aluminium. The diagram of the cage rotoris shown below:



The rotor slots are usually not parallel to the shaft but are skewed. The skewing of the rotor conductors has the following advantages given below:

- It reduces humming and provides smooth and noise-free operation.
- It results in a uniform torque curve for different positions of the rotor.
- The locking tendency of the rotor is reduced. As the teeth of the rotor and the stator attract eachother and lock.
- It increases the rotor resistance due to the increased length of the rotor bar conductors.

Advantages of Squirrel Cage Rotor:

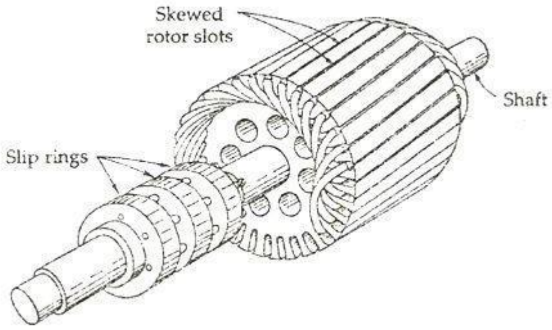
The following advantages of the cage rotor are given below:

- The cage rotor is cheaper, and the construction is robust.
- The absence of the brushes reduces the risk of sparking.
- Its maintenance is less.
- The power factor is higher.
- The efficiency of the cage rotor is higher.

Phase Wound Rotor:

The phase wound rotor is also called a Slip Ring Rotor. It consists of a cylindrical core that is laminated. Theouter periphery of the rotor has a semi-closed slot that carries 3 phase insulated windings. The rotor windingsare connected to the star.

The slip ring induction motor is shown in the figure below:



The slip rings are mounted on the shaft with brushes resting on them. The brushes are connected to the variableresistor. The function of the slip rings and the brushes is to provide a means of connecting external resistors in the rotor circuit. The resistor enables the variation of each rotor phase resistance to serve the following purposes given below:

- It increases the starting torque and decreases the starting current.
- It is used to control the speed of the motor.

In this type also, the rotor is skewed. A mild steel shaft is passed through the center of the rotor and is fixed to it. The purpose of the shaft is to transfer mechanical power.

Advantages of Phase Wound Rotor:

Following are the advantages of the Phase Wound Rotor.

- High starting torque and low starting current.
- For controlling the speed of the motor, an external resistance can be added in the circuit.Hence, in this way, an induction motor is constructed.

Comparison between Squirrel Cage and Slip Ring Induction Motor:

S. No	Squirrel cage rotor	Wound or Slip ring rotor
1.	Rotor consists of bars, which are shorted at the endswith the help of end rings.	Rotor consists of a three-phase winding similar to the stator winding.
2.	Construction is simple	Construction is complicated.
3.	As permanently shorted, external resistancecannotbe added	Resistance can be added externally:
4.	Slip rings and brushes are absent	Slip rings and brushes are present to addexternal resistance.
5.	Maintenance free	Frequent maintenance is necessary
6.	Rotors are cheap	Rotors are costly
7.	Moderate starting torque	High starting torque can be obtained
8.	The rotor automatically adjusts itself for the samenumber of poles as that of stator	Rotor must be wound for same number of poles
9.	Rotor resistance starter cannot be used	Rotor resistance starter can be used

10.	Rotor copper losses are less hence efficiencyis high	Rotor copper losses are high hence efficiency is less
11.	Speed control by rotor resistance is not possible	Speed control by rotor resistance is possible
12.	Used for lathes, drilling machines, fans, blowers,water pumps, grinders, printing machines etc.	Used for lifts, hoists, cranes, elevators, compressorsetc.

Production of Rotating Magnetic Field:

The rotating magnetic field can be defined as the field or flux having constant amplitude but whose axis is continuously rotating in a plane with a certain speed.

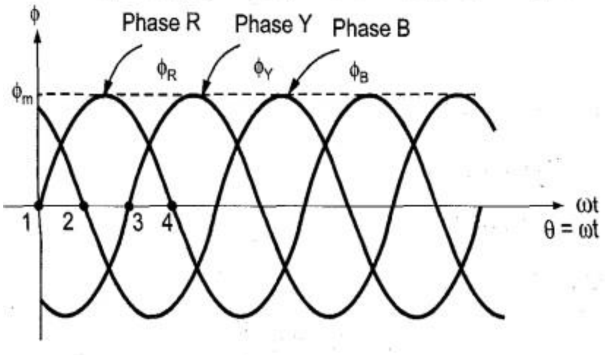
A three-phase induction motor consists of three phase winding as its stationary part called stator. The three-phase stator winding is connected in star or delta. The three phase windings are displaced from each other by 120°.

The windings are supplied by a balanced three phase AC supply. The three phase currents flow simultaneously through the windings and are displaced from each other by 120^0 electrical. Each alternating phase current produces its own flux which is sinusoidal. So, all three fluxes are sinusoidal and are separatedfrom 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 and Φ_B can be written as,

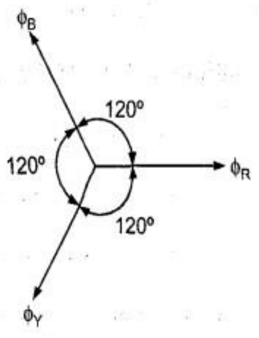
$\Phi_R = \Phi_m \sin(\omega t)$...............................(i)

$\Phi_Y = \Phi_m \sin(\omega t - 120^0)$............................ (ii)

$\Phi_B = \Phi_m \sin(\omega t - 240^0)$................................(iii)



(a) Waveforms of three fluxes



(b) Assumed positive directions

Let Φ_R, Φ_Y and Φ_B be the instantaneous values of three fluxes. The resultant flux is the phasor addition of allthree.

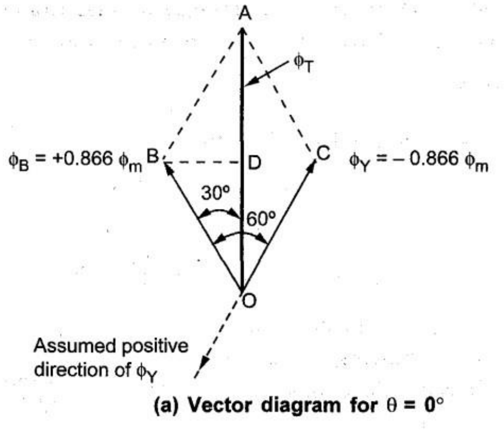
Case 1: $\omega t = 0^0$

Substituting in equation (i), (ii) and (iii),$\Phi_R = \Phi_m \sin\theta$

$\Phi_Y = \Phi_m \sin(-120^0) = -0.866\Phi_m$ $\Phi_B = \Phi_m \sin(-240^0) = +0.866\,\Phi_m$

BD is drawn perpendicular from B on Φ_T.It bisects Φ_T, as OD = DA= $\Phi_T/2$

In triangle OBD, ∟BOD = 30°Cos 30^0 = OD/OB



(a) Vector diagram for θ = 0°

= $(\Phi_T/2)/\ 0.866\ \Phi_m$

$\Phi_T = 2 \times 0.866\ \Phi_m \times \cos 30^0 = 1.5\ \Phi_m$

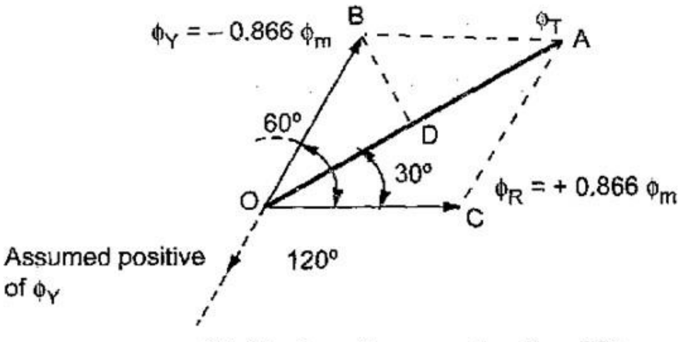
So, magnitude of Φ_T is 1.5 Φ_m and its position is vertically upwardsat θ = 0°.

Case 2: $\omega t = 60^0$

$\Phi_R = \Phi_m \sin 60^0 = 0.866\ \Phi_m$ $\Phi_Y = \Phi_m \sin(-60^0) = -0.866\ \Phi_m$$\Phi_B = \Phi_m \sin(-180^0) = 0$

Doing the same construction, drawing perpendicular from B on Φ_T at D we get the same result as,$\Phi_T = 1.5\ \Phi_m$

But it can be seen that though its magnitude is 1.5 Φ_m, it has rotated through 60^0 in space, in clockwisedirection, from its previous position.



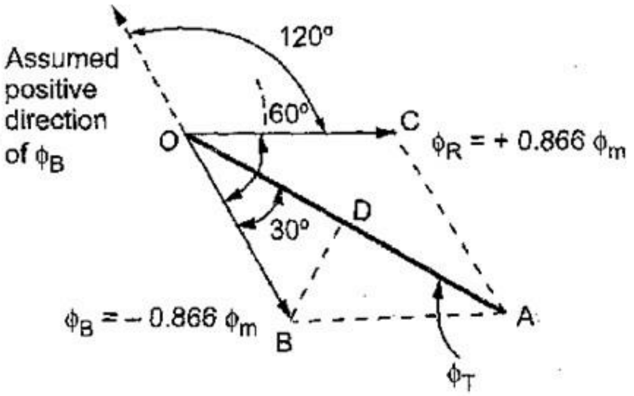
(b) Vector diagram for θ = 60°

Case 3: $\omega t = 120^0$
$\Phi_R = \Phi_m \sin 120^0 = 0.866\ \Phi_m$
$\Phi_Y = \Phi_m \sin 0 = 0$
$\Phi_B = \Phi_m \sin(-120^0) = -0.866\ \Phi_m$

Doing the same construction, drawing perpendicular from B on Φ_T at D weget the same result as,

$\Phi_T = 1.5\ \Phi_m$

But it can be seen that though its magnitude is 1.5 Φ_m, it has rotated through 60^0 in space, in clockwisedirection, from its previous position.
And from its position at $\theta = 0^0$, it has rotated through 120^0 in space, inclockwise direction.



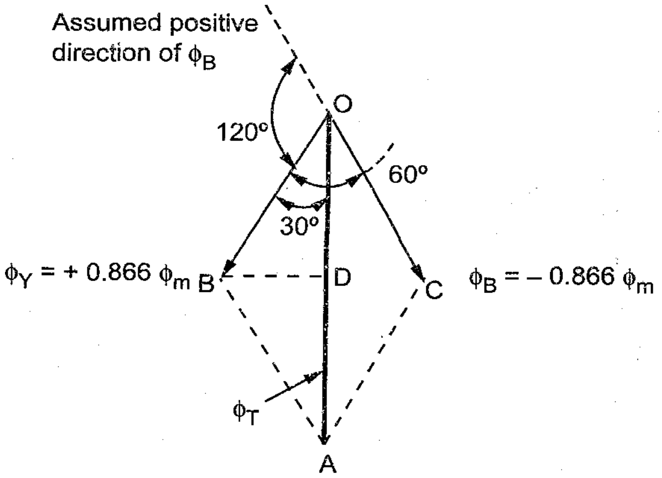
(c) Vector diagram for θ = 120°

Case 4: $\omega t = 180^0$
$\Phi_R = \Phi_m \sin 180^0 = 0$
$\Phi_Y = \Phi_m \sin (60^0) = 0.866\ \Phi_m$ $\Phi_B = \Phi_m \sin (-60^0) = -0.866\ \Phi_m$

Doing the same construction, drawing perpendicular from B on Φ_T at D weget the same result as,

$\Phi_T = 1.5\ \Phi_m$

But it can be seen that though its magnitude is 1.5 Φ_m, it has rotated through60^0 in space, in clockwisedirection, from its previous position.
And from its position at $\theta = 0^0$, it has rotated through 180^0 in space, inclockwise direction.
So for an electrical half cycle of 1800, the resultant ΦT has also rotated through 1800.

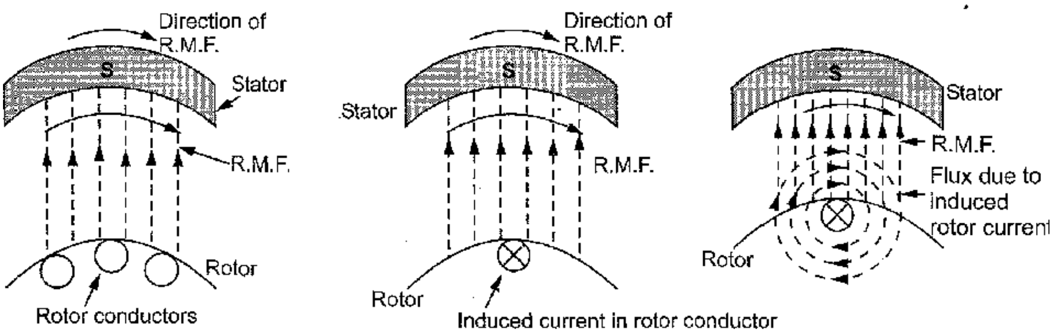


(d) Vector diagram for θ = 180°

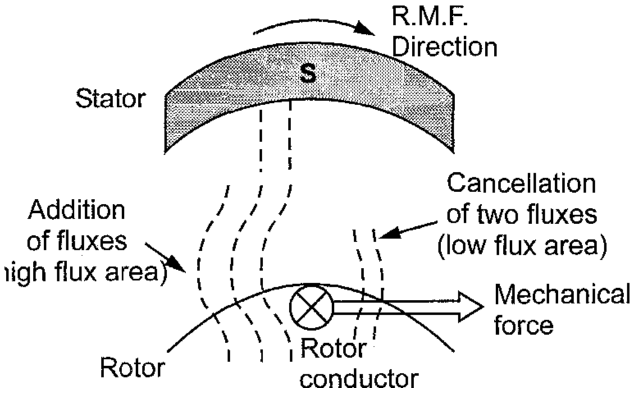
So, from the above phasor diagrams, it can be conculded that, a Rotating Magnetic Field (RMF) of constant magnitude (1.5 Φ_m), is set up, when a three phase balanced supply is given to three- phase distributed windings.
The speed at which the RMF rotates is known as Synchronous Speed (N_s).

Principle of Operation:

When a three-phase supply is given to the three-phase stator winding, a rotating magnetic field of constant magnitude is produced. The speed of this rotating magnetic field is synchronous speed, N_s
r.p.m. The R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever conductor cuts the flux, e.m.f. gets induced in it according to Faraday’s Law of electro-magnetic induction.



As rotor forms closed circuit, induced e.m.f. circulates current through rotor called rotor current whose direction is given by Lenz’s law. According to Lenz’s law thedirection of induced current in the rotor is so as oppose the cause producing it. The cause of rotor current is theinduced e.m.f. which is induced because of relative motion present between the rotating magnetic field and the rotor conductors. Hence to oppose the relative motion i.e., to reduce the relative speed, the rotor experiences a torque in the same direction as that of R.M.F. and tries to catch up the speed of rotating magnetic field.



So,
N_s = Speed of rotating magnetic field in r.p.m.N = Speed of rotor i.e., motor in r.p.m.
N_s - N = Relative speed between the two, rotating magnetic field and the rotor conductors.

Thus, rotor always rotates in same direction as that of R.M.F.

Slip:

In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed is always less than the suitor field speed (N_s). This difference in speed depends upon load on the motor. The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed
N is called slip.
It is usually expressed as a percentage of synchronous speed i.e.,

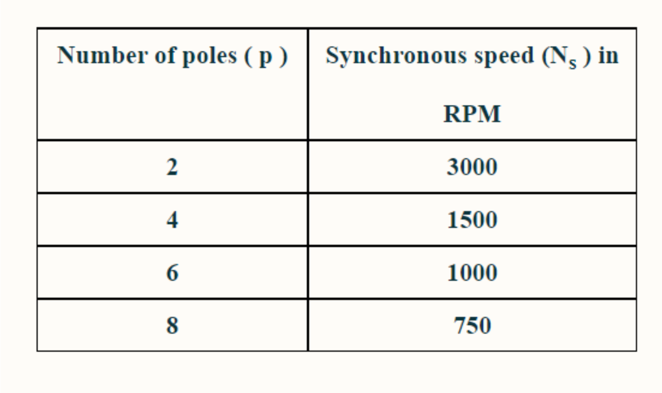
$$\%\text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

(i) The quantity Ns - N is sometimes called slip speed or Relative speed.
(ii) When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.
(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% sothat it is essentially a constant-speed motor.

From the above equation, $N_s S = N_s - N$

and, **$N = N_s(1-S)$**

The standard frequency in India is 50 Hz therefore the synchronous speed for different pole condition is



Number of poles (p)	Synchronous speed (N_s) in RPM
2	3000
4	1500
6	1000
8	750

Effect of slip on the rotor parameters:

(a) Effect on Rotor Frequency:

The speed of rotating magnetic field is,

$N_s = 120f/P$ (i) where f = frequency of supply in Hz.

At start when N = 0, s = 1 and stationary rotor has maximum relative motion with respect to

R.M.F.

Hence maximum e.m.f. gets induced in the rotor at start. The frequency of this induced e.m.f. at start issame as that of supply frequency.
In running condition, the magnitude of the induced emf decreases as its frequency,

$(Ns – N) = 120f_r / P$ (ii)
Where, f_r = frequency of rotor induced emf in running condition at slip speed (Ns – N)

Dividing equation (ii) by (i), we get

$(N_s – N) = 120\ f_r / P$
$Ns = 120\ f / P$

Therefore $s = f_r / f$
$\mathbf{f_r = sf}$

Thus, frequency of rotor induced e.m.f. in running condition (f_r) is slip times the supply frequency (f).

(b) Effect on Magnitude of Rotor Induced E.M.F:

E_2 = Rotor induced e.m.f. per phase on standstill condition

As rotor gains speed, the relative speed between rotor and rotating magnetic field decreases and hence induced
e.m.f. in rotor also decreases as it is proportional to the relative speed (Ns — N).

Let E_{2r} = Rotor induced e.m.f. per phase in running condition$E_2 \alpha N_s$ and $E_{2r} \alpha (Ns – N)$

$\mathbf{E_{2r} = SE_2}$

The magnitude of the induced e.m.f. in the rotor also reduces by slip times the magnitude of induced
e.m.f. at standstill condition.

(c) Effect on Rotor Resistance and Reactance:

R_2 = Rotor resistance per phase on standstill
X_2 = Rotor reactance per phase on standstill
Z2 = Rotor impedance on standstill
Now at standstill, $f_r = f$
hence if L_2 is the inductance of rotor per phase,$X_2 = 2лfr\ L_2 = 2лf\ L_2$

Now in running condition, $f_r = Sf$, hence$X_{2r} = 2лfr\ L_2$
$= 2лsf\ L_2$
$=S.\ 2лf\ L_2$
$\mathbf{X_{2r} = SX_2}$

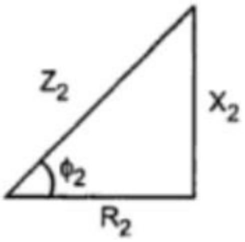
R_2 = Rotor resistance in Ω /ph.

Thus resistance as independent of frequency remains same at standstill and in running condition. While the rotor reactance decreases by slip times the rotor reactance at standstill.

Where,
$Z_2 = R_2 + j X_2$ Ω / ph.
$Z_2 = (R_2^2 + X_2^2)^{1/2}$ Ω / ph.

While Z_{2r} = rotor impedance in running conditionR_{2r} = Rotor resistance in running condition
$Z_{2r} = (R_2^2 + (SX_2)^2)^{1/2}$ Ω / ph.

(d) Effect on Rotor Power Factor:



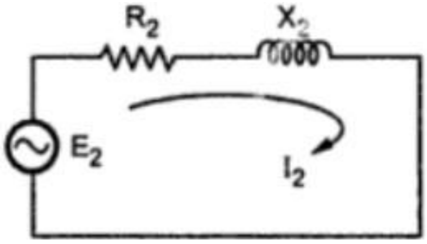
Cos φ_2 = rotor power factor on standstill

$= R_2/Z_2 = R_2/(R_2^2+X_2^2)^{1/2}$

Cos φ_{2r} = rotor power factor in running condition

Cos $\varphi_{2r} = R_2/Z_{2r} = R_2/(R_2^2+SX_2^2)^{1/2}$

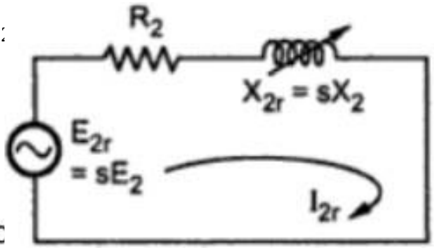
(e) Effect on Rotor Current:



I_2 = Rotor current per phase on standstill condition

$= E_2$ per phase/ Z_2 per phase

$= E_2/(R_2^2+X_2^2)^{1/2}$Amp



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

$I_{2r} = SE_2/(R_2^2+SX_2^2)^{1/2}$Amp

Examples:

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye c
motor delivers 15 kW at a slip of 5%.

Calculate:
a) Synchronous speed
b) Rotor speed
c) Frequency of rotor current

Solution:

Synchronous speed: $n_s = 120 f / p = (120*60) / 6 = 1200$ rpm
Rotor speed: $n_r = (1-s) n_s = (1- 0.05) (1200) = 1140$ rpm
Frequency of rotor current: $f_r = s f = (0.05) (60) = 3$ Hz

→ A slip ring Induction motor runs at 290 rpm at full load, when connected to 50 Hz supply. Determine the number of poles and slip.

Sol?:- Given, $N = 290\,rpm$

$f = 50\,Hz$

Poles = ? and slip.

We have, $N_s = \frac{120f}{P}$

N_s should be somewhere near to N, so assume N_s value as, $N_s = 300\,rpm$

$$\therefore\ 300 = \frac{120 \times 50}{P} \Rightarrow P = 20$$

$$\text{Now, Slip} = \frac{N_s - N}{N_s} \times 100 = \frac{300 - 290}{300} \times 100.$$

Slip = 3.33%.

* The stator of a 3-ϕ Induction motor has 3 slots per pole per phase. If supply frequency is 50 Hz, calculate

1) No. of stator poles produced and total no. of slots on stator.

2) Speed of rotating stator flux.

Sol?:- Given, slots per phase = 3, f = 50 Hz.

(1) $P = 2n = 2 \times 3 = 6$ poles where n is no. of slots/~~phase~~ pole/phase

Total no. of slots = 3 slots/pole/phase

$= 3 \times 6 \times 3 = 54.$

(2) $N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000\,rpm.$

* A 4-pole, 3-phase Induction motor operates from a supply whose frequency is 50 Hz. Calculate:

1) the speed at which the magnetic field of stator is rotating
2) the speed of the rotor when slip is 0.04.
3) The frequency of the rotor currents when slip is 0.03.
4) the frequency of the rotor at standstill.
5) The Rotor frequency when rotor runs at 600 rpm.

Soln:-

1) $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm.

2) Rotor speed $N = N_s(1-s)$

$= 1500(1-0.04) = 1440$ rpm.

3) freq. of rotor current, $f' = sf$

$= 0.03 \times 50 = 90$ rpm

4) since at stand still, $s=1$.

$\therefore f' = sf = (1) \times 50 = 50$ Hz.

5) $f' = sf$

at 600 rpm, $s = \frac{N_s - N}{N_s} = \frac{1500-600}{1500} = 0.6$

$\Rightarrow f' = 0.6 \times 50 = 30$ Hz.

UNIT – II CHARACTERISTICS OF INDUCTION MACHINES

Torque Equation:

The torque T developed by the rotor is directly proportional to:

(i) Rotor current
(ii) Rotor e.m.f
(iii) Power factor of the rotor circuit. Therefore, $T \propto E_2 I_2 \cos\varphi_2$

$T = K E_2 I_2 \cos\varphi_2$

where I_2 = rotor current at standstill E_2 = rotor e.m.f. at standstill $\cos \varphi_2$ = rotor p.f. at standstill

Note: The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

Starting Torque (T_s):

Let E_2 = rotor e.m.f. per phase at standstill
X_2 = rotor reactance per phase at standstill
R_2 = rotor resistance per phase

$$\text{Rotor impedance/phase, } Z_2 = \sqrt{R_2^2 + X_2^2} \qquad \text{...at standstill}$$

$$\text{Rotor current/phase, } I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \qquad \text{...at standstill}$$

$$\text{Rotor p.f., } \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}} \qquad \text{...at standstill}$$

$$\therefore \quad \text{Starting torque, } T_s = K E_2 I_2 \cos\phi_2$$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

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

Generally, the stator supply voltage V is constant so that flux per pole φ set up by the stator is also fixed. This in turn means that e.m.f. E_2 induced in the rotor will be constant.

$$\therefore \quad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It is clear that the magnitude of starting torque would depend upon the relative values of R_2 and X_2 i.e.,rotor resistance/phase and standstill rotor reactance/phase.

It can be shown that,

$$K = 3/2\ \pi\ N_s.$$

$$\therefore \qquad T_s = \frac{3}{2\pi\ N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

Condition for Maximum Starting Torque:

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstillrotor reactance/phase.

Now,

$$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2}$$

……….(i)

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1 \left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2} \right] = 0$$

or

$$R_2^2 + X_2^2 = 2R_2^2$$

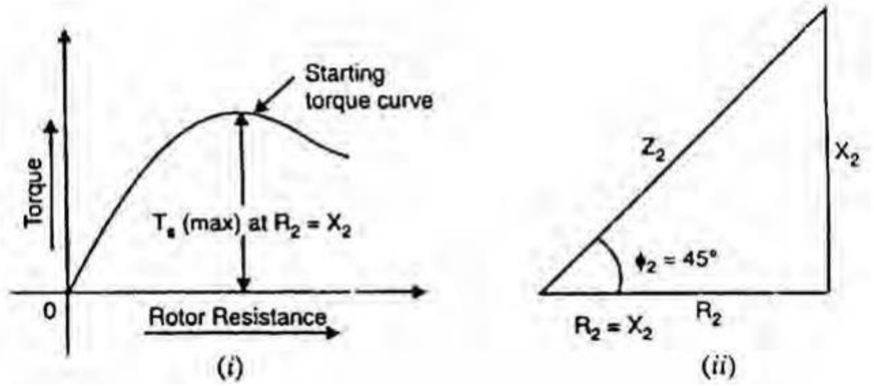
or

$$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, φ2 = 45° and rotor power factor is 0.707 lagging Fig. (i) shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when $R_2 = X_2$. If the rotor resistance is increased beyond this optimum value, the starting torque will decrease.



Effect of Change of Supply Voltage:

$$T_s = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Since E_2 is proportional to Supply voltage V,

$$T_s = \frac{K_2 V^2 R_2}{R_2^2 + X_2^2}$$

where K_2 is another constant.

$$\therefore \quad T_s \propto V^2$$

Therefore, the starting torque is very sensitive to changes in the value of supply voltage. For example, a drop of 10% in supply voltage will decrease the starting torque by about 20%. This could mean the motorfailing to start if it cannot produce a torque greater than the load torque plus friction torque.

Starting Torque of 3-Phase Induction Motors:

The rotor circuit of an induction motor has low resistance and high inductance. At starting, the rotor frequency is equal to the stator frequency (i.e., 50 Hz) so that rotor reactance is large compared with rotorresistance. Therefore, rotor current lags the rotor e.m.f. by a large angle, the power factor is low and consequently the starting torque is small. When resistance is added to the rotor circuit, the rotor power factor is improved which results in improved starting torque. This, of course, increases the rotor impedance and, therefore, decreases the value of rotor current but the effect of improved power factor predominates and the starting torque is increased.

(i) **Squirrel-cage motors:** Since the rotor bars are permanently short-circuited, it is not possible to add any external resistance in the rotor circuit at starting. Consequently, the starting torque of such motors is low. Squirrel cage motors have starting torque of 1.5 to 2 times the full-load value withstarting current of 5 to 9 times the full-load current.

(ii) Wound rotor motors: The resistance of the rotor circuit of such motors can be increased through the addition of external resistance. By inserting the proper value of external resistance (so that $R_2 = X_2$), maximum starting torque can be obtained. As the motor accelerates, the external resistance is gradually cut out until the rotor circuit is short-circuited on itself for running conditions.

Motor Under Load:

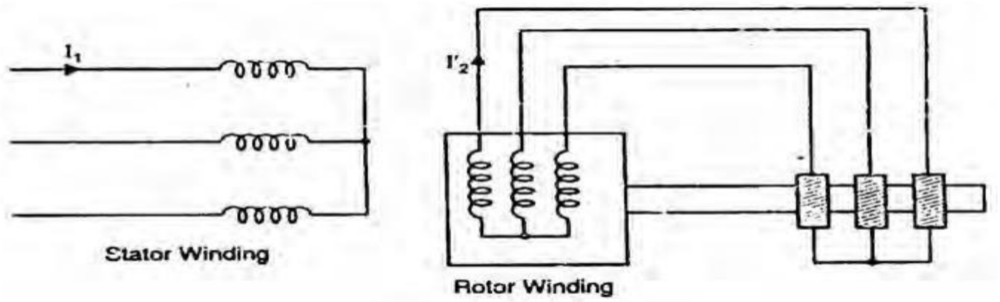
Let us now discuss the behavior of 3-phase induction motor on load.

(i) When we apply mechanical load to the shaft of the motor, it will begin to slow down and the rotating flux will cut the rotor conductors at a higher and higher rate. The induced voltage and resulting current in rotor conductors will increase progressively, producing greater and greater torque.

(ii) The motor and mechanical load will soon reach a state of equilibrium when the motor torque is exactly equal to the load torque. When this state is reached, the speed will cease to drop anymore and the motor will run at the new speed at a constant rate.

(iii) The drop in speed of the induction motor on increased load is small. It is because the rotor impedance is low and a small decrease in speed produces a large rotor current. The increased rotor current produces a higher torque to meet the increased load on the motor. This is why induction motors are considered to be constant-speed machines. However, because they never actually turn at synchronous speed, they are sometimes called asynchronous machines. Note that change in load on the induction motor is met through the adjustment of slip. When load on the motor increases, the slip increases slightly (i.e., motor speed decreases slightly). This results in greater relative speed between the rotating flux and rotor conductors. Consequently, rotor current is increased, producing a higher torque to meet the increased load. Reverse happens should the load on the motor decrease.

(iv) With increasing load, the increased load currents I'_2 as shown in the figure below, are in such a direction so as to decrease the stator flux (Lenz’s law), thereby decreasing the counter e.m.f in the stator windings. The decreased counter e.m.f. allows motor stator current I_1 to increase, thereby increasing the power input to the motor. It may be noted that action of the induction motor in adjusting its stator or primary current with changes of current in the rotor or secondary is very much similar to the changes occurring in transformer with changes in load.



Torque Under Running Conditions:

Let the rotor at standstill have per phase induced e.m.f. E_2, reactance X_2 and resistance R_2. Then under running conditions at slip s,

$$\text{Rotor e.m.f./phase, } E'_2 = sE_2$$

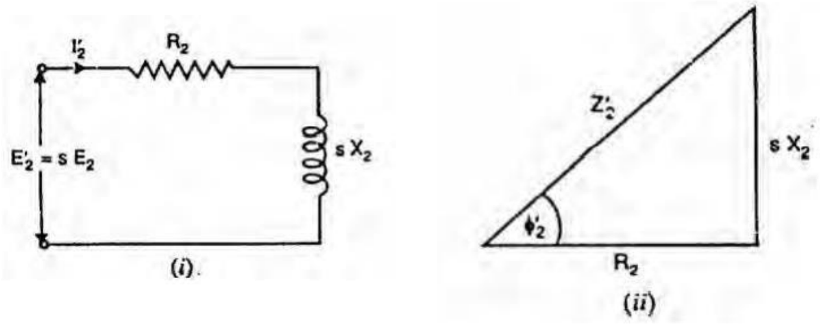
$$\text{Rotor reactance/phase, } X'_2 = sX_2$$

$$\text{Rotor impedance/phase, } Z'_2 = \sqrt{R_2^2 + (sX_2)^2}$$

$$\text{Rotor current/phase, } I'_2 = \frac{E'_2}{Z'_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor p.f., } \cos\phi'_m = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

\



(i) (ii)

$$\text{Running Torque, } T_r \propto E'_2 I'_2 \cos\phi'_2$$

since $E'_2 \propto \phi$

$$\propto \phi I'_2 \cos\phi'_2$$

$$\propto \phi \times \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

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

$$= \frac{K\,\phi\,s\,E_2\,R_2}{R_2^2 + (s\,X_2)^2}$$

$$= \frac{K.\;s\,E_2^2\,R_2}{R_2^2 + (s\,X_2)^2}$$

If the stator supply voltage V is constant, then stator flux and hence E_2 will be constant.

$$\therefore \qquad T_r = \frac{K \; s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

where K_2 is another constant.

It may be seen that running torque is:

(i) directly proportional to slip i.e., if slip increases (i.e., motor speed decreases), the torque willincrease and vice-versa.

(ii) directly proportional to square of supply voltage.

It can be shown that value of $K_1 = 3/2\Pi N_s$ where N_s is in r.p.s.

$$\therefore \qquad T_r = \frac{3}{2\pi N_s} \cdot \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

At starting, s = 1 so that starting torque is

$$T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition for Maximum Running Torque:

$$T_r = \frac{K \; s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

In order to find the value of rotor resistance that gives maximum torque under running conditions,differentiate above expression w.r.t. S and equate the result to zero i.e.,

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

$$\frac{d}{ds}\left[K \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2}\right] = 0$$

$$K \frac{d}{ds}\left[\frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2}\right] = 0$$

$$K.\left[\frac{[R_2^2+(sX_2)^2](E_2^2R_2)-(sE_2^2R_2)(0+2sX_2X_2)}{R_2^2+(sX_2)^2}\right]=0.$$

$$\left\{\text{Since}\ \frac{d\left(\frac{U}{V}\right)}{ds}=\frac{V\frac{du}{ds}-U\frac{dv}{ds}}{V^2}\right\}$$

$$\therefore\ [R_2^2+(sX_2)^2](E_2^2R_2)-(sE_2^2R_2)(2sX_2^2)=0$$

$$[R_2^2+(sX_2)^2]\cancel{E_2^2R_2}=s\cancel{E_2^2R_2}(2sX_2^2)$$

$$R_2^2+(sX_2)^2=2s^2X_2^2$$

$$R_2^2=2(sX_2)^2-(sX_2)^2$$

$$R_2^2=(sX_2)^2$$

$$\boxed{R_2=sX_2}$$

Thus, for maximum torque (T_m) under running conditions,

Rotor resistance/phase = Fractional slip ´ Standstill rotor reactance/phase

Now

$$T_r\propto\frac{s\,R_2}{R_2^2+s^2\,X_2^2}$$

For maximum torque, $R_2 = s\,X_2$. Putting $R_2 = s\,X_2$ in the above expression, the maximum torque Tm isgiven by

$$T_m\propto\frac{1}{2\,X_2}$$

Slip corresponding to maximum torque, $S = R_2/X_2$.It can be shown that:

$$T_m=\frac{3}{2\pi N_s}\cdot\frac{E_2^2}{2\,X_2}\ \text{N - m}$$

It is evident from the above equations that:

1. The value of rotor resistance does not alter the value of the maximum torque but only thevalue of the slip at which it occurs.
2. The maximum torque varies inversely as the standstill reactance. Therefore, it should bekept as small as possible.
3. The maximum torque varies directly with the square of the applied voltage.

4. To obtain maximum torque at starting (s = 1), the rotor resistance must be made equal torotor reactance at standstill.

The performance of the motor is sometime expressed interms of comparision of various torques such as F.L. torque, starting torque and maximum torque.

1. Relation Between F.L torque and Maximum Torque :

Let s_f = F.L. slip

The expressions for F.L torque, T_{FL} and max. torque, T_{max} are :

$$T_{FL} = \frac{K\ s_f E_2^2 R_2}{R_2^2 + (s_f X_2)^2} \qquad \text{and}$$

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

The ratio of F.L torque to maximum torque is

$$\frac{T_{FL}}{T_{max}} = \frac{\dfrac{K\ s_f E_2^2 R_2}{R_2^2 + (s_f X_2)^2}}{\dfrac{K\ E_2^2}{2X_2}} = \frac{K\ s_f E_2^2 R_2}{R_2^2 + (s_f X_2)^2} \times \frac{2X_2}{K\ E_2^2} = \frac{2\ s_f R_2\ X_2}{R_2^2 + (s_f X_2)^2}$$

Dividing Nr. & Dr. by X_2^2, We get

$$\frac{T_{FL}}{T_{max}} = \frac{2\ s_f \dfrac{R_2}{X_2}}{\dfrac{R_2^2}{X_2^2} + s_f^2}$$

$$\therefore \quad \boxed{\frac{T_{FL}}{T_{max}} = \frac{2\,a\,s_f}{a^2 + s_f^2}}\ , \qquad \text{Where } a = \frac{R_2}{X_2}$$

2. Relation Between Starting Torque and Maximum Torque :

The expressions for starting torque, T_{st} and max. torque, T_{max} are :

$$T_{st} = \frac{K\ E_2^2 R_2}{R_2^2 + X_2^2} \qquad \text{and}$$

$$T_{max} = \frac{K\ E_2^2}{2\,X_2}$$

$$\therefore \quad \frac{T_{st}}{T_{max}} = \frac{\dfrac{K E_2^2 R_2}{R_2^2 + X_2^2}}{\dfrac{K E_2^2}{2 X_2}} = \frac{K E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{2 X_2}{K E_2^2} = \frac{2 R_2 X_2}{R_2^2 + X_2^2}$$

Dividing Nr. & Dr. by X_2^2, We get

$$\frac{T_{st}}{T_{max}} = \frac{2 \dfrac{R_2}{X_2}}{\dfrac{R_2^2}{X_2^2} + 1}$$

$$\therefore \boxed{\frac{T_{st}}{T_{max}} = \frac{2a}{1 + a^2}} \qquad \text{Where } a = \frac{R_2}{X_2}$$

Example Problems:

A 50 Hz, 8 pole induction motor has a full load slip of 4% . The rotor resistance and reactance are 0.01 Ω and 0.01 Ω per phase respectively. Find the ratio of maximum to full load torque and speed at which the maximum torque occurs.

Solution :

No. of poles, $P = 8$

Frequency, $f = 50\ Hz$

synchronous speed, $N_s = \dfrac{120f}{P} = \dfrac{120 \times 50}{8} = 750\ rpm$

F.L. slip, $s_f = 4\% = 0.04$

Rotor resistance, $R_2 = 0.01\ \Omega$ /phase

stand still rotor reactance, $X_2 = 0.01\ \Omega$ /phase

The ratio of maximum to F.L torque is

$$\frac{T_{max}}{T_{FL}} = \frac{a^2 + s_f^2}{2 a s_f} \qquad \text{where } a = \frac{R_2}{X_2}$$

$$a = \frac{R_2}{X_2} = \frac{0.01}{0.01} = 1$$

$$\therefore \quad \frac{T_{max}}{T_{fl}} = \frac{(1)^2 + (0.04)^2}{2 \times 1 \times 0.04} = 12.52$$

Slip for maximum torque, $s_m = a = \frac{R_2}{X_2} = 1$

$\therefore$ Speed at maximum torque, $N_m = N_s (1 - s_m) = 750 (1 - 1) = 0\ rpm$

Solution :

Rotor resistance, $R_2 = 0.02\ \Omega/phase$

Stand still rotor reactance, $X_2 = 0.1\ \Omega/phase$

Starting torque, $T_{st} = T_{max}$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} = 1$$

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

$$\therefore \quad a = 1$$

Let 'r' be the external resistance then $(R_2 + r)$ will be the total resistance.

$$a = \frac{R_2 + r}{X_2} = 1$$

$$r = X_2 - R_2 = 0.1 - 0.02 = 0.08\ \Omega/\text{phase}$$

$\therefore$ External resistance to be added,

$$\mathbf{r = 0.08\ \Omega/phase}$$

The rotor resistance and stand still reactance per phase of a 3-phase slip ring induction motor are 0.02 Ω and 0.1 Ω respectively. What should be the value of the external resistance per phase to be inserted in the rotor circuit to give maximum torque at starting.

Calculate the torque exerted by 6-pole, 50 Hz, 3-phase induction motor operating with a 5% slip which develops a maximum torque of 180 kg-m at a speed of 820 rpm. The resistance per phase of the rotor is 0.5 Ω.

Solution :

No. of poles, $P = 6$

Frequency, $f = 50\ Hz$

Slip, $s = 5\% = 0.05$

Maximum torque, $T_{max} = 180 \text{ kg-m} = 180 \times 9.81 = 1765.8 \text{ N-m}$

Speed at maximum torque, $N = 820 \text{ rpm.}$

Rotor resistance/phase, $R_2 = 0.5\,\Omega$

Synchronous speed, $N_s = \dfrac{120f}{P} = \dfrac{120\times 50}{6} = 1000 \text{ rpm}$

Slip at maximum torque, $s_m = \dfrac{N_S - N}{N_S} = \dfrac{1000-820}{1000} = 0.18$

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

$\therefore$ Stand still rotor reactance, $X_2 = \dfrac{R_2}{s_m} = \dfrac{0.5}{0.18} = 2.778\,\Omega/\text{phase}$

Maximum torque, $T_{max} = \dfrac{3\times 60}{2\pi N_S}\dfrac{E_2^2}{2X_2}$

Stand still rotor induced emf/phase,

$$E_2 = \sqrt{\frac{2\pi N_S(2X_2)}{3\times 60}T_{max}}$$

$$= \sqrt{\frac{2\pi\times 1000\times 2\times 2.778\times 1765.8}{3\times 60}} = \mathbf{585.2\ V}$$

Torque, $T = \dfrac{3\times 60}{2\pi N_S}\dfrac{SE_2^2R_2}{R_2^2+(SX_2)^2}$

$$= \frac{3\times 60}{2\pi\times 1000}\frac{0.05(585.2)^2\times 0.5}{(0.5)^2+(0.05\times 2.778)^2} = \mathbf{910.79\ N\text{-}m}$$

A 12 pole 3 ϕ star connected induction motor runs at 660 V, 50 Hz. It has a slip ring rotor resistance of 0.03 Ω and a stand still reactance of 0.5 Ω per phase. Calculate.

(i) The speed at maximum torque and

(ii) The ratio of full load torque at 495 rpm to maximum torque.

Solution :

No of poles, $P = 12$

Frequency, $f = 50\ Hz$

F.L speed, $N = 495\ rpm$

Rotor resistance, $R_2 = 0.03\ \Omega/ph$

Stand still rotor reactance, $X_2 = 0.5\ \Omega/ph$

Synchronous speed, $N_s = \frac{120f}{P} = \frac{120 \times 50}{12} = 500$ rpm

$$a = \frac{R_2}{X_2} = s_m = \frac{0.03}{0.5} = 0.06$$

Speed at maximum torque, $N_m = N_s(1 - s_m) = 500(1 - 0.06) = 470\ rpm$

The ratio of F.L torque to maximum torque,

$$\frac{T_{FL}}{T_{max}} = \frac{2as_f}{a^2 + s_f^2}$$

Slip at full load, $s_f = \frac{N_s - N}{N_s} = \frac{500-495}{500} = 0.01$

$$\therefore \quad \frac{T_{FL}}{T_{max}} = \frac{2\times0.06\times0.01}{(0.06)^2+(0.01)^2} = 0.3243$$

A 4 pole, 50Hz, 7.46 kW motor has at rated voltage and frequency, a starting torque of 160 percent and a maximum torque of 200 percent of full load torque. Determine (i) F.L. speed (ii) Speed at maximum torque.

Solution :

No. of poles, $P = 4$

Frequency, $f = 50\ Hz$

$$T_{st} = 160\ \%\ \text{of F.L. torque}$$

$$T_{max} = 200\ \%\ \text{of F.L. torque}$$

$$\therefore \quad \frac{T_{st}}{T_{FL}} = 1.6 \quad \text{and}$$

$$\frac{T_{max}}{T_{FL}} = 2$$

$$\frac{T_{st}}{T_{max}} = \frac{1.6}{2} = 0.8$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} = 0.8$$

$$0.8\,a^2 - 2a + 0.8 = 0$$

$$a = 0.5$$

$$\frac{T_{FL}}{T_{max}} = \frac{2a\,s_f}{a^2+s_f^2} = \frac{1}{2} = \frac{2\times0.5\times s_f}{(0.5)^2+s_f^2} = \frac{1}{2}$$

$$s_f = 0.134$$

$\therefore$ Synchronous speed, $N_s = \frac{120f}{P} = \frac{120\times50}{4} = 1500\ r.p.m$

F.L. speed, $N = N_s(1-s_f) = 1500\,(1-0.134) = 1299\ r.p.m$

Slip at maximum torque, $s_m = \frac{R_2}{X_2} = a = 0.5$

$\therefore$ Speed at maximum torque, $N = N_s(1-s_m) = 1500\,(1-0.5) =$ **750 rpm**

A 3 ϕ 4 pole 50 Hz induction motor has a slip ring rotor with a resistance and standstill reactance of 0.04 and 0.3 Ω /phase respectively. Find the amount of resistance to be inserted in each rotor phase to obtain full load torque at starting. The slip at F.L is 4%.

Solution :

No. of poles, $P = 4$

Frequency, $f = 50\ Hz$

Rotor resistance, $R_2 = 0.04\ \Omega/\text{phase}$

stand still rotor reactance, $X_2 = 0.3\ \Omega/\text{phase}$

F.L slip, $s_f = 4\% = 0.04$

$$\frac{T_{st}}{T_{FL}} = 1$$

$$\frac{T_{st}}{T_{max}} \times \frac{T_{max}}{T_{FL}} = 1$$

$$\frac{2a}{1+a^2} \times \frac{a^2+s_f^2}{2as_f} = 1$$

$$\frac{2a[a^2+(0.04)^2]}{(1+a^2)(2a\times 0.04)} = 1$$

$$25\ [a^2 + (0.04)^2] = 1 + a^2$$

$$25\ a^2 + 0.04 = 1 + a^2$$

$$\therefore \quad a = 0.2$$

Let 'r' be the external resistance then $(R_2 + r)$ will be the total resistance.

$$\therefore \quad a = \frac{R_2 + r}{X_2} = 0.2$$

$$\frac{0.04 + r}{0.3} = 0.2$$

$$r = (0.2 \times 0.3) - 0.04 = 0.02\ \Omega$$

$\therefore$ External resistance to be added, $r = 0.02\ \Omega/\text{phase}$

A 3-phase, 50Hz, 4-pole induction motor has rotor resistance of 0.05 Ω per phase. The maximum torque occurs at a speed of 1200 r.p.m. Calculate (i) the starting torque as a percentage of maximum torque and (ii) the reactance of rotor at standstill.

Solution :

No. of poles, $P = 4$

Frequency, $f = 50\ Hz$

Rotor resistance, $R_2 = 0.05\ \Omega\ /phase$

Synchronous speed, $N_s = \dfrac{120\,f}{P} = \dfrac{120 \times 50}{4} = 1500\ r.p.m$

Speed at max. torque, $N = 1200\ r.p.m$

Slip at max. torque, $s_m = \dfrac{N_s - N}{N_s} = \dfrac{1500 - 1200}{1500} = 0.2$

$$s_m = a = \frac{R_2}{X_2} = 0.2$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1 + a^2} \qquad \text{where} \quad a = \frac{R_2}{X_2}$$

$$= \frac{2 \times 0.2}{1 + (0.2)^2} = 0.385$$

$$\mathbf{T_{st} = 0.385\ T_{max}}$$

Therefore, starting torque is 38.5 percent of the maximum torque.

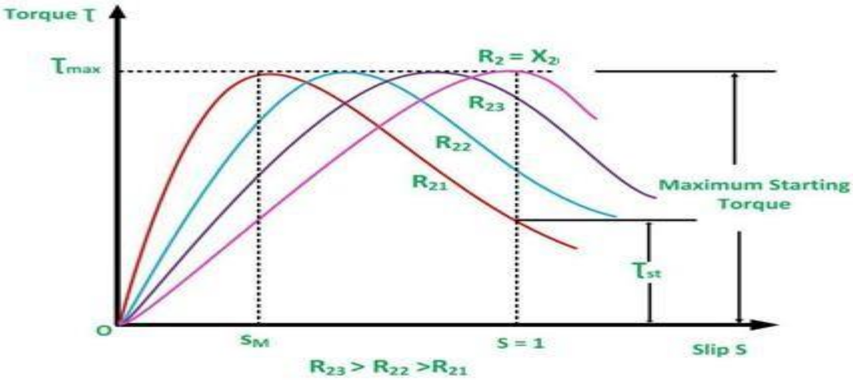
$$a = \frac{R_2}{X_2} = 0.2$$

Stand still rotor reactance, $X_2 = \dfrac{R_2}{a} = \dfrac{0.05}{0.2} = 0.25\ \Omega\ /phase$

Torque Slip Characteristic of an Induction Motor:

The Torque Slip Characteristic is represented by a rectangular hyperbola. For the immediate value of the slip, the graph changes from one form to the other. Thus, it passes through the point of maximum torque when $R_2 = SX_2$. The maximum torque developed in an induction motor is called the Pull-Out Torque or the Breakdown Torque. This torque is a measure of the short time overloading capability ofthe motor.

The curve shown below shows the Torque Slip Characteristic of the induction motor:



The torque slip characteristic curve is divided roughly into three regions. They are as follows:

- Low slip region
- Medium slip region
- High slip region

The torque equation of the induction motor is given below:

$$T = \frac{k\,s\,R_2E_2^2}{R_2^2 + (sX_2\,)^2} \;\dots\dots\dots\dots(1)$$

Low Slip Region:

At the synchronous speed, S = 0, the torque is zero. When the speed is very near to synchronous speed, the slip is very low, and $(SX_2)^2$ is negligible in comparison with R_2. Therefore,

$$T = \frac{k_1 s}{R_2}$$

If R_2 is constant, the torque becomes

$$T = k_2 s \dots\dots(2)$$

When $k_2 = k_1/R_2$

From equation (2) shown above, it is clear that the torque is proportional to slip. Hence, in the normal working region of the motor, the value of the slip is small. The torque slip curve is a straight line.

Medium Slip Region:

As the slip increases, the speed of the motor decreases with the increase in load. The term $(SX_2)^2$ becomes large. The term R_2^2 may be neglected in comparison with the term $(sX_2)^2$ and the torque equation becomes as shown below:

$$T = \frac{k_3 R_2}{sX_2^2} \dots\dots\dots(3)$$

At the standstill condition, the torque is inversely proportional to the slip.

High Slip Region:

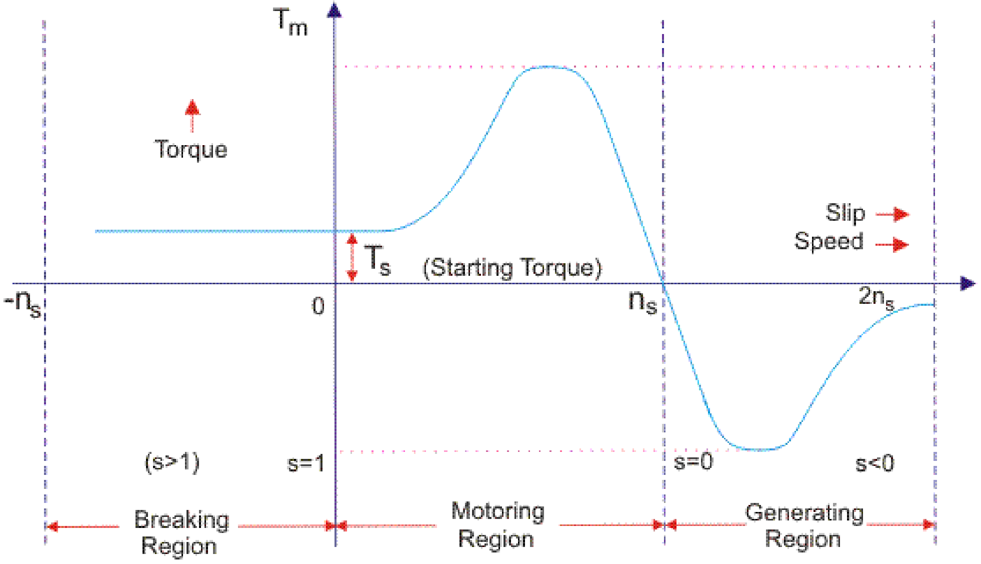
Beyond the maximum torque point, the value of torque starts decreasing. As a result, the motor slows down and stops. At this stage, the overload protection must immediately disconnect the motor from the supply to prevent damage due to overheating of the motor.

The motor operates for the values of the slip between S = 0 and S = S_m. Where S_m is the value of the slip corresponding to the maximum torque. For a typical induction motor, **the pull-out torque is 2** to **3 times the rated full load torque. The starting torque is about 1.5 times the rated full load torque.**

Torque Speed Characteristics of Three Phase Induction Motor:

The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

The curve can be described in three modes of operation-



Motoring Mode:

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

From the curve it is seen that the torque is directly proportional to the slip. That is, more is the slip, more will be the torque produced and vice-versa. The linear relationship simplifies the calculation of motor parameter to great extent.

Generating Mode:

In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three-phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation. That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

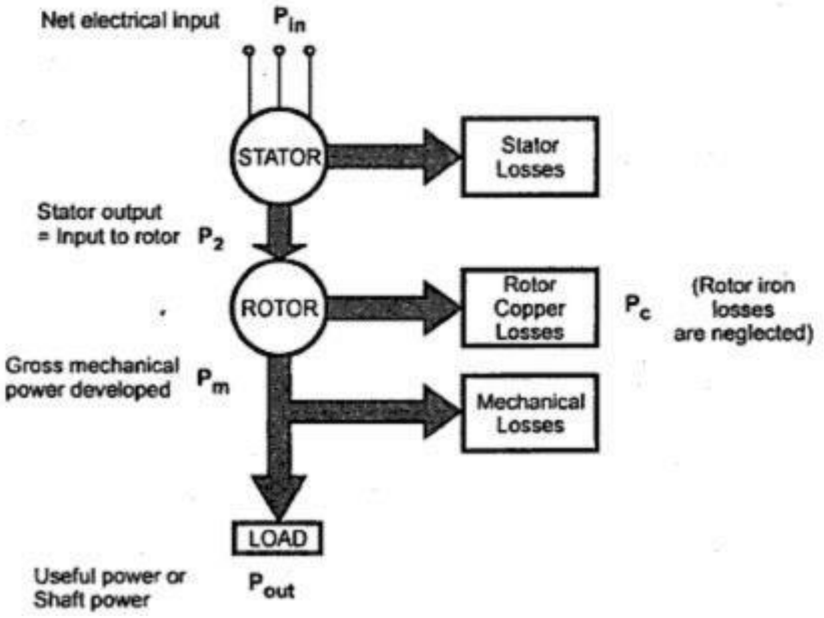
Braking Mode:

In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat. Also, motor is still receivingpower from the stator which is also dissipated as heat. So as a result of which motor develops enormous heat energy. For this stator is disconnected from the supply before motor enters the breaking mode.

If load which the motor drives accelerate the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed. In this case, it acts as an induction generator which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called dynamic or regenerative breaking.

Power Flow Diagram:

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



The three-phase supply given to the stator is the net electrical input to the motor. The net input electricalpower supplied to the motor is,

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

This is the stator input.

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

The remaining power is delivered to the rotor magnetically through the air gap with the help of rotatingmagnetic field. This is called rotor input denoted as P_2.

$P_2 = P_{in}$ – 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

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

Where I_{2r} = Rotor current per phase in running conditionR_2 = Rotor resistance per phase

After supplying these losses, the remaining part of P_2 is converted into mechanical which is called grossmechanica1 power developed by the motor denoted as Pm.

$P_m = P_2 - P_c$

Part of P_m is utilized to provide mechanical friction and windage. Finally, the power is available to theload at the shaft. This is called net output of the motor denoted as P_{out}. This is also called shaft power.

$$\text{Rotor efficiency} = \frac{\text{rotor output}}{\text{rotor input}} = \frac{\text{gross mechanical power developed}}{\text{rotor input}} = \frac{P_m}{P_2}$$

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

Relation Between Input, Rotor Copper Losses and Mechanical Power Developed:

Let T = gross torque developed by motor in N-mPower P = T x ω
Where ω = angular speed
= 2ΠN/60

N = speed in r.p.m

Input to the rotor P_2 is from stator side through rotating magnetic field which is at synchronous speed N_s.

Rotor input $P_2 = T \times \omega_s$, where $\omega_s = 2\Pi N_s/60$ rad/sec.

P_2 = T x 2ΠNs/60 .... (1)

where N_s is in r.p.m

Rotor output is gross mechanical power developed P_m, rotor gives the output at speed N.

Mechanical power developed $P_m = T \times \omega$

Where $\omega = 2\Pi N/60$

$P_m = T \times 2\Pi N/60$..(2)

From power flow diagram, Rotor copper loss $P_c = P_2 - P_m$

$= (T \times 2\Pi Ns/60) - (T \times 2\Pi N/60)$
$P_c = T \times 2\Pi/60\ (N_s-N)$...(3)

Dividing equation (3) by (1),

$P_c/P_2 = [T \times 2\Pi/60\ (Ns-N)]/[\ T \times 2\Pi Ns/60] P_c/P_2 = (Ns-N)/\ Ns = S$

$P_c = S\ P_2$

Rotor copper loss (P_c) = Slip (S) x rotor input (P_2) Thus, total rotor copper loss is slip times the rotor input. $P_2 - P_c = P_m$

$P_2 - sP_2 = P_m$

$(1-S)\ P_2 = P_m$

Thus, gross mechanical power developed is (1-S) times the rotor input.Now,

Rotor Copper loss /Rotor input = **$P_c/P_2 = (N_s-N)/N_s$**

Gross mechanical power developed/rotor input= **$P_m/P_2 = (1-S)$**

Rotor Copper loss/ Gross mechanical power developed = **$P_c/P_m = S/(1-S)$Conclusion:**

If some power P_2 is delivered to a rotor, then a part SP_2 is lost in the rotor itself as copper loss (and appears as heat) and the remaining (1-S) P_2 appears as gross mechanical power P_m (including friction and windinglosses).

$P_2 : P_m : P_c = 1:(1-S): S$

Electrical Motor Efficiency when Shaft Output is measured in Watt

If power output is measured in *Watt (W)* then efficiency can be expressed as

$\eta_m = P_{out} / P_{in}$ *(1)*

where

η_m = *motor efficiency*

P_{out} = *shaft power out (Watt, W)*

P_{in} = *electric power in to the motor (Watt, W)*

Electrical Motor Efficiency when Shaft Output is measured in Horsepower

If power output is measured in *horsepower (hp)*, efficiency can be expressed as

$\eta_m = P_{out}\ 746 / P_{in}$ (2)

where

P_{out} = *shaft power out (horsepower, hp)*

P_{in} = *electric power in to the motor (Watt, W)*

Primary and Secondary Resistance Losses

The electrical power lost in the primary rotor and secondary stator winding resistance are also called **copper losses**. The copper loss varies with the load in proportion to the current squared - and can be expressed as

$P_{cl} = R\ I^2$ (3)

where

P_{cl} = *stator winding - copper loss (W, watts)*

R = *resistance (Ω)*

I = *current (A, amps)*

Iron Losses

These losses are the result of magnetic energy dissipated when when the motors magnetic field is applied to the stator core.

Stray Losses

Stray losses are the losses that remains after primary copper and secondary losses, iron losses and mechanical losses. The largest contribution to the stray losses is harmonic energies generated when the motor operates under load. These energies are dissipated as currents in the copper winding, harmonic flux components in the iron parts, leakage in the laminate core.

Mechanical Losses

Mechanical losses includes friction in the motor bearings and the fan for air cooling.

Problems:1.

The power input to a 3 ϕ induction motor is 60 kW. The total stator losses is 1 kW. Find the rotor copper loss per phase if the motor is running wth a slip of 3%.

Solution:

Motor input or stator input, $P_{in} = 60\ kW$

Total stator losses $= 1\ kW$

Slip, $s = 3\% = 0.03$

Rotor Input, P_2 = Stator Input – Stator losses $= 60 - 1 = 59\ kW = 59 \times 10^3\ W$

∴ Rotor copper losses,

$$P_c = s\,P_2 = 0.03 \times 59 \times 10^3 = 1770\ W$$

Rotor copper loss / phase $= \dfrac{1770}{3} = \mathbf{590\ W}$

2. *A 15 kW, 400 V, 3 phase, 6-pole 50Hz induction motor runs at 970 rpm at full load. The total mechanical losses is 520 W. Calculate the rotor loss and the efficiency of the motor at full load if the stator losses are 750W.*

Solution:

Motor output, $P_{out} = 15\ kW$

$= 15 \times 1000 = 15000\ W$

Mechanical losses $= 520\ W$

Stator losses $= 750\ W$

No. of poles, $P = 6$

frequency, $f = 50\ Hz$

Motor speed, $N = 970\ rpm$

Synchronous speed, $N_S = \dfrac{120f}{P} = \dfrac{120 \times 50}{6} = 1000$ rpm

slip, $s = \dfrac{N_S - N}{N_S} = \dfrac{1000 - 970}{1000} = 0.03$

Mechanical power developed,

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

$$= 15000 + 520 = 15520\ W$$

Rotor input, $$P_2 = \frac{P_m}{1-s} = \frac{15520}{1-0.03} = 16000W$$

Rotor copper loss, $$P_c = sP_2 = 0.03 \times 16000 = 480\ W$$

Motor input or stator input, $$P_{in} = P_2 + \text{stator losses}$$

$$= 16000 + 750 = 16750\ W$$

$$\%\ \text{Efficiency} = \frac{\text{Motor output}}{\text{Motor input}} \times 100 = \frac{15000}{16750} \times 100 = \mathbf{89.55\ \%}$$

A 3 ϕ, 6-pole, 400V, 50 Hz induction motor takes a line current of 40A at 0.8 p.f. and runs at 950 rpm. Find its efficiency and output if the frictional losses are 4 kW and stator losses is 3 kW.

Solution :

No. of poles, $P = 6$

Frequency $f = 50$ Hz

Line voltage, $V_L = 400$ V

Line current, $I_L = 40$ A

p.f, $\cos\phi = 0.8$

Motor speed, $N = 950\ rpm$

Frictional losses $= 4\ kW$

Stator losses $= 3\ kW$

Motor input or stator input, $$P_{in} = \sqrt{3}V_L I_L \cos\phi$$

$$= \sqrt{3} \times 400 \times 40 \times 0.8$$

$$= 22170\ W = 22.17\ kW$$

Rotor input, $P_2 = P_{in} - \text{Stator losses}$

$= 22.17 - 3 = 19.17\ kW$

Synchronous speed, $N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000\ rpm$

Slip, $s = \frac{N_S - N}{N_S} = \frac{1000 - 950}{1000} = 0.05$

Mech. power developed, $P_m = (1 - s)\ P_2$

$= (1 - 0.05)\ 19.17 - 18.212\ kW$

Motor output, $P_{out} = P_m - \text{Frictional losses}$

$= 18.212 - 4$

$= \mathbf{14.212\ kW}$

% Efficiency, $\eta = \frac{\text{Motor output}}{\text{Motor input}} \times 100 = \frac{14.212}{22.17} \times 100$

$= \mathbf{64.1\ \%}$

4. *A 3 - phase induction motor has an output 10 kW at 1450 rpm if the mechanical losses are 700 watt and stator losses are 900 watt. Calcualte motor efficiency and line current, supply is 440V, 50 Hz and p.f is 0.72, the motor has 4 poles.*

Solution :

Motor output $P_{out} = 10\ kW = 10000\ W$

Mechanical losses = $700\ W$

Stator losses = $900\ W$

Motor speed, $N = 1450\ rpm$

No. of poles, $P = 4$ poles

Frequency , $f = 50$ Hz

Line voltage, $V_L = 440$ V,

p.f., $Cos\ \phi = 0.72$ lagging

Synchronous speed, $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\ rpm$

∴ Slip, $s = \frac{N_s - N}{N_s} = \frac{1500 - 1450}{1500} = 0.033$

Mechanical power developed,

$P_m = P_{out} + \text{Mechanical losses} = 10000 + 700 = 10700\ w$

Rotor input, $P_2 = \frac{P_m}{1 - s} = \frac{10700}{1 - 0.033} = 11065.15\ w$

Motor input or stator input = P_2 + Stator losses = 11065.15 + 900 = 11965.15 w

% Efficiency, $\eta = \dfrac{Motor\ output}{Motor\,input} \times 100 = \dfrac{10000}{11965.15} \times 100 = 83.58\ \%$

Motor input $= \sqrt{3}\ V_L\ I_L\ cos\,\phi = 11965.15\ w$

$\therefore$ line current, $I_L = \dfrac{11965.15}{\sqrt{3} \times 440 \times 0.72} = 21.8\ A$

Induction Motor as a Generalized Transformer & their Comparison:

The working principle of an induction motor is similar to a transformer i.e., the primary and secondary windings of a transformer are referred to as stator and rotor in the case of an induction motor. The transformer works on the principle of mutual induction i.e., the flux generated by the primary winding links with the secondary and induces a voltage in it.

Similar to the transformer the flux produced by the induction motor stator links with the rotor. Since the rotor is short-circuited there will be a circulation of currents in the rotor, thereby transferringthe energy by mutual induction. This is the main reason for an induction motor to be referred to as a transformer.

Similarities Between Induction Motor with that of a Transformer:

- In an induction machine, the synchronously rotating air gap flux is due to the combined action of both stator and rotor MMFs. Similarly, the resultant mutual flux in a transformeris due to the combined action of primary and secondary MMFs.
- The rotating airgap flux generates counter emf in the stator winding similar to the counter emf induced by the mutual flux in the primary winding of a transformer.
- The short-circuit test performed on the high-voltage side of the transformer is similar to the blocked rotor test of an induction motor where the rotor of the motor is blocked to rotate.
- The stator and rotor windings of an induction machine possess resistances and leakage reactances just like the resistances and leakage reactances of the primary and secondary windings of a transformer.
- As the transformer is loaded, the MMF of the secondary current reacts on the primary to draw more power from the ac source. Similarly, with the increase in the shaft load, the rotor MMF reacts with the stator winding to extract more power from the ac source.
- Both induction motors and transformers work on the principle of Faraday's laws of electromagnetic induction. Due to the above similarities, the induction machine is referredto as a generalized transformer.

When a 3-phase induction motor is connected across the supply. The stator winding will set up a rotating magnetic field, and the speed of rotation depends upon supply frequency and the number of stator poles of the machine i.e., synchronous speed (N_s = 120f/P). This rotating magnetic field will induce EMFs (E_1 & E_2) in the stator and rotor.

$$E_1 = 4.44\ kW_1\ N_1\ f_1\ \phi$$

$$E_2 = 4.44\ kW_2\ N_2\ f_2\ \phi$$

Where $kW1_1$ and kW_2 are winding factors for the stator and rotor windings respectively.

$$\frac{E_1}{E_2} = \frac{kW_1\ N_1}{kW_2\ N_2}$$

Therefore,

The above equation can be compared with the voltage equation of the transformer. But, the emf induced in the case of induction motor is due to stator distributed windings, whereas in the transformerthe primary and secondary use concentrated coils.

Therefore, the characteristics of both the machines with and without load conditions are similar.

The phasor diagram of the induction motor can be developed similarly to that of a transformer.

Difference Between Induction Motor and Transformer:

Induction Motor	**Transformer**
Induction has rotating parts in it.	The transformer has no rotating parts in it i.e., it isstationary static device.
The voltage ratio of the induction motor includeswinding factors.	It requires no winding factors.
The per-phase values of emf induced in stator androtor windings are given by, $E_1 = \sqrt{2}\pi\ f_1\ K_{\omega 1}\ N_1\ \Phi$ $E_2 = \sqrt{2}\pi\ f_2\ K_{\omega 2}\ N_2\ \Phi$ Where Φ is the average value of the rotating flux per pole.	The RMS values of emf's induced in primary andsecondary windings are given by, $E_1 = \sqrt{2}\pi\ f_1\ N_1\ \Phi_{max}$ $E_2 = \sqrt{2}\pi\ f_2\ N_2\ \Phi_{max}$ Where Φ is the maximum value of the core flux used.

The no-load current in the induction motor varies between 30 to 50% of the full-load current.	In transformer no-load current varies from 0 to 6% of full-load current.

Equivalent Circuit:

Induction motor is an asynchronous motor i.e., its speed change with a change in load. It always runs on a lagging power factor. The principle of working of an induction motor to similar to the transformer, i.e., on electromagnetic induction.

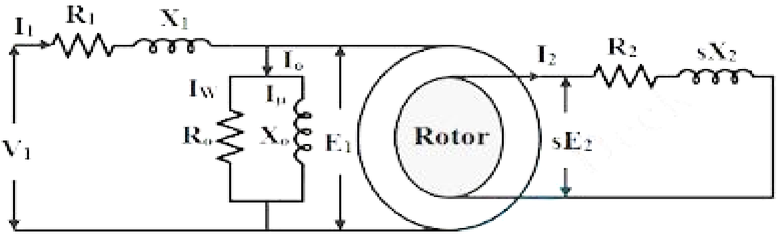
The equivalent circuit of an induction motor is similar to a transformer equivalent circuit because the energy is transferred from stator to rotor is essential as a transformer operation from primary to the secondary winding. An equivalent circuit enables the performance characteristics of the induction motor. The data obtained from the equivalent circuit can be used to calculate efficiency, torque, losses, rotor output, etc. All per phase quantities are used in representing the equivalent circuit.

Equivalent Circuit of induction Motor:

The various parameters used for developing the equivalent circuit of an induction motor are,

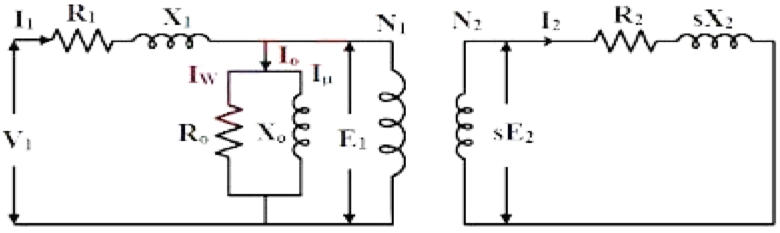
- R_1 & X_1: Stator winding resistance and leakage reactance.
- R_2 & X_2: Rotor winding resistance and leakage reactance at standstill (i.e., s = 1).
- sX_2: Rotor leakage reactance at slip s (under running condition).
- R_o: No-load branch resistance and it carries working component (I_w) of no-load current I_o account for the losses on no-load.
- X_o: No-load branch reactance and it carries magnetizing component (I_μ) of no-load to produce the flux.
- E_1 and SE_2: Stator induced emf and rotor induced emf at slip s.

From the above parameters, the equivalent circuit of an induction motor can be drawn as



,

OR



Equivalent Circuit

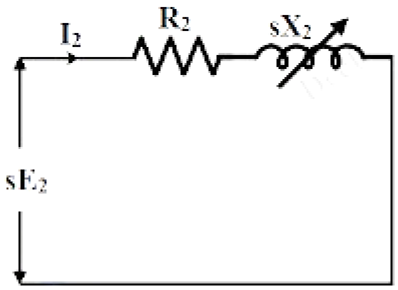
Let us consider the actual rotor circuit of the motor, From the below diagram, the rotor current I_2 isgiven by,

$$I_2 = \frac{sE_2}{R_2 + j\,sX_2}$$

Dividing numerator &

denominator by ‘s’

$$I_2 = \frac{E_2}{\frac{R_2}{s} + j\,X_2}$$



Actual Rotor Circuit

Here we know that the rotor input, P_2 is the sum of rotor copper losses P_c and mechanical power developed P_m. Thus, it is possible to represent the electrical equivalent of mechanical power developedas follows,

$$P_2 = P_c + P_m$$

$$\frac{I_2^2 R_2}{s} = I_2^2 R_2 + I_2^2 R_2$$

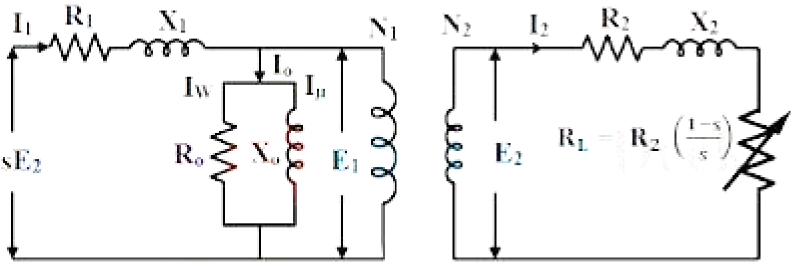
$\frac{R_2}{s}$ can be expressed as,

$$\frac{R_2}{s} = R_2 + R_2\left(\frac{1-s}{s}\right) \quad R_L = \text{Equivalent mechanical load.}$$

$$= R_2 + R_L$$

$$i.e., \quad R_L = R_2\left(\frac{1-s}{s}\right)$$

To show the equivalent mechanical load (mechanical power conversion) in the rotor circuit. Themotor equivalent circuit can be modified as,



Modified Equivalent Circuit

Now transfer the rotor side parameters to the stator side. While shifting the rotor side parameters towards the stator side we have to divide it with value "K^2" (Where K = Ratio of the effective rotor to stator turns per phase) except the rotor current where it is multiplied with "K". When the rotor parameters are shifted, they can be represented as,

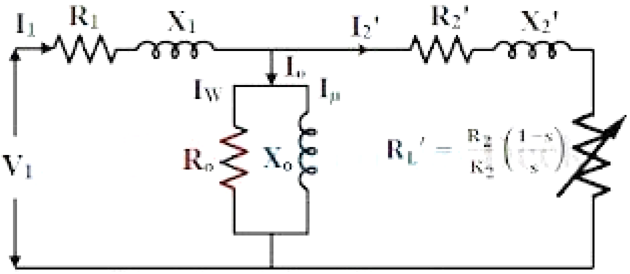
- R'_2 = Rotor resistance referred to the stator.
- X'_2 = Rotor reactance referred to the stator.
- E'_2 = Rotor induced e.m.f. referred to the stator.
- I'_2 = Rotor current referred to the stator.
- R'_L = Rotor equivalent mechanical load referred to the stator.

The equivalent circuit can be further modified as shown below, and it is known as Exact Equivalent Circuit as referred to the stator.

$$R'_2 = \frac{R_2}{K^2} \qquad X'_2 = \frac{X_2}{K^2}$$

$$E'_2 = \frac{E_2}{K^2} = E_1$$

$$R_L = \frac{R_L}{K^2} \qquad I'_2 = I_2K$$



Exact Equivalent Circuit

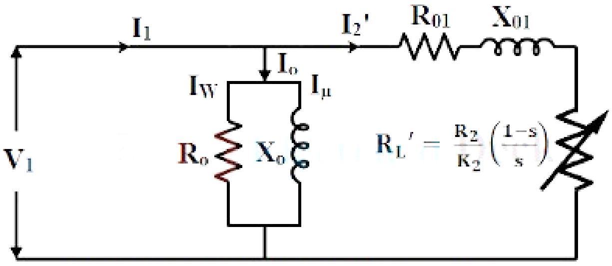
Therefore, the approximate equivalent circuit is obtained by shifting the shunt branch (consists of R_0 &X_0) to the supply terminals as shown in the below figure. Therefore,

the total resistance referred to the stator side is,

$$R_{01} = R_1 + R'_2$$

or

$$R_{01} = R_1 + \frac{R_2}{K^2}$$



Approximate Equivalent Circuit

Similarly, the total reactance referred to the stator side is,

$$X_{01} = X_1 + X'_2$$

or

$$X_{01} = X_1 + \frac{X_2}{K^2}$$

Phasor Diagram Induction Motor:

As we know that principle of induction motor is very similar to the transformer with some differences. An induction motor at standstill condition is similar to a transformer at no load condition. Therefore, the method of drawing the induction motor phasor diagram is also same as that of a transformer phasordiagram. In this post we will discuss the phasor diagram of induction motor at standstill condition andat full load slip.

Induction Motor Phasor Diagram at Standstill Condition:

Before going into the phasor diagram, there are some important points to be taken care: Per phase value of induced emf E_1 in the stator winding is given as below

$E_1 = \sqrt{2}\pi f_1 k_{w1} N_1 Ø$ where f_1 = supply frequency

N_1 = Number of series turns per phase Ø = resultant air gap flux per pole

k_{w1} = Stator winding factor

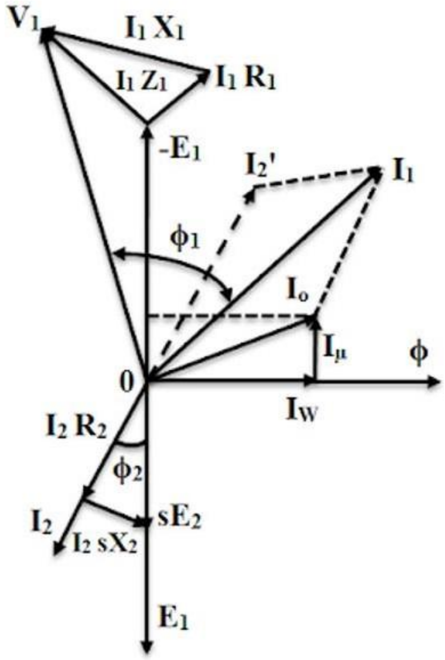
- Per phase value of induced emf E2 in rotor winding is given as $E_2 = \sqrt{2}\pi f_2 k_{w2} N_2 Ø$

where f_2 = frequency of induced emf in rotor = sf_1 N_2 = Number of series turns per phase

Ø = resultant air gap flux per pole k_{w2} = Rotor winding factor

- Total air gap mmf F_r of induction motor is the sum of stator mmf (F_1) and rotor mmf(F_2).
- Magnetizing current I_m taken by stator winding from the supply always remains in phase with the resultant flux Ø.
- The induced emf always lags behind the resultant flux Ø by 90°.

Now we are at a stage to draw the induction motor phasor diagram. Let us take the resultant air gap flux Ø as the reference. This flux Ø will be in phase with the resultant mmf F_r. Also, the induced emf E_1 and E_2 in stator and rotor winding will lag behind the Ø by 90°. This is shown in the below phasor diagram of induction motor.



Crawling in Induction Motor (or Effect of Harmonics on the Performance of 3- Phase Induction Motor):

The flux in the air-gap of an induction motor set up by the 3-phase stator windings carrying sinusoidal currents is of non-sinusoidal wave shape. According to the Fourier series analysis, any non-sinusoidal flux is equivalent to the combination of a number of sinusoidal fluxes of fundamentaland higher order harmonics.

Since the wave shapes of the air-gap flux have half-wave symmetry, hence all the even harmonics (i.e., 2nd, 4th, 6th, … etc.) are absent in the Fourier series. Thus, a non-sinusoidal flux wave can be resolved into fluxes of fundamental and higher-order odd harmonics (i.e., 3rd, 5th, 7th, 11th, …, etc.)

The 3rd harmonic flux wave produced by each of the three phases neutralize one another. Hence, the resultant air gap flux is free from the third and its multiples (i.e., 3rd, 9th, etc.) harmonics. It is becausethe third harmonic in the flux wave of all the three phases are in the space phase, but they differ in time phase by 120°.

The space harmonics are produced by windings, slotting, magnetic saturation and inequalities in the air gap length etc. These harmonic flux waves induce EMFs and circulate harmonic currents in rotor windings. These harmonic currents in the rotor windings interact with the harmonic fluxes to produce harmonic torques, vibrations and noise.

The order of the space harmonic which is produced by a 3-phase winding carrying sinusoidal currents is given by,

$h=6x\pm1$

Where, x is a positive integer (1, 2, 3, …). The synchronous speed of the h^{th} harmonic is (1/h) timesof the speed of the fundamental harmonic wave.

If

$h=6x+1$

Then, the space harmonic waves rotate in the same direction as the fundamental wave, and when,

$h=6x-1$

Then, the space harmonic waves rotate in the opposite direction of the fundamental wave.

A space harmonic wave of the order of h is equivalent to a machine with the number poles equal toh times of the number of poles of the stator. Thus, the synchronous speed of the h^{th} harmonic wave is given by,

$N_{s(h)}=N_s/h=120f/h\times p$

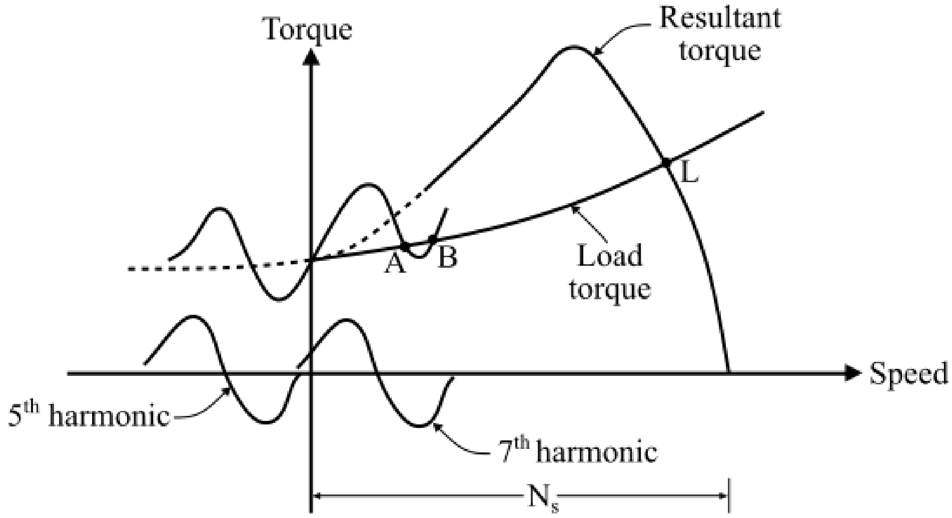
Where,

- f = stator frequency,
- P = number of stator poles,

- N_s = synchronous speed of the motor of P-poles.

Thus, for x = 1, a 3-phase winding will produce a predominant backward rotating 5th harmonic whichis rotating at a speed of (1/5) of the synchronous speed and a forward rotating seventh harmonic which is rotating at a speed of (1/7) of the synchronous speed. These harmonics alone will have littleeffect on the operation of the induction motor.

The figure shows the torque-speed characteristics for the fundamental flux wave, 5th and7th harmonics flux wave. The shape of the torque of 5th and 7th harmonics is same as that of the fundamental flux.



Since the 5th harmonic flux rotates in opposite direction to the rotation of the rotor, thus the 5th harmonic torque opposes the fundamental torque. Whereas, the 7th harmonic flux rotates in the same direction as the fundamental flux. Hence, the 7th harmonic induction torque aids the fundamental torque. Therefore, the resultant torque-speed characteristics will be the combination of the fundamental, 5th and 7th harmonic characteristics (see the figure above).

The resultant torque-speed characteristics has two dips, one is near (1/5) of the synchronous speed and the other is near (1/7) of the synchronous speed. The dip near (1/5) of the synchronous speed occurs in the negative direction of the rotation of the motor.

If the torque in the motor is developed only due to the fundamental flux, then the motor will accelerate to the point L which is the intersection of the load-torque characteristics and the torque- speed curve of the motor.

Due to the presence of the 7th harmonic torque, the load torque curve intersects the torque-speed curve of the motor at point A. Since the 7th harmonic flux-torque curve has a negative slope at the point A, it results in the stable running condition over the torque range between the maximum and minimum points. Consequently, the motor torque falls below the load torque. At this stage, the motor will not accelerate up to its normal speed, but will remain running at a speed which is nearly (1/7) of its normal speed and hence the operating point would be the point A.

Therefore, the tendency of the motor to run at a stable speed as low as (1/7) of the synchronous speed (Ns) and being unable to pick up its normal speed is called as crawling of the induction motor**.**

By reducing the 5th and 7th harmonics, the crawling in the induction motor can be reduced.

This canbe done by using a chorded or short pitched winding.

Cogging in Induction Motor:

The cogging in the induction motor is also known as magnetic locking or teeth locking.

Sometimes, even with the full voltage applied to the stator winding, the rotor of a 3-phase squirrel cage induction motor fails to start. This happens when the number of stator and rotor slots are equalor when the stator slots are an integral multiples of rotor slots.

When the stator and rotor slots are equal or have an integral ratio, then the strong alignment forces are produced between the stator and the rotor at the instant of starting. These forces may create an alignment torque greater than the accelerating torque, which results in the failure of the motor to start. This phenomenon of the magnetic locking between the stator and rotor teeth of an induction motor at the time starting is known as cogging or teeth locking.

Methods to overcome cogging:

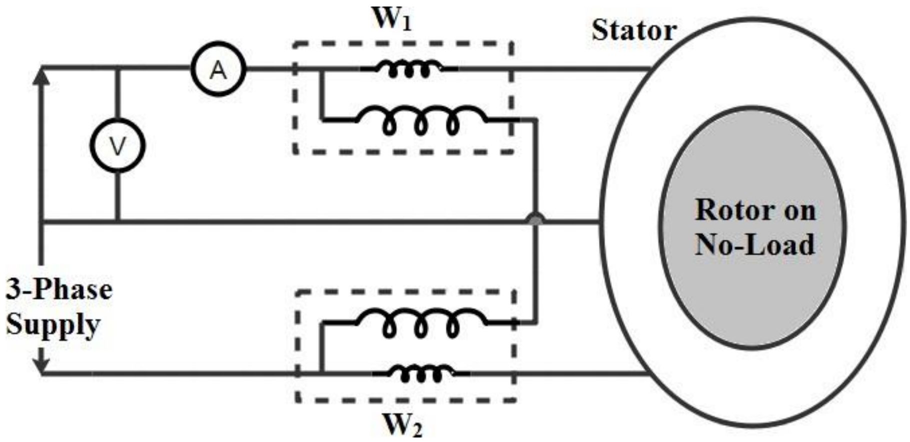
- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angledwith the axis of the rotation.

Testing of Induction motors:

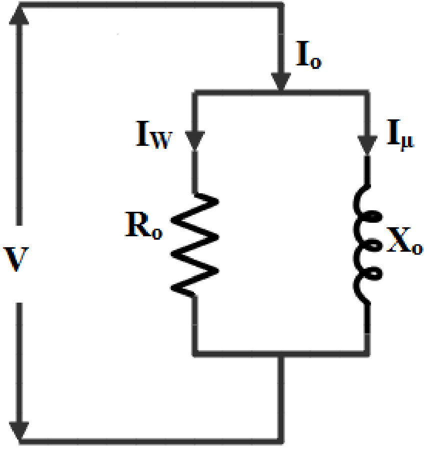
1. No Load Test:

This test is similar to the no-load test performed on a transformer. The purpose of this test is to determine the no-load losses, no-load power factor, and constants Ro and Xo of the equivalent circuit.

The no-load losses include frictional windage loss, core loss, and a small copper loss in the stator winding. As the slip at no-load is very small and negligible, the rotor copper loss is negligibleas the rotor current at no-load is very small and neglected.



The figure above shows the connection diagram and equivalent circuit of the motor at no-load. The normal voltage is applied to the stator winding and the rotor is allowed to rotate freely without any mechanical load on its shaft. Two wattmeters W_1 and W_2 measure the power input to the motor.



Equivalent Circuit

Since the motor is not supplying any load, the no-load current is small and stator copper losses are negligible. The input power, W_o equals mechanical and core losses. To be more accurate the stator copper loss at no-load current should be deducted from the input when calculating the above losses.

Calculation of No-Load Test of Induction Motor:Let,

- W_o = Power input
- V_1 = Applied voltage per phase
- I_o = Applied current per phase under no-load conditions. Then the no-load power factor is,

$$\cos \phi_o = \frac{W_o}{3\, V_1\, I_o}$$

$$R_o = \frac{V_1}{I_W} = \frac{V_1}{I_o \cos \phi_o}$$

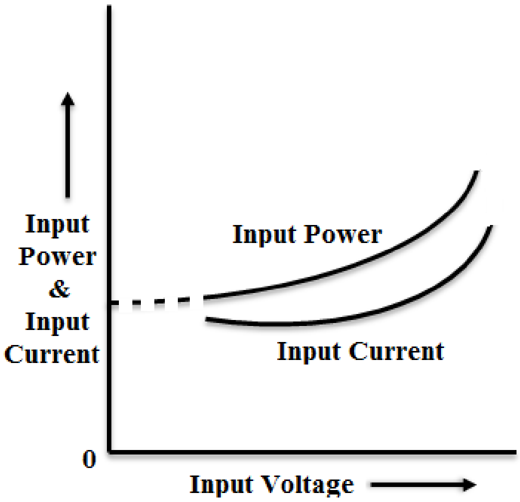
$$X_o = \frac{V_1}{I_\mu} = \frac{V_1}{I_o \sin \phi_o}$$

Where,

I_W = Working component of no-load current Io

I_μ = Magnetizing component of no-load current Io

The no-load losses for different voltages are plotted as,



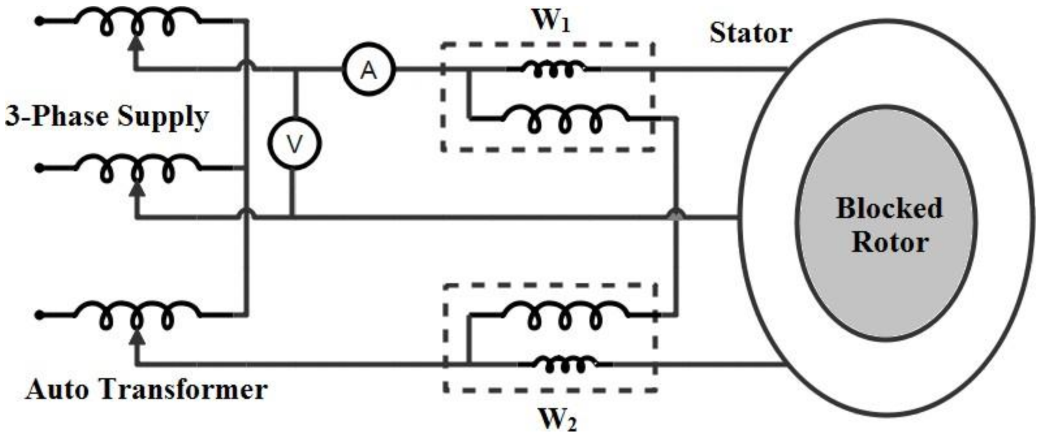
But there is a thing you have to remember while performing the no-load test on an induction motor, i.e., changes in speed, power factor, stator current, and rotor current due to fluctuations in applied voltage. When there are changes (fluctuations) in the applied voltage the readings noted from the test will be more accurate. Hence it also increases the accuracy of the calculations made from the test.

- While performing a no-load test, the speed of an induction motor obviously remains constant during the test. The speed of an induction motor changes when there is a heavy load on the motor. Therefore, here the applied voltage should remain constant so that the speed of the motor will remain unchanged.
- When there is an increase in the applied voltage to a larger value, the stator current that supplies the magnetizing component of the stator winding will also increase. Thus, there we can see a fall in the power factor.
- The torque of an induction motor is proportional to the rotor current and flux generated by the stator winding. Here flux in an induction motor will depend upon the amount of applied voltage to the stator. When the applied voltage is kept minimum the torque generated will remain constant, but the rotor current will go on increasing.

2. Blocked Rotor Test:

Blocked rotor test, it is quite opposite to the no-load test of the induction motor. Usually in transformer tests, if we want to find the behavior of a transformer on loading and on no-load, it can be done by using open circuit and short circuit tests. Here to know the behavior of a transformer when it is in the fully-loaded condition we have to perform the short-circuit test.

Similarly, the blocked rotor test is performed to know the behavior of an induction motor when it is fully-loaded i.e., as same as the short-circuit test. The purpose of this is to determine the total resistance (R_{01}) and reactance (X_{01}) of the motor as referred to the stator. This test is also used to know the amount of sound produced by the motor when it is fully-loaded and also used to draw thecircle diagram.



The rotor, in this test, is prevented from rotating by a brake, and therefore it is called a blocked rotortest. The induction motor in this case acts like a short-circuited transformer.

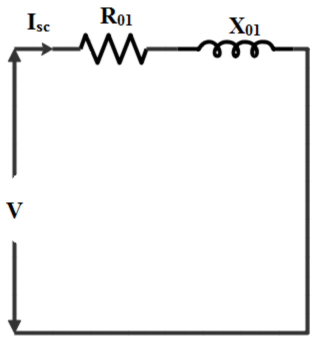
Process of Blocked Rotor Test:

A low voltage 3-phase supply (obtained from a 3-phase auto-transformer) is applied to the stator. So that full load current flows through the stator winding. The power input is measured by the two wattmeters. The short circuit current corresponding to the rated voltage can be calculated by direct proportion.

In the blocked rotor test, its voltage applied to the stator terminals must be low otherwise it can lead to damage to the stator winding. In this test, the low voltage is applied so that the there rotationof the rotor and motor draws a full load current through the stator winding.

Calculation of Blocked Rotor Test:

When the rotor is blocked, slip s = 1 and the approximate equivalent circuit referred to the statoris shown below.



Let,

W_{sc} = Total power input
V_{sc} = Per phase values of applied voltage and
I_{sc} = Per phase values of applied current under blocked rotor conditions. Then the power factor,

$$\cos\phi_{sc} = \frac{W_{sc}}{3\,V_{sc}\,sc}$$

Total resistance as referred to stator,

$$R_{01} = Z_{01}\cos\phi_{sc}$$

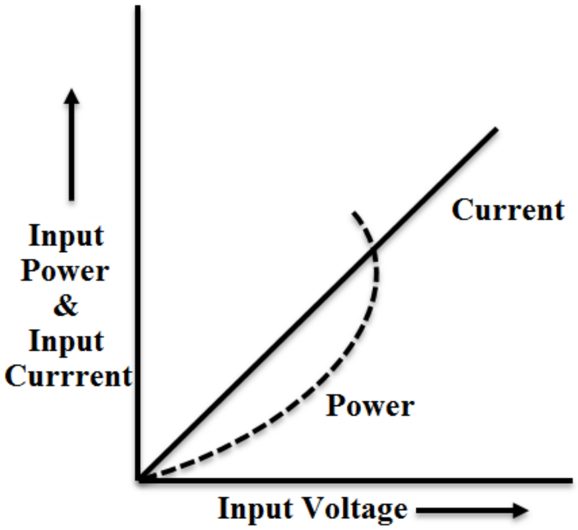
$$= \frac{V_{sc}}{I_{sc}}\cos\phi_{sc} = R_1 + R_2'$$

Total reactance as referred to stator,

$$X_{01} = Z_{01}\sin\phi_{sc}$$

$$= \frac{V_{sc}}{I_{sc}}\sin\phi_{sc} = X_1 + X_2'$$

The curves from the blocked rotor test by varying the voltage is shown below.



While performing a blocked rotor test on an induction motor. The following effects on the motorare to be noted i.e., due to,

i. Increase in losses due to an increase in applied voltage.

ii. Change in stator and rotor current due to change in applied voltage.

Effect on Losses in Motor:

In the blocked rotor test of an induction motor, the rotor is blocked i.e., it cannot able to rotate.

As the rotor is blocked the voltage applied to the motor is of a very small amount to reach the motor up to its full-load current rating. Therefore, the iron losses in the core material of the motorwill be low as the voltage applied is low.

Here, the copper losses in the motor will responsible for the total power taken by the motor.

Also, this loss is directly proportional to the applied voltage.

Effect on Stator and Rotor Current:

As the applied voltage to the motor increases the current taken by the rotor will also rise.

Therefore, the stator current will also increase in proportion to the rotor current.

Methods of starting of Induction Motor:

Necessity of Starting a Three-phase Induction Motor:

In a 3-phase Induction motor, the magnitude of rotor induced emf depends upon slip.Rotor current,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad at\ start\ s = 1$$

At starting, the magnitude of rotor induced emf and slip will be maximum. This emf circulates very high current through the rotor. The induction motor acts as a transformer having short-circuited secondary at start. Hence a rotor current is high, consequently, the stator draws a very high current of the order of 5 to 8 times full load current.

Damage to the stator winding and large voltage drop can occur when such huge currents are taken by the stator winding at starting. It may also affect the working of other equipment connected to thesame line. Therefore, a starter is necessary to limit the current drawn by the motor at the start.

Starters not only limit the starting current but also provide protection to the motor against overloading and low voltage conditions.

Advantages of Using Starters for Induction Motor:

The functions of the starter are

1. To start and stop the motor.
2. To limit the starting (or in rush) current, when necessary.
3. To permit automatic speed control when required, and
4. To protect the motor and other connected equipment from sustained overload, low voltage,etc conditions.

Methods of Starting a Three Phase Induction Motor:

From the expression of current, it can be seen that starting current can be limited to a safe value,

1. By applying a reduced voltage to the stator consequently reduces E_2 or,
2. By adding resistance in the rotor circuit at the start

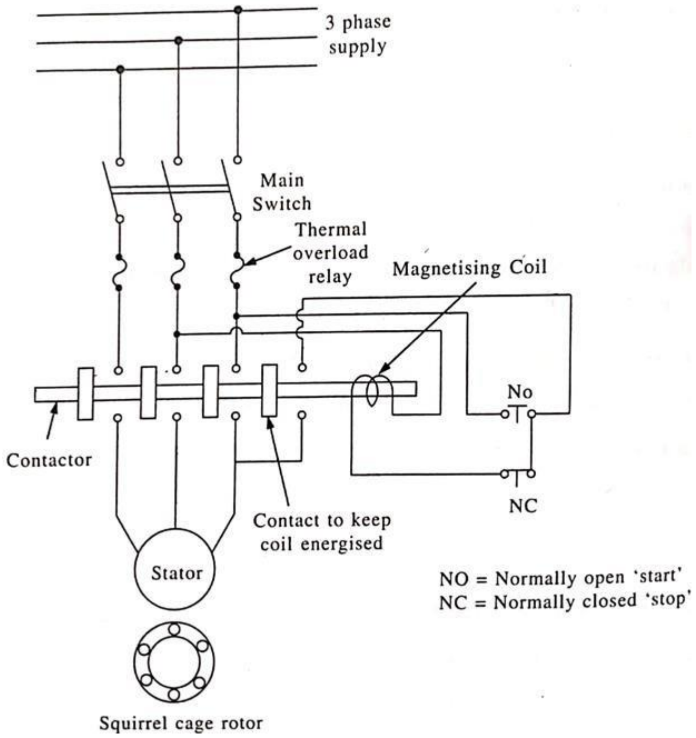
The various types of starters are,

1. Direct-on-line (D.O.L) Starter (full voltage starting)
2. Auto Transformer Starter
3. Star-delta Starter (Reduced voltage starting)
4. Rotor Resistance Starter (Used for slip ring motors)

First three starters are used for both Squirrel Cage and Slip Ring Induction motors.

1. Direct-on-line (D.O.L) Starter:

For small capacity motors having rating less than 5 *h.p.*, the motors can withstand high starting currents due to robust construction. Motors are directly switched on supply lines hence the starter is called as ***Direct Online Starter***.



It does not reduce the starting current, it consists of over load and no load release coils which protect the motor from overload and low voltage conditions Fig 2.30 shows schematic diagram of *D.O.L* starter.

The '*NO*' contact is normally open and '*NC*' is normally closed. At start '*NO*' is pressed, the coil gets energized and attracts the contactor. So stator directly gets supply and keeps contactor in '*ON*' position.

When '*NC*' is pressed, the circuit gets opened due to which coil gets de-energised and motor gets switched '*OFF*' from the supply.

Under over load condition, current drawn by the motor increases due to which there is a excessive heat produced. Thermal relays get opened due to high temperature, protecting the motor from over load condition. If supply fails or low voltage situations, the circuit gets opened and is called as under voltage or no. voltage protection.

Torque Developed on Starting the Motor by Direct Switching

We know that

Rotor input, $$P_2 = \frac{2\pi N_S T}{60}$$

$$\therefore \quad \text{Torque } T \,\alpha\, P_2$$

But $$P_2 : P_c : P_m = I : s : I - s$$

$$\therefore \quad P_2 = \frac{P_C}{s} = \frac{3 I_2^2 R_2}{s}$$

$$\therefore \quad T \,\alpha\, \frac{I_2^2}{s}$$ If rotor resistance R_2 is constant.

Now rotor current I_2 is proportional to stator current I_1

$$\therefore \quad T \,\alpha\, \frac{I_1^2}{s}$$

or $$T = \frac{K I_1^2}{s}$$ Where K is constant

At start, $s = 1$ and $I_1 = I_{st}$, starting current

∴ Starting torque,

$$T_{st} = K I_{st}^2$$

On full load, $s = s_f$ and $I_1 = I_{FL}$, full load current

∴ F.L. torque, $T_{FL} = \frac{K I_{FL}^2}{s_f}$

$$\frac{T_{st}}{T_{FL}} = \frac{K I_{st}^2}{(K I_{FL}^2 / s_f)} = \left(\frac{I_{st}}{I_{FL}}\right)^2 \times s_f$$

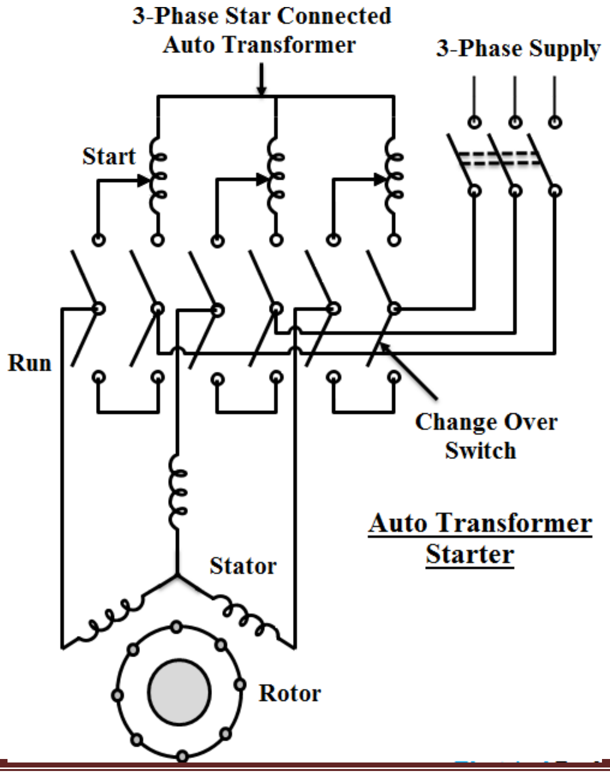
When motor is direct switched on to rated voltge, then starting current

$$I_{st} = \text{Short circuit current } I_{sc}$$

Starting torque; $T_{st} = T_{FL} \times \left(\frac{I_{sc}}{I_{FL}}\right)^2 \times s_f$

2. Auto Transformer Starter:

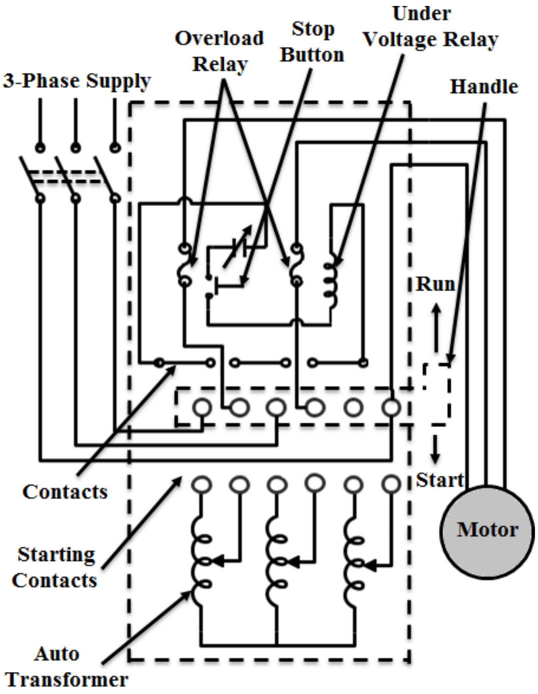
The voltage applied to the stator can be reduced to the desired value by using a 3-phase star-connected auto-transformer. It contains a suitable change over switch as shown in the below figure.



Auto Transformer Starter

When the switch is in the 'START' position, a reduced voltage is applied across the stator winding. The amount of voltage applied can be controlled by changing tappings on the auto-transformer. When the motor attains 80% of its normal speed, the change-over switch is thrown intothe 'RUN' position.

In the RUN position rated voltage gets applied across the stator winding and the auto-transformer is disconnected from the circuit. The operation of the change-over switch is automatic by using timers and relays. This type of starter is suitable for both start and delta-connected motors.The wiring diagram of an auto-transformer is shown below.



Wiring Diagram of Auto Transformer Starter

Relation between Starting and Full-load Torque :

Let 'x' be the transformation ratio of the autotransformer. So voltage applied to the stator gets reducedby the fraction 'x'. So if I_{sc} is starting current with rated voltage, then motor starting current,

$$I_{st} = x\, I_{sc}$$

$$\frac{T_{st}}{T_{FL}} = \left(\frac{Motor\ starting\ current, I_{st}}{Full\ load\ current,\ I_{FL}}\right)^2 \times s_f$$

$$\frac{T_{st}}{T_{FL}} = X^2 \left(\frac{I_{sc}}{I_{FL}}\right)^2 \times s_f$$

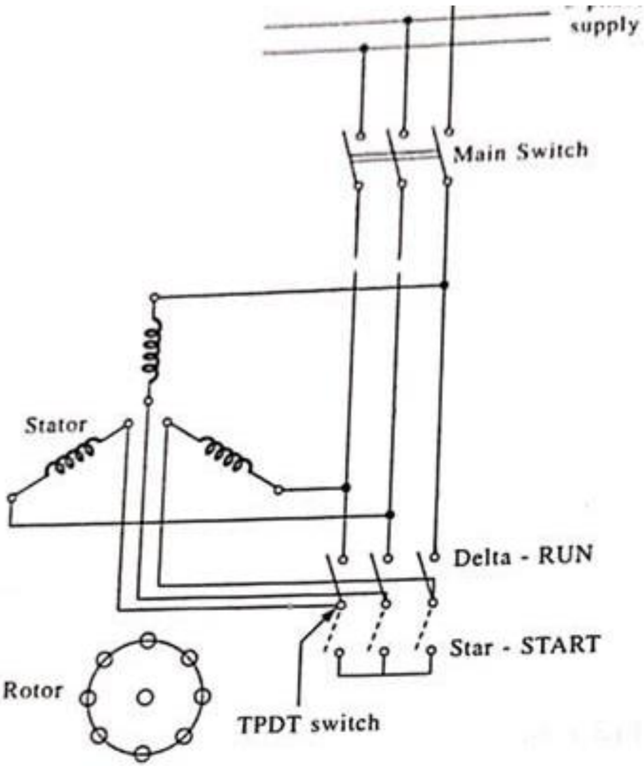
$$T_{st} = X^2 \left[T_{FL} \times \left(\frac{I_{sc}}{I_{FL}}\right)^2 \times s_f\right]$$

$$= X^2\ (Starting\ torque\ with\ direct\ switching\ )$$

Starting torque reduces by X^2 if the applied voltage is reduced by fraction 'X'.

3. Star-delta Starter:

It was *TPDT* (Triple Pole Double Through Switch) which connects the stator winding in **'STAR'** at start and then in **"DELTA"** while normal running. Hence this starter is suitable



Initially when switch is in the '*START*' position, the stator winding gets connected in star.

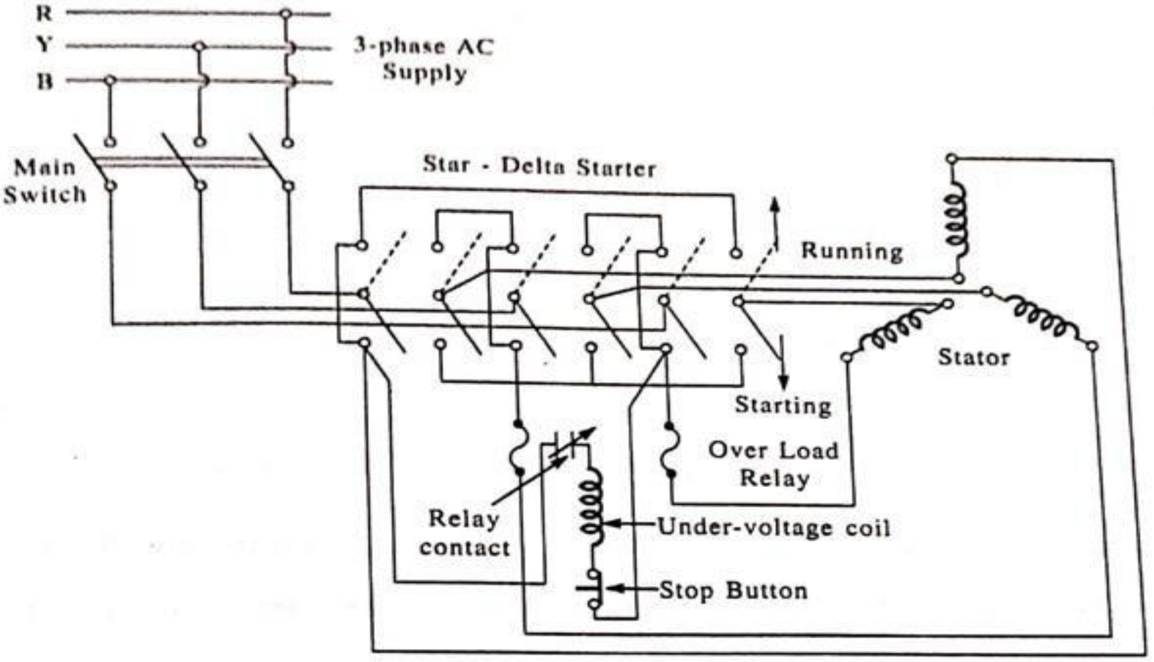
Hence $$V_{ph} = \frac{V_L}{\sqrt{3}}$$

The voltage across each phase gets reduced by factor $\frac{1}{\sqrt{3}}$. Due to this, starting current also gets reduced.

When the motor picks up speed, switch is thrown to '*RUN*' position. Hence, stator winding gets connected in delta.

$$V_{ph} = V_L = \text{rated voltage.}$$

Each phase of the winding gets rated voltage. The operation of switch can be automatic by using relays which ensures that motor will not start with switch in '*RUN*' position. Its cost is cheap as compared to auto–transformer starter.

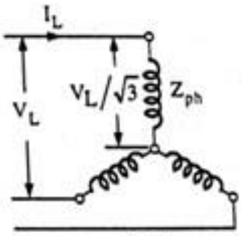


Starting Current :

In star connection :

$$I_{ph} = \frac{V_{ph}}{Z_{ph}} = \frac{V_L/\sqrt{3}}{Z_{ph}} = \frac{V_L}{\sqrt{3}Z_{ph}}$$

$$I_L = I_{ph}$$

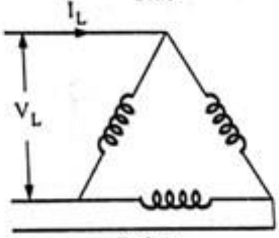


Star

In delta connection :

$$V_{ph} = V_L$$

$$I_L = \sqrt{3}I_{ph} = \sqrt{3}\frac{V_{ph}}{Z_{ph}} = \frac{\sqrt{3}V_L}{Z_{ph}}$$



Delta

$$\therefore \qquad \frac{(I_L)_{star}}{(I_L)_{delta}} = \frac{V_L/\sqrt{3}Z_{ph}}{\sqrt{3}V_L/Z_{ph}} = \frac{1}{3}$$

$$\text{or} \qquad (I_L)_{\text{star}} = \frac{1}{3}(I_L)_{\text{delta}}$$

Thus this method reduces starting line current to one third

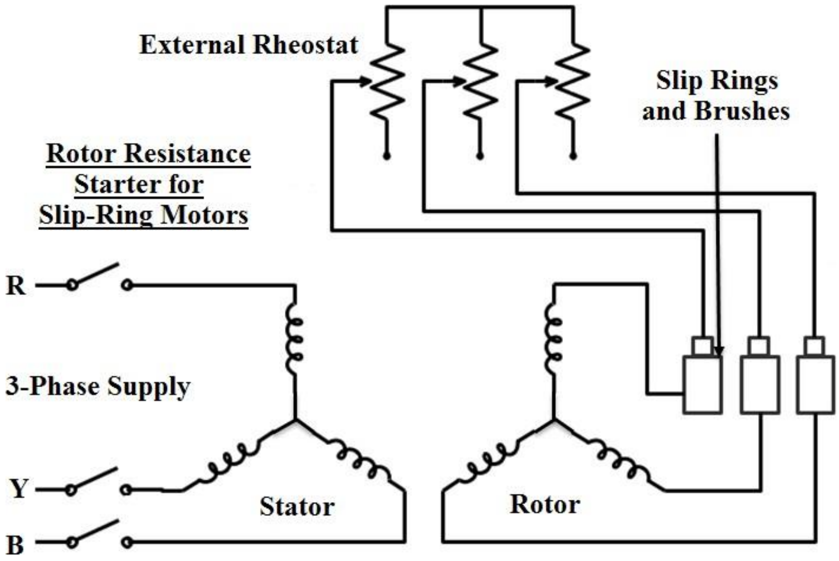
Relation between starting and F.L. torque

As we have seen that

$$\frac{T_{st}}{T_{FL}} = x^2\left(\frac{I_{sc}}{I_{FL}}\right)^2 \times s_f$$

4. Rotor Resistance Starter (for slip ring motor):

In the rotor resistance stator, a variable resistance is connected with the rotor circuit to limit the rotor current. The arrangement is shown in the below figure. The external resistance is inserted in each phase of the rotor circuit through slip rings and brush. At starting the resistance is kept to its maximum value. As the motor picks up speed, the resistance is gradually down to a low value and finally cut off.



When the motor attains normal speed, the rotor windings are short-circuited through the slip rings and brushes as the external resistance has been removed. This operation may be manual or automatic.

This method not only limits the starting current but also increases the starting torque due to added rotor resistance. This starter is not suitable for squirrel cage induction motors because externalresistance cannot be inserted in the squirrel-cage rotor.

Comparison Between Various Starters:

Direct Online Starting	**Auto Transformer Starting**	**Star-delta Starting**
Full voltage is applied to the motor at the time of starting requirement.	The starting voltage can be adjusted according to the starting.	Each winding gets 58% (1/√3) of the rated line voltage at the time of starting.

The starting current is 5-6 times the full-load current.	The starting current can be reduced as desired.	The starting current is reduced to 1/3 rd that of direct online starting.
Only three wires are to be brought out from the motor.	Only three wires are to be brought out from the motor.	Six wires are to be brought out from the motor.
Low cost.	High cost.	Low cost.
Very easy operation.	Not so easy to operate, a skilled operator is needed.	Not so easy to operate, since the connections are first to be made in star and then in delta either manually or automatically.
Used for motors up to 5 HP.	Used for large motor ratings.	Used up to 10 HP motors.

Speed Control of an Induction Motor:

There is a various method of speed control of an Induction Motor. The rotor speed of an induction motor is given by the equation shown below. From equation (1) it is clear that the motor speed can be changed by a change in frequency f, a number of poles P, and slip s.

$$N_r = (1 - s)\, N_s \quad \text{and}$$

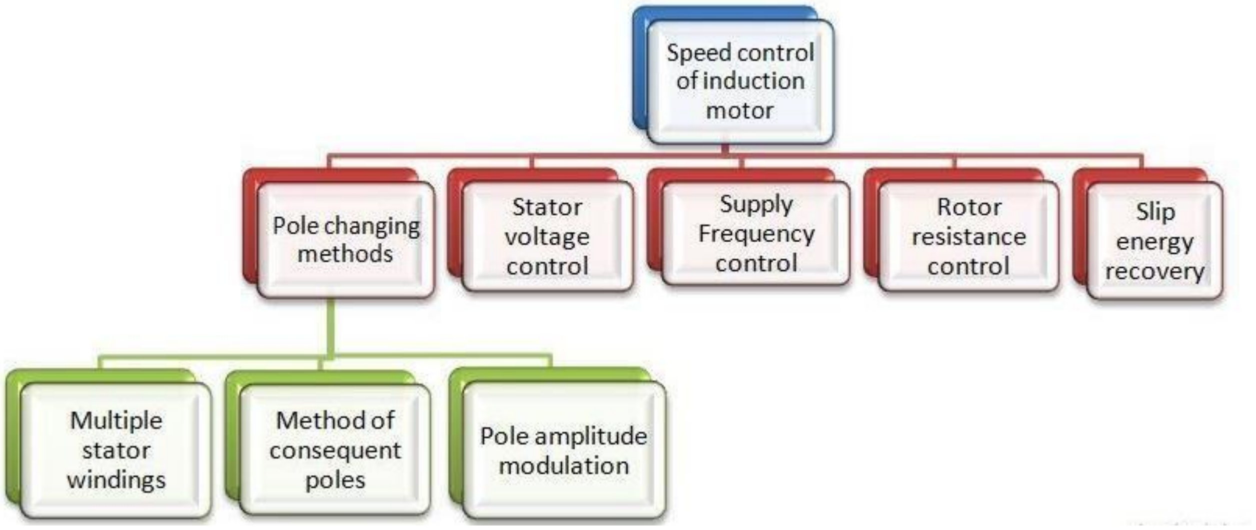
$$N_s = \frac{120f}{P}$$

Therefore,

$$N_r = \frac{120f}{P}(1 - s) \;\ldots\ldots (1)$$

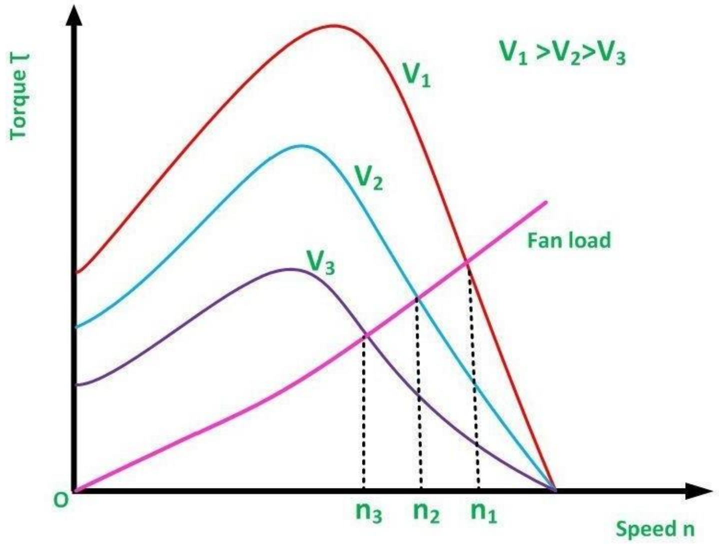
Any one or combinations of the below methods listed can be used to change the motor speed. Allthe methods of speed control of an induction motor are used in actual practice.

Stator Voltage Control of an Induction Motor:



Stator Voltage Control is a method used to control the speed of an Induction Motor. The speed of a three-phase induction motor can be varied by varying the supply voltage. As we already know that the torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage. The variation in the supply voltage does not alter the synchronous speed of the motor.

The **Torque-Speed Characteristics** of the three-phase induction motors for varying supply voltage and also for fan load are shown below:



By varying the **supplying voltage**, the speed can be controlled. The voltage is varied until the torque required by the load is developed, at the desired speed. The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.

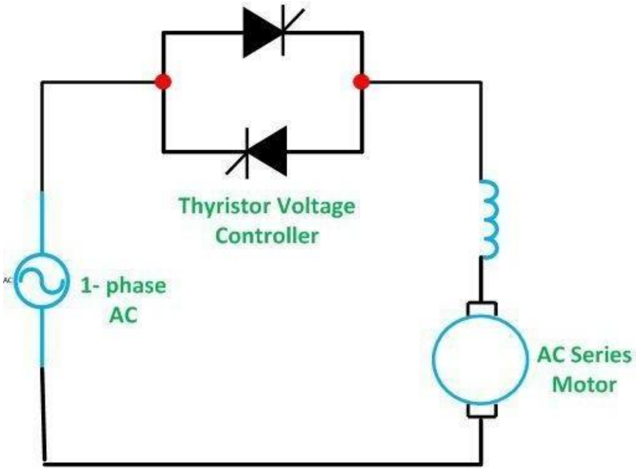
Hence, to reduce the speed for the same value of the same current, the value of the voltage is reduced and as a result, the torque developed by the motor is reduced. This stator voltage control method is suitable for applications where the load torque decreases with the speed. **For example-** In the fan load.

This method gives a **speed control** only below the normal rated speed as the operation of the voltages if higher than the rated voltage is not admissible. This method is suitable where the intermittent operation of the drive is required and also for the fan and pump drives. As in fan and pump the load torque varies as the square of the speed. These types of drives required low torque at lower speeds. This condition can be obtained by applying a lower voltage without exceeding themotor current.

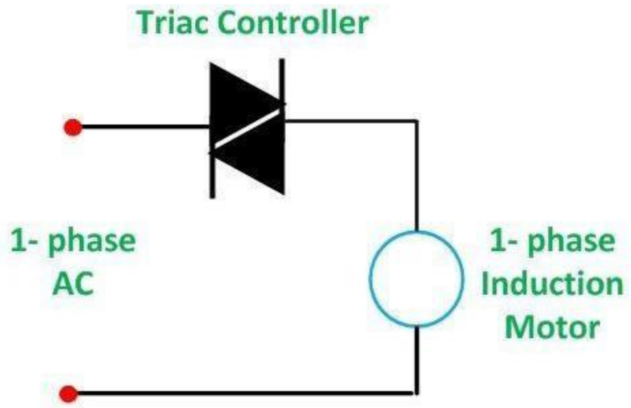
The variable voltage for speed control of small size motors mainly for single-phase can be obtained by the following methods given below:

- By connecting an external resistance in the stator circuit of the motor.
- By using an Auto-transformer.
- By using a Thyristor voltage controller.
- By using a Triac Controller.

Nowadays the **Thyristor voltage controller** method is preferred for varying the voltage. For a single-phase supply, two thyristors are connected back-to-back as shown in the figure below:

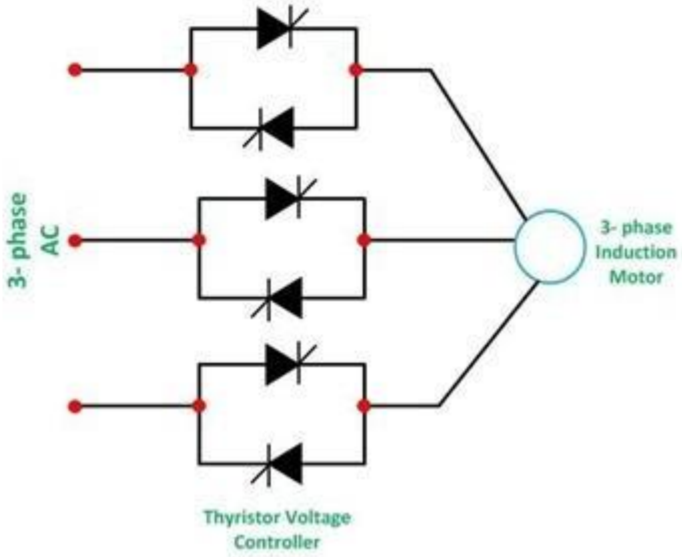


The domestic fan motors, which are single-phase are controlled by a single-phase Triac VoltageController as shown in the figure below:



Speed control is obtained by varying the firing angle of the Triac. These controllers are known as Solid State fan regulators. As the solid-state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.

In the case of a three-phase induction motor, three pairs of thyristors are required which are connected back-to-back. Each pair consists of two thyristors. The diagram below shows the Stator Voltage Control of the three-phase induction motors by Thyristor Voltage Controller.



Each pair of the thyristor controls the voltage of the phase to which it is connected. Speed control is obtained by varying the conduction period of the Thyristor. For lower power ratings, the back- to-back thyristor pairs connected in each phase are replaced by the Traic.

Speed Control of Induction Motor by Variable Frequency Control:

Variable Frequency Control is a method that is used to control the speed of an induction motor. The synchronous speed and therefore, the speed of the motor can be controlled by varying the supply frequency. The synchronous speed of an induction motor is given by the relation shown below

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

The EMF induced in the stator of the induction motor is given by the equation shown below.

$$E_1 = 4.44k_{w1}f\varphi T_1$$

Therefore, if the supply frequency is changed, induced EMF will also change to maintain the same air gap flux. The terminal voltage V_1 is equal to the induced EMF E_1 if the stator voltage drop is neglected.

In order to minimize the losses and to avoid saturation, the motor is operated at rated air gap flux. This condition is obtained by varying the terminal voltage with frequency so as to maintain the (V/f)ratio constant at the rated value. This type of control is known as Constant Volts Per Hertz. Thus, the speed control of an induction motor using a variable-frequency supply requires a variable voltage power source. The variable-frequency supply is obtained by the following converters.

- Voltage source inverter
- Current source inverter
- Cycloconverter

An inverter converts a fixed voltage DC to a fixed or variable voltage AC with variable frequency. Cyclo converter converts a fixed voltage and fixed frequency AC to a variable voltage and variableAC frequency.

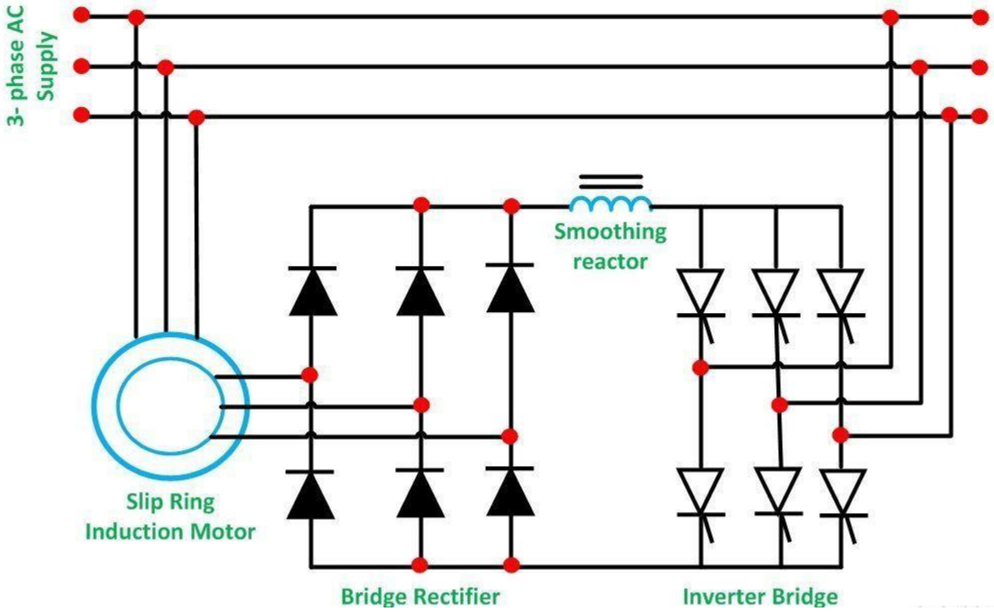
The variable frequency control allows good running and transient performance to be obtained from a cage induction motor. Cycloconverter controlled induction motor drive is suitable only for large power drives and to get lower speeds.

Slip Energy Recovery of an Induction Motor:

Slip Energy Recovery is one of the methods of controlling the speed of an Induction motor. This method is also known as Static Scherbius Drive. In the rotor resistance control method, the slip power in the rotor circuit is wasted as I^2R losses during the low-speed operation.

The efficiency is also reduced. The slip power from the rotor circuit can be recovered and fed back to the AC sourceso as to utilize it outside the motor. Thus, the overall efficiency of the drive system can be increased.

The figure below shows the connection and method for recovering the slip energy and power recovery of an Induction Motor.



The basic principle of slip power recovery is to connect an external source of the EMF of the slip frequency of the rotor circuit. The slip energy recovery method provides the speed control of a slip ring induction motor below its synchronous speed. A portion of rotor AC power (slip power) is converted into DC by a diode bridge.

The smoothing reactor is provided to smoothen the rectified current. The output of the rectifier is then connected to the DC terminals of the inverter. The inverter inverts the DC power to the AC power and feeds it back to the AC source. The inverter is a controlled rectifier operated inthe inversion mode.

This method of speed control is used in large power applications where the variation of speed over a wide range involves a large amount of slip power.

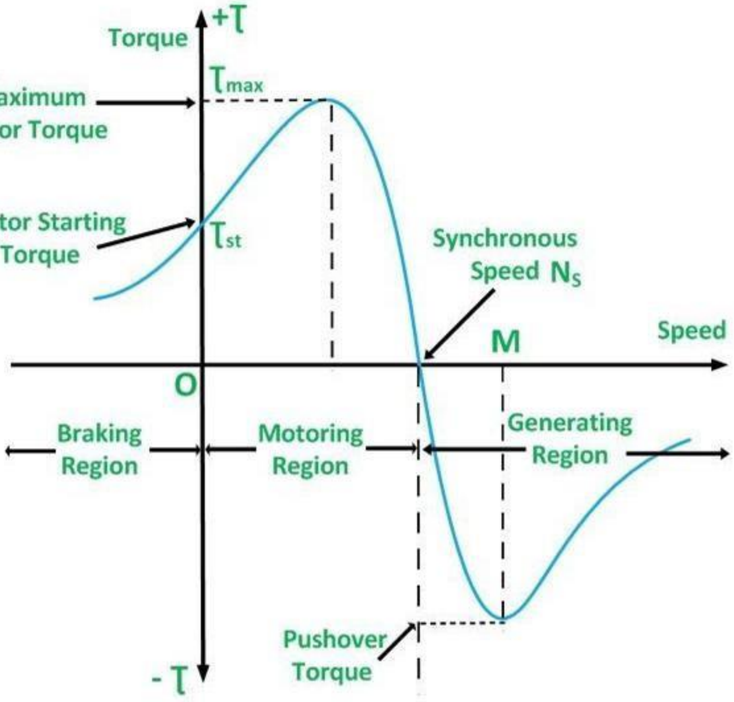
Induction Generator:

The induction Generator is also known as Asynchronous Generator. An Induction Machine sometimes is used as a generator. Initially, an induction generator or 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.

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.

Working Principle:

The torque-speed characteristics of a 3-phase induction machine for all ranges of speed is shown below.



In an equivalent circuit of an induction motor, the mechanical shaft load has been replaced by a resistor of the value given below.

$$R_{mech} = \frac{R_2}{s}(1-s)$$

In an induction generator, the slip (s) is negative, and therefore, the load resistance R_{mech} is also negative. This shows that the load resistance does not absorb the power, but starts acting as a sourceof power. It starts supplying the electrical energy to the supply mains to which it is connected.

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 thesame 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 ofthe induction generator is different from the synchronous speed, it is known as an Asynchronous generator.

From the characteristic curve, it is seen that the operating range of the induction generator is limitedto the maximum value of the pushover torque corresponding to slip at a speed **OM** as shown in thetorque-speed characteristic curve.

UNIT-III

SYNCHRONOUS MACHINE

Synchronous Machine constitutes of both synchronous motors as well as synchronous generators. An AC system has some advantages over a DC system. Therefore, the AC system is exclusively used for the generation, transmission, and distribution of electric power. The machine which converts mechanical power into AC electrical power is called a Synchronous Generator or Alternator. However, if the same machine can be operated as a motor is known as Synchronous Motor.

Synchronous machine is an AC machine whose satisfactory operation depends upon the maintenance of the following relationship.

$$N_s = \frac{120f}{P} \dots\dots\dots (1) \quad \text{or}$$

$$f = \frac{PN_s}{120}$$

Where,

- N_s is the synchronous speed in revolution per minute (r.p.m)
- f is the supply frequency
- P is the number of poles of the machine.

When connected to an electric power system, a synchronous machine always maintains the aboverelationship shown in equation (1).

If the synchronous machine working as a motor fails to maintain the average speed (N_s) the machine will not develop sufficient torque to maintain its rotation and will stop. Then the motor issaid to be **Pulled Out of Step.**

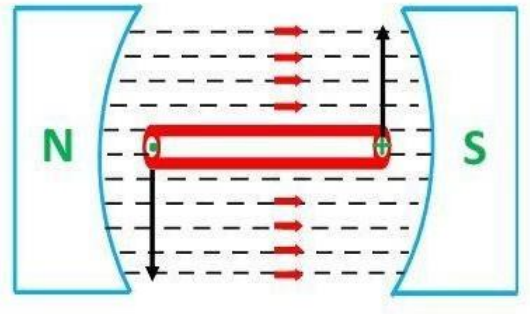
In case, when the synchronous machine is operating as a generator, it has to run at a fixed speed called Synchronous speed to generate the power at a particular frequency. As all the appliances or machines are designed to operate at this frequency. In some countries, the value of the frequency is **50 hertz**.

Basic Principles of Synchronous Machine:

A synchronous machine is just an electromechanical transducer that converts mechanical energy into electrical energy or vice versa. The fundamental phenomenon or law which makes these conversions possible is known as the **Law of Electromagnetic Induction** and **Law of interaction.**

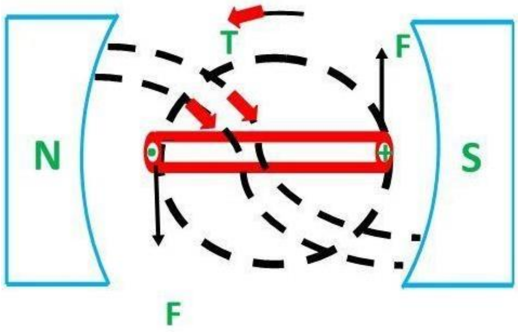
Law of Electro-Magnetic Induction:

This law is also called Faraday's First Law of Electromagnetic Induction. This law relates to the production of emf, i.e.; emf is induced in a conductor whenever it cuts across the magnetic field as shown below:



Law of Interaction:

This law relates to the production of force or torque, i.e., whenever a current-carrying conductor is placed in the magnetic field, by the interaction of the magnetic field produced by the current- carrying conductor and the main field, force is exerted on the conductor producing torque. The figure is shown below:



Three-Phase Synchronous Machine:

- The machine which is used in the household appliance such as the small machine used in air coolers, refrigeration, fans, air conditioners, etc.
- However, large AC machines are three-phase type synchronous machines because of the following reasons.
- For the same size of the frame, three-phase machines have nearly 1.5 times the output than that of the single-phase machine.
- Three-phase power is transmitted and distributed more economical than single-phase power.
- Three-phase motors are self-starting (except synchronous motors).
- Three-phase motors have an absolute uniform continuous torque, whereas, single-phase motors have pulsating torque.

In a small synchronous machine, the fielding winding is placed on the stator, and the armature winding is placed on the rotor whereas for the large synchronous machine the field winding is placed on the rotor, and the armature winding is placed on the stator.

Construction of a Synchronous Machine:

Construction of a Synchronous Machine, i.e., alternator or motor 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.

The important parts of the Synchronous Machine are given below:

- Stator
- Rotor
- Miscellaneous

Stator Construction:

The stationary part of the machine is called Stator. It includes various parts like stator frame, statorcore, stator windings, and cooling arrangement.

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 that 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:

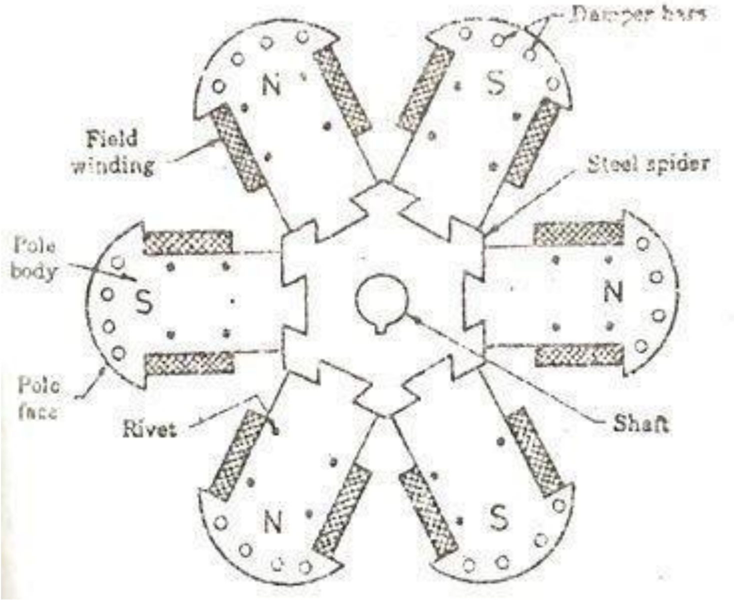
Slots are cut on the inner periphery of the stator core in which 3 phase or 1 phase winding is placed.Enameled copper is used as a winding material. The winding is star-connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces 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, namelythe salient pole type and the cylindrical rotor type.

Salient Pole Rotor:

The term salient means projecting. Thus, a salient pole rotor consists of poles projecting out from the surface of the rotor core. The end view of a typical 6 pole salient pole rotor is shown below inthe figure.



Since the rotor is subjected to changing magnetic fields, it is made of steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length. A salient pole synchronous machine has a non-uniform air gap. The air gap is minimized under the pole centers and it is maximum in between the poles.

They are constructed for medium and low speeds as they have a large number of poles. A salient pole generator has a large diameter. The salient pole rotor has the following important parts.

Spider: It is made of cast iron to provide an easy path for magnetic flux. It is keyed to the shaft and at the outer surface, pole core and pole shoe are keyed to it.

Pole Core and Pole Shoe: It is made of laminated steel sheet material. The Pole core provides theleast reluctance path for the magnetic field and the pole shoe distributes the field over the whole periphery uniformly to produce a sinusoidal wave.

Field Winding or Exciting Winding: It is wound on the former and then placed around the polecore. DC supply is given to it through slip rings. When direct current flows through the field winding, it produces the required magnetic field.

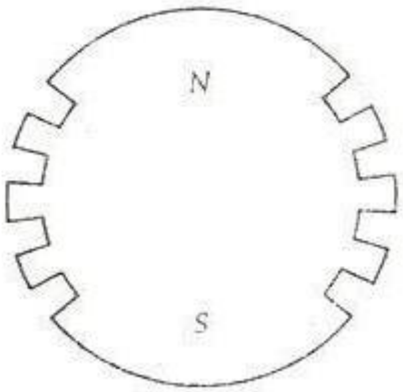
Damper Winding: At the outermost periphery, holes are provided in which copper bars are inserted and short-circuited at both sides by rings forming Damper winding.

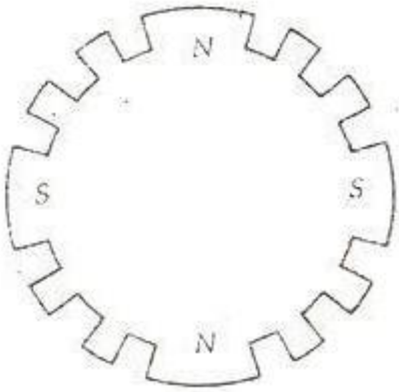
Non- Salient Pole Rotor or Cylindrical Rotor:

In this type of rotor, there are no projected poles, but the poles are formed by the current flowing through the rotor exciting winding. Cylindrical rotors are made from solid forgings of high-grade nickel chrome-molybdenum steel. It has a comparatively small diameter and long axial length.

They are useful in high-speed machines. The cylindrical rotor type alternator has two or four poles on the rotor. Such a construction provides greater mechanical strength and permits more accurate dynamic balancing. The smooth rotor of the machine makes fewer windage losses and the operation is less noisy because of the uniform air gap.

The figure below shows the end view of the 2 poles and 4 pole cylindrical rotors.





They are driven by steam or gas turbines. Cylindrical synchronous rotor synchronous generators are called turbo-alternators and turbo generators. The machines are built in a number of ratings from 10 MVA to over 1500 MVA. The biggest size used in India has a rating of 500 MVA installedin the super thermal power plant.

Non-salient pole-type rotors have the following parts. They are as follows:

Rotor Core: The rotor core is made of silicon steel stampings. It is placed on the shaft. At the outer periphery, slots are cut in which exciting coils are placed.

Rotor Winding or Exciting Winding: It is placed on the rotor slots, and the current is passed through the winding in such a way that the poles are formed according to the requirement.

Slip Rings: Slip rings provide DC supply to the rotor windings.

Miscellaneous Parts:

The miscellaneous parts are given below:

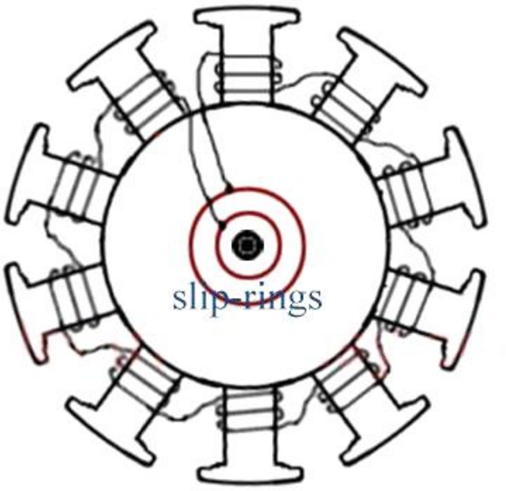
Brushes: Brushes are made of carbon, and they slip over the slip rings. A DC supply is given to the brushes. Current flows from the brushes to the slip rings and then to the exciting windings.

Bearings: Bearings are provided between the shaft and the outer stationary body to reduce the friction. They are made of high carbon steel.

Shaft: The shaft is made of mild steel. Mechanical power is taken or given to the machine throughthe shaft.

Salient Pole Rotor Vs. Non-Salient Pole Rotor

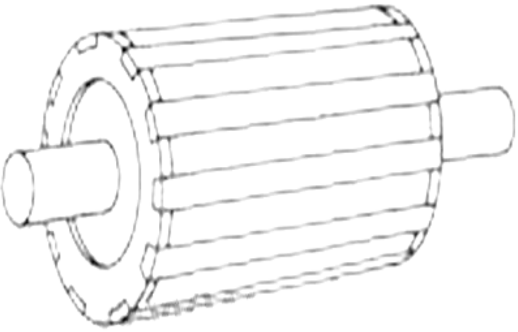
Salient Pole Rotor:



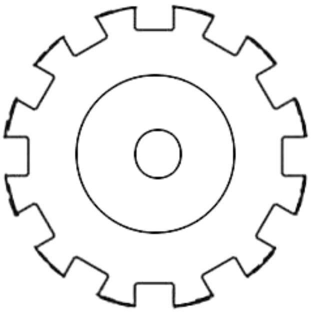
In salient pole type of rotor consist of large number of projected poles (salient poles) mounted ona magnetic wheel. Construction of a salient pole rotor is as shown in the figure at left. The projected poles are made up from laminations of steel. The rotor winding is provided on these poles and it is supported by pole shoes.

- 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.
- As the rotor speed is lower, more number of poles are required to attain the required frequency. ($N_s = 120f / P$ therefore, $f = N_s*p/120$ i.e., frequency is proportional tonumber of poles). Typically, number of salient poles is between 4 to 60.
- 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:



Cylindrical rotor



Cross sectional view

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 above. 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.

Working Principle of Synchronous generator:

The alternators work on the principle of electromagnetic induction. When there is a relative motion between the conductors and the flux, emf gets induced in the conductors. The dc generatorsalso work on the same principle. The only difference in the practical synchronous generator and adc generator is that in an alternator the conductors are stationary and field is rotating. But for understanding, the purpose we can always consider relative motion of conductors w.r.t the flux produced by the field winding.

Consider a relative motion of a single conductor under the magnetic field producedby two stationary poles. The magnetic axis of two poles produced by field is vertical, shown dottedin below figure.

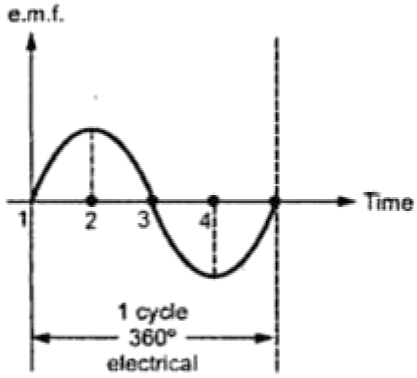
Let conductor starts rotating from position 1.at this instant, the entire velocity component is parallel to the flux lines. Hence there is no cutting of flux lines by the conductor. So dφ/dt at this instant is zero and hence induced emf in the conductor is also zero. As the conductor moves from position 1 to position 2, the part of the velocity component becomes perpendicular to the flux lines and proportional to that, emf gets induced in the conductor. The magnitude of such an inducedemf increases as conductor moves from position 1 to 2.

At position 2, the entire velocity component is perpendicular to the flux lines. Hence there exists cutting of the flux lines. And at this instant, the induced emf in the conductor is at its maximum.

As the position of conductor changes from 2 to 3, the velocity component perpendicular to the fluxstarts decreasing and hence induced emf magnitude also starts decreasing.

At position 3, again the entire velocity component is parallel to the flux lines and hence at thisinstant induced emf in the conductor is zero.

As the conductor moves from 3 to 4, velocity component perpendicular to the flux lines again starts increasing. But the direction of velocity component now is opposite to the direction of velocity component existing during the movement of the conductor from position 1 to 2. Hence,an induced emf in the conductor increase but in the opposite direction.



At position 4, it achieves maximum in the opposite direction, as the entire velocity component becomes perpendicular to flux lines. Again, from position 4 to 1, induced emf decreases and finally at the position again becomes zero. This cycle continues as conductor rotatesat a certain speed. So, if we plot the magnitudes of the induced emf against the time, we get an alternating nature of the induced emf shown figure above.

Armature Windings:

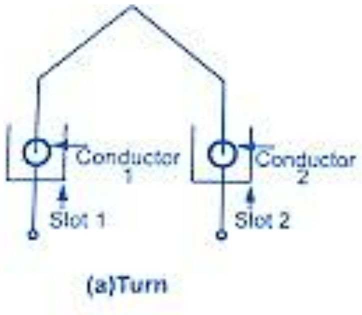
Armature windings of alternators are different from that of d.c. machines. Basically, three phase alternators carry three sets of windings arranged in the slots in such a way that there exists a phase difference of 120° between the induced e.m.f.s in them. In a dc machine, winding is closed while in 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 connectedin 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

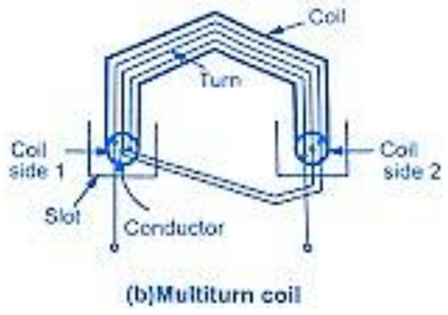
E_{ph}. All the coils used for one phase must be connected in such a way that their e.m.f.s help each other and overall design should be in such a way that the waveform of an induced emf is almost sinusoidal in nature.

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.

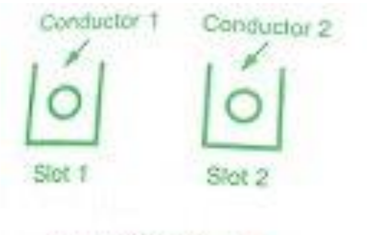
For example let us consider 2 poles, 18 slots armature of an alternator. Then under 1 pole, there are 18/2 i.e., 9 slots. So, pole pitch is 9 slots or 180° electrical. This means 9 slots are responsible for producing a phase difference of 180° between the emfs induced in different conductors.

This number of slots/poles is denoted as 'n'.Pole pitch = 180° electrical
=slots per. pole (no. of slots/P) = n

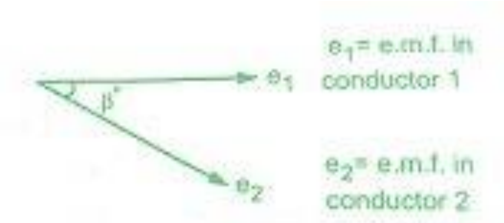
6) **Slot angle (β):** The phase difference contributed by one slot in degrees electrical is called slot angle as slots per pole contributes 180° electrical which is denoted as 'n', we can write,

1 slot angle = 180°/n
β = 180°/n
In the above example,
n = 18/2 = 9,
while β = 180°/n = 20°

Note: This means that if we consider an induced e.m.f. in the conductors which are placed in the slots which are adjacent to each other, there will exist a phase difference of 180^0 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.



(a) Adjacent slots



(b) Indication of phase differe

Types of Armature Windings in Alternator:

The different types of armature windings in alternators are,

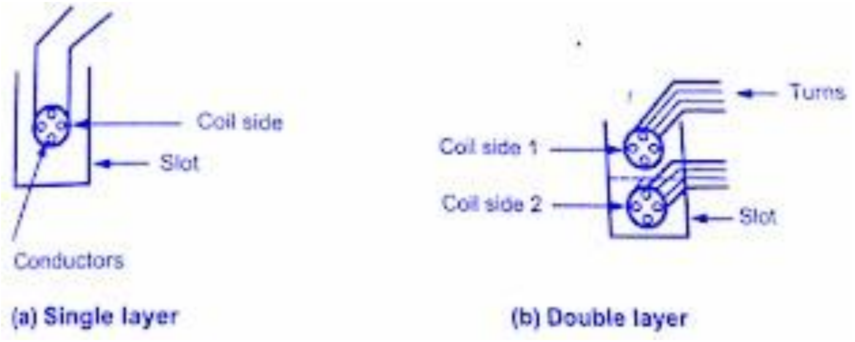
1) Single layer and double layer winding

2) Full pitch and short pitch winding

3) Concentrated and distributed winding

1) 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.

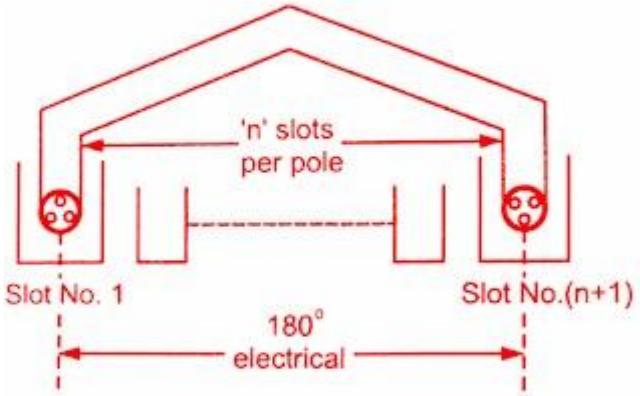


2) Full Pitch and Short Pitch Winding:

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.

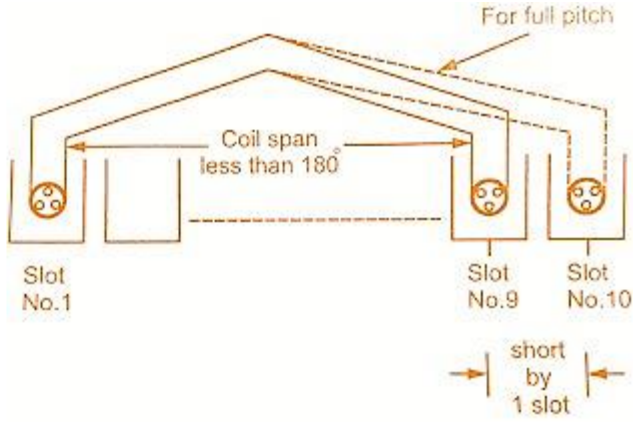
For example, in 2 poles, 18 slots alternator, the pole pitch is n = 18/2 = 9 slots. So if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one polepitch or n slots or 180° electrical apart, the coil is called full pitch coil.

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. As against this if coilsare 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 slotNo.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,

1) The length required for the end connections of coils is less i.e. the inactive length of winding isless. So less copper is required. Hence economical.

2) Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f.Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.

3) As high frequency harmonics get eliminated, eddy current and hysteresis losses which dependon frequency also get minimized. This increases the efficiency.

3)Concentrated and distributed winding:

In three phase alternators, we have seen that there are three different sets of windings, eachfor 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, 8

n = 18/2 = 9

and m = 9/3 =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 placedin one slot under every pole.

But in practice, an attempt is always made to use all the 'm' slots per pole per phase availablefor 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
e.m.f. 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 ispreferred for the alternators..

Integral and Fractional slot winding:

The value of slots per pole per phase decides the class of the winding.m = slots / pole / phase

Key Point: When the value of m is an integer, then the winding is called Integral slot winding.Consider 2 pole, 12 slots alternator hence,

n = slots / pole = 12/2 = 6 Pole pitch = 180° = 6 slotsm = n/3 = 6/3 =2

As m is an integer, the type of winding is integral slot winding. This winding can be full pitchwinding or short pitch winding.

Fractional Slot Winding:

This is another type of winding which depends on the value of m.

Key Point: The winding in which slots per pole per phase (m) is a fractional number is called Fractional slot winding.

Advantages of Fractional slot Windings:

The various advantages of fractional slot winding are,

1. Though appearing to be complicated, easy to manufacture.
2. The number of armature slots (S) need not be an integral multiple of number of poles (P).
3. The number of slots can be selected for which notching gear is available, which is economical.
4. There is saving in machine tools.
5. High frequency harmonics are considerably reduced.
6. The voltage waveform available is sinusoidal in nature.

Distribution Factor:

The Distribution Factor or the Breadth Factor is defined as the ratio of the actual voltage obtainedto the possible voltage if all the coils of a polar group were concentrated in a single slot.

It is denoted by $\mathbf{K}_d$ and is given by the equation shown below.

$$K_d = \frac{\text{Phasor Sum of the coil volatges per phase}}{\text{Arithmetic sum of coil voltages per phase}} \;\ldots\ldots\ldots.(1)$$

In a concentrated winding, each phase of a coil is concentrated in a single slot. The individual coil voltages induced are in phase with each other. These voltages must be added arithmetically. In order to determine the induced voltage per phase, a given coil voltage is multiplied by the number of series-connected coils per phase. In actual practice, in each phase, coils are not concentrated ina single slot. They are distributed in a number of slots in space to form a polar group under each pole.

The voltages induced in coil sides are not in phase, but they differ by an angle β which is known as the angular displacement of the slots. The phasor sum of the individual coil voltages is equal tothe total voltage induced in any phase of the coil.

Let,

$$m = \frac{\text{slots}}{\text{poles x phases}} \;\ldots\ldots.(2)$$

m = slots per pole per phase

β = angular displacement between adjacent slots in electrical degrees

$$\beta = \frac{180^\circ}{\text{slots/pole}} = \frac{180^\circ \text{ x poles}}{\text{slots}} \;\ldots\ldots.(3)$$

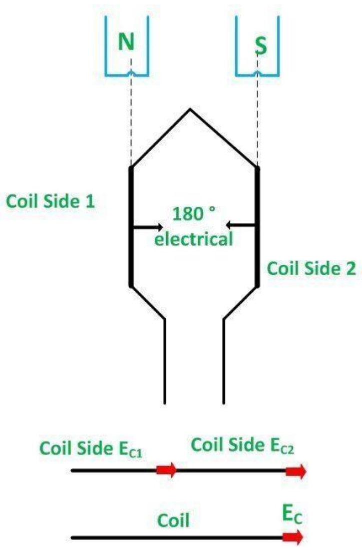
Thus, one phase of the winding consists of coils arranged in m consecutive slots. Voltages E_{C1}, E_{C2}, $E_{C3\ldots}$ are the individual coil voltages. Each coil voltage E_C will be out of phase with the
next coil voltages by the slot pitch β.

Coil Span Factor (Pitch Factor):

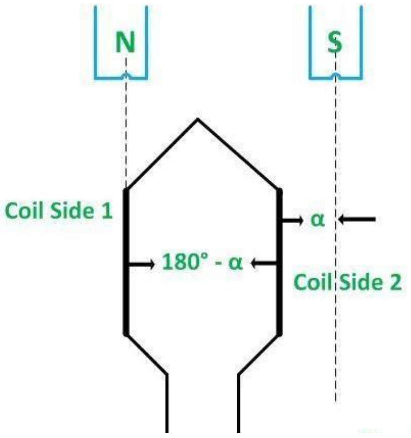
The Coil Span Factor or Pitch Factor K_C is defined as the ratio of the voltage generated in the shortpitch coil to the voltage generated in the full pitch coil.

The distance between the two sides of a coil is called the Coil Span or Coil Pitch Factor. It is alsoknown as Chording Factor.

The angular distance between the central line of one pole to the central line of the next pole is called Pole Pitch. A pole pitch is always 180 electrical degrees, regardless of the number of poleson the machine. A coil having a span equal to 180º electrical is called a full pitch coil as shown inthe figure below:



A coil having a span less than 180º electrical is called a short pitch coil or fractional pitch coil. It is also called a chorded coil. The short pitch coil factor is shown in the figure below:



A stator winding using fractional pitch coil is called a chorded winding. If the span of the coil is reduced by an angle α electrical degrees, the coil span will be (180 – α) electrical degrees.

In case of a full pitch coil, the distance between the two sides of the coil is exactly equal to the pole pitch of 180º electrical. As a result, the voltage in a full pitch coil is such that the voltage of each side of the coil is in phase.

Let E_{C1} and E_{C2} be the voltages generated in the coil sides, and E_C is the resultant coil voltage.

Then the equation is given as shown below:

$$E_C = E_{C1} + E_{C2}$$

$$|E_{C1}| = |E_{C2}| = E_1 \quad \text{(Say)}$$

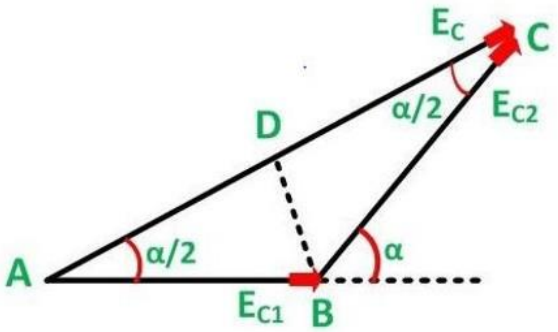
Since E_{C1} and E_{C2} are in phase, the resultant coil voltage E_C is equal to their arithmetic sum.

Therefore,

$$E_C = E_{C1} + E_{C2} = 2E_1$$

If the coil span of a single coil is less than the pole pitch of 180° electrical, the voltages generated on each coil side are not in phase. The resultant coil voltage E_C is equal to the phasor sum of E_{C1} and E_{C2}

If the coil span is reduced by an angle α electrical degrees, the coil span is (180 – α) electrical degrees. The voltage generated E_{C1} and E_{C2} in the two coil sides will be out of phase with respect to each other by an angle α electrical degrees. The phasor sum of E_{C1} and E_{C2} is E_C, which is equal to AC as shown in the phasor diagram below.



The coil span factor is represented as:

$$K_C = \frac{\text{Actual Voltage Generated in the Coil}}{\text{Voltage Generated in the coil of span 180° electrical}}$$

$$K_C = \frac{\text{Phasor sum of the voltages of two coil sides}}{\text{Arithmetic sum of the voltages of two coil sides}}$$

$$K_C = \frac{AC}{2AB} = \frac{2AD}{2AB} = \text{COS}\ \frac{\alpha}{2}$$

$$K_C = \text{COS}\ \frac{\alpha}{2}$$

For full pitch coil, the value of α will be 0°, cos α/2 = 1 and $K_C = 1$.For a short pitch coil $K_C < 1$.

Advantages of Short Pitch Coil or Chording:

- It shortens the ends of the winding and, therefore, there is a saving in the conductor's material.
- It reduces the effects of distorting harmonics and thus the waveform of the generated voltage isimproved and making it a sine wave.

Winding Factor:

The winding factor is the method of improving the rms generated voltage in a three-phase AC machine so that the torque and the output voltage do not consist of any harmonics which reduces the efficiency of the machine.

Winding Factor is defined as the product of the Distribution factor (K_d) and the coil span factor (K_c). The distribution factor measured the resultant voltage of the distributed winding regards concentrate winding and the coil span is the measure of the number of armature slots between thetwo sides of a coil. It is denoted by K_w. The EMF equation is given below:

$$E_p = 4.44 K_w f \varphi T_p \;\ldots\ldots(1)$$

It is assumed that the induced voltage is sinusoidal. However, if the flux density distribution is non-sinusoidal, the induced voltage in the winding will be non-sinusoidal. The coil span factor, distribution factor, and winding factor will be different for each harmonic voltage. From equation(1), the fundamental EMF per phase is given by the equation shown below:

$$E_{p1} = 4.44 K_{w1} f \varphi_1 T_p \;\ldots\ldots(2)$$

The third harmonic, EMF per phase will be:

$$E_{p3} = 4.44 K_{w3} (3f) \varphi_3 T_p \;\ldots\ldots(3)$$

The nth harmonic, EMF per phase will be here subscript 1,3 and n denote fundamental, third, andnth harmonics respectively.

Therefore,

$$\frac{E_{pn}}{E_{p1}} = \frac{K_{wn}}{K_{w1}} \text{ x } \frac{n\varphi_n}{\varphi_1} \;\ldots\ldots\ldots(5)$$

Where,

- $\phi 1$ is the total fundamental flux per pole.
- $\phi 1$ = average flux density x area under one pole

$$\varphi_1 = \left(\frac{\text{peak flux density}}{\pi/2}\right) \text{ x (area under one pole)}$$

$$\varphi_1 = \left(\frac{B_{m1}}{\pi/2}\right)\left(\frac{\pi DL}{P}\right)$$

$$\varphi_1 = \frac{2\,DL}{P}\,B_{m1} \ldots\ldots(6)$$

Where,

- B_{m1} is the peak value of the fundamental component of the flux density wave
- D is the diameter of the armature or the mean air gap diameter
- L is the axial length of the armature or the active coil side length Similarly for the nth harmonic

$$\text{Pole pitch} = \frac{\pi\,D}{P_n} \ldots\ldots\ldots(7)$$

$$\varphi_n = \frac{2\,DL}{nP}\,B_{mn} \ldots\ldots(8)$$

Therefore,

$$\frac{E_{pn}}{E_{p1}} = \frac{K_{wn}B_{mn}}{K_{w1}B_{m1}} \ldots\ldots\ldots(9)$$

Where,

B_{mn} is the peak value of the nth harmonic flux density

EMF Equation of a Synchronous Generator:

The generator which runs at a synchronous speed is known as the synchronous generator. Thesynchronous generator converts the mechanical power into electrical energy for the grid.

Let,

- P be the number of poles
- ϕ is Flux per pole in Webers
- N is the speed in revolution per minute (r.p.m)
- f be the frequency in Hertz
- Z_{ph} is the number of conductors connected in series per phase

- T_{ph} is the number of turns connected in series per phase
- K_c is the coil span factor
- K_d is the distribution factor

Flux cut by each conductor during one revolution is given as Pϕ Weber. Time taken to completeone revolution is given by 60/N sec

Average EMF induced per conductor will be given by the equation shown below:

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

Average EMF induced per phase will be given by the equation shown below:

$$\frac{P\varphi N}{60} \text{ x } Z_{ph} = \frac{P\varphi N}{60} \text{ x } 2T_{ph} \quad \text{and}$$

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

$$\text{Average EMF} = 4 \text{ x } \varphi \text{ x } T_{ph} \text{ x } \frac{PN}{120} = 4\varphi f T_{ph}$$

The average EMF equation is derived with the following assumptions given below.

- Coils have got the full pitch.
- All the conductors are concentrated in one stator slot.

Root mean square (R.M.S) value of the EMF induced per phase is given by the equation shownbelow:

E_{ph} = Average value x form factor

Therefore,

$$E_{ph} = 4\varphi f T_{ph} \text{ x } 1.11 = 4.44\, \varphi\, f\, T_{ph} \quad \text{volts}$$

If the coil span factor K_c and the distribution factor K_d , are taken into consideration then the ActualEMF induced per phase is given as:

$$E_{ph} = 4.44\, K_c K_d \varphi\, f\, T_{ph} \quad \text{volts} \;\ldots\ldots..(1)$$

Equation (1) shown above is the EMF equation of the Synchronous Generator.

Harmonics in Synchronous Machines:

We know that in synchronous machines or alternators, the voltage and currents are induced. These voltage and currents are sinusoidal waveforms. But practically this doesn't happen and sinusoidal waveforms are not produced when such alternators are loaded. Due to the loading condition, the generated waveform deviates from the ideal waveform. Such a non-sinusoidal waveform is called complex wave.

By Fourier transform, this complex waveform can be shown to be built of a series of sinusoidal waves whose frequencies are integral multiples of the frequency of fundamental wave. These sinusoidal components or harmonic functions are called harmonics of the complex wave.

The fundamental wave is defined as that component which is having same frequency as that of complex wave. The component which is having double the frequency of that of fundamental wave called second harmonic. While the component which is having the frequency three times that of fundamental is called third harmonic and so on. The complex waveform contains both the even aswell as odd harmonics.

Consider a complex wave which is represented by,

$$\mathbf{e = E_{1m} \sin(\omega t + \Phi_1) + E_{2m} \sin(\omega t + \Phi_2) + E_{3m} \sin(\omega t + \Phi_3) + \ldots\ldots\ldots\ldots + E_{nm} \sin(\omega t + \Phi_n)}$$

where $E_{1m} \sin(\omega t + \Phi_1)$ is the fundamental component of maximum value E_{1m} having an angle Φ_1 from the instant of zero of the complex wave.

Similarly, $E_{nm} \sin(\omega t + \Phi_n)$ represents n^{th} harmonic of maximum value E_{nm} and having phase angle Φ_n with respect to complex wave.

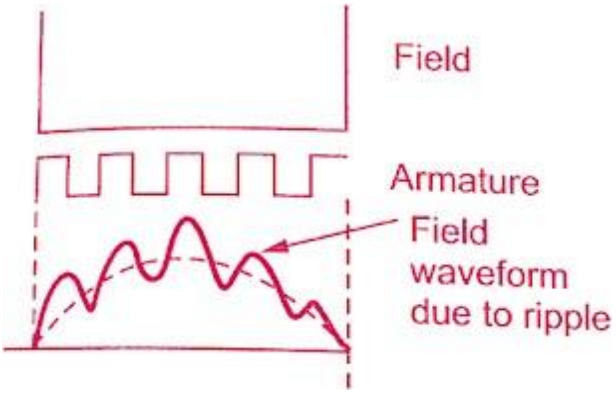
Out of the even and odd harmonics, a complex wave containing fundamental component and even harmonics only are always unsymmetrical about x-axis whereas a complex wave containingfundamental component and odd harmonics only is always symmetrical about the x-axis. In case of alternators, the voltage generated is mostly symmetrical as the field system and coils are all symmetrical. So, the generated voltage or current will not have any even harmonics in most of thecases.

The complex waveform of voltage can be analyzed experimentally by using the phenomenon of resonance. If voltage waveform containing harmonic content is applied to the circuit containingresistance, inductance and capacitance, then the circuit will resonate at one of the harmonic frequencies. The voltage drop across the resistance can be analyzed by using an oscillograph. The values of inductance and capacitance can be changed so that resonance can be obtained at fundamental, third harmonic, fifth harmonic etc. The voltage on the oscillograph indicates the presence of particular harmonics.

Slot Harmonics in Synchronous Machines:

The voltage generated in armature windings is derived assuming that the surface of the armature to be smooth. However, in practice armature is not smooth but is made slotted. Due to this slotting, certain harmonic EMFs of undesirable order are produced.

The reluctance at any point in the air gap depends on whether there is a slot or teeth in the magnetic path. Since in case of alternators armature is moving, the teeth and slots alternately occupy positions at this point. This will vary the reluctance. The ripples will be formed due to thevariation of reluctance from point to Field point in the air gap which is shown in the below figure.These ripples will not move with respect to Armature conductors but glide on the distribution of flux.



These ripples due to slotting of the armature are always due to ripple opposite to slots andteeth which are causing them. Thus, the harmonics which are generated in the EMF due to slotting is called slot harmonics. It can be seen that the main source of harmonics is the non-sinusoidal field form which can be made sinusoidal and the harmonics can be eliminated.

The air gap offers maximum reluctance to the flux path. This air gap if made to vary sinusoidally around the machine, the field form would also be sinusoidal. Even the air gap is madeto vary sinusoidally, the field form cannot be sinusoidal due to saturation in iron parts which is unavoidable. But there should not be the high degree of saturation so that approximately sinusoidalwaveform will be obtained.

Thus, in general, it can be seen that ideal sinusoidal field form is very difficult to obtain whether the machine is salient pole type or cylindrical rotor construction. Now here we will learn how to minimize or eliminate harmonic components in synchronous machines.

Harmonics Minimization from induced voltages:

To eliminate or minimize the harmonics from the voltage waveform, the windings must be properly designed. The different ways to eliminate the harmonics from generated voltage are,

1) Distribution of armature windings:

Instead of having concentrated type of windings, they should be distributed in different slots.

The distribution factor for harmonics is comparatively less than that of the fundamental and hencemagnitude of harmonic e.m.f. is small.

2) Chording:

The e.m.f. generated in the winding is proportional to cos (x /2) where a is angle of chording and x is order of harmonic. If proper value of angle of chording is selected then harmonic e..m.f.scan be reduced significantly.

3) Fractional slot windings:

The output voltage waveform will be free of harmonics by facilitating the use of fractional slot windings as the distribution factor will be smaller compared to that with the fundamental.

4) Skewing:

Skewing the pole face will help in eliminating the slot harmonics.

5) Large length of air gap:

The reluctance will be increased by increasing the air gap and slot harmonics can be reduced.

Armature reaction in Alternator or Synchronous Generator:

Armature reaction is an important aspect in DC generator and AC synchronous Generator or Alternator. Armature reaction in alternator is defined as the effect of armature flux on the mainflux produced by the field poles.

An electric machine normally consists of field winding and armature winding. DC supply is given to the field winding to produce magnetic flux. The armature conductor is rotated at a synchronousspeed with the aid of a prime mover.

When there exists a relative motion between the magnetic flux and armature winding, the armature conductor cuts the field flux. Hence there will be a change in flux linkage in the conductor.

According to Faraday’s law of Electromagnetic induction, an emf is induced in the armature conductors. When the load is applied to the armature terminals, the current starts flowing through the armature winding. Since the current is alternating in nature, it induces a flux in the conductor,called armature flux.

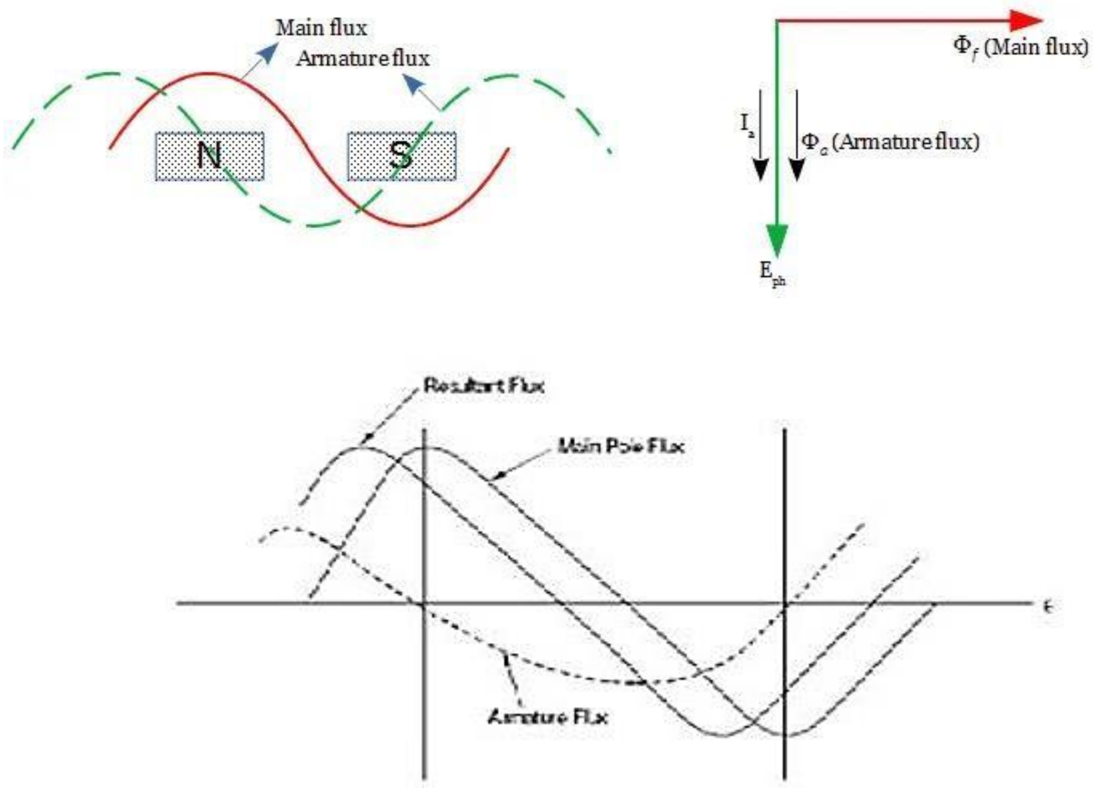
The armature flux thus produced will react with the main field flux and distort the effect of the main flux, called armature reaction in alternator or synchronous generator. Due to this distortion, the resultant flux will either strengthen or weaken.

The distortion may depend on the type of load applied to the alternator. A DC Generator also has more or less similar armature reaction effects. In this section, let us discuss the different armaturereaction effects, that can be seen at different loads in detail.

Armature reaction at unity power factor load:

When a resistive load with a unity power factor is connected to the alternator, the load current will start to flow through the armature winding. As it is a pure resistive load, the armature current will be in phase with the induced voltage.

The armature current will produce its own flux in the conductor, which will also be in phase withthe induced voltage. Since the induced emf lags behind the main field flux by 90^0, the armature flux produced will also be delayed by 90^0 with respect to the main flux. The below shows the phasor diagram at unity power factor load.



Waveform and phasor diagram for distorting effect

As the armature flux act on the main field flux perpendicularly, the distribution of main field flux under a pole face does not remain uniformly distributed. As you can see from the waveform that, the armature flux will cross and distorts the main field flux at one point, thereby weakening the main flux. This is said to be a cross magnetizing effect.

You can also notice; the armature flux also assists the main flux at another point. In this case, thearmature reaction strengthens the main field flux. Due to these effects, the main field flux will getdistorted, without causing much change to the generated voltage.

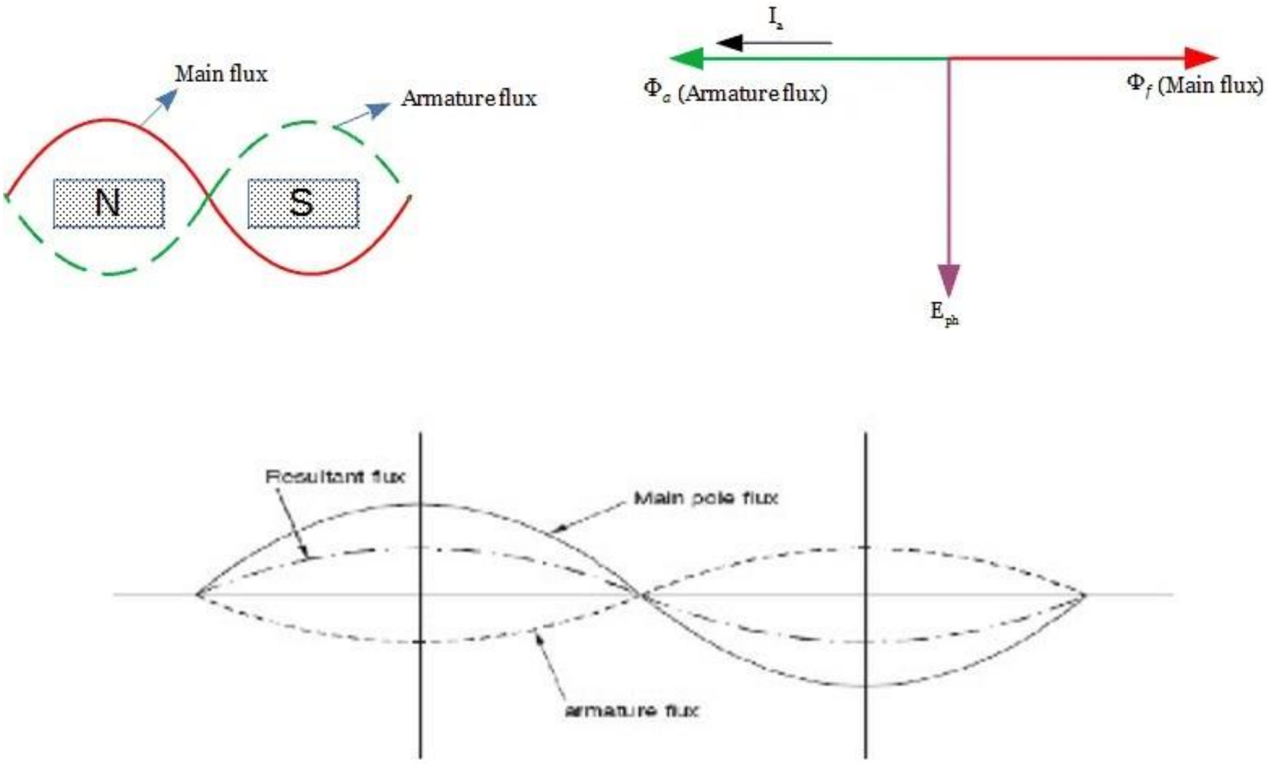
In other words, flux density at the trailing tip of the pole is increased while flux at the leading tip of the pole decreases. Due to this, the armature reaction at resistive load is said to have a distortingeffect maintaining the constant average field strength.

Armature reaction at zero power factor lagging load:

When a pure inductive load with zero lagging power factor is connected to the alternator, the loadcurrent starts to flow through the armature conductors.

The armature current will be delayed by 90^0 and so the armature flux produced will also be shiftedby 90^0 with respect to the poles.

There will be a phase difference of 90^0 between the armature flux and main field flux. It can be seen that the armature flux will be in direct opposition to the main flux. The below shows the phasor diagram at lagging power factor load.



Waveform and phasor diagram for demagnetizing effect

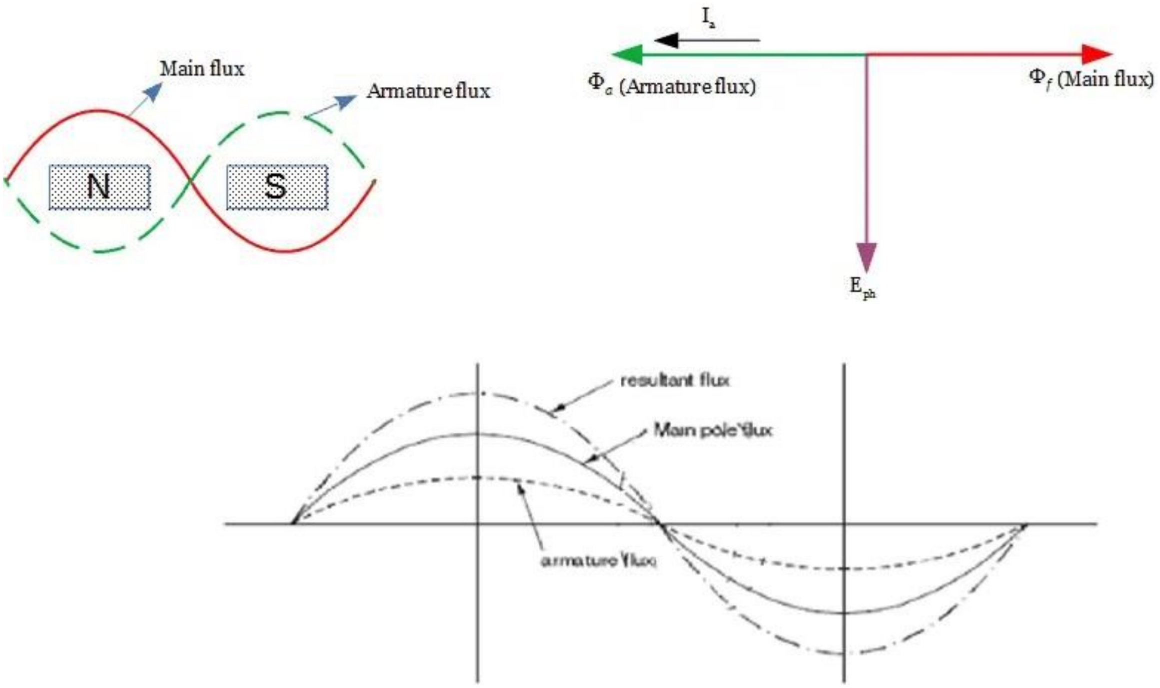
Thus, the main flux gets decreased in this loading condition. This effect of armature reaction on this load is said to be a demagnetizing effect.

Due to this, the main field flux gets weaken and so the emf induced will be reduced. To maintain the same value of generated emf, filed excitation will have to be increased to overcome the demagnetizing effect.

Armature reaction at zero power factor leading load:

When a pure capacitive load with zero leading power factor is connected, the load current starts toflow through the armature conductors.

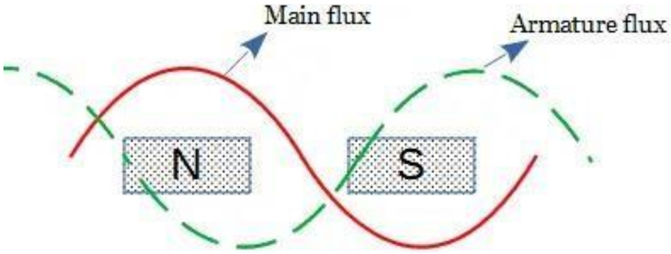
In this load condition, the load current will be advanced by 90^0 and so the armature flux produced will also be advanced by 90^0 with respect to emf induced. So the armature flux will be in phase with the main field flux, resulting in strengthening of the field flux. Thus the main flux gets increased in this loading condition. The below shows the phasor diagram at leading power factor load.



Waveform and phasor diagram for magnetizing effect

The armature reaction in this load is said to be a magnetizing effect. Due to this effect, the main field flux gets weaken and so the emf induced will be reduced. To maintain the same value of generated emf, filed excitation will have to be reduced to overcome the magnetizing effect.

For any intermediate power factor, the effect of armature reaction in alternator will be partly distorting and partly demagnetizing.



From the explanations, we can summarize that

1. When an alternator supplies a load at the unity power factor, the effect of armature reactionis partly cross magnetizing and partly distorting.
2. The effect of armature reaction is demagnetizing when an alternator supplies a load at alagging power factor.
3. When an alternator supplies a load at the leading power factor, the effect of armaturereaction is magnetizing.
4. When an alternator supplies a load at the intermediate power factor, the effect of armaturereaction is partly distorting and partly demagnetizing.
5. The effects of armature reaction may cause the generated emf to vary. In order to overcomethat, the main flux is varied to generate the rated voltage.

Armature Leakage Reactance:

In an AC electrical machine, the magnetic flux set up by the load current which does not contributeto the useful magnetic flux of the machine is known as leakage flux. This leakage flux sets up a self-induced EMF in the armature winding of the machine. The leakage flux may be classified into three categories as follows −

- Slot leakage
- Tooth head leakage
- Overhang or coil end leakage

The leakage fluxes in the electrical machines induce EMFs in the armature windings. These leakage EMFs are taken into account by introduction of leakage reactance drops and lead the current producing them by 90°.

Synchronous Reactance and Synchronous Impedance:

The Synchronous Reactance (X_S) is the imaginary reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and by the changein the air gap flux caused by the armature reaction.

Similarly, the Synchronous Impedance Z_S is a fictitious impedance employed to account for the voltage effects in the armature circuit produced by the actual armature resistance, the actual armature leakage reactance, and the change in the air gap flux produced by the armature reaction.

The actual generated voltage consists of the summation of the two-component voltages. One of these component voltages would be generated if there were no armature reaction. It is the voltage that would be generated because of only the field excitation. This component of the generated voltage is called the Excitation Voltage (E_{exc}).

The other component of the generated voltage is known as the Armature Reaction Voltage (E_{AR}). Thus, the two voltages that are the armature reaction voltage and the excitation voltage are added to keep a check on the effect of armature reaction upon the generated voltage. The equation is shown below.

$$E_a = E_{exc} + E_{AR} \dots\dots\dots (1)$$

The voltage in a circuit caused by the change in the flux by the current is a result of armature reaction. The nature of this effect is inductive reactance. Therefore, E_{AR} is equivalent to a voltage of inductive reactance asnd is given by the equation shown below.

$$E_{AR} = -jX_{AR}I_a \dots\dots (2)$$

The Inductive Reactance X_{AR} is a fictitious reactance. As a result, a voltage is generated in the armature circuit. Therefore, armature reaction voltage can be modeled as an inductor in series withthe internally generated voltage.

In addition to the effects of armature reaction, the stator winding also has a self-inductance and resistance.

Let,

- L_a is the self-inductance of the stator winding
- X_a is the self-inductive reactance of stator winding
- R_a is the armature stator resistance.

The terminal voltage V is given by the equation shown below.

$$V = E_a - jX_{AR}I_a - jX_aI_a - R_aI_a \dots\dots (3)$$

Where,

- R_aI_a is the armature resistance drop
- X_aI_a is the armature leakage reactance drop
- $X_{AR}I_a$ is the armature reaction voltage

The armature reaction and the leakage flux effects on the machine are both represented by inductive reactance. Therefore, all these combine to form a single reactance called Synchronous Reactance of the machine X_S.

$$X_S = X_a + X_{AR} \dots\dots (4)$$

Therefore,

$$V = E_a - jX_S I_a - R_a I_a \quad \text{or}$$

$$V = E_a - (R_a + jX_S) I_a \quad \dots\dots\dots (5)$$

$$V = E_a - Z_S I_a \quad \dots\dots.(6)$$

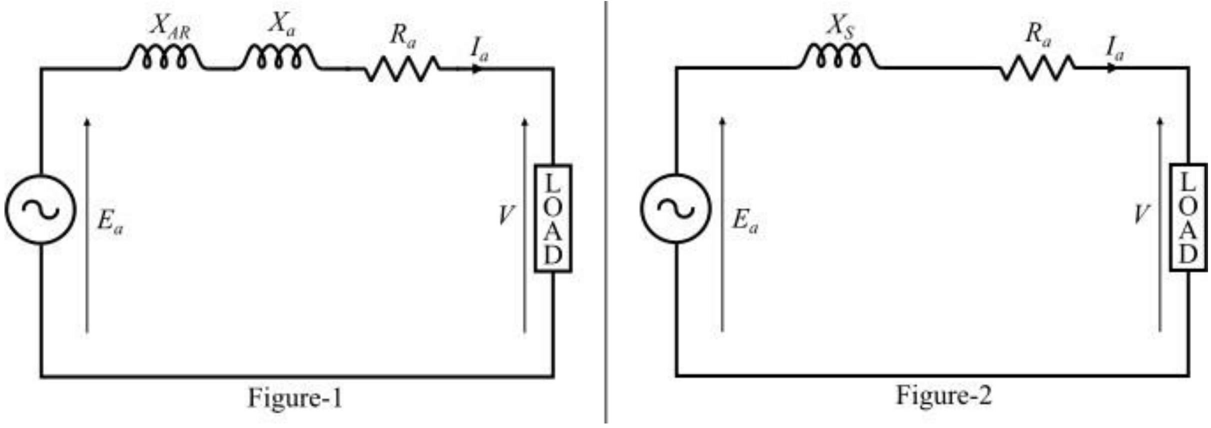
$$Z_S = R_a + jX_S \quad \dots\dots.(7)$$

Where,

The impedance Z_S in the above equation (7) is the Synchronous Impedance, and X_S isthe Synchronous Reactance.

Equivalent Circuit and Phasor Diagram of Synchronous Generator or Alternator:

The equivalent circuit of an alternator or synchronous generator is shown in Figure-1. The equivalent circuit of the alternator is redrawn in Figure-2 by taking synchronous reactance $X_S=X_{AR}+X_a$. By using the equivalent circuit, the phasor diagram of the alternator can be drawn as given below.



By referring the equivalent circuit, we can write,

$$V=E_a-I_a\,(R_a+jX_S)\ \dots\ (1)$$

Phasor Diagram of Alternator for Lagging Power Factor Load:

The phasor diagram of an alternator supplying a load of lagging power factor is shown in Figure-

3. Here, the power factor is φ lagging. To draw this phasor diagram, the terminal voltage V is taken as reference phasor and its direction is along OA where, OA = V.

Since the power factor is φ lagging, the armature current IaIa lags behind the voltage V by an angle equal to the power factor angle φ and the direction of the armature current phasor is along OB, where OB = I_a. The armature resistance I_aR_a voltage drop is represented by phasor ACand it is in phase with the armature current.

The voltage drop in the synchronous reactance is I_aX_S is represented by phasor CD and it leads the armature current I_a by 90°, thus the phasor CD is drawn in a direction perpendicular to OB. The total voltage drop in the synchronous impedance is the phasor sum of I_aR_a and I_aX_S and it is represented by the phasor AD. The actual generated voltage E_a in the alternator is representedby the phasor OD.

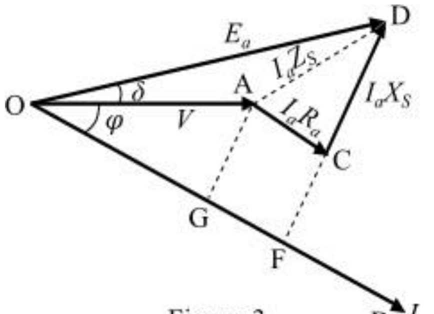


Figure-3

The magnitude of the actual generated voltage **E_a** can be determined from the triangle OFD as follows –

$OD^2=OF^2+FD^2=(OG+GF)^2+(FC+CD)^2$

$E_a^2=(V\cos\varphi+I_aR_a)^2+(V\sin\varphi+I_aX_S)^2$

$\Rightarrow Ea=\sqrt{}\,(V\cos\varphi+I_aR_a)^2+(V\sin\varphi+I_aX_S)^2\ldots$ (2)

Phasor Diagram of Alternator for Unity Power Factor Load

The phasor diagram of the alternator supplying a load of unity power factor is shown in Figure-4.

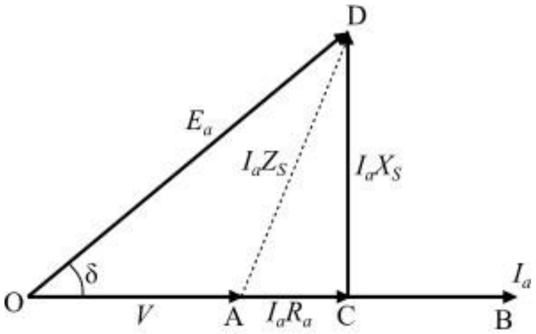


Figure-4

From the right-angled triangle OCD, the magnitude of the actual generated voltage can bedetermined as follows –

$OD^2=OC^2+CD^2$

$=(OA+AC)^2+(CD)^2Ea^2=(V+I_aR_a)^2+(I_aX_S)^2$

$\Rightarrow E_a=\sqrt{}\,(V+I_aR_a)^2+(I_aX_S)^2\ldots$ (3)

Phasor Diagram of Alternator for Leading Power Factor Load

The phasor diagram of the alternator supplying a load of leading power factor is shown in Figure-5.

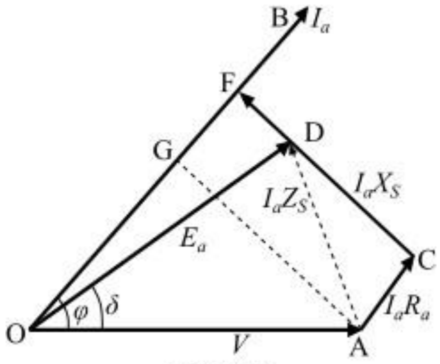


Figure-5

From the right-angled triangle OFD, the magnitude of the actual generated voltage can bedetermined as follows –

$OD^2=OF^2+FD^2$

$=(OG+GF)^2+(FC-CD)^2$

$Ea^2=(V\cos\varphi+I_aR_a)^2+(V\sin\varphi-(I_aX_S)^2$

$\Rightarrow E_a=\sqrt{(V\cos\varphi+I_aR_a)^2+(V\sin\varphi-I_aX_S)^2}$… (4)

Here, the angle between the actual generated voltage (E_a) and the terminal voltage (V) is known as power angle or torque angle of the alternator. The power angle (δ) changes with the load and is a measure of air-gap power developed in the machine.

Voltage Regulation:

Voltage regulation is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation.

% Regulation = (E_{ph} – V_{ph} / $V_{ph)}$ x 100

where,

E_{ph} = induced EMF /phase,
V_{ph} = rated terminal voltage/phase

Different methods used for predetermination of regulation of alternators.

- EMF method or Synchronous impedance method
- MMF method or Ampere turns method
- ZPF method or Potier triangle method

- ASA modified MMF method

Voltage Regulation of a Synchronous Generator:

The Voltage Regulation of a Synchronous Generator is the rise in voltage at the terminals when the load is reduced from full load rated value to zero, speed and field current remaining constant. It depends upon the power factor of the load. For unity and lagging power factors, there is always a voltage drop with the increase of load, but for a certain leading power, the full load voltage regulation is zero.

The voltage regulation is given by the equation shown below:

$$\text{Per Unit Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \quad \ldots\ldots\ldots (1)$$

$$\text{Percentage Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \quad \ldots\ldots\ldots (2)$$

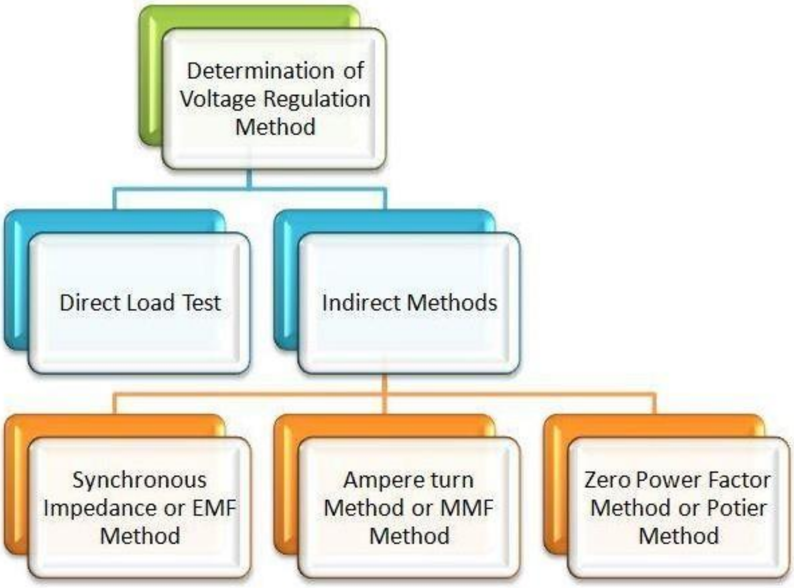
Where,

- **$|E_a|$** is the magnitude of a generated voltage per phase.
- **$|V|$** is the magnitude of rated terminal voltage per phase.

In this case, the terminal voltage is the same for both full load and no-load conditions. At lower leading power factors, the voltage rises with the increase of load, and the regulation is negative.

Determination of Voltage Regulation:

There are mainly two methods that are used to determine the regulation of voltage of smooth cylindrical rotor type alternators. They are named as a direct load test method and indirect methods of voltage regulation. The indirect method is further classified as Synchronous Impedance Method**,** Ampere-turn Method, and Zero Power Factor Method.



Direct Load Test:

The alternator runs at synchronous speed, and its terminal voltage is adjusted to its rated value **V**.The load is varied until the Ammeter and Wattmeter indicate the rated values at the given power factor. The load is removed, the speed and the field excitation are kept constant. The value of theopen circuit and no-load voltage is recorded.

It can be also found from the percentage voltage regulation and is given by the equation shownbelow:

$$\%\ \text{Voltage Regulation} = \frac{E_a - V}{V} \text{ x } 100\%$$

The method of direct loading is suitable only for small alternators of the power rating less than 5kVA**.**

Indirect Methods of Voltage Regulation:

For large alternators, the three indirect methods are used to determine the voltage regulation theyare as follows:

1. Synchronous Impedance Method or EMF method.
2. Ampere-turn method or MMF method of Voltage Regulation.
3. Zero Power Factor method or Potier Method.
4. ASA Method

1. Synchronous Impedance Method:

The Synchronous Impedance Method or Emf Method is based on the concept of replacing the effect of armature reaction with an imaginary reactance. For calculating the regulation, the synchronous method requires the following data; they are the armature resistance per phase and the open-circuit characteristic. The open-circuit characteristic is the graph of the circuit voltage and the field current. This method also requires a short circuit characteristic which is the graph ofthe short circuit and the field current.

For a synchronous generator, we know that, given below:

Where,

$$V = E_a - Z_s I_a$$

$$Z_s = R_a + jX_s$$

The synchronous impedance, Z_s is measured, and then the value of E_a is calculated. From the values of E_a and V, the voltage regulation is calculated.

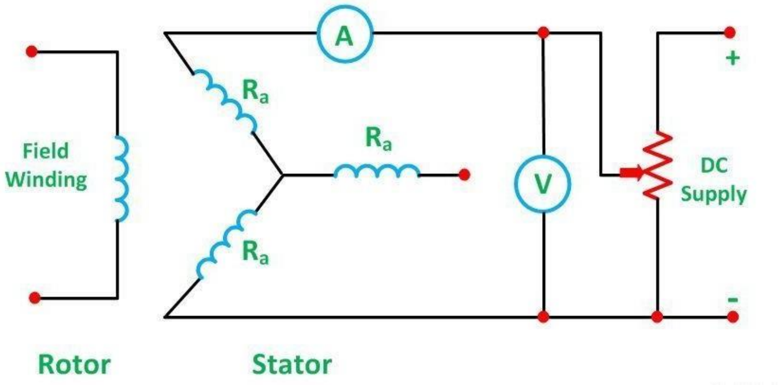
Measurement of Synchronous Impedance:

The measurement of synchronous impedance is done by the following methods. They are knownas:

- DC resistance test
- Open circuit test
- Short circuit test

DC resistance test:

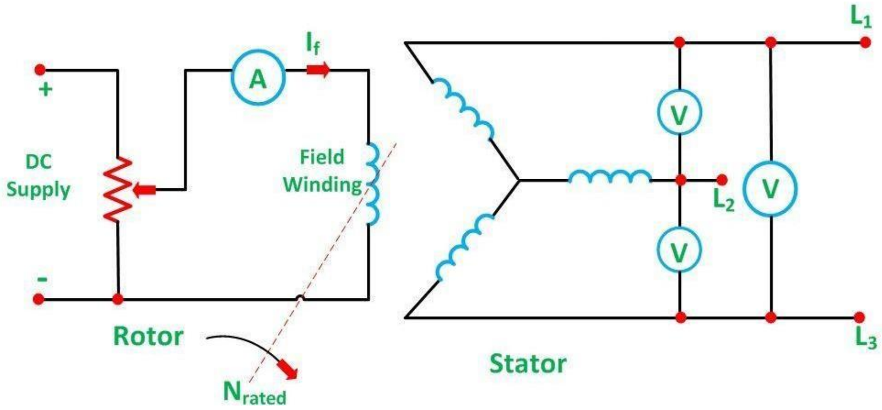
In this test, it is assumed that the alternator is star connected with the DC field winding open as shown in the circuit diagram below:



It measures the DC resistance between each pair of terminals either by using an ammeter – voltmeter method or by using the Wheatstone's bridge. The average of three sets of resistance value R_t is taken. The value of R_t is divided by 2 to obtain a value of DC resistance per phase. Since the effective AC resistance is larger than the DC resistance due to skin effect. Therefore, the effective AC resistance per phase is obtained by multiplying the DC resistance by a factor 1.20 to 1.75 depending on the size of the machine. A typical value to use in the calculation would be 1.25.

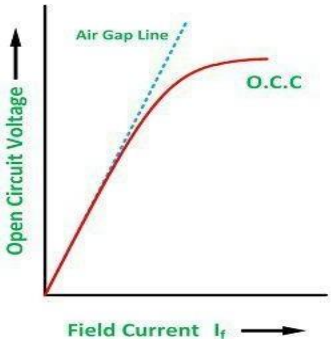
Open Circuit Test:

In the open-circuit **test** for determining the synchronous impedance, the alternator is running at therated synchronous speed, and the load terminals are kept open. This means that the loads are disconnected, and the field current is set to zero. The circuit diagram is shown below:



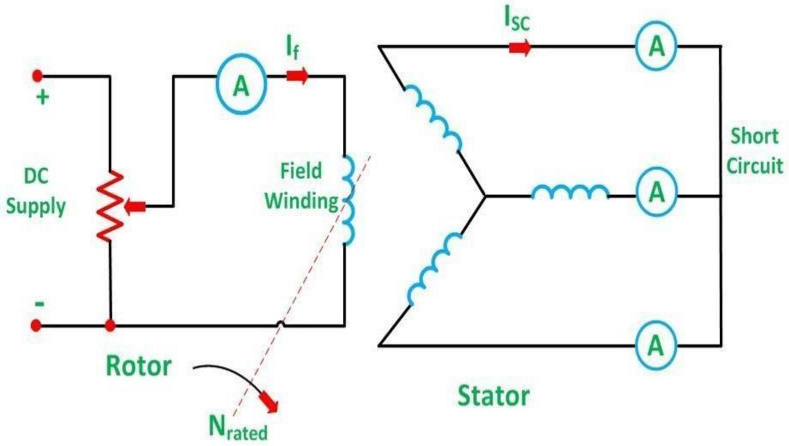
After setting the field current to zero, the field current is gradually increased step by step. The terminal voltage E_t is measured at each step. The excitation current may be increased to get 25% more than the rated voltage. A graph is drawn between the open circuit phase voltage $E_p = E_t/\sqrt{3}$ and the field current I_f. The curve so obtained called Open Circuit Characteristic (O.C.C). The shape is the same as the normal magnetization curve. The linear portion of the O.C.C is extendedto form an air gap line.

The Open Circuit Characteristic (O.C.C) and the air gap line is shown in the figure below:



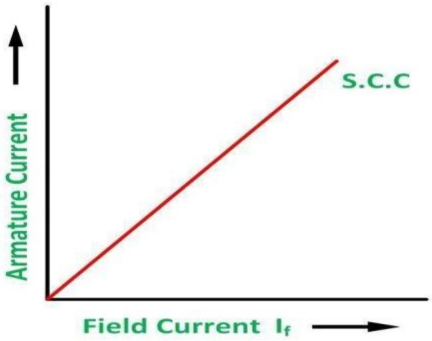
Short Circuit Test:

In the short circuit test**,** the armature terminals are shorted through three ammeters as shown in thefigure below:



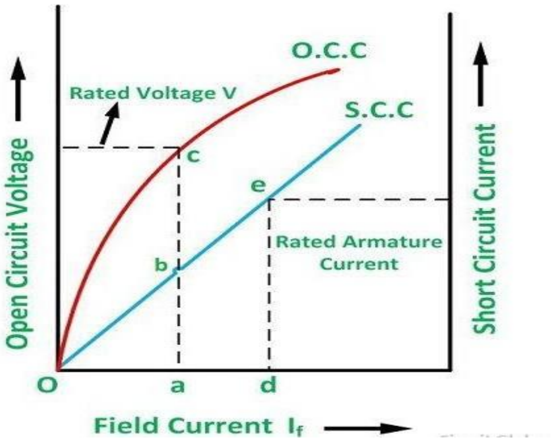
The field current should first be decreased to zero before starting the alternator. Each ammeter should have a range greater than the rated full load value. The alternator is then run at synchronous speed. Same as in an open circuit test that the field current is increased gradually in steps and the armature current is measured at each step. The field current is increased to get armature currents up to 125% of the rated value.

The value of field current I_f and the average of three ammeter readings at each step is taken. A graph is plotted between the armature current Ia and the field current I_f. The characteristic so obtained is called Short Circuit Characteristic (S.C.C). This characteristic is a straight line as shown in the figure below.



Short Circuit Ratio of a Synchronous Machine:

The Short Circuit Ratio (SCR) of a synchronous machine is defined as the ratio of the field current required to generate rated voltage on an open circuit to the field current required to circulate rated armature current on a short circuit. The short circuit ratio can be calculated from the open-circuit characteristic (O.C.C) at rated speed and the short circuit characteristic (S.C.C) of a three-phase synchronous machine as shown in the figure below:



From the above figure, the short circuit ratio is given by the equation shown below.

$$SCR = \frac{I_f \text{ for rated O.C volatge}}{I_f \text{ for rated S.C current}} = \frac{Oa}{Od} \ldots\ldots\ldots(1)$$

Since the triangles Oab and Ode are similar. Therefore,

$$\mathrm{SCR} = \frac{\mathrm{Oa}}{\mathrm{Od}} = \frac{\mathrm{ab}}{\mathrm{de}} \ldots \ldots .(2)$$

Calculation of Synchronous Impedance:

The following steps are given below for the calculation of the synchronous impedance.

- The open-circuit characteristics and the short circuit characteristic are drawn on thesame curve.
- Determine the value of short circuit current I_{sc} and gives the rated alternator voltageper phase.
- The synchronous impedance Z_S will then be equal to the open-circuit voltage divided by the short circuit current at that field current which gives the rated EMF per phase.

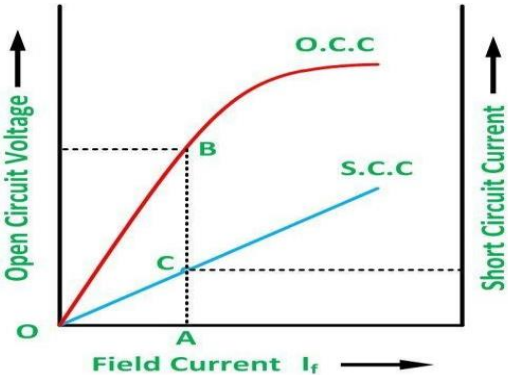
$$Z_S = \frac{\text{Open circuit voltgae per phase}}{\text{Short circuit armature current}} \quad \text{(for the same value of field current)}$$

The synchronous reactance is determined as

$$\mathbf{Z_s = \sqrt{(R_a)^2 + (X_S)^2}}$$

$$X_S = \sqrt{Z_S^2 - R_a^2}$$

The graph is shown below:



From the above figure, consider the field current I_f = OA that produces rated alternator voltageper phase. Corresponding to this field current, the open-circuit voltage is AB

Therefore,

$$Z_S = \frac{\text{AB (in volts)}}{\text{AC (in amperes)}}$$

Hence induced EMF per phase can be found as

$E_{ph} = \sqrt{}* [(V \cos\varphi + IR_a)^2 + (V \sin\varphi \pm IX_S)^2]$

where V = phase voltage per phase = V_{ph},I = load current per phase

In the above expression in second term + sign is for lagging power factor and – sign is for leadingpower factor.

Where,**% Regulation = $[(E_{ph} – V_{ph} / V_{ph})] \times 100$**

E_{ph} = induced EMF /phase,

V_{ph} = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results**.** This method gives the value of regulation which is greater than the actual value and hence this method is called pessimistic method.

2. MMF Method of Voltage Regulation:

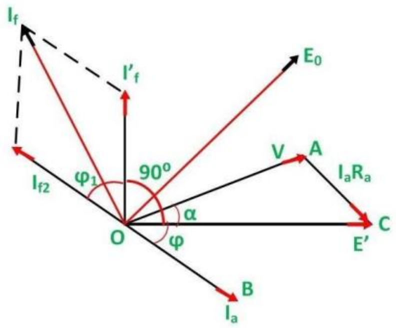
MMF Method is also known as Ampere Turn Method. The synchronous impedance method is based on the concept of replacing the effect of armature reaction with an imaginary reactance, the Magnetomotive force (MMF). The MMF method replaces the effect of armature leakage reactancewith an equivalent additional armature reaction MMF so that this MMF may be combined with the armature reaction MMF.

To calculate the voltage regulation by MMF Method, the following information is required. Theyare as follows:

- The resistance of the stator winding per phase.
- Open circuit characteristics at synchronous speed.
- Short circuit characteristic

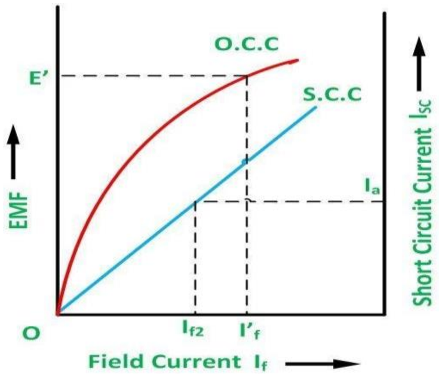
Step to Draw Phasor Diagram of MMF Method

The phasor diagram at a lagging power factor is shown below:



The armature terminal voltage per phase (V) is taken as the reference phasor along OA.

- The armature current phasor Ia is drawn lagging the phasor voltage for lagging power factor angle ϕ for which the regulation is to be calculated.
- The armature resistance drop phasor IaRa is drawn in phase with Ia along the line AC. JoinO and C. OC represents the emf E'.
- Considering the open current characteristics shown below, the field current I_f' corresponding to the voltage E' is calculated.
- Draw the field current I_f' leading the voltage E' by 90 degrees. It is assumed that on a shortcircuit all the excitation is opposed by the MMF of armature reaction.



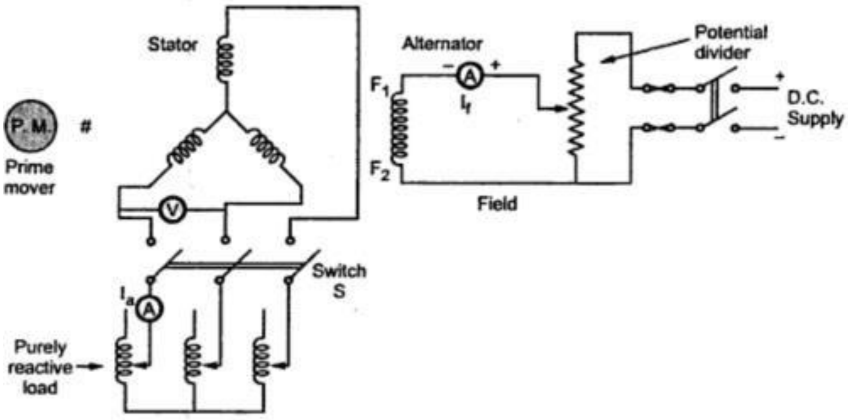
- From the short circuit current characteristics (SSC) shown above, determine the field current I_{f2} required to circulate the rated current on short circuit. This is the field current required to overcome the synchronous reactance drop IaXa.
- Draw the field current I_{f2} in phase in opposition to the current armature current Ia.
- Determine the phasor sum of the field currents I_f' and I_{f2}. This gives the resultant field current If which would generate a voltage E_0 under no-load conditions of the alternator.
- The open-circuit emf E_0 corresponding to the field current If is found from the open circuit characteristics.
- The regulation of the alternator is found from the relation shown below:

$$\text{Regulation} = \frac{E_0 - V}{V} \text{ x } 100\%$$

3. Potier Triangle or Zero Power Factor Method:

This Zero power factor (ZPF) method is used to determine the voltage regulation of synchronous generator or alternator. This method is also called Potier method. In the operation of an alternator, the armature resistance drop IRa and armature leakage reactance drop IX_L are actually emf quantities while the armature reaction is basically MMF quantity.

In the synchronous Impedance, all the quantities are treated as EMF quantities as against this in MMF method all are treated as MMF quantities.



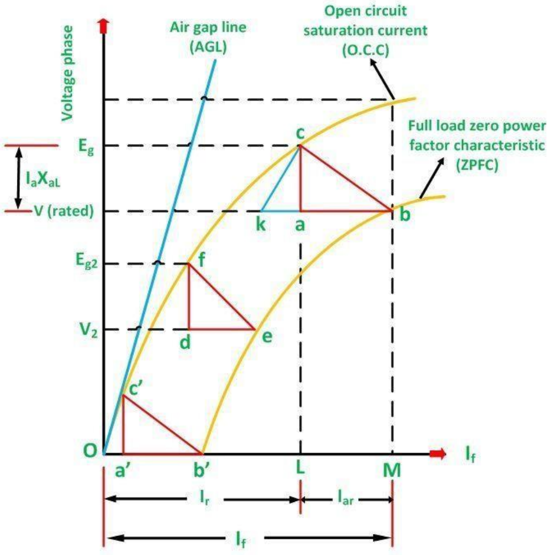
Key Point: This ZPF method is based on the separation of armature leakage reactance and armature reaction effects. The armature leakage reactance X_L is called Potier reactance in this method, hence ZPF method is also called Potier reactance method.

Zero Power Factor Test:

To conduct zero power factor test, the switch S is kept closed. Due to this, a purely inductive load gets connected to an alternator through an ammeter. A purely inductive load has a power factor ofcos 90° i.e., zero lagging hence the test is called zero power factor test.

The machine speed is maintained constant at its synchronous value. The load current delivered by an alternator to purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive load.

Note that, due to purely inductive load, an alternator will always operate at zero power factor lagging.



Consider a point B on the Zero Power Factor Curve corresponding to rated terminal voltage V anda field current of OM = $I_f = F_f/T_f$. I_f for this condition of operation, the armature reaction MMF has a value expressed in equivalent field current will be given as:

$$LM \left[= I_{ar} = \frac{F_{ar}}{T_f}\right]$$

.

Then the equivalent field current of the resultant MMF would be represented as shown below:

$$OL \left[= I_r = \frac{F_r}{T_f}\right]$$

This field current OL would result in a generated voltage Eg = LC from the no-load saturation curve. Since for lagging zero power factor operation, the generated voltage will be:

$$E_g = V + I_a X_{aL}$$

The vertical distance ac must be equal to the leakage reactance voltage drop IaXaL where Ia is therated armature current.

Therefore,

$$X_{aL} = \frac{\text{Voltage ac per phase}}{\text{Rated armature current}}$$

For Zero Power Factor operation with the rated current at any other terminal voltage, such as V_2. As the armature current is of the same value, both the I_a and X_{aL} voltage and the armature MMF must be of the same value. Therefore, for all the conditions of operation with rated armature current at zero lagging power factor, the Potier Triangle must be located between the terminal voltage V, a point on the ZPFC, and the corresponding E_g point on the O.C.C.

If the Potier triangle "cab" is moved downward so that the side ab is kept horizontal and b is kept on the ZPFC, the point c will move on the O.C.C. When the point b, reaches the point e, the Potier triangle cab will move on the position fde shown in the figure.

The location of point f on the O.C.C will determine the voltage E_{g2}. When the point b, reaches the point b', the Potier Triangle will be in the position c'a'b'. This is the limiting position that corresponds to short the circuit condition because the terminal voltage is zero at the point b'.

The initial part of the O.C.C is almost linear, another triangle Oc'b' is formed by the O.C.C. The hypotenuse of the Potier triangle and the baseline, a similar triangle such as ckb, can constructfrom the Potier triangle in any other location by drawing a line kc parallel to Oc'.

Steps for Construction of Potier Triangle on ZPFC:

- Take a point b on the ZPFC preferably well upon the knee of the curve.
- Draw bk equal to b'O. (b' is the point for zero voltage, full load current). Ob' is the short circuit excitation Fsc.
- Through k draw, kc parallel to Oc' to meet O.C.C in c.
- Drop the perpendicular ca on to bk.

- Then, to scale ca is the leakage reactance drop I_aX_{aL} and ab is the armature reaction MMF F_{aR} or the field current I_{faR} equivalent to armature reaction MMF at rated current.
- The effect of field leakage flux in combination with the armature leakage flux gives rise toan equivalent leakage reactance Xp, known as the Potier Reactance. It is greater than the armature leakage reactance.

$$\text{Potier Reactance Xp} = \frac{\text{Voltage drop per phase which is equal to (ac)}}{\text{(ZPF rzted armature current per phase Ia)}}$$

- For cylindrical rotor machines, the Potier reactance X_p is approximately equal to the leakage reactance X_{aL}. in salient pole machine, X_p may be as large as 3 times X_{aL}.

Assumptions for Potier Triangle:

The following assumptions are made in the Potier Triangle Method. They are as follows: -

- The armature resistance R_a is neglected.
- The O.C.C taken on no-load accurately represents the relation between MMF and Voltageon load.
- The leakage reactance voltage I_a X_{aL} is independent of excitation.
- The armature reaction MMF is constant.

Important Points:

- It is not necessary to plot the entire ZPFC for determining X_{aL} and F_a, only two points b and b’ are sufficient.
- Point b corresponds to a field current which gives the rated terminal voltage while the ZPF load is adjusted to draw rated current.
- Point b’ corresponds to the short circuit condition (V = 0) on the machine.
- Thus, Ob’ is the field current required to circulate the short circuit current equal to the **rated current.**

4. ASA Method:

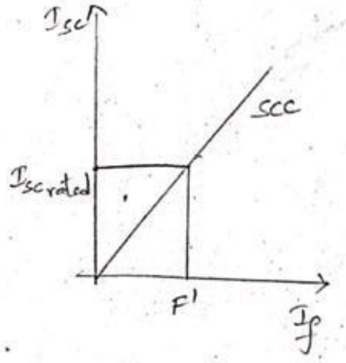
ASA stands for American Standard Association. In this effect of saturation in OCC is also considered. It is a combination of ZPF and MMF method. Actually, it is a modified MMF method. Compared to all the previous methods ASA method gives better results for both salient and non- salient synchronous machines. whereas the previous methods are used for non-salient machines because there occur some errors.

Requirements:

1. Open circuit characteristics (OCC)
2. Zero power factor characteristics (ZPFC) The two points A and F' is required to draw ZPFC

POINT A: load the overexcited generator by under excited synchronous motor till full loadarmature current is reached at rated voltage.

POINT F': Field current required to circulate the full load current when alternator is short circuited (OR) F' can be calculated using short circuit characteristics in which F' is field current at rated short circuit current as shown below.



Steps to draw potier triangle in ASA method:

1. Draw a line DA parallel and equal in magnitude of OF'
2. Draw a line DC parallel to is airgap line. The line DC intersects OCC at Point C.
3. Join CA.
4. Draw a perpendicular bisector from Point C to B, which divides line DA into two parts atpoint B.
5. Triangle ABC is called as potier triangle.
6. Now CB is the drop due to X_L (from ZPF method).

CB= $I_a X_L$
=>X_L=CB/I_a

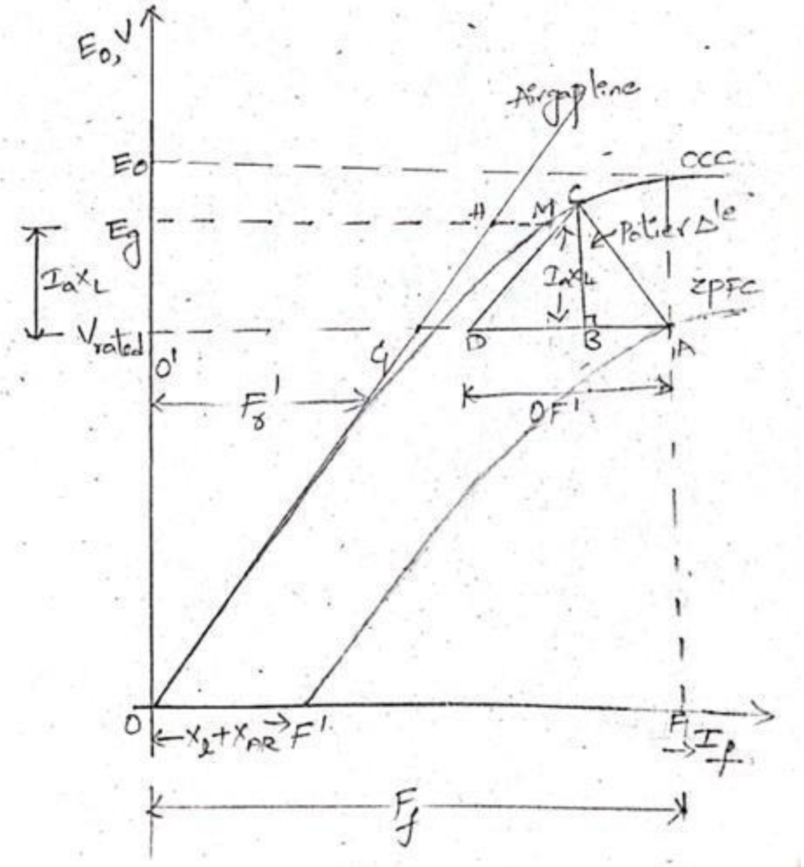
Now calculate E_g from

$E_{ph} = \sqrt{[(V \cos\varphi + I_aR_a)^2 + (V \sin\varphi \pm I_aX_L)^2]}$Here, Plus is used for lagging power factor

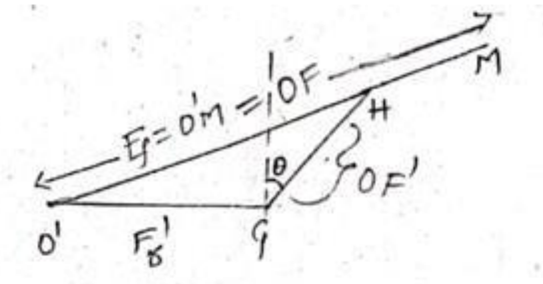
Minus is used for leading power factor

7. Once E_g is obtained, corresponding to E_g draw a line on to air gap line and OCC it H andM respectively.

8. Name the point where V_{rated} line intersects the Y axis and air gap line as O’ and Grespectively and this O’G is F_r’.



9. Now in the vector diagram shown below, O’G is the field current required to produce ratedvoltage without considering the saturation.



10. GH=OF’
11. draw the resultant vector of the current from O’.
12. To the resultant vector of current add HM which indicates the effect of saturation.
13. O’M=OF=F_f (main MMF)
14. Draw a vertical line from point F on to I_f line to OCC it corresponds to E_0.

Now, **% reg = (E_0-V)/V *100**

The voltage regulation of alternator using all the four methods can be concluded as,

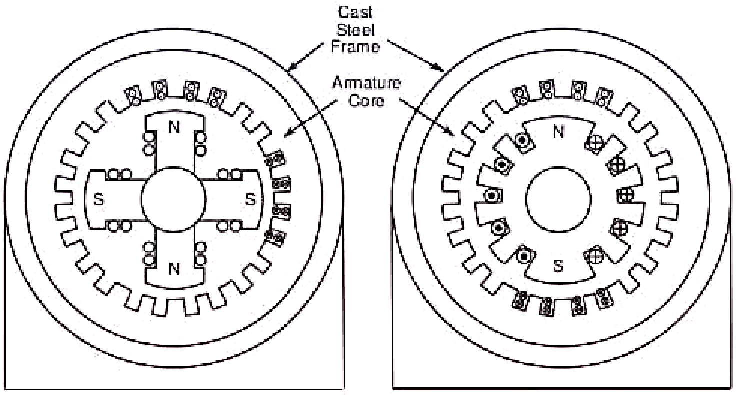
$Reg_{EMF} > Reg_{ASA} > Reg_{ZPF} > Reg_{MMF}$

Salient Pole Alternator-Two Reaction Theory:

In the cylindrical or non-salient pole synchronous machine, the airgap is uniform and due to which the flux produced will be also uniform. Hence the reactance due to the armature reactioncan be considered as single reactance.

But in the salient pole synchronous machine, the airgap is non- uniform and due to which the flux produced will be also non-uniform. Hence the reactance due to the armature reaction can be resolved into two components.

These components are taken as X_d and X_q.



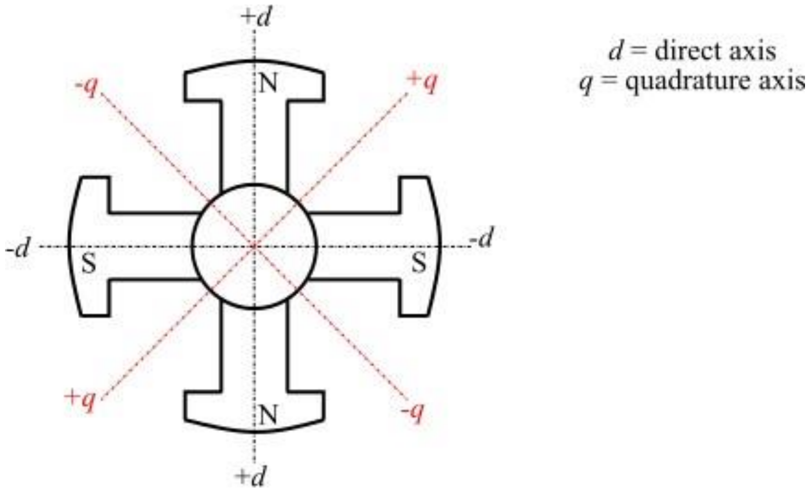
Salient Pole Construction

Cylindrical Rotor Construction

Two Reaction Theory was proposed by Andre Blondel. The theory proposes to resolve the given armature MMFs into two mutually perpendicular components, with one located along the axis of the rotor of the salient pole. It is known as the direct axis or d axis component. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature axis or q axis component.

Magnetic Axes of Rotor:

The figure shows the direct axis and the quadrature axis of a rotor −



Direct Axis

The axis of symmetry of the magnetic poles of the rotor is called as direct axis or d-axis. The axis of symmetry of the north magnetic poles of the rotor is known as the positive d-axis while theaxis of symmetry of the south magnetic poles is known as the negative d-axis.

Quadrature Axis

The axis of symmetry halfway between the adjacent north and south poles is known as quadrature axis or q-axis. The q-axis lagging the north pole is taken as the positive q-axis. Thequadrature axis is so name since it is 90° electrical or one-quarter cycle away from the direct axis.

Blondel's Two Reaction Theory:

Andre Blondel proposed the Two Reaction Theory of synchronous machines. The Two-reaction theory was proposed to resolve the given armature MMF (F_a) into two mutually perpendicular components, with one located along the d-axis of the salient-pole rotor. This component is known as the direct axis or d-axis component and is denoted by (F_d). The other component is located perpendicular to the d-axis of the salient pole rotor. It is known asthe quadrature axis or q-axis component and denoted by (F_q).

The d-axis component (F_d) is either magnetizing or de-magnetizing while the q-axis component (F_q) results in a cross-magnetizing effect. If ψ is the angle between the armature current(I_a) and the excitation voltage (E_f) and the amplitude of the armature MMF is given by (Fa), then,

The d-axis component (Fd) is given by,

$F_d = F_a \sin\psi$And the q-axis component (F_q) is given by,

$F_q = F_a \cos\psi$

Two Reaction Theory of Salient Pole Synchronous Machine (Alternator):

In a salient-pole rotor synchronous machine, the air-gap is highly non-uniform. Consider a synchronous machine having a 2-pole salient-pole rotor rotating in the anti-clockwise direction within a 2-pole stator, as shown in Figure-1.

In Figure-1, the axis shown along the axis of the rotor is known as direct axis or d-axis and the axis perpendicular to the d-axis is called quadrature axis or q-axis. It can be seen that the two small air-gaps are involved in the path of d-axis flux (φ_d), thus the reluctance of the path is minimum. The q-axis flux (φ_q) path has two large air-gaps and it is the path of maximum reluctance.

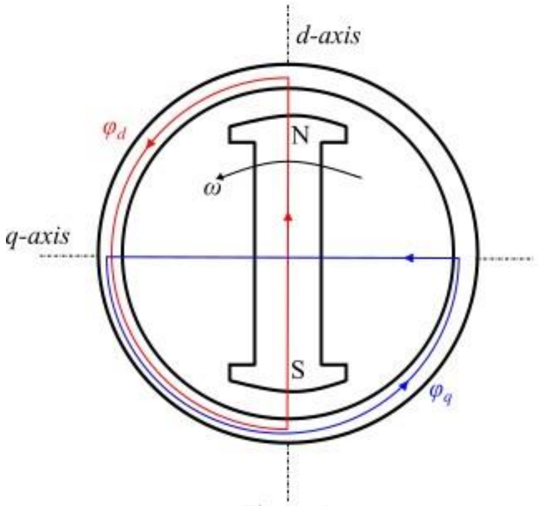


Figure-1

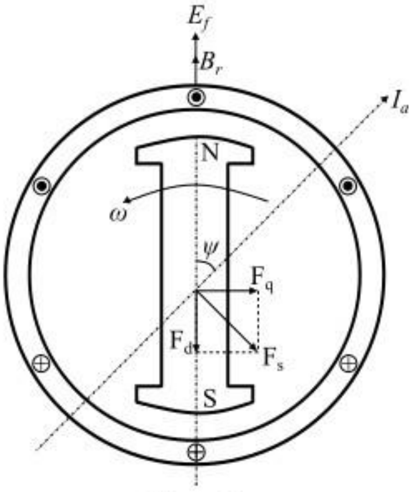


Figure-2

The rotor magnetic field (B_r) is shown directed vertically upward in Figure-2. This rotor magnetic field induces an EMF in the armature (or stator winding). If a lagging power factor load is connected to the alternator, an armature current (I_a) will flow. The armature current (I_a) lags behind the excitation voltage (E_f) by an angle ψ (see Figure-2).

The armature current (I_a) produces the stator MMF (F_s) which lags behind I_a by 90°. The stator MMF (F_s) produces the stator magnetic field (B_s) along the direction of F_s.

According to Blondel's Two Reaction Theory, the stator MMF (F_s) can be resolved into two components viz. the direct-axis component (F_d) and the quadrature axis component (F_q).

If

φ_d = Direct axis flux
φ_q = Quadrature axis flux
S_d = Reluctance of direct axis flux path
S_q = Reluctance of quadrature axis flux path

Then,
Direct axis flux, $\varphi_d = F_d S_d$… (1)

And,

Quadrature axis flux, $\varphi_q = F_q S_q$… (2)

Since $S_d < S_q$, the direct axis component (F_d) of stator MMF produces more flux than the quadrature axis component (F_q) of the stator MMF. The direct axis and quadrature axis components of the stator fluxes produce voltages in the stator winding by armature reaction.

Let,

E_{ad}= Direct axis component of armature reaction voltage
E_{aq} = Quadrature axis component of armature reaction voltage

Since each armature reaction voltage is directly proportional to respective armature current and lags behind the armature current by 90°, the armature reaction voltages can be written as,

$E_{ad} = -j\, I_d\, X_{ad}$… (3)$E_{aq} = -j\, I_q\, X_{aq}$… (4)

Where,

X_{ad} is the armature reaction reactance in the direct axis per phase.
X_{aq} is the armature reaction reactance in the quadrature axis per phase.

Here, $X_{aq} < X_{ad}$ because the EMF induced by a given MMF acting on the direct axis is smaller than the EMF on the quadrature axis due to its higher reluctance.

Now, the resultant EMF induced in the machine is,

$E_R = E_f + E_{ad} + E_{aq}$

$\Rightarrow E_R = E_f - j\, I_d\, X_{ad} - j\, I_q\, X_{aq} \ldots$ (5)

Also, the resultant voltage (E_R) is equal to the phasor sum of terminal voltage and the voltage drops in the resistance and leakage reactance of the armature, thus,

$E_R = V + I_a R_a + j I_a X_l \ldots$(6)

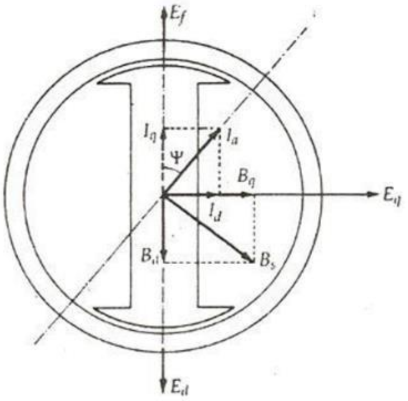
The armature current (I_a) is split into two components, one in phase with the excitation voltage(E_f) and the other in phase quadrature to it, as shown in the figure below.

If

I_q = quadrature axis component of I_a in phase with E_f I_d = direct axis component of I_a lagging E_f by 90°

Then, the total armature current is the phasor sum of I_q and I_d, i.e.,

$I_a = I_q + I_d \ldots$ (7)Now, from eqns. (5) and (6), we get,



$E_f = V + I_a R_a + j I_a X_l + j I_d X_{ad} + j I_q X_{aq} \ldots$ (8)

And, from Eqns. (7) and (8), we get,

$E_f = V + (I_q + I_d)\, R_a + j(I_q + I_d)\, X_l + j I_d X_{ad} + j I_q X_{aq}$

$\Rightarrow E_f = V + (I_q + I_d)\, Ra + j I_d\, (X_l + X_{ad}) + j I_q\, (X_l + X_{aq})$

$\Rightarrow E_f = V + (I_q + I_d)\, Ra + j I_d X_{ad} + j I_q X_{aq} \ldots$ (9)

Where,

and

$X_d = X_l + X_{ad}$

$X_q = X_l + X_{aq}$

The reactance X_d is known as the direct-axis synchronous reactance and the reactance X_q is calledthe quadrature-axis synchronous reactance.

$\therefore E_f = V + I_aR_a + jI_d X_d + jI_q X_q \ldots$ (10)

Equation (10) is the final form of the voltage equation for a salient-pole synchronous generator.

- Generally, X_d= (1.5-2) Xq
- And (X_d-X_q) is called as saliency
- If saliency is 0, that means $X_d = X_q$ which is in the case of cylindrical type of rotor.

Phasor Diagram for Salient pole alternator:

The excitation voltage equation can be shown in the form of phasor diagram as below.

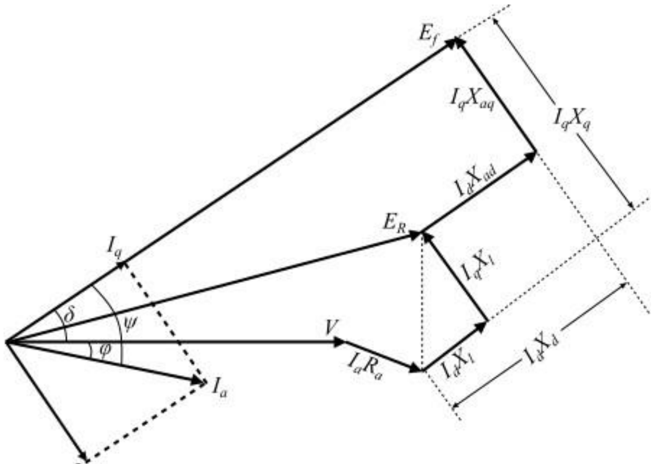
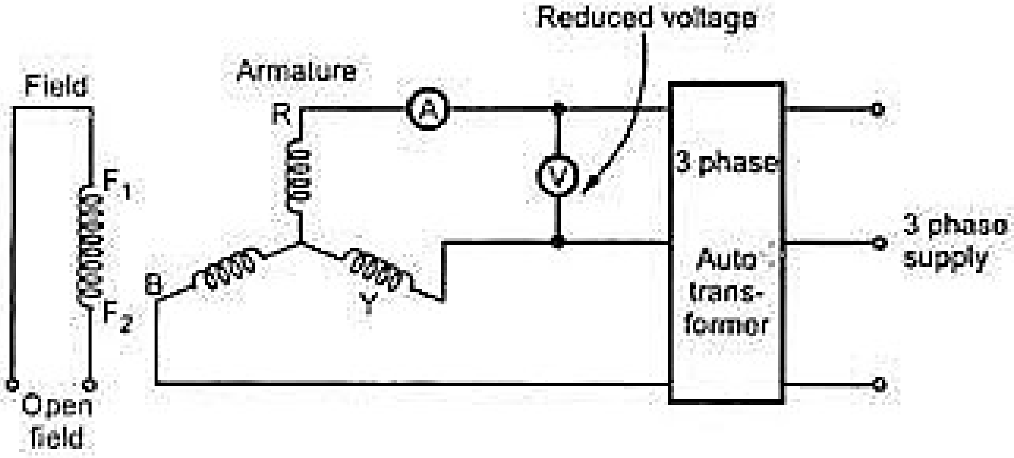


Figure-3

Slip Test: Determination of Xd and Xq:

Direct and quadrature axis reactances of a salient-pole synchronous machine can be estimated by means of a test known as the Slip Test on Synchronous Machine. The machine armature is connected to a 3-phase supply whose voltage is much less than the rated voltage of the machine. The rotor is driven by an auxiliary motor (preferably DC motor) at a speed slightly less than the synchronous speed. The connection diagram is shown below.

The field winding is kept open circuited and a low voltage 3-phase supply (about (20-25) % of therated voltage) is applied to the armature terminals. Since the excitation emf is zero, heavy currentswould be drawn by the armature if connected to the rated voltage supply.



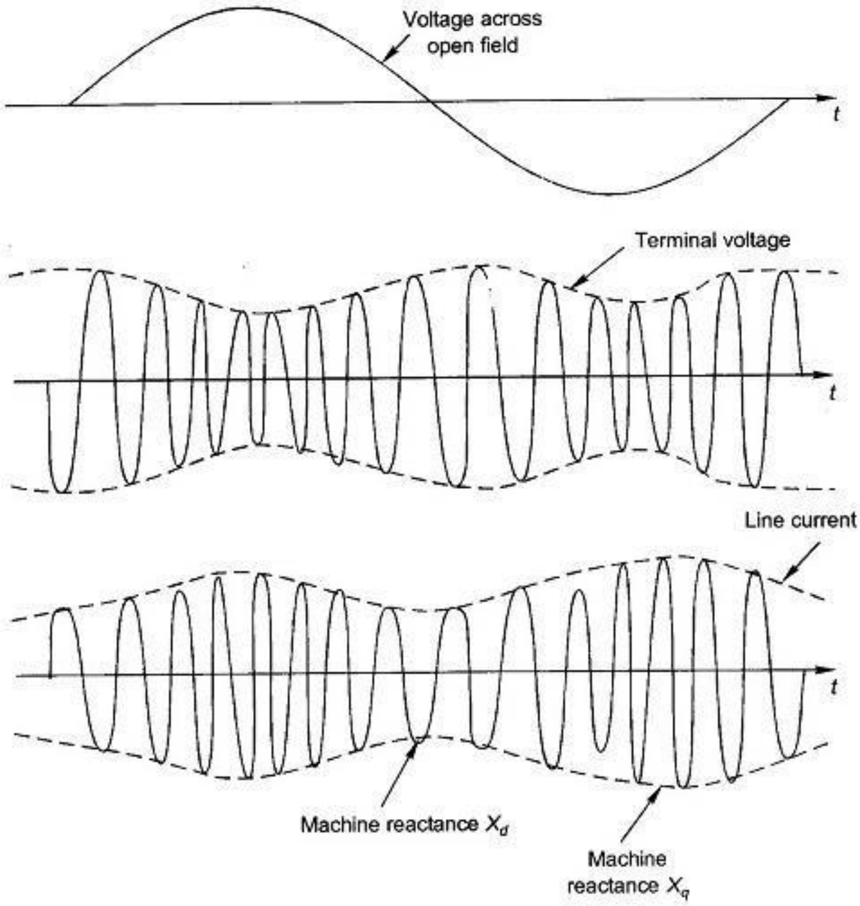
The direction of rotation of rotor should be the same as the direction of rotating field in stator. If this condition is fulfilled a small AC voltage would be indicated by the voltmeter across the field winding.

The currents drawn by the armature set up an mmf wave rotating at synchronous speed. Since the rotor is being run at a speed close to synchronous, the stator mmf moves slowly past the field poles at slip speed (N_s~N). This would cause the armature current to vary cyclically as shown in below figure.

When the stator mmf is aligned with the d-axis (field poles), flux Φ_d/pole is set up so that effective reactance offered by the machine is X_d. When the peak of the armature mmf is in line with the field poles, the reluctance offered by the magnetic circuit is minimum, then the armature current is minimum. Hence the voltage drop across armature will be maximum. The ratio of armature terminal voltage per phase to armature phase current gives X_d. when the armature mmf is in line with field poles, the armature flux linkage with field winding is maximum and rate of change of this flux linkage is zero.

Similarly, when the stator mmf aligns with the q-axis, the flux set up is Φ_d/pole and the machine reactance is X_q. The peak of armature mmf is in line with q-axis and the reluctance offered by the magnetic circuit is maximum, then the armature current is maximum. Hence the voltage drop across armature will be minimum. The ratio of armature terminal voltage per phase to armature phase current gives Xq. When the armature mmf is in line with q-axis, the armature flux linkage with field winding is minimum and rate of change of this flux linkage is maximum.

The current drawn by the armature therefore varies cyclically at twice the slip frequency as shown by the current waveform drawn in Fig. above, the rms current is minimum when machine reactance is X_d and is maximum when it is X_q. Because of cyclic current variations and consequent voltage drop in the impedance of supply lines (behind the mains), the voltage at machine terminals also varies cyclically and has a minimum value at maximum current and maximum value at minimum current as shown by the voltage waveform.



The machine reactances can be found as

$$X_d = \frac{\text{Maximum armature terminal voltage per phase}}{\text{Minimum armature current per phase}}$$

Similarly

$$X_q = \frac{\text{Minimum armature terminal voltage per phase}}{\text{Maximum armature current per phase}}$$

$$X_d = \frac{V_{max}}{\sqrt{3}\ I_{min}}$$

$$X_q = \frac{V_{min}}{\sqrt{3}\ I_{max}}$$

For locating the points of maximum and minimum on armature voltage and current, the slip should be very small. so that inertia of moving parts of instruments does not cause errors in measurements.Greater accuracy can be achieved by using recording oscillogram.

In view of the error involved in reading oscillograms. This test should be used only to find the ratio of $Xd\ /Xq$. The value of Xd can be found from the open circuit and short circuit tests, as in the case of cylindrical rotor machine.

The slip test is conducted to find

- X_d and X_q
- Armature Resistance (if required)

Steps:

- Energise the alternator with field unexcited and driven close to synchronous speed by a primemover.
- Measure the line voltage and line current of the alternator.
- Find X_d and X_q by the following expressions,

$$X_d = \frac{V_{max}}{\sqrt{3}\ I_{min}} \qquad X_q = \frac{V_{min}}{\sqrt{3}\ I_{max}}$$

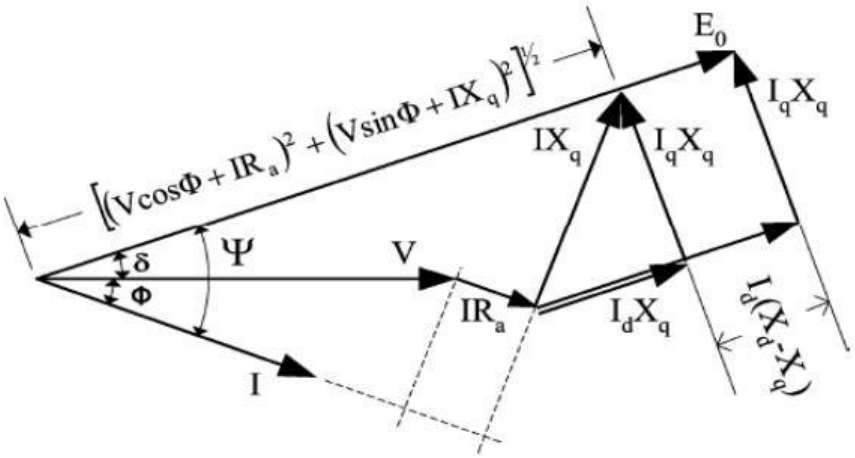
- Find I_d as follows

$$\Psi = \tan^{-1}\frac{V\sin\Phi + I X_q}{V\cos\Phi + I R_a}$$

$$I_d = I\sin\Psi$$

Then expression for E_0 is,

$$E_0 = [(V\cos\Phi + I R_a)^2 + (V\sin\Phi + I X_q)^2]^{1/2} + I_d(X_d - X_q)$$



UNIT-IV

PARALLEL OPERATION OF THE ALTERNATORS AND SYNCHRONOUS MOTORS

Parallel Operation of the Alternators:

Interconnection of the electric power systems is essential from the economical point of view and also for reliable and Parallel Operation. Interconnection of AC power systems requires synchronous generators to operate in parallel with each other. In generating stations, two or more generators are connected in parallel. The alternators are located at different locations forminga grid connected system.

They are connected parallel by means of transformer and transmission lines. Under normal operating conditions all the generators and synchronous motors in an interconnected system operate in synchronism with each other. A machine has to be adjusted for optimum operating efficiency and greater reliability if the generators are connected in parallel.

As the load increases beyond the generated capacity of the connected units, additional generatorsare parallel to carry the load. Similarly, if the load demand decreases, one or more machines are taken off the line as per the requirement. It allows the units to operate at a higher efficiency.

Infinite Bus:

Definition: The bus whose voltage and frequency remain constant even after the variation in the load is known as the infinite bus. The alternators operating in parallel in a power system are the example of the infinite bus. The on and off of any of the alternators will not affect the working ofthe power system.

The capacity of a parallel operating system is enormous, their voltage and frequency remain constant even after the disturbance of the load. The connection and disconnection of any of the machines will not affect the magnitude and phase of voltage and frequency of an infinite bus. In an infinite bus system

- The voltage and frequency always remain constant.
- The synchronous impedance of the bus is low because of the parallel operations of themachine.

Synchronous machine on Infinite Bus:

The performance of the synchronous machine varies on the infinite bus. When the synchronous machine operates independently, variation in their excitation causes the changes in their terminal voltage. The power factor of the synchronous machine depends only on their load. But when the synchronous machines are operating in parallel, the change in their excitation changes the power factor of the load.

Reasons of Parallel Operation:

Alternators are operated in parallel for the following reasons:

- 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, theremaining 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.
- A number of machines can be added without 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 energygeneration.
- 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 the load is known as Running Machines while thealternator which is to be connected in parallel with the system is known as the Incoming machine**.**

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

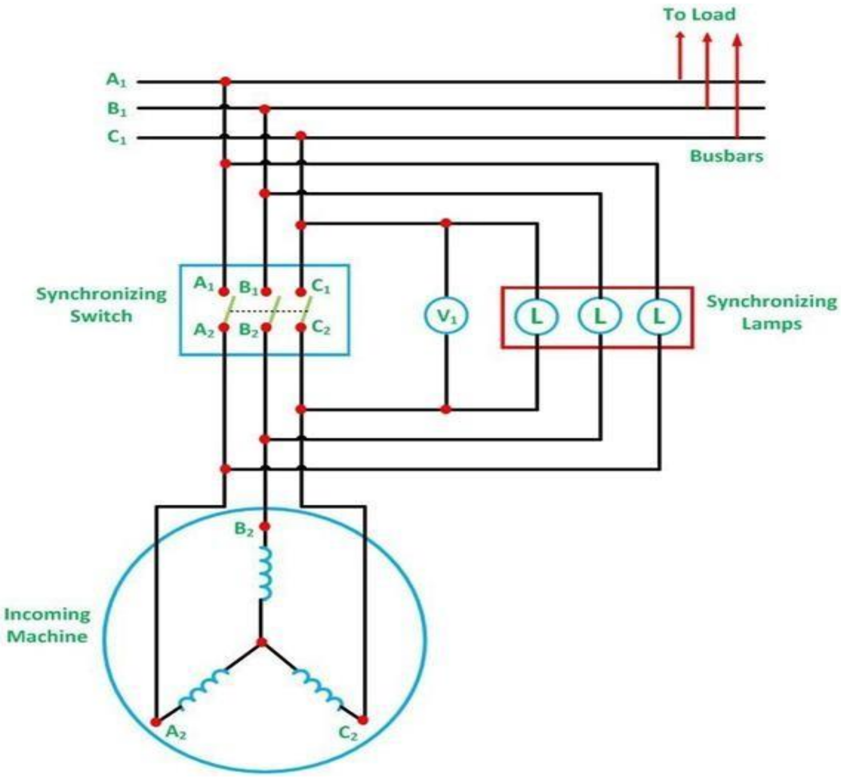
- The phase sequence of the Busbar voltages and the incoming machine voltage mustbe the same.
- The Busbar voltages and the incoming machine terminal voltage must be in phase.
- The terminal voltage of the incoming machine and the alternator which is to beconnected in parallel or with the busbar voltage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

- The frequency of the generated voltage of the incoming machine and the frequencyof the voltage of the busbar should be equal.

Synchronization Methods:

1. Dark Lamp Method

A set of three synchronizing lamps can be used to check the conditions for paralleling or synchronization of the incoming machine with the other machine. A dark lamp method along witha voltmeter used for synchronizing is shown below. This method is used for low-power machines.



The prime mover of the incoming machine is started and brought nearer to its rated speed. A fieldcurrent of the incoming machine is adjusted in such a way so that it becomes equal to the bus voltage. The flicker of the three lamps occurs at a rate that is equal to the difference in the frequencies of the incoming machine and the bus. All the lamps will glow and off at the same time if the phases are properly connected. If this condition does not satisfy, then the phase sequence isnot connected correctly.

Thus, in order to connect the machine in the correct phase sequence, two leads to the line of the incoming machine should be interchanged. The frequency of the incoming machine is adjusted until the lamp flicker at a slow rate. The flicker rate should be less than one dark period per second. After finally adjusting the incoming voltage, the synchronizing switch is closed in the middle of their dark period.

Advantages of the Dark Lamp Method:

- This method is cheaper.
- The correct phase sequence is easily determined.

Disadvantages of the Dark Lamp Method:

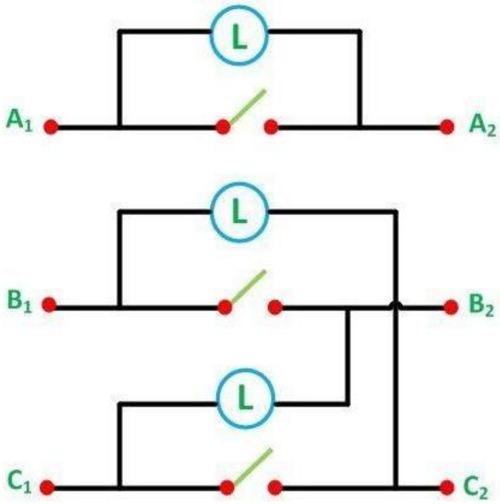
- The lamp becomes dark at about half of its rated voltage. Hence, it is possible that the synchronizing switch might be switched off even when there is a phase difference between the machine.
- The filament of the lamp might burn out.
- The flicker of the lamps does not indicate which lamp has the higher frequency.

2. Three Bright Lamp Method

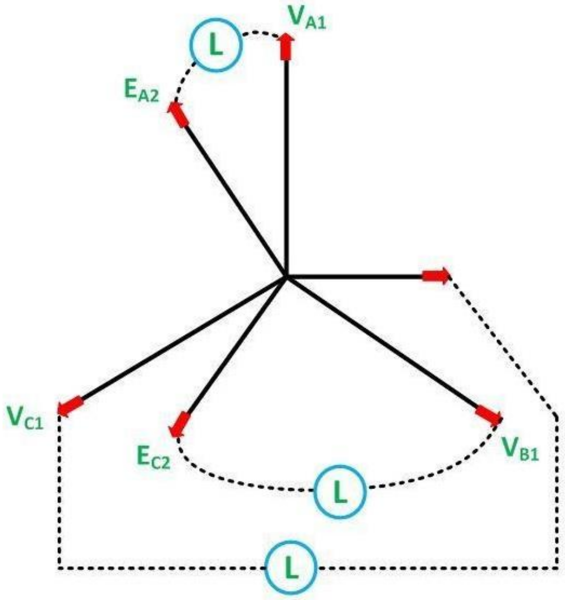
In this method, the lamps are connected across the phases such as A_1 is connected to B_2, B_1 is connected to C_2, and C_1 is connected to A_2. If all the three lamps get bright and dark together, this means that the phase sequence is correct. The correct instant of closing the synchronizing switch is in the middle of the bright period.

3. Two Bright One Dark Lamp Method

In this method, one lamp is connected between corresponding phases while the two others are cross-connected between the other two phases as shown in the figure below:



Here, A_1 is connected to A_2, B_1 to C_2, and C_1 to B_2. The prime mover of the incoming machine is started and brought up to its rated speed. The excitation of the incoming machine is adjusted in such a way that the incoming machine induces the voltage E_{A1}, E_{B2}, E_{C3}, which is equal to the Busbar voltages V_{A1}, V_{B1} and V_{C1}. The diagram is shown below.



The correct moment to close the switch is obtained at the instant when the straight connected lamp is dark, and the connected cross lamps are equally bright. If the phase sequence is incorrect, no such instant will take place, and all the lamps will be dark simultaneously.

The direction of rotation of the incoming machine is changed by interchanging the two lines of the machine. Since the dark range of the lamp extends to a considerable voltage range, a voltmeter V_1 is connected across the straight lamp. The synchronizing switch is closed when the voltmeter reading is zero.

Thus, the incoming machine is now floating on the Busbar and is ready to take up the load as a generator. If the prime mover is disconnected, it behaves as a motor. For paralleling small machines in power stations, three lamps along with the synchroscope are used. For synchronizing very large machines in power stations, the whole procedure is performed automatically by the computer.

4. Synchroscope Synchronizing

The Synchroscope is a device used for determining the phase angle differences between two or more machines at the time of the synchronization. The synchronization is essential for sharing theload on the bus bar of the power system.

For the parallel operation of the three-phase machines, it is essential that they are in phase with each other. The phase sequence of the device is correct at the time of the installation.

The Synchroscope compares the incoming voltage of the machines concerning the three-phase system. The figure of the synchroscope shown below. It has a dial places on the circular calibrated scale on the motor. The position of the dial shows the phase difference between the incoming voltage and the infinite machines.

The scale of the Synchroscope marks with two arrows which indicate the direction of rotation of the pointer. The arrow indicates the clockwise and the anti-clockwise direction of the pointer. The clockwise arrows show too fast movement and the anti-clockwise direction shows slow rotation of the incoming machine.

The arrow shows the movement of the machine concerning the bus bar. If the frequency of the incoming machine is more than that of the generator, the pointer deflects towards the fast mark.

And if the frequency of the incoming machine is less then, the pointer deflects towards the slow mark.

When the frequency of the incoming machine voltage and the infinite machine becomes equal, the pointer becomes stationary. When their frequency differs then the pointer deflects in one direction.

The deflection of the pointer shows the speed of the incoming machines, i.e., the frequency of the incoming machine is higher or lower than that of the infinite bus or not. The frequency and phaseposition are controlled by the input of the prime mover.

When the pointer moves slowly and passes through the zero-phase point, the circuit breaker is closed, and the incoming alternator connects to the bus. The Synchroscope does not give any information about the phase sequence. It shows relation only on one phase.

Synchronizing Power and Torque Coefficient:

Definition: – Synchronizing Power is defined as the varying of the synchronous power P on varying in the load angle δ. It is also called the Stiffness of Coupling**,** Stability or Rigidity factor**.** It is represented as **P_{syn}**. A synchronous machine, whether a generator or a motor, when synchronized to infinite busbars has an inherent tendency to remain in synchronism**.**

Consider asynchronous generator transferring a steady power P_a at a steady load angle δ_0. Suppose that, due to a transient disturbance, the rotor of the generator accelerates, resulting from an increase in the load angle by dδ. The operating point of the machine shifts to a new constant power line and the load on the machine increases to $P_a + \delta P$. The steady power input of the machine does not change, and the additional load which is added decreases the speed of the machine and brings it back to synchronism.

Similarly, if due to a transient disturbance, the rotor of the machine retards resulting a decrease in the load angle. The operating point of the machine shifts to a new constant power line and the load on the machine decreases to $(P_a – \delta P)$. Since the input remains unchanged, the reduction in load accelerates the rotor. The machine again comes in synchronism.

The effectiveness of this correcting action depends on the change in power transfer for a given change in load angle. The measure of effectiveness is given by Synchronizing Power Coefficient**.**

$$P_{syn} \triangleq \frac{d\,P}{d\,\delta} \;\ldots\ldots.\,(1)$$

Power output per phase of the cylindrical rotor generator synchronizing torque coefficient

$$\tau_{syn} \triangleq \frac{d\,\tau}{d\,\delta} = \frac{1}{2\pi n_s}\frac{d\,P}{d\,\delta} \;\ldots\ldots\ldots(4) \quad \text{or}$$

$$\tau_{syn} = \frac{V\,E_f}{2\,\pi\,n_s Z_s}\sin(\theta_Z - \delta) \;\ldots\ldots\ldots(5)$$

In many synchronous machines $X_s >> R$. Therefore, for a cylindrical rotor machine, neglecting saturation and stator resistance equation (3) and (5) become

$$P_{syn} = \frac{V\,E_f}{X_s}\cos\delta \;\ldots\ldots(6)$$

$$\tau_{syn} = \frac{V\,E_f}{2\text{ pi }n_s\,X_s}\cos\delta \;\ldots\ldots.\,(7)$$

For a salient pole machine

$$P = \frac{V\,E_f}{X_s}\sin\delta + \frac{1}{2}V^2\left(\frac{1}{X_d} - \frac{1}{X_q}\right)\sin 2\delta \;\ldots\ldots(8)$$

$$P_{syn} = \frac{V\,E_f}{X_s}\cos\delta + V^2\left(\frac{1}{X_d} - \frac{1}{X_q}\right)\cos 2\delta \ldots\ldots(9)$$

Unit of Synchronizing Power Coefficient P_{syn}:

The synchronizing power coefficient is expressed in watts per electrical radian.Therefore,

$$P_{syn\,1} = \frac{V\,E_f}{X_s}\cos\delta \quad \frac{W}{elec}.\text{radian} \;\ldots\ldots (10)$$

Since, π radians = 180º 1 radian = 180/π degrees

$$P_{syn\,2} = \left(\frac{d\,P}{d\,\delta}\right) \quad {}^{W}\!\Big/\!\left(\frac{180}{\pi}\text{ degrees}\right) \quad \text{or}$$

$$P_{syn\,2} = \left(\frac{d\,P}{d\,\delta}\right)\frac{\pi}{180} \quad \text{W/elec. degree} \quad \ldots\ldots\ldots..(11)$$

If P is the total number of pair of poles of the machine.

$$\theta_{electrical} = p\,\theta_{mechanical}$$

Synchronizing Power Coefficient per mechanical radian is given by the equation shown below:

$$P_{syn\,3} = p\,\frac{d\,P}{d\,\delta} \quad W \;\ldots\ldots..(12)$$

Synchronizing Power Coefficient per mechanical degree is given as:

$$P_{syn\,4} = \frac{p\,\pi}{180}\,\frac{d\,P}{d\,\delta} \quad W \;\ldots\ldots..(13)$$

Synchronizing Torque Coefficient:

Synchronizing Torque Coefficient gives rise to the synchronizing torque coefficient at synchronous speed. That is, the Synchronizing Torque is the torque at which synchronous speed gives the synchronizing power. If τ_{syn} is the synchronizing torque coefficient then the equation isgiven as shown below:

$$\tau_{syn} = \frac{1}{\omega_s}\,m\,\frac{d\,P}{d\,\delta} \quad \text{Nm/elect. radian} \;\ldots\ldots.(14) \quad \text{or}$$

$$\tau_{syn} = \left(\frac{1}{\omega_s}\,m\,\frac{d\,P}{d\,\delta}\right)\frac{p\,\pi}{180} \quad \text{Nm/mech. radian} \;\ldots\ldots.(15)$$

Where,

- m is the number of phases of the machine
- $\omega_s = 2\pi n_s$
- n_s is the synchronous speed in revolution per second

$$\tau_{syn} = \frac{P_{syn}}{\omega_s} = \frac{P_{syn}}{2\pi n_s} \;\ldots\ldots..(16)$$

Significance of Synchronous Power Coefficient:

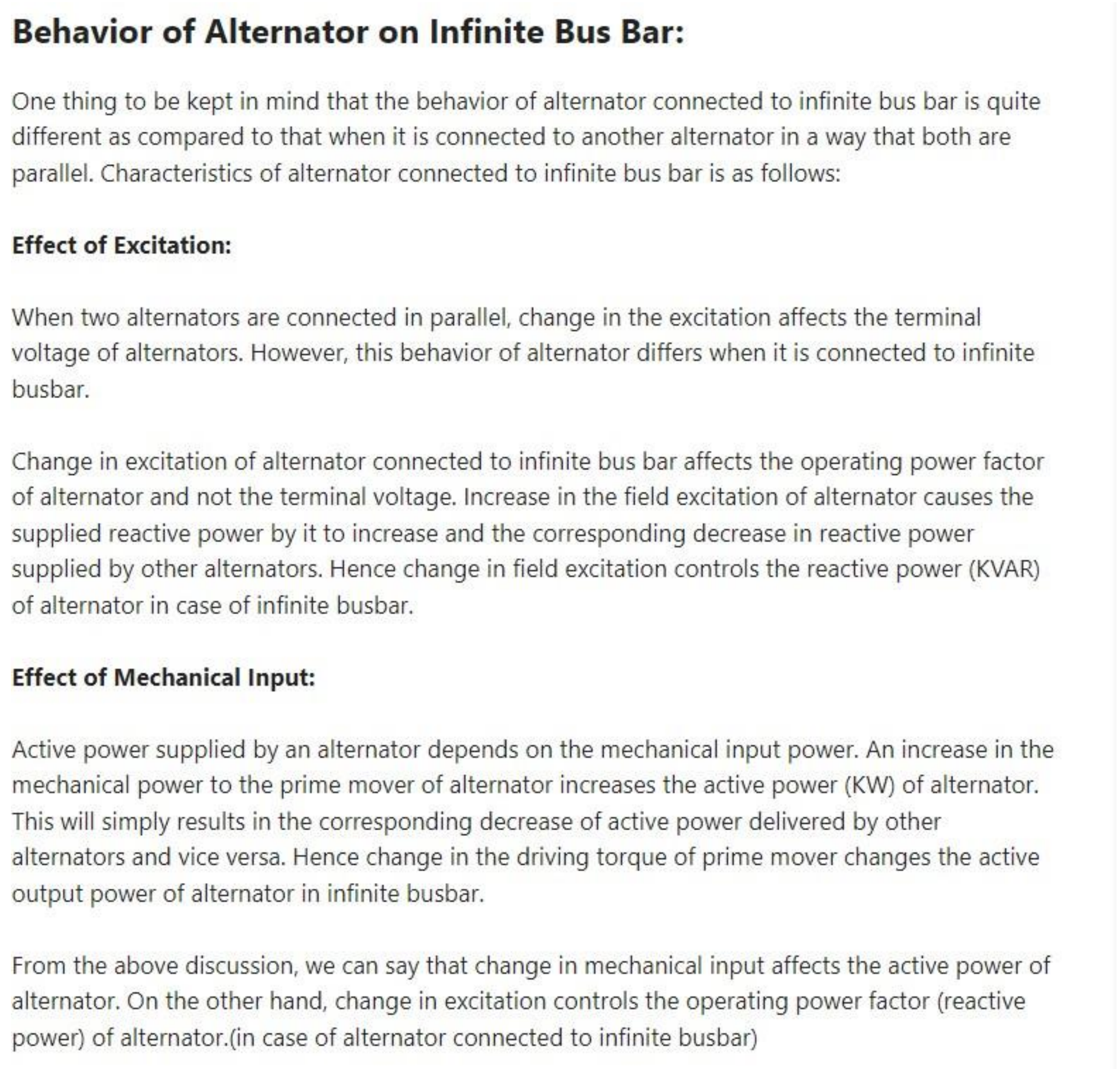
The Synchronous Power Coefficient P_{syn} is the measure of the stiffness between the rotor and thestator coupling. A large value of P_{syn} indicates that the coupling is stiff or rigid. Too rigid a coupling means and the machine will be subjected to shock, with the change of load or supply. These shocks may damage the rotor or the windings. We have,

$$P_{syn} = \frac{3\,V\,E_f}{X_s}\cos\delta \;\ldots\ldots.(17)$$

$$\tau_{syn} = \frac{3}{2\pi n_s}\,\frac{V\,E_s}{X_s}\cos\delta \;\ldots\ldots(18)$$

The above two equations (17) and (18) show that P_{syn} is inversely proportional to the synchronous reactance. A machine with large air gaps has relatively small reactance. The synchronous machine with the larger air gap is stiffer than a machine with a smaller air gap. Since P_{syn} is directly proportional to E_f, an overexcited machine is stiffer than an under excited machine.

The restoring action is great when $\delta = 0$, that is at no load. When the value of $\delta = \pm 90^o$, the restoring action is zero. At this condition, the machine is in unstable equilibrium and at a steady-state limitof stability. Therefore, it is impossible to run a machine at the steady-state limit of stability since its ability to resist small changes is zero unless the machine provided with a special fast-acting excitation system.



Behavior of Alternator on Infinite Bus Bar:

One thing to be kept in mind that the behavior of alternator connected to infinite bus bar is quite different as compared to that when it is connected to another alternator in a way that both are parallel. Characteristics of alternator connected to infinite bus bar is as follows:

Effect of Excitation:

When two alternators are connected in parallel, change in the excitation affects the terminal voltage of alternators. However, this behavior of alternator differs when it is connected to infinite busbar.

Change in excitation of alternator connected to infinite bus bar affects the operating power factor of alternator and not the terminal voltage. Increase in the field excitation of alternator causes the supplied reactive power by it to increase and the corresponding decrease in reactive power supplied by other alternators. Hence change in field excitation controls the reactive power (KVAR) of alternator in case of infinite busbar.

Effect of Mechanical Input:

Active power supplied by an alternator depends on the mechanical input power. An increase in the mechanical power to the prime mover of alternator increases the active power (KW) of alternator. This will simply results in the corresponding decrease of active power delivered by other alternators and vice versa. Hence change in the driving torque of prime mover changes the active output power of alternator in infinite busbar.

From the above discussion, we can say that change in mechanical input affects the active power of alternator. On the other hand, change in excitation controls the operating power factor (reactive power) of alternator.(in case of alternator connected to infinite busbar)

Analysis Of Short Circuit Current Wave Form:

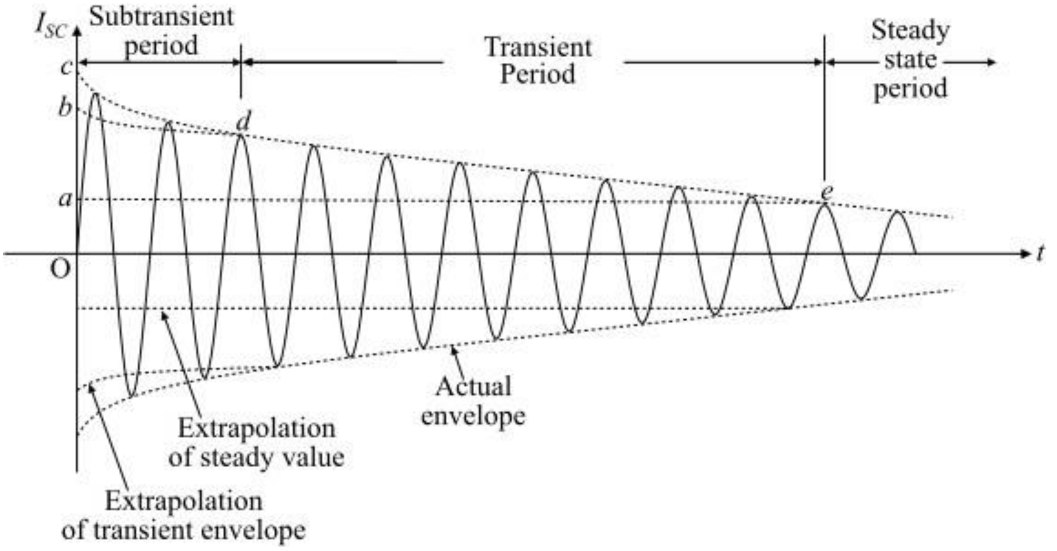
A sudden 3-phase short-circuit at the armature terminals of a synchronous machine is used to analyze the transient phenomenon. This is the most severe transient condition that can occur in a synchronous generator. It is assumed that the machine is to be initially unloaded and to continueoperating at synchronous speed after short-circuit occurs.

The machine being producing normal voltage under no-load condition and their instantaneousvalues are given by,

$e_R=E_m\sin\omega t$ $e_Y=E_m\sin(\omega t-120°)$$e_B=E_m\sin(\omega t+120°)$

Since the machine is initially unloaded, the only pre-disturbance current in the machine is the fieldcurrent. When the rotor rotates, each phase sees a resultant time varying flux linkage.

Now, if the armature terminals are short-circuited, a large transient current will flow through them. According to the constant flux linkage theorem, the currents flowing through the armature windings maintain their flux linkage constant at the prefault values. The transient current in each phase consists of an AC component and a DC component. Since, the three phase voltages are displaced by 120°, thus short-circuit occurs at different points on the voltage waves of each phase. As a result, the DC component of the armature current is also different in each phase.



The above figure shows the AC component of the symmetrical short circuit current and it may be divided into roughly three periods viz. sub transient period, transient period and steady-state period.

1. Sub transient Period:

The sub transient period lasts for only about 2 cycles after the fault occurs. During this period, the current in the armature is very large and decays very rapidly. The RMS value of initial current, which is the current at the instant of short-circuit, is known as the sub-transient current and is denoted by I''.

The time constant of the sub-transient current is denoted by τ'' and it is determined from the slopeof the sub-transient current. The reactance of the winding corresponding to I'' is called the sub- transient reactance (X_d''). The sub-transient reactance is due to the presence of damper windings.If E_0 is the open-circuit phase voltage, then

Sub transient reactance, $X_d''=E_0/I''$

Where I'' is the sub transient current without DC offset. This current is about 5 to 10 times of therated current. Hence, during the sub transient period, there is a large initial current flow in the armature. This current lag 90° behind the voltage.

The sub transient current produces a large demagnetizing MMF in the direct axis, which tends to reduce the main field pole MMF. But the main field flux cannot decrease suddenly because the stored energy associated with this flux takes some time to dissipate.

Also, according to the constant-flux linkage theorem, currents are induced in the field and damper windings which will try to maintain the flux linkage conditions in the machine exactly as they were at the instant of short-circuit at the armature terminals. Since, these transients disappear after few cycles, thus these are called sub transients.

2. Transient Period:

The transient period is the period of time during which current falls at a slow rate. The transient period lasts for about 30 cycles. During this period, current flowing in the machine is called the transient current and is denoted by I′I′. The transient current is caused by a DC component of current induced in the field winding at the instant of short-circuit. The transient period is much greater than the sub transient period because the time constant of the DC field winding is much greater than the time constant of the damper windings. The time constant of the transient current is denoted by τ′.

The value of the RMS current during the transient period is about 5 times of the steady-state fault current. The reactance of the winding corresponding to I’ is called the transient reactance and is denoted by X_d'. Now, if E_0 is open-circuit phase voltage, then

Transient reactance, $X'_d = E_0/I'$

3. Steady-State Period:

After the transient period, the fault current reaches its new steady-state value. The steady state current is denoted by I_{ss}. The reactance corresponding to I_{ss} is called synchronous reactance (X_d) and is given by,

Synchronous reactance, $X_d = E_0/I_{ss}$

Where, E_0 is the open circuit phase voltage.

Again, the RMS value of the fault current varies continuously with time. At any instant after a short-circuit fault occurs at the terminals of the machine, the fault current is given by,

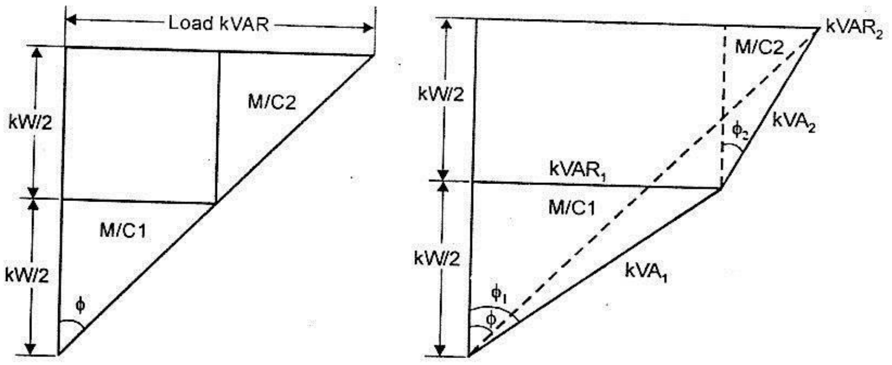
$$I_{sc}(t) = (I'' - I')e^{-t/\tau''} + (I' - I_{ss})e^{-t/\tau'} + I_{ss}$$

Change In Excitation and Mechanical Input in Synchronous Machine:

When an alternator is running in parallel with other alternator, the load taken up by it is totally determined by driving torque or the power input of the prime mover. If any change of excitation is carried out, it does not change its kW output but merely changes kVA or merely changes the power factor at which the load is delivered.

Change of excitation:

Let us assume that the two alternators operating in parallel are identical, that is, they are supplyinghalf of the active load and reactive load or, equal to the power factor of the load. If the excitation of the alternator 1 is increased $E_1 > E_2$ and it causes a circulating current ( ) which flows through



the armature and round the bus bars. From the shown in the below diagram, (Ic) is added vectorially to the load current of alternator 1 and subtracted from the load current of alternator 2 which causes a change in load current. Therefore, alternator 1 and alternator 2 will deliver the loadcurrent at power factor cos Ø1 and cos Ø2 respectively where cos Ø1 > cos Ø2. Although the two machines deliver the load currents at different power factors, it has no effect on kW output, but kVAR supplied by alternator 1 is increased whereas kVAR supplied by alternator 2 is decreased as shown in the below diagram.

FIG: Effect of change in excitations

Change In Mechanical Input or Steam Supply:

Let us assume that the excitation of the alternators remains unaltered during their operation in parallel. Let the steam supply to alternator 1 be increased, so that input to its prime mover is increased. Alternator 1 cannot over run alternator 2 because the speeds of the two alternators are tied by their synchronous bond. E_1 advances E_2 by a small angle δ.

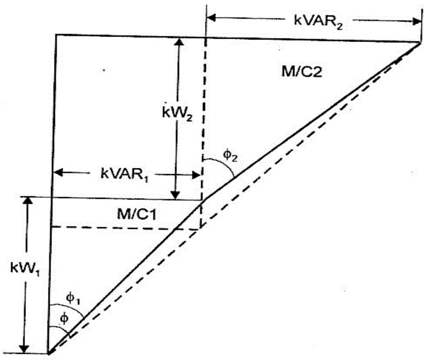


Fig: Effect of change of stream supply

Hence resultant voltage (Er) is produced and it acts on the local circuit resulting in a current

Ir which lags Er by an angle 90˚. Therefore, power per phase of alternator 1 is increased whereas power per phase of alternator 2 is decreased. Since the increase in steam input has no effect on the division of reactive power, the active power output of alternator 1 is increased whereas active power output of alternator 2 is decreased.

Synchronous Motors:

Definition: The motor which runs at synchronous speed is known as the synchronous motor. The synchronous speed is the constant speed at which the motor generates the electromotive force. The synchronous motor is used for converting the electrical energy into mechanical energy.

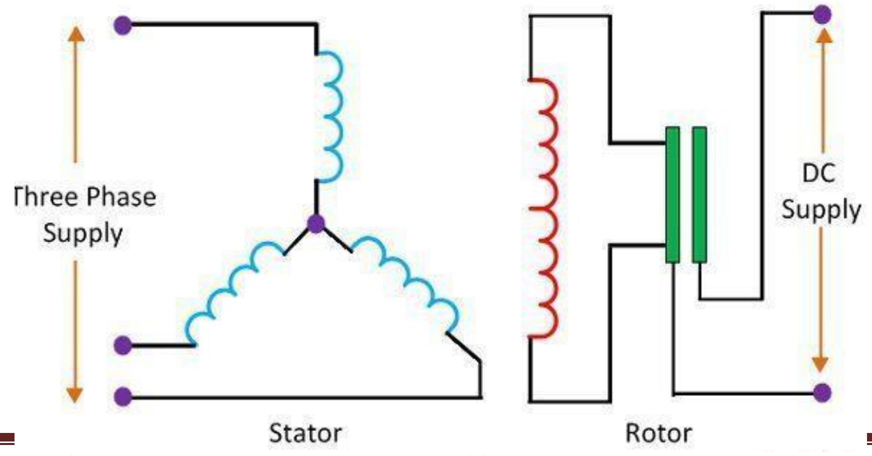
Construction of Synchronous Motor:

The stator and the rotor are the two main parts of the synchronous motor. The stator becomes stationary, and it carries the armature winding of the motor. The armature winding is the main winding because of which the EMF induces in the motor. The rotor carries the field windings. The main field flux induces in the rotor. The rotor is designed in two ways, i.e., the salient pole rotor and the non-salient pole rotor.

The synchronous motor uses the salient pole rotor. The word salient means the poles of the rotor projected towards the armature windings. The rotor of the synchronous motor is made with the laminations of the steel. The laminations reduce the eddy current loss that occurs on the winding of the transformer. The salient pole rotor is mostly used for designing the medium and low-speed motor. For obtaining the high-speed cylindrical rotor is used in the motor.

Working Principle of a Synchronous Motor:

The stator and the rotor are the two main parts of the synchronous motor. The stator is the stationary part of the motor and the rotor is their rotating part. The stator is excited by the three- phase supply, and the rotor is excited by the DC supply. The term excitation means the magnetic field induces in the stator and rotor of the motor. The main aim of the excitation is to convert the stator and rotor into an electromagnet.



The three-phase supply induces the north and south poles on the stator. The three-phase supply is sinusoidal. The polarity (positive and negative) of their wave changes after every half cycle and because of this reason, the north and south pole also varies. Thus, we can say that the rotating magnetic field develops on the stator.

The magnetic field develops on the rotor because of the DC supply. The polarity of the DC supplybecomes fixed, and thus the stationary magnetic field develops on the rotor**.** The term stationary means their north and south pole remains fixed.

The speed at which the rotating magnetic field rotates is known as the synchronous speed. The synchronous speed of the motor depends on the frequency of the supply and the number of poles of the motor.

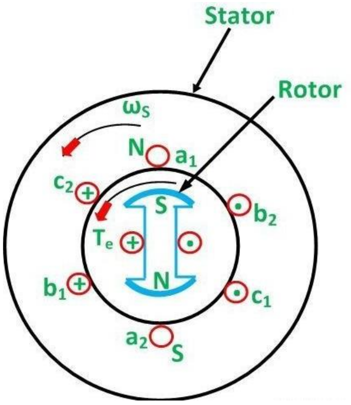
$$\mathbf{N_S = 120f/P}$$

When the opposite pole of the stator and rotor face each other, the force of attraction occurs between them. The attraction force develops the torque in the anti-clockwise direction. The torque is the kind of force that moves the object in rotation. Thus, the poles of the rotor dragged towardsthe poles of the stator.

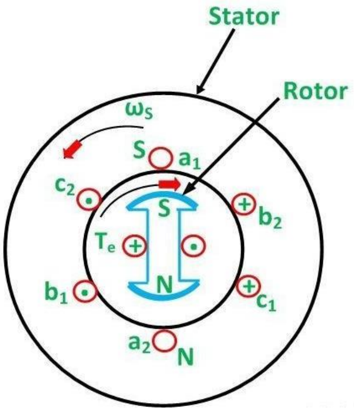
After every half cycle, the pole on the stator is reversed. The position of the rotor remains the same because of the inertia. The inertia is the tendency of an object to remain fixed in one position.

When the like pole of the stator and rotor face each other, the force of repulsion occurs between them and the torque develops in the clockwise direction.

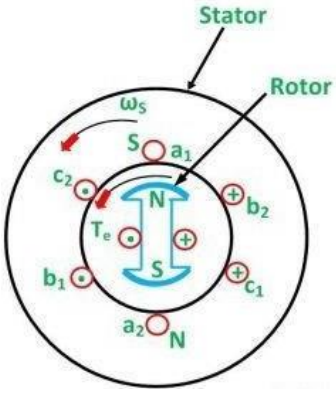
Let understand this with the help of the diagram. For simplicity, consider the motor has two poles. In the below figure, the opposite pole of the stator and rotor face each other. So the attraction forcedevelops between them.



After the half cycle, the poles on the stator reverse. The same pole of the stator and rotor face eachother, and the force of repulsion develops between them.



The non-unidirectional torque pulsates the rotor only in one place and because of this reason thesynchronous motor is not self-starting.



For starting the motor, the rotor is rotated by some external means. Thus, the polarity of the rotoralso changed along with the stator. The pole of the stator and rotor interlock each other and the unidirectional torque induces in the motor. The rotor starts rotating at the speed of the rotating magnetic field, or we can say at synchronous speed.

The speed of the motor is fixed, and the motor continuously rotates at the synchronous speed.

Synchronous Motor Excitation:

For a constant field excitation, when the load on the synchronous motor increases the current drawn by the motor increases. But by keeping the load constant we can operate a synchronous motor at different power factors by varying the field excitation. Let us see such a desirable operation of a synchronous motor.

Effect of Excitation on Synchronous Motor at Constant Load:

When a synchronous motor is loaded and load is kept constant, the input power drawn by the motorwill remain constant i.e., $\sqrt{3}$ VI cos φ is constant. Since the input voltage V and input power are constant, I cos φ i.e., the active component of current is constant, for a constant load.

When excitation is changed, the magnitude of induced emf changes. The load angle, α is alsoconstant for a constant load.

- E_r = Resultant voltage between $\overline{V}$ and $\overline{E}_b = I_a Z_a$
- θ = Internal angle = Angle between $\overline{E}_r$ and $\overline{I}_a = \tan^{-1} (X_s / R_a)$
- I_a = Armature current
- φ = Power factor angle = Angle between $\overline{V}$ and $\overline{I}_a$

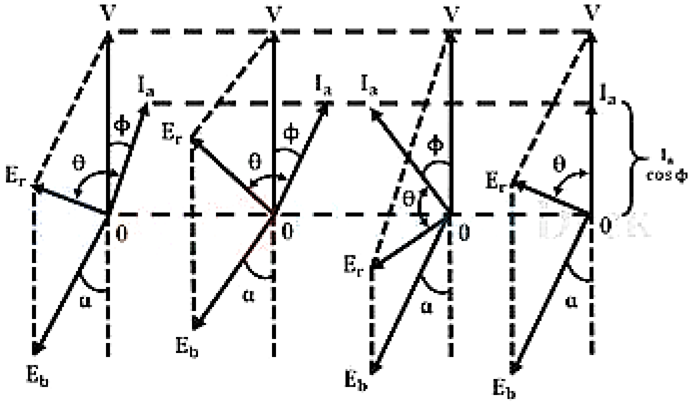
Case - 1:

When the excitation is reduced in such a way that induced emf is equal to applied voltage$E_b = V$ as shown in the below figure (a). Such excitation is called 'Normal Excitation'. At this condition motor works at lagging power factor i.e., Ia lags V by an angle φ.

Case - 2:

When the excitation is reduced in such a way that $E_b < V$, the motor is said to 'Under Excited'. The resultant emf E_r advanced in a clockwise direction and as an angle θ is constant, I_a also moves in the clockwise direction.

As seen from figure (b) angle φ is increased and the power factor is decreased. To maintain $I_a\cos\varphi$ constant, I_a is increased. Therefore, for low values of excitation, I_a increases and the power factor is lagging in nature.



(a) $E_b = V$ (b) $E_b < V$ (c) $E_b > V$ (d) $E_b \simeq V$

Case - 3:

When excitation is increased in such a way that $E_b > V$, the motor is said to be 'Over-Excited'. The resultant emf E_r is moved in the anti-clockwise direction and so the I_a also moves in an anti-clockwise direction (as an angle between E_r and I_a is θ). Current I_a leads voltage by an angle φ asshown in figure (c).As excit
values of excitation, current I_a increases and power factor is leading in nature.

Case - 4:

For the unity power factor, E_b is slightly greater than V ($E_b \cong V$). This is shown in figure (d). The excitation for which the motor is operated at unity p.f. is called 'Critical Excitation'. Then I_a is in phase with V. Now $I_a \cos \varphi$ = constant, $\cos \varphi = 1$ is at its maximum hence I_a is minimum at this condition.

The Above Conditions Clearly Indicates the Following:

Under Excitation	Lagging p.f.	Eb < V
Over Excitation	Leading p.f.	Eb > V
Critical Excitation	Unity p.f.	Eb ≅ V
Normal Excitation	Lagging p.f.	Eb = V

- A synchronous motor draws a lagging current when it is under-excited.
- At critical excitation, it draws a minimum armature current and the power factor isunity.
- The motor draws a leading current when it is over-excited.

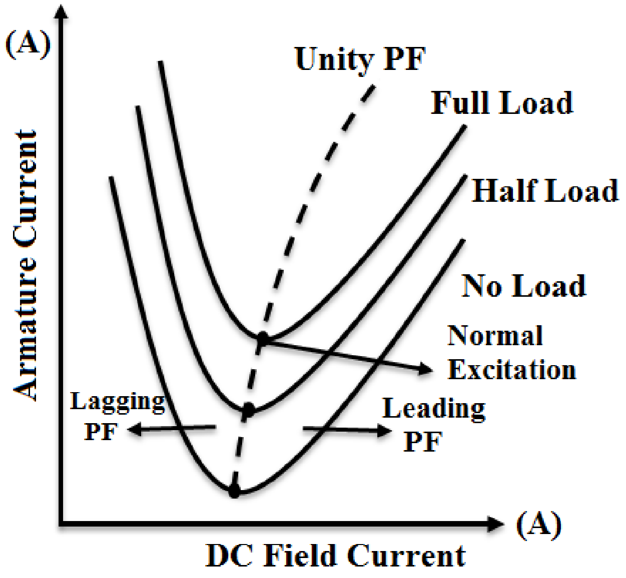
V Curves and Inverted V Curves of Synchronous Motor:

The performance characteristics of a synchronous motor are obtained by v-curves and inverted v- curves. Synchronous machines have parabolic type characteristics (the graph drawn is in the shape of parabolic). If the excitation is varied from low (under-excitation) to high (over-excitation) value, then the current I_a also changes i.e., becomes minimum at unity p.f. and then again increases. But at starting lagging current becomes unity and then becomes leading in nature. V-curves and inverted V-curves of a synchronous motor are used to analyze efficiency on no-load and on-load conditions.

V-Curves of Synchronous Motor:

If the armature current Ia is plotted against excitation or field current for various load conditions, we obtain a set of curves known as 'V-Curves'.

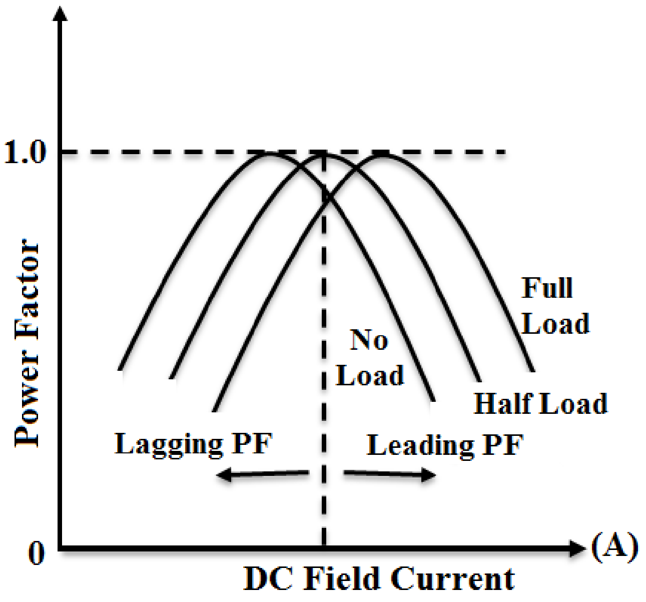
In the below figure V-Curve of a synchronous motor shows how armature current Ia changes with excitation for the same input, at no-load, half full-load, and full-load**.**



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'.

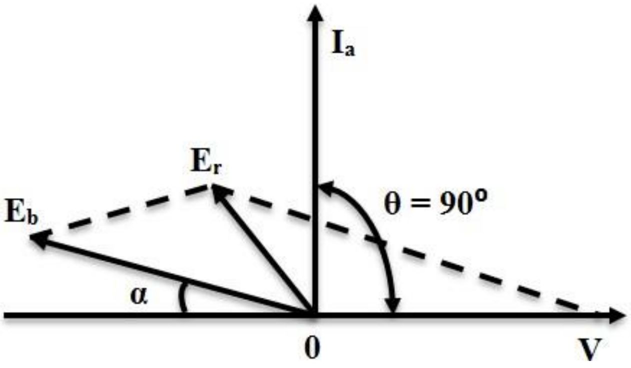


The inverted V-Curves of synchronous motor shows how the power factor varies with excitation.From inverted V-curves, it is observed that the power factor is lagging when the motor is under excited and leading when it is over-excited. In between, the power factor is unity.

Synchronous Condenser (or) Synchronous Capacitor:

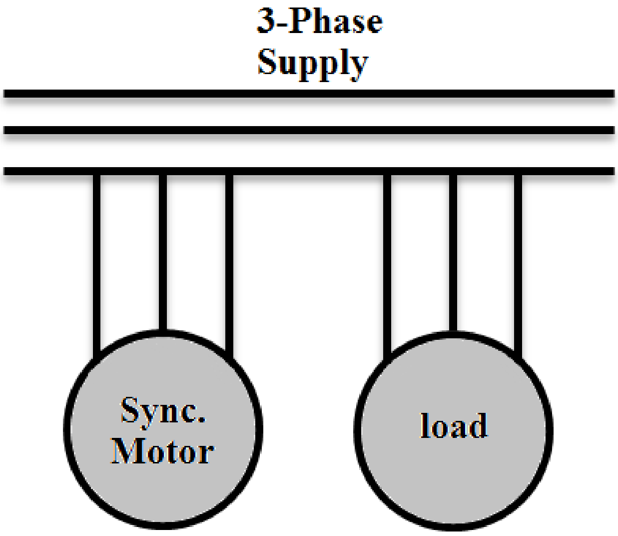
If a synchronous motor is on no-load and over-excited ($E_b > V$) then the current drawn by it leads the voltage by nearly 90°. The phasor diagram of the motor at no-load is shown below. Therefore, at this condition when a synchronous motor is over-excited it is called a synchronous condenser.

The characteristics of a synchronous motor at this instant will equal to the characteristics of the capacitor. Hence as the capacitor, an over-excited synchronous motor can be used as a power factorcorrection device.

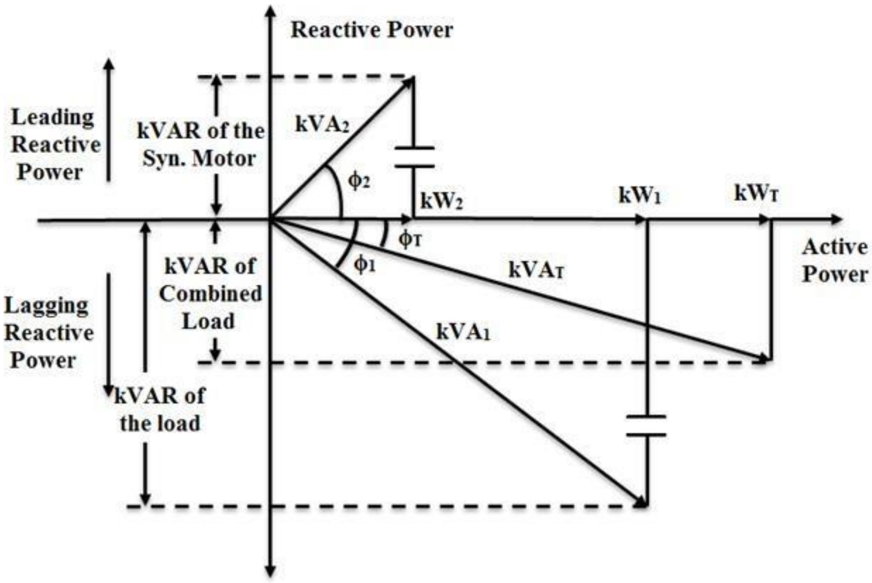


Power Factor Correction:

As we see in industries most of the motors used are induction motors and load such as lights, fans, heaters, etc. will draw lagging currents. These lagging currents will decrease the power factorof the whole unit due to large reactive component. Hence the overall efficiency of the system maydecrease.



The power factor correction is possible by using a synchronous motor (Operating on no-load with over-excitation) in parallel with induction motors or transformers, the leading reactive volt- amperes supplied by the synchronous motor compensate for the lagging reactive volt-amperes of other power apparatus. In this way, a synchronous motor as a synchronous condenser is helpful in improving the overall power factor of the system.



The Figure above shows the phasor diagram of an arrangement for improving the overall power factor of the electrical system using a synchronous system.

The subscript '1' refers to the induction motor (lagging) load. the subscript '2' refers to the synchronous motor and the subscript 'T' to the total load.

Therefore,

- kVA_1, kW_1, and $kVAR_1$ = Apparent active and reactive powers of induction motor load,

- kVA_2, kW_2, $kVAR_2$ = Apparent, active and reactive power of the synchronous motor,

- kVA_T, $kVAR_T$, kW_T = Total apparent, active, and reactive loads.

It is seen that the addition of a synchronous motor improves the power factor from Cos φ_1 to Cos φ_T.

Sign Convention: Lagging kVAR is taken as 'negative' and leading kVAR is taken as 'positive'sign.
kW of the combined (or) total load, kW_T = kW of the load + kW of the synchronous motor

$= kW_1 + kW_2$

kVAR of the synchronous motor, $kVAR_2$ = kVAR of the combined load - kVAR of the load

$= kVAR_T - kVAR_1$

kVA rating of the synchronous motor,

$kVA_2 = \sqrt{(kW_2)^2 + (kVAR_2)^2}$

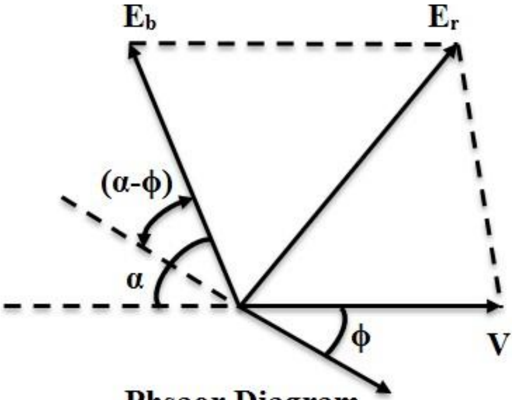
Power factor of the synchronous motor,

$Cos\ \varphi_2 = kW_2 / kVA_2$

Power Flow Diagram & Power Developed by Synchronous Motor:

The phasor diagram of a synchronous motor is shown below. From the phasor diagram,let,

- V = Supply voltage / phase
- Ia = Armature current / phase
- Ra = Armature resistance / phase
- α = Load angle
- φ = Power factor angle



Phsaor Diagram

Input Power to Motor:

Motor input power per phase is $V I_a Cos\ \varphi$. 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

$= E_b I_a \cos(\alpha - \varphi)$ for lagging p.f
$= E_b I_a \cos(\alpha + \varphi)$ 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 developedby a synchronous motor as,
$P_m = P - P_{cu}$

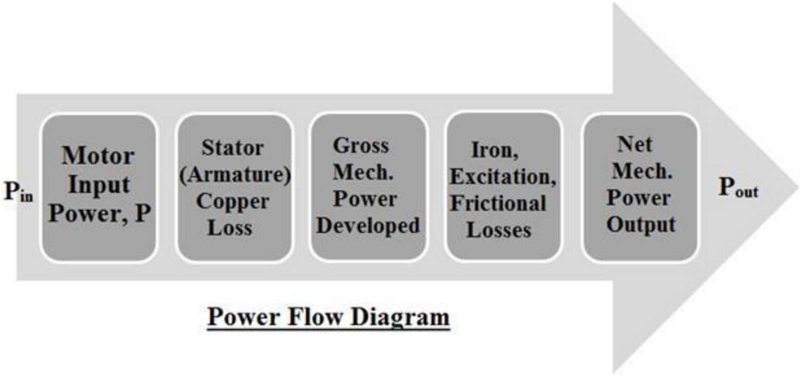
For three-phase,

Power Output of the Motor:
$P_m = \sqrt{3} V_L I_L \cos\varphi - 3 I_a^2 R_a$

To obtain the power output we subtract the iron, friction, and excitation losses from thepower 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, Pout

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 (Xs / Z_s)
- Ia = Armature current / phase = Er / Zs
- $Z_s = R_a + J X_s$ = 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

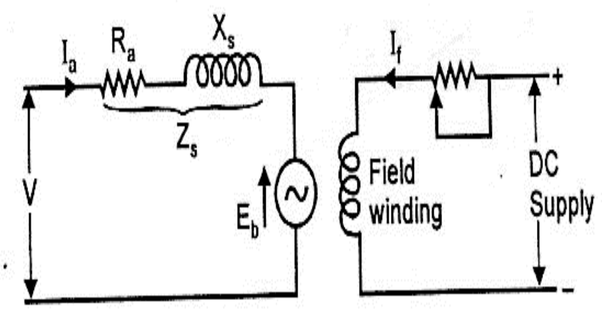
If R_a is neglected, then $Z_s \approx X_s$ and θ = 90°. substituting these values in the above equation.

$$P_m = \frac{E_b V}{X_s}\cos(90 - \alpha) - \frac{E_b^2}{X_s}\cos 90^0$$

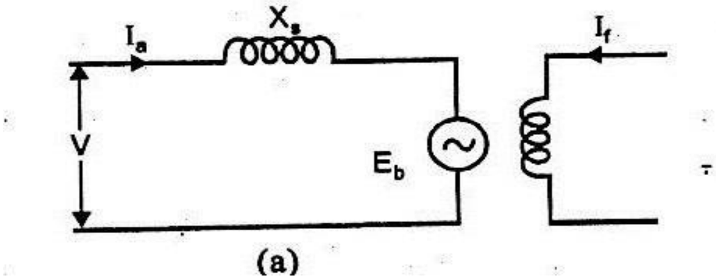
$$P_m = \frac{E_b V}{X_s}\sin\alpha$$

Torque equation for synchronous motor:

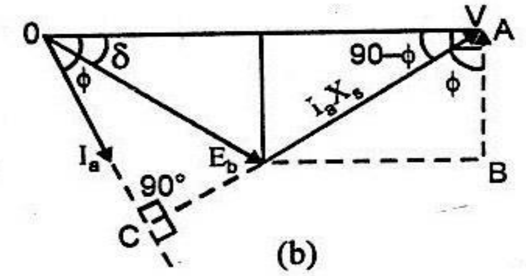
From the equivqlent circuit, the applied voltage V is the vector sum of reversed back emf (ie) –Eband the impedance drop Ia Zs. In other words, V = - Eb + Ia Zs. The angle δ between the phasorsV and Eb is called the load angle or power angle of the synchronous motor.



Except for very small machines,the armature resistance of a synchronous motor is negligible as compared to its synchronous reactance.Hence the equivalent circuit for the motor become as shown in below figureFrom the phasor diagram



(a)

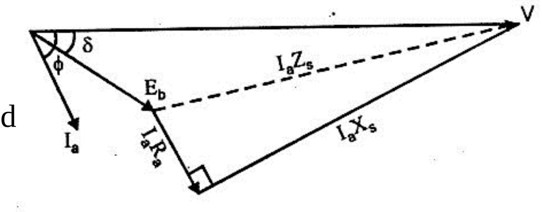


(b)

$$AB = E_b sin\delta\ \ and$$

$$cos\phi = \frac{AB}{I_a X_s}$$

So, AB = $Ia\ Xscos\phi$



Equating above equations for AB and solving for Ia and substituting in P we get,

$$P = VI_a cos\phi$$

$$P = \frac{VE_b sin\delta}{X_s}$$

$$P_{in} = \frac{3E_b V}{X_s} sin\delta\ \ for\ 3\ phases$$

Since stator copper loss has been neglected, $Pin\ also$ representes the gross mechanical power(Pm)developed by the motor

$$P_m = \frac{3E_b V}{X_s} sin\delta$$

Gross torque developed by the motor

$$T = \frac{P_m}{\omega_m}$$

$$T = \frac{3E_b V}{\omega_{m\,X_s}}$$

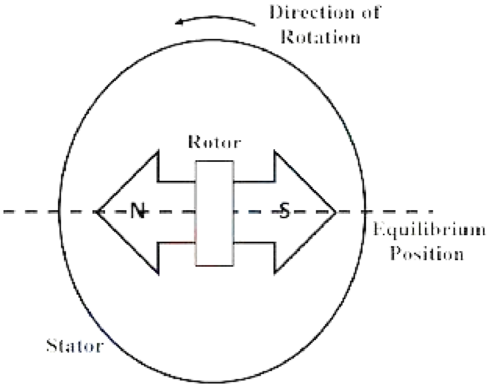
$$\therefore \omega_m = \frac{2\pi N}{60}$$

$$T = \frac{9.55 P_m}{N} Nm$$

Hunting in Synchronous Motor

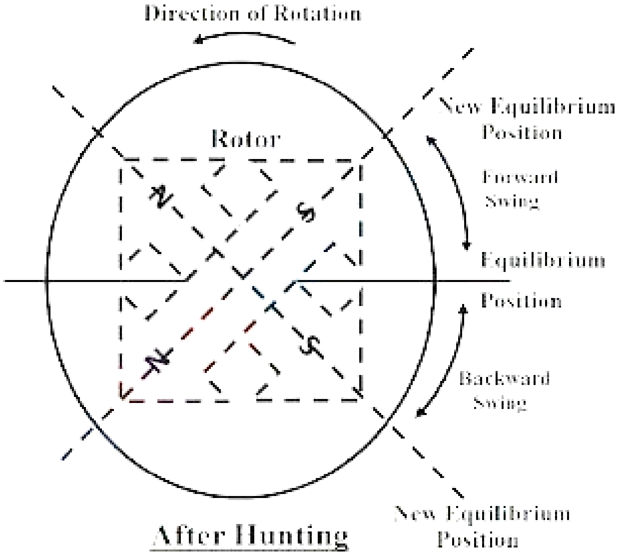
When a synchronous motor is loaded, there exists a phase angle between rotor and field ' α '. When load increases slowly, angle ' α ' also increases so that torque produced is more. So that it can maintain synchronism between the stator and rotating fields and running the load without anyvariation in speed.

Consider a synchronous motor whose rotor is rotating at a synchronous speed. Let, rotor be at an equilibrium position as shown in the below figure.



Before Hunting

When this load on the motor suddenly falls then angle ' α ' also changes accordingly to the new load. But in this process, the rotor overshoots, and the shaft of the motor starts oscillating from itsposition (swinging forward and backward like a pendulum) as shown in the below figure. These oscillations make the motor cause 'hunting' for the right position. This phenomenon is also knownas phase swinging (or) surging.



After Hunting

If this frequency of oscillations is equal to the natural frequency, then mechanical resonance is setup and the amplitude of the swing of the rotor poles relative to the poles of the rotating field becomes so great that the machine is thrown out of synchronism.

Hunting is an objectionable characteristic of synchronous motors, due to this the power drawn bythe motor can vary which can change the working performance of the motor.

Causes of Hunting:

i.Driving a motor for varying load:

The main cause of the hunting or phase swinging in a synchronous motor is due to changing load conditions. Frequent variation of load on a synchronous motor can affect its speed. Also, synchronous motor can withstand the changes in load condition. But, when it reaches a certain permissible value it may affect motor performance.

ii. If the frequency is pulsating:

If the nature of the supplied frequency is pulsating it may result in hunting. Due to which there will be a production of vibrations on the rotor shaft and it starts swinging. The variable frequencypower supply causes the torque pulse vibrations on the rotor.

iii. Change in field current:

We know that the internal generated voltage or EMF is directly proportional to the field current. Due to variation in supply current to the field poles varies the strength of the poles. But, when this variation is more than withstand value. The motor becomes unstable and thrown out of synchronism.

iv. Faults in supply given:

Hunting in the synchronous motor is also caused when there is a fault in the supply given to the motor. This changes the normal working conditions of the motor.

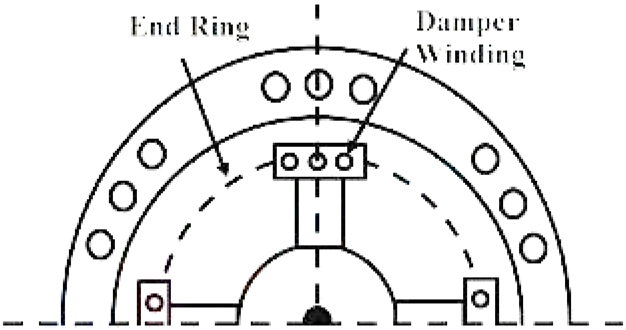
Prevention of Hunting in Synchronous Motor:

1. Use of Damper Winding:

Hunting or Phase swinging in a synchronous motor is prevented by making a change in theconstruction of the rotor.

Special bars of conductors are embedded in the field poles of the motor. The ends of these conductors are short-circuited without any electrical connection as seen in the construction of a squirrel cage rotor in a squirrel cage induction motor. This arrangement in a synchronous motoris known as ' Damper Winding '.

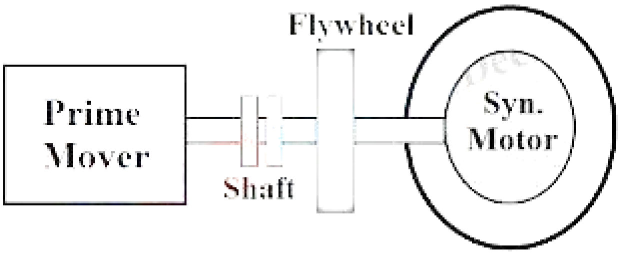
The damper winding is not only used for starting the synchronous motor. When there are any oscillations in the rotor as the damper winding is short-circuited. Due to the relative motion, the damper winding generates a rotating mmf that suppresses out the oscillations as shown in the below figure.



Damper Winding Placed on Poles

Under normal conditions i.e., when the motor runs at synchronous speed, no such currents are induced in it, and there is no effect of damper winding on the main winding. However, the damper winding cannot prevent the oscillations completely. But it can prevent the motor from running outof its synchronism.

2. **Use of Flywheel:**



A flywheel is an external arrangement connected between the motor and prime mover of that motor. Usually, a high weighted flywheel is used for this purpose. Due to its great inertia, it stabilizes the relative motion of the rotor due to oscillations, and it controls the rotation without any variation in speed.

Starting Methods of Synchronous Motor:

A device that converts electrical energy into mechanical energy running at synchronous speed is called Synchronous Motor. Its speed is constant irrespective of load. It is a doubly excited machinebecause its field winding is excited from a separate dc source. But the synchronous motor is not self-starting. The average synchronous motor torque is zero at the start. For a net average torque, it is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible throughvarious methods in practice.

The different methods used to start a synchronous motor are :

1. Using Pony Motors:

By using the small pony motors like a small induction motor, we can start the synchronous motor. This small induction motor is coupled to the rotor of the synchronous motor. The function of this induction motor is to bring the rotor of the synchronous motor to the synchronous speed.

Once the rotor attains the synchronous speed the pony motor is dis-coupled from the rotor. The synchronous motor continues to rotate at synchronous speed, by supplying d.c. excitation to the rotor through the slip-rings. One should remember that the motor used as the pony motor must have less number of poles than the synchronous motor used.

2. Using Small D.C. Machine:

In the above method, we have a seen small induction motor to start the motor. Here we use d.c. motor instead of induction motor to bring the motor to synchronous motor.

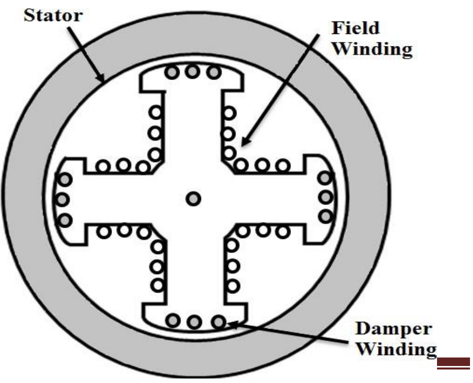
Once the d.c. motor brings the rotor of the synchronous motor to synchronous speed. Themotor starts acting as the d.c. generator and starts giving excitation to the field winding of thesynchronous motor.

3. Using Damper Winding:

When a 3-phase supply is given to the synchronous motor it fails to start. In order to make it start copper bars circuited at both ends (similar to the squirrel cage rotor of an induction motor) are placed on the rotor, these bars or winding are known as 'Damper Winding'.

Now when the supply is given the field winding setups a rotating magnetic field. Due to the damper winding used, the rotor starts rotating as an induction motor i.e., less than the synchronous speed at starting. Once d.c. excitation is given to the field winding and the motor is then pulled into synchronism.

The damper winding is used to start the motor and hence can be used for starting purposes only. Because once the rotor rotates at synchronous speed the relative motion between the damper winding and rotating magnetic will be equal, and hence induced emf and current will be zero. The damper winding will be out of

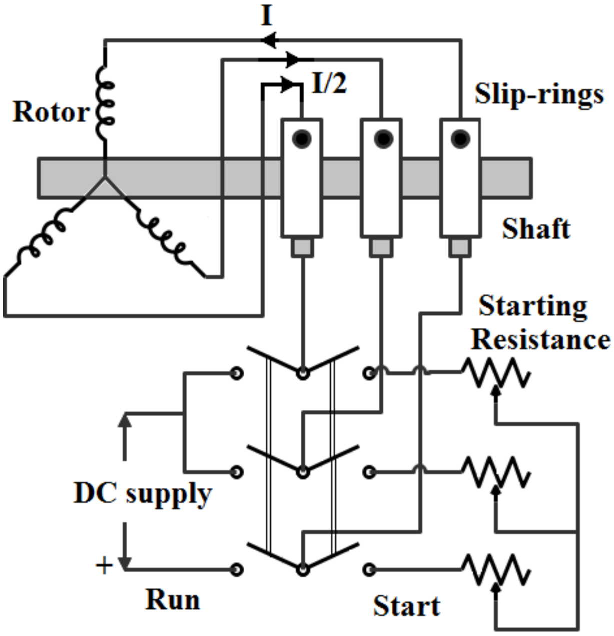


the circuit.

4. As a Slip Ring Induction Motor (Synchronous Induction Motor):

In this method, an external rheostat is connected to the rotor through slip-rings. Here, ends of the damper winding are brought of the motor and connected either in star or delta. The rheostat isconnected in series with the rotor. At starting high resistance is connected with the rotor to limitedthe current drawn by the motor. As the motor starts as a slip ring induction motor at starting, it draws large currents.

When the motor picks up its speed, resistance is gradually cut off from the rotor circuit. As the speed reaches near to synchronous speed, d.c. excitation is given to the rotor and it is pulled into synchronism.



The above figure shows the rheostat connected with the rotor circuit through slip-rings. From the figure as the dc supply is given current 'I' flows through the positive terminal, then it divides as 'I/2' through each phase at star point.

From these methods, damper winding is the most common method of starting a synchronous motor.

Difference Between Synchronous and Asynchronous Motor:

BASIS	**SYNCHRONOUS MOTOR**	**ASYNCHRONOUS MOTOR**
Definition	Synchronous motor is a machine whose rotor speed and the speed of the stator magnetic field is equal. N= NS = 120f/P	Asynchronous motor is a machine whose rotor rotates at the speed less than the synchronous speed. N < NS
Type	Brushless motor, Variable Reluctance Motor, Switched Reluctance Motor and Hysteresis motor are the synchronous motor.	AC Induction Motor is known as the Asynchronous Motor.
Slip	Does not have slip. The value of slip is zero.	Have slip therefore the value of slip is not equal to zero.
Additional power source	It requires an additional DC power source to initially rotate the rotor near tothe synchronous speed.	It does not require any additional starting source.
Slip ring and brushes	Slip ring and brushes are required	Slip ring and brushes are notrequired.
Cost	Synchronous motor is costly as compared to Asynchronous motor	Less costly
Efficiency	Efficiency is greater than Asynchronous motor.	Less efficient

BASIS	**SYNCHRONOUS MOTOR**	**ASYNCHRONOUS MOTOR**
Power factor	By changing excitation, the power factor can be adjusted accordingly as lagging, leading or unity.	Asynchronous motor runs only at a lagging power factor.
Current supply	Current is given to the rotor of the synchronous motor	The rotor of Asynchronous motor does not require any current.
Speed	The Speed of the motor does not depend on the variation in the load. It is constant.	The Speed of the Asynchronous motor decreases with the increasing load.
Self-starting	Synchronous motor is not self-starting	It is self-starting
Affect in torque	Change in applied voltage does not affect the torque of the synchronous motor	Change in applied voltage does affect the torque of the Asynchronous motor
Operational speed	They operate smoothly and relatively good at low speed that is below 300 rpm.	Above 600 rpm speed motor operation is excellent.
Applications	Synchronous motors are used in Power stations, manufacturing industries etc. itis also used as voltage controller.	Used in Centrifugal pumps and fans, blowers, paper and textile mills, compressors and lifts. etc

- Synchronous motor is a motor that operates at synchronous speed, i.e., speed of the rotor is equal to the stator speed of the motor. It follows the relation $N = N_S = 120f/P$, where N is the rotor speed and Ns is the synchronous speed.
- Asynchronous motor is an AC Induction motor. The rotor of the Asynchronous motor rotates at the speed less than the synchronous speed, i.e., $N < N_S$

UNIT – V

SINGLE PHASE & SPECIAL MACHINES

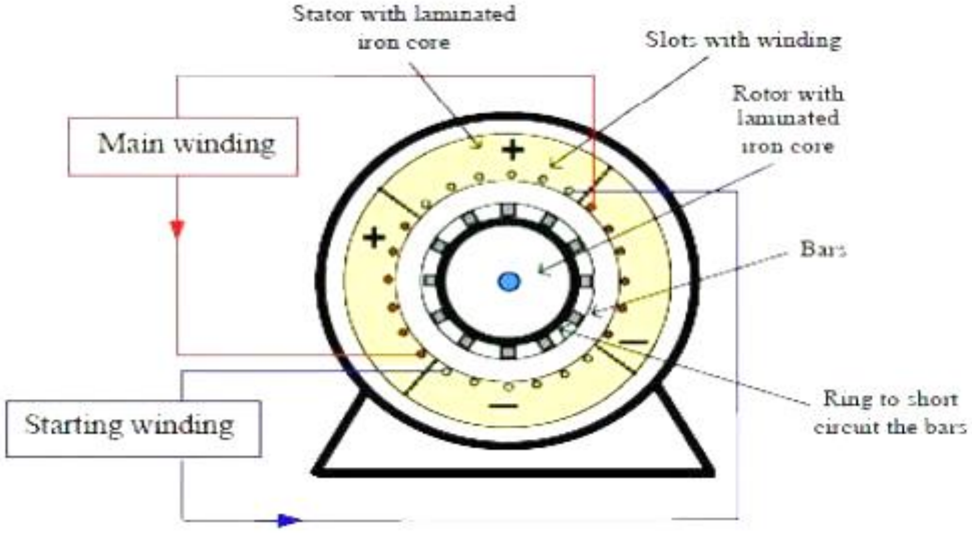
Introduction:

The single-phase motors are more preferred over a three-phase induction motor for domestic, commercial applications. Because form utility, only single-phase supply is available. So, in this type of application, the three-phase induction motor cannot be used.

Construction of Single-Phase Induction Motor:

A single-phase induction motor is similar to the three-phase squirrel cage induction motor except there is single phase two windings (instead of one three phase winding in 3-phase motors) mounted on the stator and the cage winding rotor is placed inside the stator which freely rotates with the help of mounted bearings on the motor shaft.

The construction of a single-phase induction motor is similar to the construction of a three-phase induction motor.



Similar to a three-phase induction motor, single-phase induction motor also has two main parts;

- Stator
- Rotor

Stator:

In stator, the only difference is in the stator winding. The stator winding is single-phase winding instead of three-phase winding. The stator core is the same as the core of the three-phase induction motor.

In a single-phase induction motor, there are two winding are used in stator except in shaded-pole induction motor. Out of these two windings, one winding is the main winding and the second is auxiliary winding.

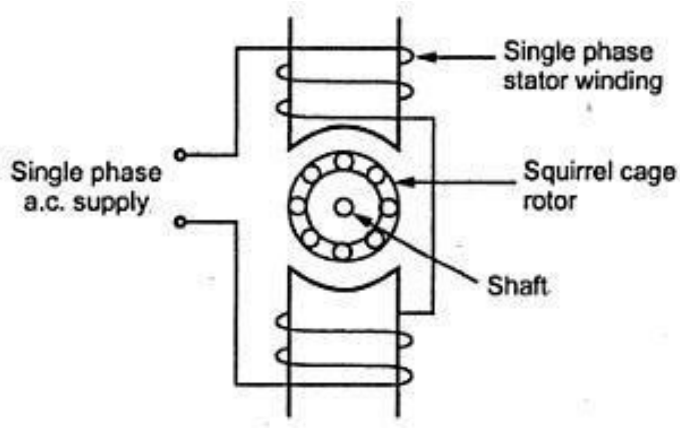
The stator core is laminated to reduce the eddy current loss. The single-phase supply is given to the stator winding (main winding)

Rotor:

Rotor of single-phase induction motor is the same as a rotor of squirrel cage induction motor. Instead of rotor winding, rotor bars are used and it is short-circuited at the end by end-rings. Hence, it makes a complete path in the rotor circuit. The rotor bars are braced to the end-rings to increase the mechanical strength of the motor.

The rotor slots are skewed at some angle to avoid magnetic coupling. And it also used to make a motor run smooth and quiet.

The following fig shows the stator and rotor of a 1-phase induction motor.



Working of Single-phase Induction Motor:

When a single-phase ac supply is given to the single-phase stator winding, a sinusoidally pulsating magnetic field varying with time is produced. As the produced magnetic very two times in a cycle, therefore, no torque will be produced in the rotor and hence the rotor doesn't rotate. Therefore, single-phase induction motors are not self-starting motors.

However, when an initial rotation is given to the rotor, it starts rotating in that direction which can be explained by the double-revolving field theory.

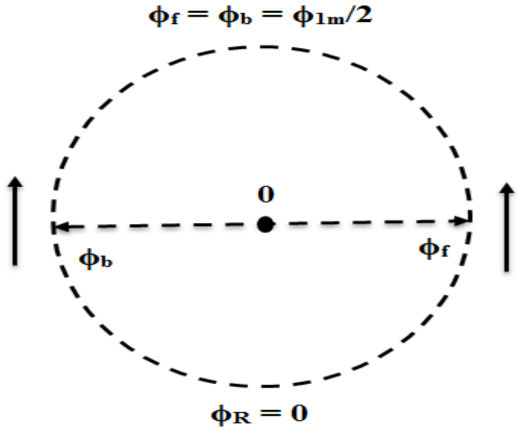
The magnetic field produced by the stator winding when an alternating supply is given is equal to the sum of the two revolving fields rotating at synchronous speed in the opposite direction of equal magnitude. The magnitude of each revolving field is equal to one-half of the maximum value of the alternating field, i.e., $\Phi_{1m}/2$, where Φ_{1m} is the maximum value of an alternating field.

Double Revolving Theory or Double Field Revolving Theory:

Let us consider the two revolving fields as Φ_f (rotating in an anti-clockwise direction) and Φ_b (rotating in a clockwise direction). The resultant Φ_R of these two fields gives the value of the magnetic field produced by the alternating supply (i.e., alternating field).

Consider the Different Instances as Shown Below:

i. The two fields Φ_f and Φ_b are shown opposite to each other at the start, and the resultant magnetic field $\Phi_R = 0$.

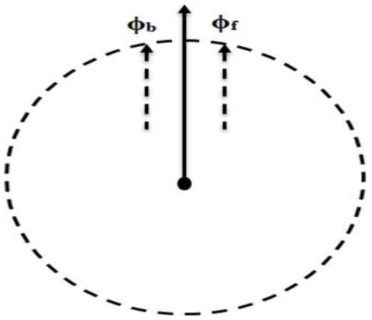


ii. After 90°, the two fields are rotated in such a way that both of them are now pointing in thesame direction. The resultant magnetic field,

$$\phi_R = \phi_f + \phi_b$$

$$= \frac{\phi_{1m}}{2} + \frac{\phi_{1m}}{2} = \phi_{1m}$$

$$\phi_R = \phi_{1m}$$

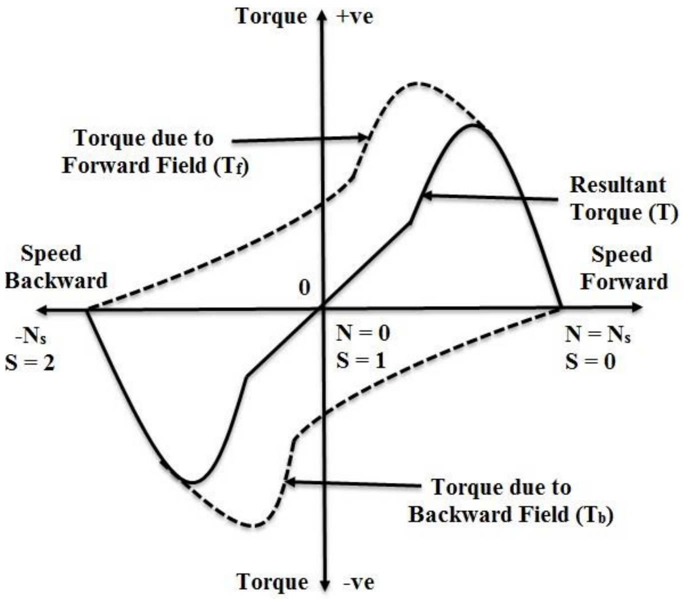


This instant gives maximum the magnitude of the original alternating field. So the continuous rotation of these two fields (components) gives the original stator magnetic field. This is purely alternating in nature.

Now each separate component is rotated and hence gets cut by the rotor conductors. Due to cutting of flux emf gets induced in rotor conductors which circulate in the rotor current. The rotor current produces rotor flux.

The rotor flux interacts with one component Φ_f produces a torque in an anti-clockwise direction and the rotor flux interacts with the second component Φ_b produces a torque in a clockwise direction.

If anticlockwise torque is assumed positive, then the clockwise torque produced by another is negative. The resultant of the two torques at the start is zero. Torque-speed characteristics are shown below.



Following are Important Points About the Resultant Magnetic Field:

1. At the start, the two torques are equal in magnitude but opposite in direction. These two torques try to rotate the rotor in different directions. Hence net torque experienced by the rotor is zero. Therefore, it is said that single-phase induction motors are not self-starting.
2. When initial rotation is given to the rotor in any direction, the overall torque increases in that direction and the motor starts giving performance similar to the 3- phase induction motor.

Types of Single-phase Induction Motors:

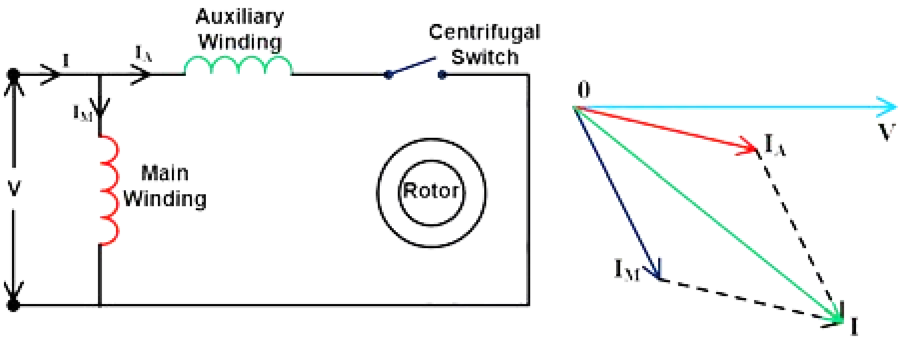
The single-phase induction motors are classified as;

- Split Phase Induction Motor
- Capacitor Start Induction Motor
- Capacitor Start Capacitor Run Induction Motor
- Permanent Capacitor Induction Motor

1. Split Phase Induction Motor:

In this type of motor, an extra winding is wounded on the same core of the stator. So, there are two windings in the stator. One winding is known as the main winding or running winding and second winding is known as starting winding or auxiliary winding. A centrifugal switch is connected in series with the auxiliary winding.

The auxiliary winding is highly resistive winding and the main winding is highly inductive winding. The auxiliary winding has few turns with a small diameter. The aim of auxiliary winding is to create a phase difference between both fluxes produced by the main winding and rotor winding.



The connection diagram is as shown in the above figure. The current flowing through the main winding is I_M and current flowing through the auxiliary winding is I_A. Both windings are parallel and supplied by voltage V. The auxiliary winding is highly resistive in nature. So, the current I_A is almost in phase with supply voltage V.

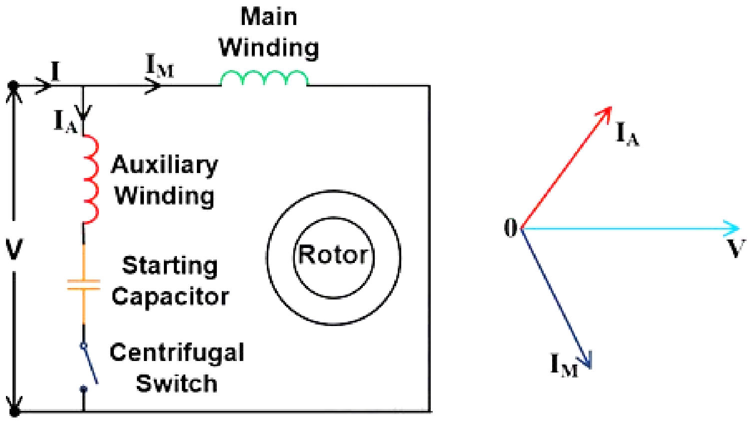
The main winding is highly inductive in nature. So, the current I_M lags behind the supply voltage with a large angle. The total stator flux is induced by the resultant current of these two winding. As shown in the phasor diagram, the resultant current is represented as (I). It will createa phase difference between fluxes and resultant flux produces a rotating magnetic field. And the motor starts rotating.Auxiliary winding only uses to start the motor. This winding is not useful in running condition. When the motor reaches 75 to 80 % of synchronous speed, the centrifugal switch opens. So, the auxiliary winding is out from the circuit. And motor runs on only main winding.

The phase difference creates by this method is very small. Hence, the starting torque of this motor is poor. So, this motor is used in low starting torque applications like a fan, blower, grinder, pumps, etc.

Capacitor Start Induction Motor:

This type of motor is an advanced version of the Split phase induction motor. The disadvantage of split-phase induction is low torque production. Because in this motor, the phase difference created is very less.

This disadvantage compensates in this motor with the help of a capacitor connected in series with auxiliary winding. The circuit diagram of this motor is as shown in the below figure.



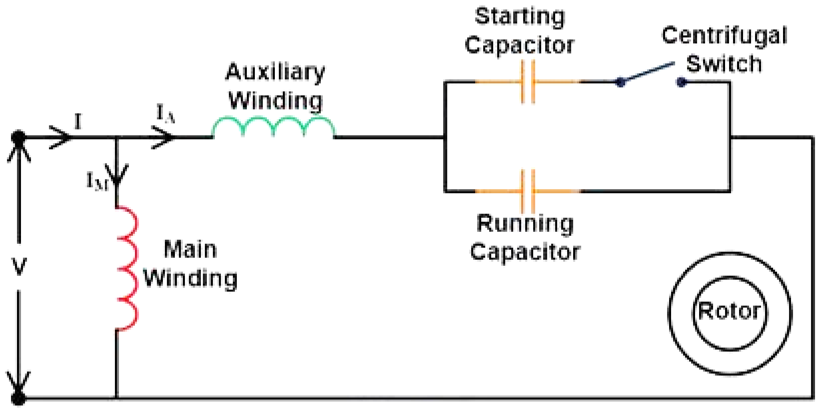
The capacitor used in this motor is a dry-type capacitor. This is designed to use with alternating current. But this capacitor is not used for continuous operation. In this method also, a centrifugal switch is used which disconnects the capacitor and auxiliary winding when the motor runs 75- 80% of synchronous speed.

The current through auxiliary will lead the supply voltage by some angle. This angle is more than the angle increased in a split-phase induction motor. So, the starting torque of this motor is very high compared to the split-phase induction motor. The starting torque of this motoris 300% more than the full load torque.

Due to high starting torque, this motor is used in the applications where high starting torque is required like, a Lath machine, compressor, drilling machines, etc.

Capacitor Start Capacitor Run Induction Motor:

In this type of motor, two capacitors are connected in parallel with series in auxiliary winding. Out of these two capacitors, one capacitor is used only for starting (starting capacitor) and another capacitor is connected permanently with the motor (running capacitor). The circuitdiagram of this figure is as shown in the below figure.

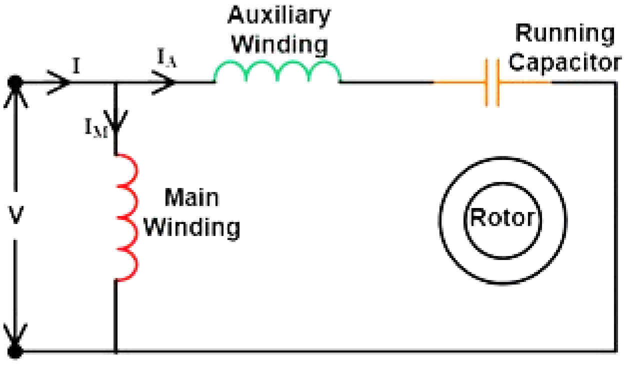


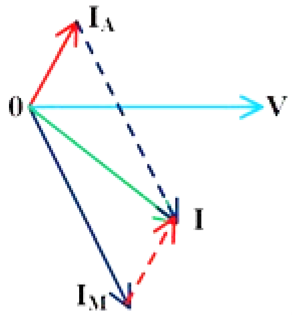
The starting capacitor has high capacitance value and a running capacitor has low capacitance value. The starting capacitor is connected in series with a centrifugal switch that will open when the speed of the motor is 70% of synchronous speed. During running conditions, bothrunning winding and auxiliary winding connected with motor. The starting torque and efficiency of this motor are very high.

Therefore, this can be used in the application where high starting torque is required like a refrigerator, air conditioner, ceiling fan, compressor, etc.

Permanent Capacitor Induction Motor:

The low-value capacitor is connected constantly with the auxiliary winding. Here, the capacitor has low capacitance. The capacitor is used to increase the starting torque but it is low compared to the capacitor start induction motor. The circuit diagram and phasor diagram of this motor is as shown in the below figure.





The power factor and efficiency of this motor are very high and also it has a high starting torquethat is 80% of full load torque.

This type of motor is used in the application like an exhaust fan, blower, heater, etc.

Applications of Single-Phase Induction Motors:

Single phase motors are not self-starting and less efficient than three phase induction motor andavailable in 0.5HP to 15HP and still they are widely used for multiple purposes such as:

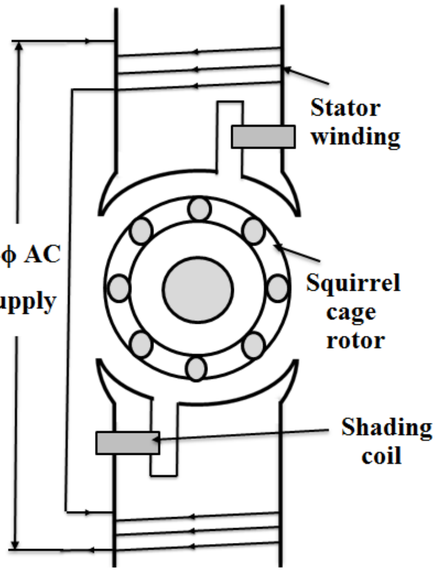
- Clocks
- Refrigerators, freezers and heaters
- Fans, table fans, ceiling fan, exhaust fans, air coolers and water coolers.
- Blowers
- Washing machines
- machine tools
- Dryers
- Type writers, photostats and printers
- Water pumps and submersible
- Computers
- Grinders
- Drilling machines
- Other Home instrument, equipment and devices etc.

Shaded Pole Induction Motor:

As we know that a single-phase induction motor is not a self-starting motor. In order to make it self-starting, changes are to be done to the construction.

Construction of Shaded Pole Induction Motor:

The construction of a shaded type induction motor is similar to a normal single-phase induction motor, except for its stator pole. The stator poles of a shaded pole motor are divided into two parts. One part of the pole consists of a short-circuited coil made up of copper which is known as the shading coil (shaded part) and the remaining part is known as the unshaded part of the pole, hence the motor is known as a shaded pole induction motor.

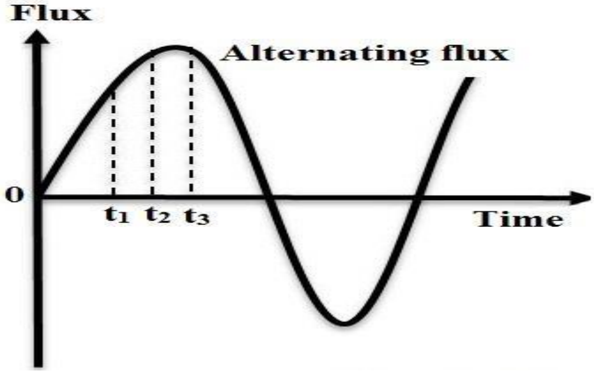


The construction of the rotor is of a normal squirrel cage type of a 3-phase induction motor. The below figure shows the single-phase two-pole induction motor with a shading coil on both the stator poles.

Working Principle of Shaded Pole Induction Motor:

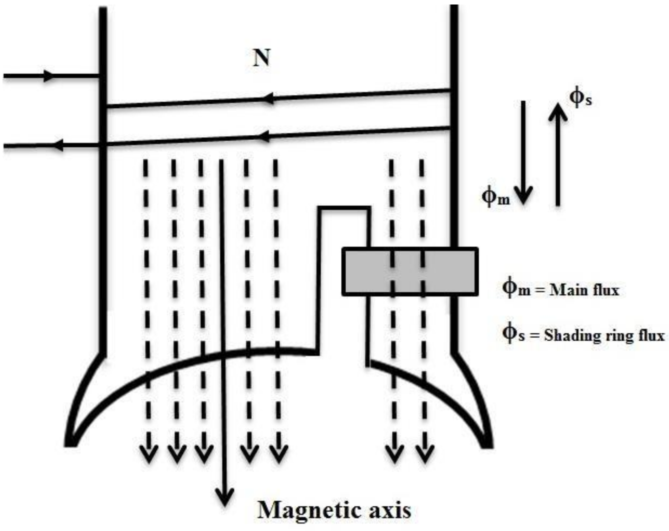
When a single-phase A.C supply is given to the stator winding. The poles of the motor generate a magnetic field Φ_m, but there is one more magnetic field Φ_s produced by shading coils either in the same or opposite direction. The combination of these fields makes a rotating magnetic field which makes the rotor rotate.

Let us consider three different cases at different time instants t_1, t_2, and t_3 on a positive half cycle of an ac supply.



Case-1 (At instant $t = t_1$):

As seen from the waveform, at instant $t = t_1$. The current in the coil increases, which in turn increases the flux Φ_m produced by the coil. Now due to supply is alternating, the rate of change of flux will tends to cause an emf induced in a shading coil of that pole. As the shading coil is short-circuited, currents will flow through it. Simultaneously causes to produces another flux Φ_s by the shading coil, which in the opposite direction to the main flux as shown below.



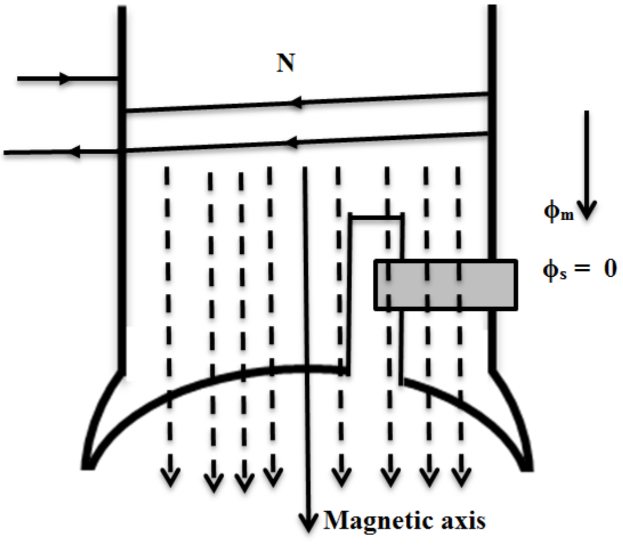
At $t = t_1$

Now due to the opposition of these two fluxes produced by the shading coil and main winding. The net flux across the area of the shading coil will be zero. Therefore, the magnetic axis of the net flux will be at the center of the unshaded part.

Case-2 (At instant $t = t_2$):

Now, at instant $t = t_2$ i.e., the maximum or peak value of the cycle or current. Here further there will be no increase in the current (no change of current). So, it decreases the rate of change of flux, which also decreases the emf induced in the shading coil. At this point, the flux Φ_s produced by the shading coil will be almost negligible.

Hence the flux Φ_m produced by the main winding will be uniformly distributed along the pole. Therefore, the magnetic axis of the pole will be at the center of the whole pole (with shadedand unshaded parts) as shown below.

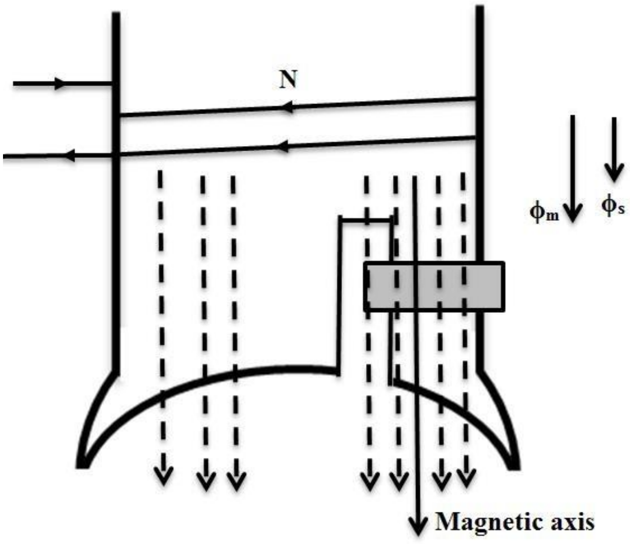


At $t = t_2$

Case-3 (At instant t = t₃):

At this instant, the rate of change of current will be in decreasing. As the current changes, there will be an induced emf in the shading coil due to the change of flux.

But here the direction of the fluxes Φ_m and Φ_s produced by both the main winding and shading coil will be in the same direction. Also, there will be crowding of flux in the shaded part as compared to the unshaded part. Due to this, the net magnetic axis of the pole will be at the center of the shading part of that pole, as shown below.



At $t = t_3$

This sequence of instants keeps on repeating for the negative half cycle also. As it will result in the production of a rotating magnetic field. By which the motor tends to start on its own. The starting torque produced by this type of motor will be 50% to 60% of the full-load torque.

Advantages of Shaded Pole Induction Motor:

1. Simple in construction.
2. Cheap.
3. Extremely rugged.
4. No centrifugal switch is required.

Disadvantages of Shaded Pole Induction Motor:

1. Starting torque is poor.
2. Efficiency is very low due to copper losses in the shading ring.
3. Very limited over-load capacity.

Speed Reversal:

The speed reversal is very difficult. To reverse the direction of rotation. two sets of shading rings are to be provided on both portions of the poles. By opening any ring and closing the other ring particular direction of rotation can be achieved. But the method is complicated and expensive.

Applications of Shaded Pole Induction Motor:

These are used in small fans, toys, hair, dryers film projectors. advertising displays etc., where starting torque required is very low.

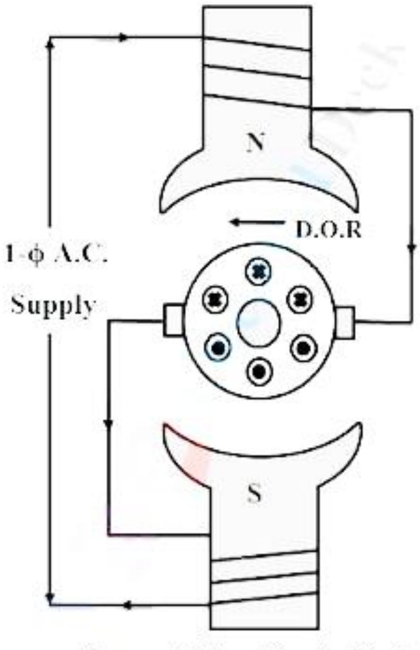
Ac Series Motor

Principle of Operation:

An ordinary d.c. series motor will run in the same direction regardless of the polarity of the supply. The direction of the torque depends upon the relative directions in space of flux and armature current. If the line terminals are reversed, both the field and armature current are reversed, and the direction of torque remains unchanged. Therefore, the motor continues to rotatein the same direction.

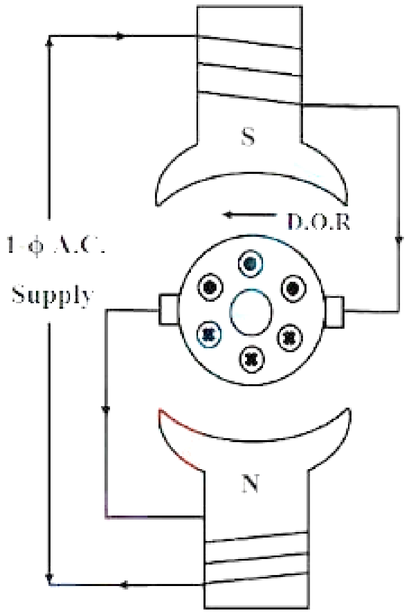
So, when normal d.c. series motor is connected to an a.c. supply, both field and armature currents reverse simultaneously and unidirectional torque is produced in the motor.

Consider the case of a two-pole motor and let the alternating current be in its positive half, then the polarity of the field poles and the currents flowing through the armature conductors be as indicated in Figure. The armature conductors carry inward currents +ve under N-pole and outward currents -ve under S-pole. By applying Fleming's left-hand rule, it will be seen that the torque developed in the armature will try to rotate in an anti-clockwise direction.



Current Direction in First Half Cycle

During the next instant, the alternating current goes through the negative half cycle Now the current through the field winding and armature will also change. It will be again seen that the armature will tend to rotate in the same direction because of the uniform torque produced by the two halves of the cycle.



Current Direction in Other Half Cycle

Thus, a series motor can run on both the d.c. supply and a.c. supply. The performance of dc Series motor works on A.C. supply is not satisfactory due to the following reasons,

1. The efficiency is low. This is because of the increase in core losses due to alternating flux.

2. The reactance of the field and armature winding increases as the supply given is alternating, which makes the machine run at a low power factor.

3. Considerable sparking at brushes will occur. This is due to poor commutation. The voltage induced by transformer action in the coil undergoing commutation further intensifies commutation difficulties.

Constructional Features:

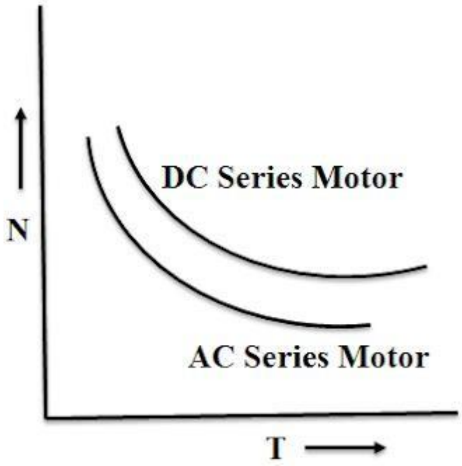
Modification in Design of A.C. Series Motor:

Some modifications are required to have a satisfactory performance of d.c. series motor on a.c supply, when it is called as a.c. series motor. The modifications are :

- Fully laminated poles and yokes must be used in order to reduce eddy current losses.
- The power factor can be improved by reducing field and armature reactances. In order to reduce field reactance, the field winding is designed with less number of turns. Lower pole flux also reduces the transformer emf in the commutating coil.
- The motor should be provided with a large number of poles each supplying less flux per pole.
- A reduction in the number of turns on the field winding would also reduce field flux. To keep the torque constant on the shaft, the armature turns should be increased proportionately. This increases the armature reaction and armature reactance.
- Compensating winding should be employed to lower the armature reactance as far aspossible. Compensation also improves commutation. The flux produced by compensating winding is opposite to that produced by the armature and effectively neutralizes the armature reaction.
- The armature coils are single turn coils and brushes of less width are used not toshort circuit more than two coils at a time.
- The air gap is made very small so that fewer field turns can be used per pole.
- The frequency of supply used is reduced. The transformer emf is proportional to frequency and hence good commutation is easy at lower frequencies.

Characteristics of A.C. Series Motor:

The characteristics of a.c. series motor is similar to that of d.c. series motor. The torque is proportional to the square of the armature current and speed is inversely proportional to the armature current. The series motors must always be started with some load on them because the starting speed of the motor is very high due to high starting torque i.e., 3 to 4 times the full load torque.



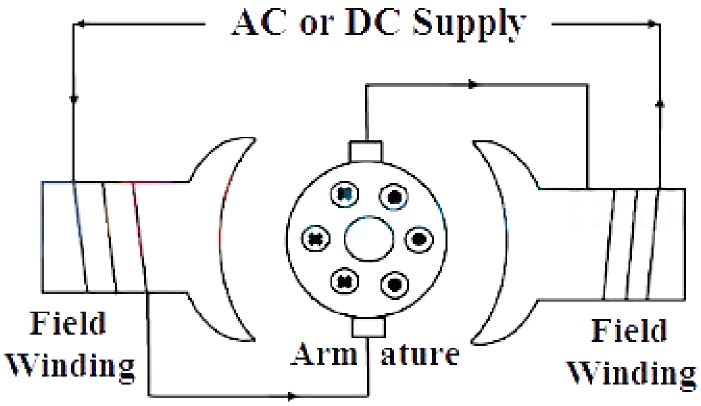
Universal Motor

Universal Motor is a single-phase commutator-type motor. It is a special type of motor because either it can be run on a.c. or d.c. supply. The main advantage of this type of motor is that it can be developed in ratings of some fractional kilowatt.

A series motor with a small fractional kilowatt rating (about 1/2 kW) that can run on both d.c. or 1-Φ a.c. supply is said to be a universal motor. This type of motor can usually operate up to the speed of 20000 rpm. Hence, they are used where there is a need for small motors with low ratings like motors used in electric shavers, hair driers, etc.

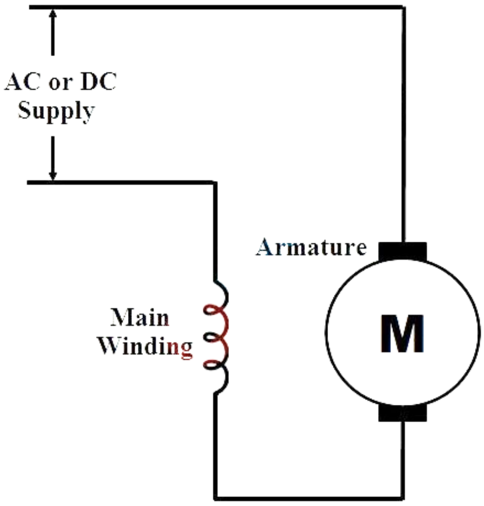
Construction of Universal Motor:

Generally, there is no constructional difference between a universal motor and an ac series motor. We know that modifications are done to the dc series motor to work as an ac series motor. Similarly, small ratings (less than 1 kW) of such motors are known as universal motors. These motors are modified again so that they can operate on both ac and dc supply.



The field winding (series field) of a universal motor consists of fewer turns and increased armature turns. So that it provides a low reluctance magnetic path with laminated armature and field circuits. Due to reduced series field turns, the motors produce a field with low flux density. The construction of universal motors can be manufactured in two ways. They are,

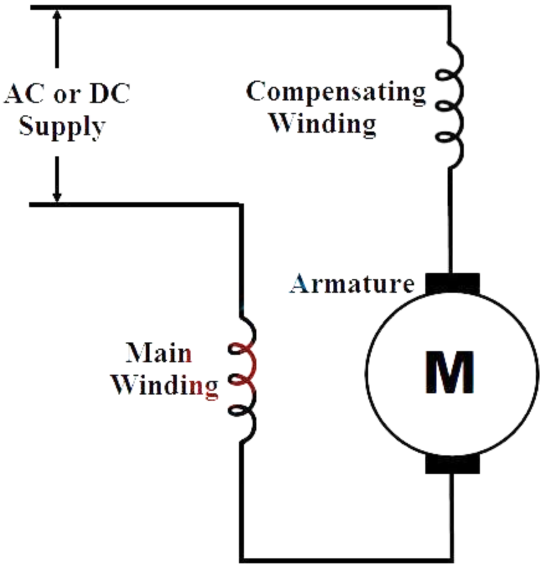
1. Non compensated type (concentrated field), low power rating :



Non-compensated Type

The construction of a non-compensated type of motor is the same as a normal dc series motor. Generally, it consists of 2 poles with a laminated magnetic path, the armature is wounded and connected in series with the field winding (main winding). The terminals of the armature are brought out through commutator segments and brushes as shown above.

2. Compensated type (distributed field), high power rating:



Compensated Type

The compensated type motor consists of two windings namely compensating and field (main) winding. The armature is of wound type as seen in non-compensated type motor. The three windings (main, compensated, and armature) are connected in series as shown in the above figure. The characteristics of this type of motor are better than the non-compensated type of motor, with high full-load operating speed, but the cost of this motor is more.

Working of Universal Motor:

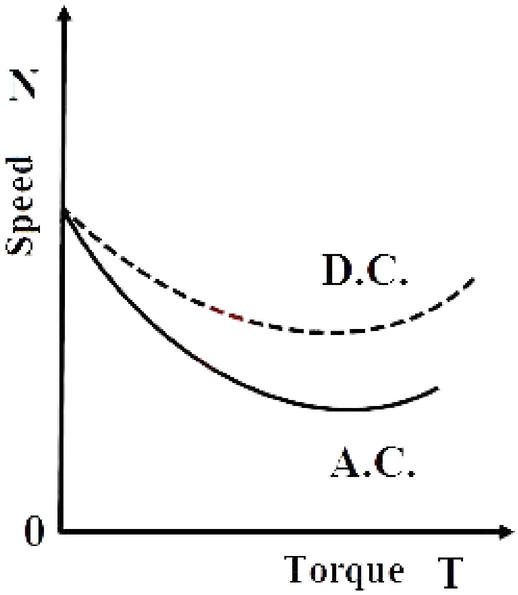
The working principle of a universal motor is the same as dc series motor i.e., Lorentz Law. When either of the supply (AC or DC) is given to the motor. The main winding generates magnetic lines of force.

When the armature is placed in the lines of force produced by the field winding. Due to the series connection of armature conductors with the field conductors, the same current flows through the armature and field conductors. Therefore, torque is produced on the current-carrying armature according to Lorentz Law.

Here the direction of torque produced on the armature will be in the same direction even though the supply given is alternating. These motors can be available at speeds ranging from 3000 to 20000 rpm. As the speed ratings of this motor are very high, speed control methods are adopted to control the speed of the motor.

Characteristics of Universal Motor:

Universal motors are easily recognized because they use a commutator and brushes. Compensated type universal motor has better speed-torque characteristics compared to non-compensated type. Very high torque at low speeds can, therefore, be achieved. The no-load speeds of small universal motors may be much higher than their full-load speeds.



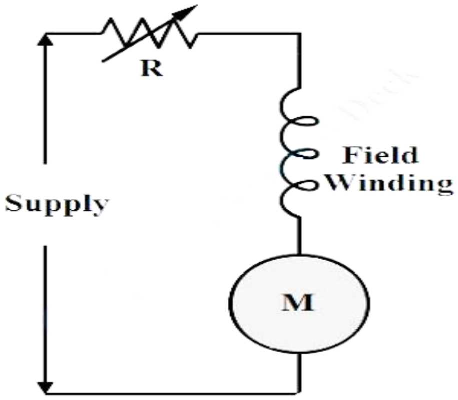
The full-load speed of a universal motor may be as high as 10.000 r.p.m When such high speeds are not required, gear trains are used to reduce the speed. The no-load speeds of small universal motors may be much higher than their full load speeds.

Speed Control of Universal Motor:

The following methods are used for speed control purposes of a universal motor,

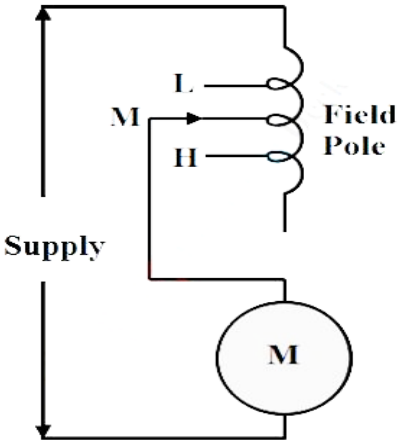
- Resistance Method
- Tapped Field Method and
- Governor Mechanism Method

1. Resistance Method:



By varying the resistance R connected in series with the motor, the speed can be varied. It is used for sewing machines, and the variation of resistance is affected by means of a foot-pedal.

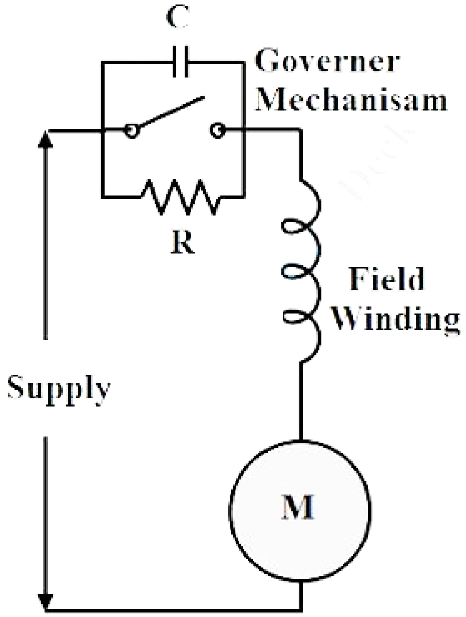
2. Tapped Field Method:



In this method, tappings are made on the field winding of the motor. Speed can be controlled by changing the tappings of the winding so that flux produced by the winding is changed, hence it changes the speed of the motor.

3. Governer Mechanism (Centrifugal Mechanism):

We can see in home mixers or grinders that a switch is provided on the motor to control the speed at different levels this can be done by the mechanism of the governer.



A centrifugal switch is placed with the governer mechanism to keep the resistance in the circuit, and out of the circuit. It is used to control the speed of the motor by inserting the resistance in the circuit (which decreases the current flow value thereby decreasing the speed) and by removing the resistance from the circuit (i.e., when the switch is closed the current used to flow through the switch by decreasing the resistance and increasing the speed). A capacitor is used to reduce the sparking produced while switching.

Applications of Universal Motor:

The most common applications of universal motors are,

- Vacuum cleaners.
- Electric shavers.
- Portable drives.
- Mixers or grinders.
- Hairdryers etc.