LECTURE NOTE ON
ENERGY CONVERSION-II
5TH SEM ELECTRICAL ENGINEERING

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Three phase induction motor

3 ϕ induction motor => It is an electrical machine which converts 3 phase electrical energy into mechanical energy. It is also considered as a rotating transformer.

classification of 3 ϕ induction motor =>

There are two types of 3 ϕ induction motor

① Squirrel cage type ② Slip ring type

principle of operation =>

When 3 ϕ stator winding is energised from a 3 ϕ supply, a rotating magnetic field is produced which rotates around the stator at synchronous speed N_s. The rotating field passes through the airgap and cuts the rotor conductor. Due to relative speed between the rotating flux and stationary rotor, emf are induced in the rotor conductors. Since rotor ckt is short circuited, current starts flowing in the rotor conductor.

Now the current carrying rotor conductors are placed in the magnetic field produced by stator. Therefore mechanical force acts on the rotor conductor. The rotor tends to rotate in the same direction as stator field, which explained by Lenz's law. Hence to reduce relative speed, the rotor starts running in the same direction as the stator field.

Rotor ⇒ The rotor is a hollow laminated core which is mounted on the shaft having slots on its outer periphery.

The rotor is classified into two types

→ Squirrel cage type

→ Slip ring type

(i) Squirrel cage rotor ⇒ It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminium bar is placed in each slots. All these bars are joined at each ends by end rings. This will form a permanently short circuited winding.

The induction motor which employs squirrel cage rotor are called squirrel cage induction motor.

Disadvantage ⇒ It has low starting torque.

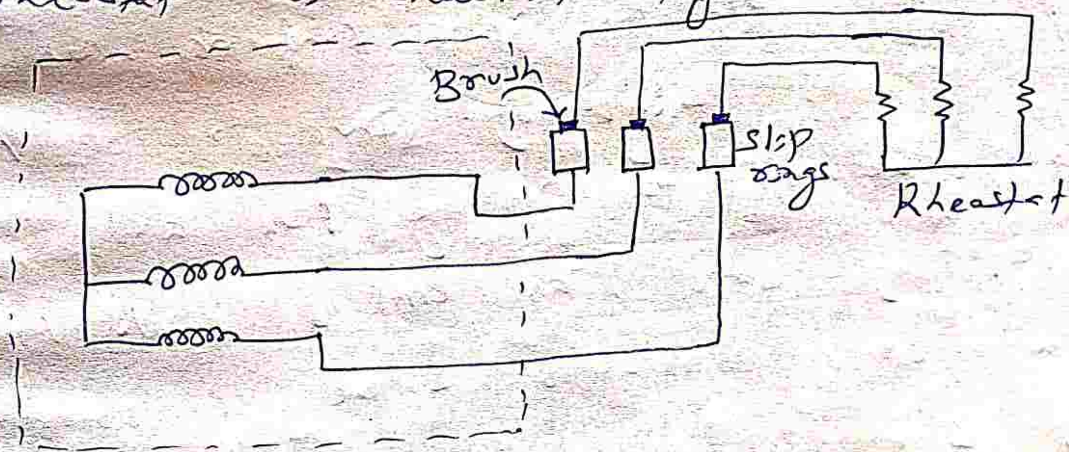
→ External resistance cannot be connected to the rotor circuit.

(ii) Slip ring rotor ⇒

It consists of a laminated cylindrical core and carries a 3 phase winding. The rotor winding is uniformly distributed in the slots and it is usually ~~short~~ star connected.

~~The coil ends are~~

The open ends of the rotor winding are brought out and joined to three insulated slip rings which is mounted on the rotor shaft and one brush resting on each slip rings. The three brushes are connected to a 3 phase star connected rheostat as shown in fig below.



At starting external resistance are included in the rotor circuit so as to give large starting torque. These resistance are gradually reduced to zero as the motor picks up speed.

The external resistance are used during starting period only. When the motor attains normal speed, the three brushes are short circuited so that wound rotor runs like a squirrel cage rotor.

Slip ⇒ The difference between the Synchronous speed N_s of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed

$$\%\text{age Slip } S = \frac{N_s - N}{N_s} \times 100$$

Rotor current frequency ⇒

$$\text{frequency} = \frac{NP}{120}$$

where N = Relative speed between magnetic field and the winding

P = No of poles

$$\text{rotor current frequency } f' = \frac{(N_s - N)P}{120}$$

$$\Rightarrow f' = S\frac{N_s P}{120} = Sf$$

⇒ Rotor current frequency = fractional slip × supply frequency

Starting torque (T_s) ⇒

Let E_2 = rotor emf/ph at standstill

X_2 = rotor reactance/ph " "

R_2 = rotor resistance/ph

Rotor impedance/ph $Z_2 = \sqrt{R_2^2 + X_2^2}$

rotor current/ph $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$

Rotor p.f. $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$

Starting torque $T_s = K E_2 I_2 \cos\phi_2$

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

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

E_2 = constant

$$T_S = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 = constant

It can be shown that $K = \frac{3}{2\pi N_S}$

$$T_S = \frac{3}{2\pi N_S} \times \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$ where N_S is in RPS

Condition for maximum starting torque ⇒

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 it to zero

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

$$\Rightarrow R_2^2 + X_2^2 = 2R_2^2 \Rightarrow \boxed{R_2 = X_2}$$

Maximum torque under running condition ⇒

$$T_r = \frac{K_2 S R_2}{R_2^2 + S^2 X_2^2} \quad .... (i)$$

Differentiating eq(i) w.r.t S and equating it to zero

$$\Rightarrow \frac{dT_r}{dS} = \frac{K_2 \left[R_2 (R_2^2 + S^2 X_2^2) - 2S X_2^2 (S R_2) \right]}{(R_2^2 + S^2 X_2^2)^2} = 0$$

$$\Rightarrow (R_2^2 + S^2 X_2^2) - 2S^2 X_2^2 = 0$$

$$\Rightarrow R_2^2 = S^2 X_2^2$$

$$\Rightarrow R_2 = S X_2$$

⇒ Rotor resistance/ph = Fractional Slip × Standstill rotor reactance/ph

Full load, starting and maximum torque ⇒

$$T_f = \frac{SR_2}{R_2^2 + (SX_2)^2} \quad \text{--- (i)}$$

$$T_s = \frac{R_2}{R_2^2 + X_2^2} \quad \text{--- (ii)}$$

$$T_m = \frac{1}{2X_2} \quad \text{--- (iii)}$$

Where S = Full load slip

Now $$\frac{T_m}{T_f} = \frac{R_2^2 + (SX_2)^2}{2SR_2X_2}$$

Dividing X_2^2 in numerator and denominator

$$\frac{T_m}{T_f} = \frac{\left(\frac{R_2}{X_2}\right)^2 + S^2}{2S\left(\frac{R_2}{X_2}\right)} = \frac{a^2 + S^2}{2aS}$$

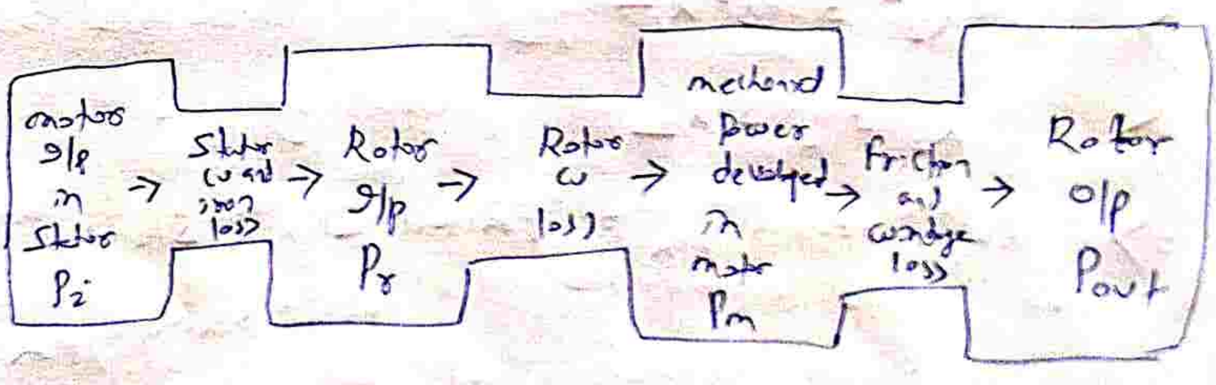
Where $$a = \frac{R_2}{X_2} = \frac{\text{Rotor resistance/ph}}{\text{Standstill rotor reactance/ph}}$$

Now $$\frac{T_m}{T_s} = \frac{R_2^2 + X_2^2}{2R_2X_2}$$

Dividing X_2^2

$$\Rightarrow \frac{T_m}{T_s} = \frac{\left(\frac{R_2}{X_2}\right)^2 + 1}{2(R_2/X_2)} = \frac{a^2+1}{2a}$$

Power stages in an induction motor ⇒



Rotor output =>

Gross rotor o/p $= \frac{2\pi N T_g}{60}$ watt

If Copper loss = 0

then Rotor i/p $= \frac{2\pi N_s T_g}{60}$ W

Rotor Cu loss = Rotor i/p − Rotor o/p

$= \frac{2\pi T_g}{60}(N_s - N)$

(i) $\frac{\text{Rotor Cu loss}}{\text{Rotor i/p}} = \frac{N_s - N}{N_s} = S$

=> Rotor Cu loss = S × rotor i/p

(ii) Gross rotor o/p P_m = Rotor i/p − Rotor Cu loss

= Rotor i/p − S × rotor i/p

=> P_m = Rotor i/p (1 − S)

(iii) $\frac{\text{Gross rotor o/p}}{\text{rotor i/p}} = 1 - S = \frac{N}{N_s}$

(iv) $\frac{\text{Rotor Cu loss}}{\text{Gross rotor o/p}} = \frac{S}{1-S}$

Alternator

Alternator => Alternator is an electrical machine which converts mechanical energy into 3 phase electrical enenergy.

It operates on the principle of electromagnetic induction, i.e when the flux linking a conductor changes, an emf is induced in the conductor.

In an alternator the armature remains stationary while the field system is rotating.

Advantage of stationary armature and rotating field system =>

① It is very easy to insulate the stationary winding for high voltage.
② Stationary 3ϕ armature can be directly connected to load without using brushes and slip rings.
③ Only two slip rings are required for d.c supply to the rotor field winding.
④ Due to simple and robust construction of the rotor, higher speed can be possible.

Constructional details of alternator ⇒

Mainly An alternator has two Parts. Stator and rotor.

Stator ⇒ It is the stationary Part of the machine. It is built up of sheet steel lamination having slots on its inner periphery. A 3 ϕ winding is placed on these slots. The armature winding is always star connected.

Rotor ⇒

Rotor has two types
- Salient pole type
- Non Salient pole type.

Salient pole type (Projecting pole) ⇒

Salient poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator. The field pole windings are connected in such a way that when d.c supply is given, then the adjacent pole becomes opposite pole. Low and medium speed alternator (120 - 400 rpm) have Salient pole type rotor. This type of rotor is used in hydroelectric Power Plant. It has large diameter and short axial length.

Non Salient pole type (Smooth cylindrical) ⇒

This rotor is a forged steel radial cylinder having number of slots on its outer peripheory as shown in fig below.

High speed alternator (1500-3000 rpm) which is used in thermal power plant has Non salient pole type rotor. It has small diameter and large axial length.

Principle of operation of Alternator ⇒

In an alternator the rotor winding is energised from a d.c source and alternate N and S poles are developed on the rotor. When the rotor is rotated by a prime mover, then the stator or armature conductor are cut by the magnetic flux of rotor poles. Therefore an emf is induced in the stator winding due to electromagnetic induction. This induced emf is alternating since N and S pole alternately passes the armature conductor. The magnitude of emf depends upon the speed of rotation and d.c exciting current.

Frequency of induced emf =>

Let N = rotor speed in rpm

P = Number of rotor poles

f = frequency of emf in Hz

Consider a stator conductor. If a positive voltage is induced when N-pole sweeps across the conductor then a similar negative voltage will be induced when S-pole sweeps across the conductor. It means that one complete cycle of emf is generated when one pole pair passes.

Thus No. of cycles/rev = No of pair poles = $\frac{P}{2}$

No of rev/sec = $\frac{N}{60}$

$\therefore$ No of cycles/sec = $\frac{P}{2} \times \frac{N}{60}$

$\Rightarrow$ frequency = $\frac{NP}{120}$.

Armature winding =>

Generally armature windings are of non-salient pole type and it is symmetrically distributed in slots. A distributed winding has two advantages.

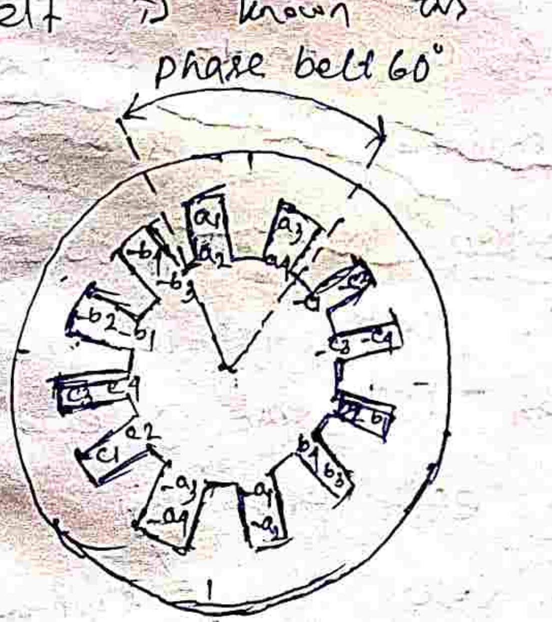
(i) It generates a voltage wave nearly equal to sine wave.

(ii) Copper is properly distributed. Thus heating will be uniform and it is easily cooled.

Full pitch coils or fractional pitch coils are used in armature winding, if the two sides of a coil are 180° electrical apart with each other than it is called full pitch coil. A coil span less than 180° electrical is known as fractional pitch coil. Fractional pitch coils are generally used in alternator because less copper is required and the waveform of the generated voltage is improved.

Most of the alternator uses double layer winding. In this winding if one coil sides lies in the upper half of one slot than the other coil sides lies in the lower half of another slot which is spaced 180° electrical with each other.

A group of adjacent slots belonging to one phase under one pole pair is known as phase belt and the angle created by phase belt is known as phase spread.



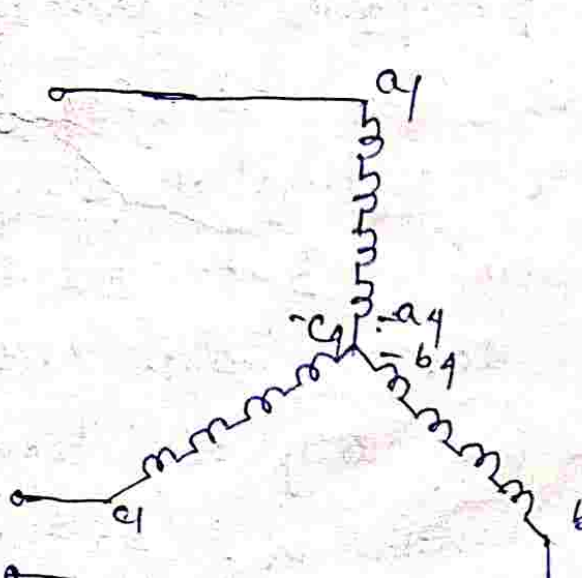


Fig 1 shows a 2 pole, 3 φ double layer full pitch distributed winding for the stator of an alternator. There are 12 slots and each slot contains two coil sides.

The coil sides a_1, a_3 or a_2, a_4 constitute a phase belt. The phase belt is always 60° electrical.

Since the total coils is 12. Therefore each phase has four coils. The four coils in each phase are connected in series. Then the three phase may be connected to form Y or Δ connection as shown in fig 2.

Winding factor ⇒

Winding factors are of two types

(1) Distribution factor K_d.

(2) Pitch factor K_p.

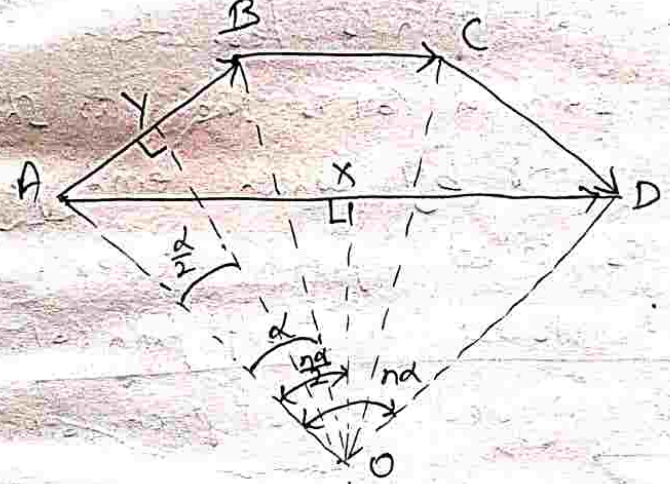
Distribution factor ⇒

A winding with only one slot per pole per phase is called a concentrated winding. In this case the emf generated/phase is equal to the arithmatical summation of individual coil emf. But if the coils are distributed over several slots, then the emf in each coil are displaced from each other by slot angle α. In this case the emf/phase is equal to the phasor summation of the coil emf.

$$K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$$

$$= \frac{\text{Phasor Summation of coil emf}}{\text{Arithmatic Summation of coil emf.}}$$

The distribution factor can be determined from the phasor diagram shown below.



Let α = slot angle = $\frac{180° \text{ electrical}}{\text{No of slots/pole}}$

n = slots/pole/phase = 3

The three coil emf are shown as AB, BC, & CD which is the chord of a circle with centre O. The phasor summation of the coil emf creates an angle $n\alpha$ at O. Perpendicular has been drawn from O to AD and AB which bisects AD at X and AB at Y.

then $K_d = \frac{AD}{n \times AB} = \frac{2 \times AX}{n \times (2AY)} = \frac{AX}{n \times AY}$

$$= \frac{OA \sin\left(\frac{n\alpha}{2}\right)}{n \times OA \sin\left(\frac{\alpha}{2}\right)}$$

$$\Rightarrow \boxed{K_d = \frac{\sin\left(\frac{n\alpha}{2}\right)}{n \sin\frac{\alpha}{2}}}$$

Pitch Factor ⇒ If the coil sides of a coil are separated by 180° electrical, then it is called a full pitch coil. In this case the emf induced in two coil sides are in phase with each other and the resultant emf is the arithmetical summation of individual emf.

But if the coil pitch is less than a pole pitch, then such a coil is known as short pitch coil. The factor by which emf per coil is reduced is called pitch factor.

$$K_p = \frac{\text{emf induced in short pitch coil}}{\text{emf induced in full pitch coil}}$$

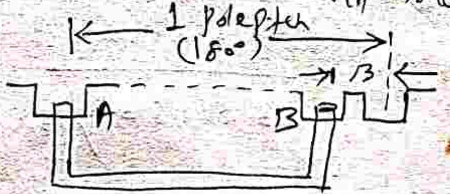


Fig 1

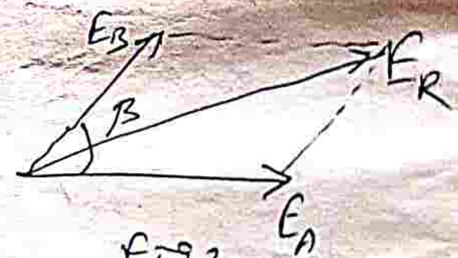


Fig 2

As shown in fig 1, consider a coil AB which is short pitched by an angle B. The emf generated in coil sides A and B is E_A and E_B respectively which is differ in phase by B.

Since $E_A = E_B$

$$E_R = 2 E_A \cos\frac{B}{2}$$

$$\therefore K_p = \frac{\text{Emf in short pitch coil}}{\text{emf in full pitch coil}}$$

$$= \frac{2 E_A \cos\frac{B}{2}}{E_A + E_B} = \frac{2 E_A \cos\frac{B}{2}}{[illegible]}$$

⇒ $K_p = \cos\frac{B}{2}$ [illegible]

Emf Equation of an Alternator ⇒

Let Z = no of conductors connected in series per phase.

ϕ = flux per pole in wb.

P = no of rotor poles.

N = Rotor speed in Rpm

In one revolution (i.e $\frac{60}{N}$ sec) each stator conductor is cut by $P\phi$ wb.

$\therefore d\phi = P\phi$ and $dt = \frac{60}{N}$

$\therefore$ Average emf induced in one stator conductor

$$= \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60} \text{ volt}$$

Since there are Z number conductors/phase

$$\therefore \text{Average emf/phase} = \frac{P\phi Z N}{60} = \frac{P\phi Z}{60} \times \frac{120f}{P}$$

$$= 2f\phi Z \text{ Volts}$$

Rms value of emf/phase = Form Factor × Av. value

$$E_{ph} = 1.11 \times 2f\phi Z = 2.22 f\phi Z \text{ Volts}$$

Considering K_p and K_d

$$E_{rms}/\text{phase} = 2.22 K_p K_d f\phi Z \text{ volts.}$$

Putting $Z = 2T$.

$$E_{rms}/\text{phase} = 4.44 K_p K_d f\phi T \text{ Volts}$$

Armature Reaction →

The effect of armature flux on the flux produced by the field ampere turns is called armature reaction. In this case the p.f plays an important role in armature reaction.

Consider a 3φ 2pole alternator having a single layer winding as shown in fig 1. Assume the winding is concentrated and the number of turns per phase is N.

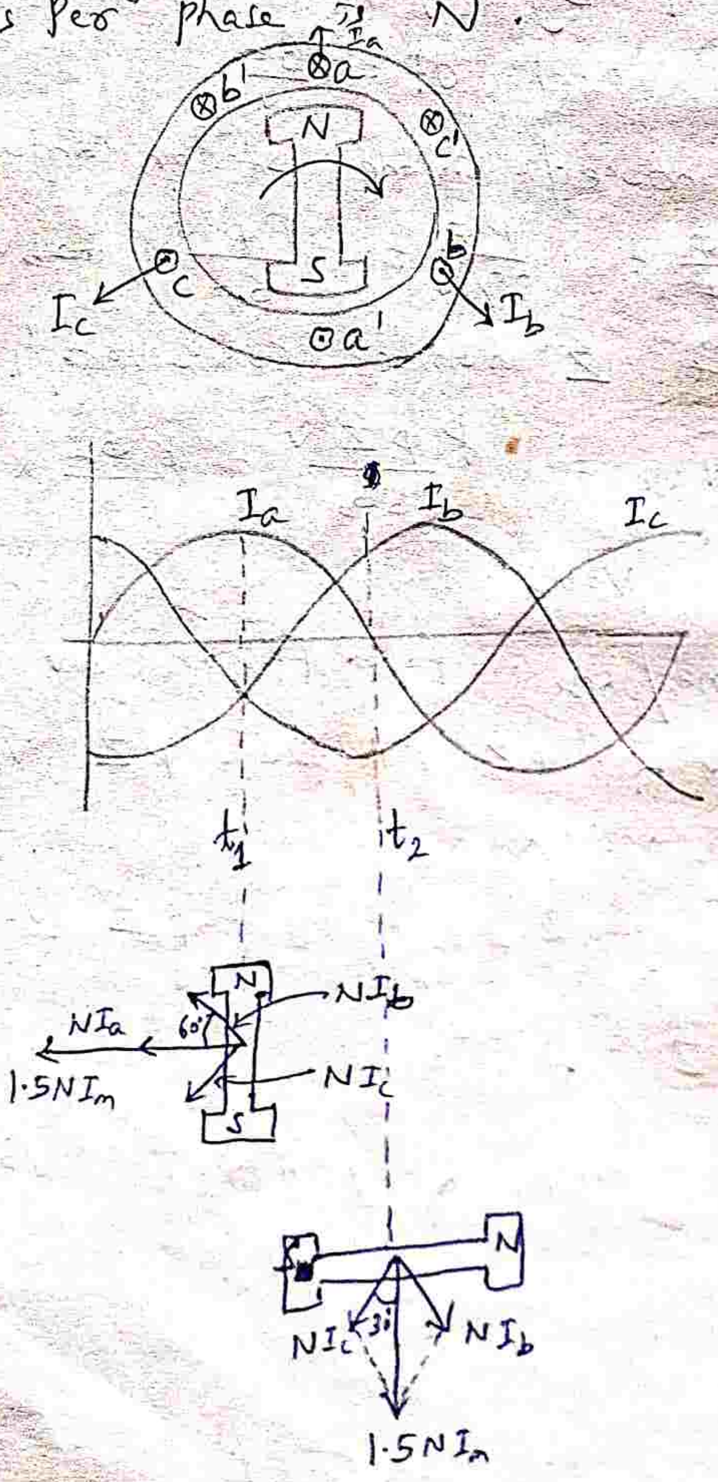


Fig 1

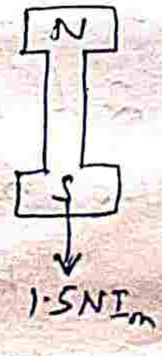


Fig 2

Fig 3

At unity P.F ⇒ When the alternator is loaded with a resistive load, then the phase currents I_a, I_b and I_c are in phase with their respective phase voltage.

At time t_1, I_a has max. value whereas I_b and I_c have one half their maximum value.

In this position, the mmf produced by phase aa' is horizontal where as by the other two phases is $(\frac{I_m}{2})N$ each at 60° to the horizontal.

$\therefore$ total Arm. mmf $= NI_m + 2(\frac{1}{2} I_m N)\cos 60°$

$= 1.5 NI_m$.

So at this instant the main field mmf is upward while Armature mmf is lagging behind it by 90° electrical.

At time t_2, $I_a = 0$ while I_b and I_c are each equal to 0.866 of their max. value

$\therefore$ Armature mmf $= 2(0.866 NI_m)\cos 30°$

$= 1.5 NI_m$.

So we have found from the above discussion that Armature mmf remains constant with time. It is 90° behind the main field mmf. So it is only distortional in nature.

At lagging load of zero P.F ⇒

In this case all the currents will delayed in time 90° and armature mmf will

In this case Armature flux opposes the main field flux. Therefore main field flux is weakened. Here armature reaction is directly demagnetising in nature. This reduces the generated voltage

At leading load of zero power factor =>

When a pure capacitive load is connected across the alternator terminals, then the current in the armature winding leads the induced emf by 90°. In this case armature flux is in the same direction as the main field flux as shown in fig 3. Here armature reaction strengthen the main flux and hence the generated voltage increases.

Synchronous motor

Synchronous motor ⇒

A synchronous motor is an electrical machine that operates at synchronous speed and convert electrical energy into mechanical energy.

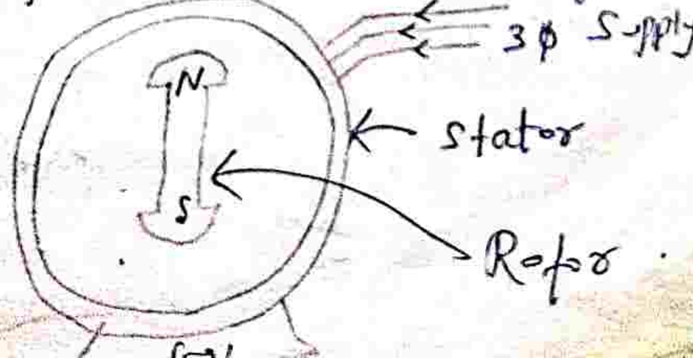
Construction ⇒

A synchronous motor has two parts stator and rotor.

Stator ⇒ Stator houses the 3 ϕ armature winding in slots and it receives power from a 3 ϕ supply.

Rotor ⇒ Rotor has a set of salient poles which is excited by direct current to form alternate N and S pole. The exciting coils are connected in series to two slip rings. The direct current is fed onto the slip rings from an exciter which is mounted on the shaft of the motor.

The stator is wound for the same number of poles as the rotor poles.



Characteristics of Synchronous motor =>

(1) A synchronous motor runs at synchronous speed. Its speed is constant at all loads.

(2) It can be operated over a wide range of power factor by adjusting its field excitation. Also it improves the power factor of the system.

(3) It is generally of salient pole type.

(4) It is not self starting. Therefore an auxiliary means has to be used for starting.

Principle of operation =>

Consider a 3 ϕ synchronous motor having two rotor poles N_R and S_R. Then the stator will also wound for two poles N_S and S_S. 3 ϕ voltage is applied to the stator winding while direct voltage is applied to the rotor winding. Then in stator winding, a rotating magnetic field is produced which revolves around the stator at synchronous speed N_s. The direct current sets up a two pole field which remain stationary so long as the rotor is not turning. Thus we have a situation where there are a pair of revolving armature pole ($N_S - S_S$) and pair of stationary rotor poles ($N_R - S_R$).

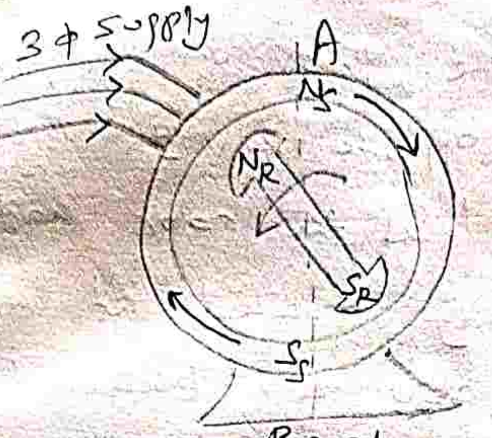


Fig 1

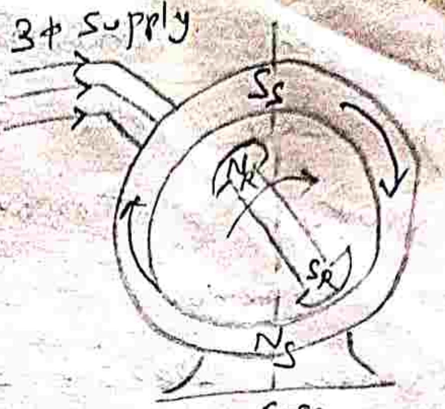


Fig 2

As shown in fig 1, the stator poles are at position A and B. It is seen that N_S and N_R repel each other and so the poles S_S and S_R. Therefore the rotor tends to move in anticlockwise direction. After a period of half cycle ($\frac{1}{2f} = \frac{1}{100}$ sec), the polarity of the stator poles are reversed while the rotor pole remains unchanged as shown in fig 2. Now S_S and N_R attract each other and so N_S and S_R. Therefore the rotor tends to move in clockwise direction.

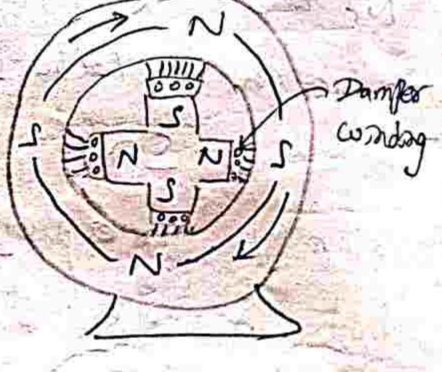
Since the stator poles changes their polarity rapidly, they tend to pull the rotor first in one direction and then in other. Due to high inertia of the rotor, the motor fails to start. Therefore a synchronous motor has no self starting torque.

If the rotor poles are rotated by some external means at such a speed that they interchange their position along with the stator poles, then the rotor will experience a continuous unidirectional torque.

Under this condition the poles on the rotor always face poles of opposite polarity of stator. Therefore the mutual attraction locks the rotor and stator together and they rotated at synchronous speed. If now the external means has been removed, then the rotor will continue to rotate at synchronous speed.

How to make Synchronous motor Self Starting =>

A synchronous motor cannot start by itself. To make the synchronous motor self starting a squirrel cage winding called damper winding is provided on the rotor. It consists of copper bars embedded in the pole faces of the salient pole as shown in fig below.



A 3 ϕ supply is given to the stator winding while the rotor field winding is left unenergised. Then the rotating magnetic field induces current in the damper winding and the motor starts as an induction motor.

When the motor approaches the synchronous speed, the rotor is excited with direct current. So that the resulting poles on the rotor face poles of opposite polarity on the stator. Therefore the rotor poles locks with the stator pole and they revolves at Synchronous Speed.

Since the bars of damper winding now rotate at the Same Speed as rotating mag. field therefore these bars donot cut any flux. Thus no current will induced in them. ultimately the damper winding is removed from the operation of the motor.

Equivalent Circuit ->

A Synchronous motor is connected to two electrical System. i,e a d.c Source is given to the rotor terminal and an a.c Source is given to the Stator terminals.

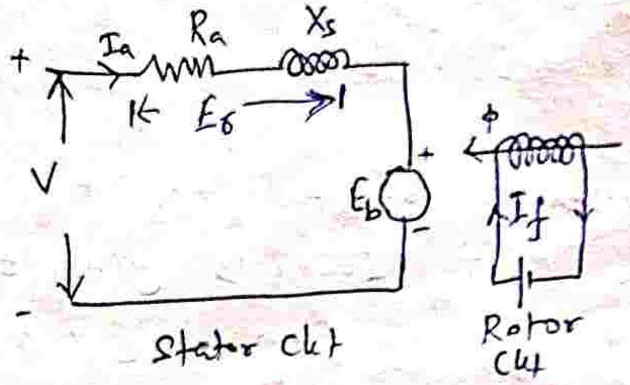
under normal conditions of operation of synchronous motor, no Voltage is induced in the rotor because the rotor winding is rotating at the Same speed as the Stator winding.

But in the Stator winding two effects are to be considered. The effect of Stator field on Stator conductor produces an Synchronous reactance X_s in Series with armature resistance R_a. The combination of R_a and X_s gives Synchronous impedance of the machine

Due to the effect of rotor field cutting the Stator conductors at synchronous Speed an emf E_b will be generated which is known as back emf and it opposes the Stator Voltage V. The magnitude of E_b depends upon rotor speed and rotor flux/pole.

Since rotor speed is constant
therefore E_b depends upon rotor flux/pole
$\Rightarrow E_b \propto I_f$

Fig 1 shows the schematic diagram of one phase of a star connected synchronous motor while Fig 2 represents its equivalent ckt.



Stator ckt
Rotor ckt
Fig 1

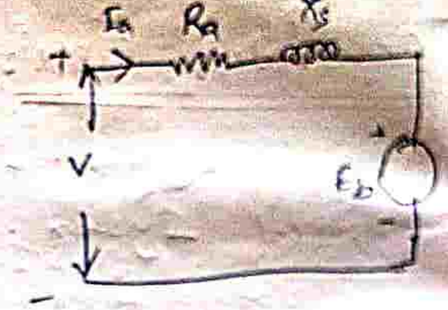
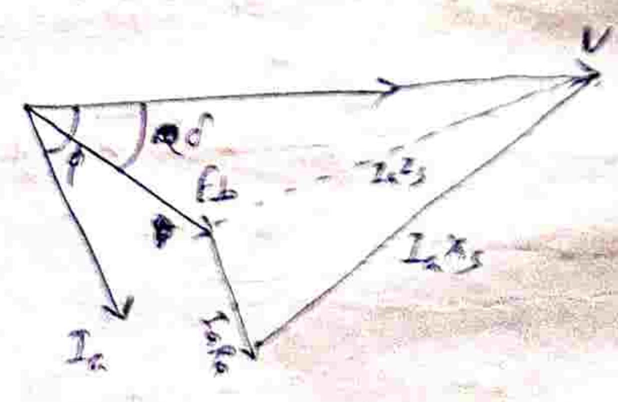


Fig 2

$\therefore$ Net voltage/phase in stator winding $E_r = V - E_b$

Armature current/phase $I_a = \frac{E_r}{Z_s} = \frac{E_r}{\sqrt{R_a^2 + X_s^2}}$

A synch. motor is said to be normally excited if $E_b = V$
" " " " under excited if $E_b < V$
" " " " over excited if $E_b > V$



δ : Load angle

Motor on Load ⇒

When we apply mechanical load to a Synchronous motor, then the rotor poles fall slightly behind the Stator poles while it continue to run at Synchronous speed. The angular displacement between stator and rotor poles is α which is known as torque angle. Due to α the phase of E_b is changed w.r.t supply voltage V.

A Synchronous motor runs at Synchronous speed at all loads. It meets the increased load not by decrease in speed but by the relative shift between stator and rotor poles.

If the load on the motor increases, then torque angle α also increased. The increased in torque angle α causes a greater phase shift of E_b w.r.t V. Thus the net voltage E_r will be increased and hence armature current I_a increases to meet the increase load.

If the load on the motor decreases, then α decreases. Thus a smaller phase shift of E_b w.r.t V. Therefore net voltage E_r will be reduced so that Armature current will be decreased by the relation $\downarrow I_a = \frac{E_r \downarrow}{Z_s}$.

Pull out torque ⇒

The load torque at which the motor pulls out of synchronism is called pull out or Breakdown torque. Its value lies in between 1.5 to 3.5 times the F.L torque.

Synchronous motor with varying load and fixed excitation

Consider an underexcited star connected synchronous motor ($E_b < V$) supplied with fixed excitation i.e E_b is constant.

Let V = Supply voltage/phase

E_b = Backemf/phase

Z_s = Synchronous impedance/phase

Motor on no load ⇒

When the motor is on no load, the torque angle α is small as shown in fig 1. fig 2 and fig 3 represents the equivalent ckt and phasor diagram respectively.

Fig 1

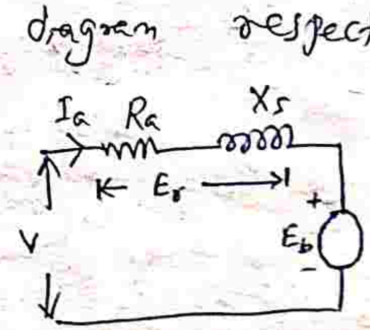


Fig 2

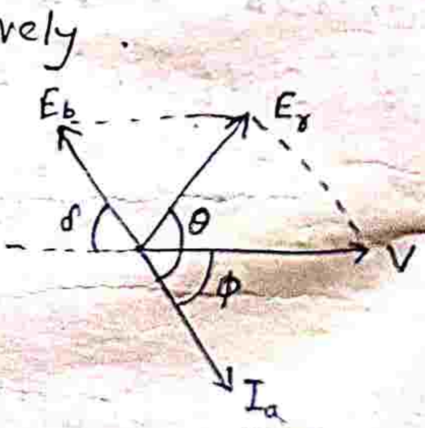


Fig 3

Therefore backemf E_b lags behind the supply voltage V by a small angle δ as shown in fig 3.

∴ the net voltage/phase in the stator winding = E_r

Armature current/phase $I_a = \frac{E_r}{Z_s}$

The armature current I_a lags behind E_r by

$\theta = \tan^{-1} \frac{X_s}{R_a}$

Since $X_s >> R_a$, therefore I_a lags behind the E_r by nearly $90°$ i.e $\theta \simeq 90°$.

The phase angle between V and I_a is ϕ, so that motor power factor is $\cos\phi$.

Input power/phase $= V I_a \cos\phi$

Thus at no load the ~~motate~~ motor takes a small power $V I_a \cos\phi$/phase while it run at synchronous speed.

<u>Motor on load</u> ⇒

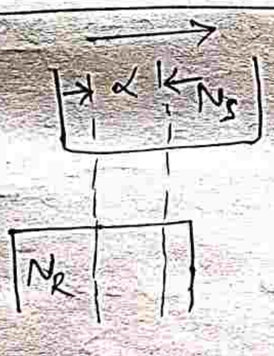


fig 1

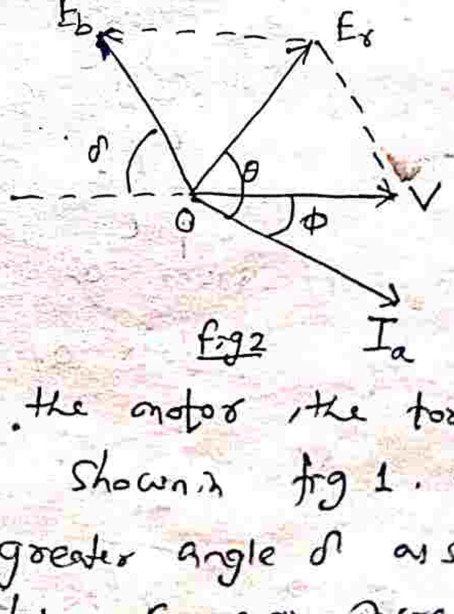


fig 2

When load is applied to the motor, the torque angle α is increases as shown in fig 1. Thus E_b lags behind V by a greater angle δ as shown in fig 2. The net voltage/phase E_r will increased. Consequently the motor draws more armature current I_a to meet the applied load.

Since $X_s >> R_a$ then I_a lags behind E_r by nearly $90°$. The p.f is $\cos\phi$

Input Power/phase $= V I_a \cos\phi$.

Mechanical power developed by the motor/ph

$= P_m = E_b I_a \cos(\delta - \phi)$

Mechanical Power developed by the motor/phase

$= P_m = E_b \times I_a \times$ cosine of angle between E_b and I_a

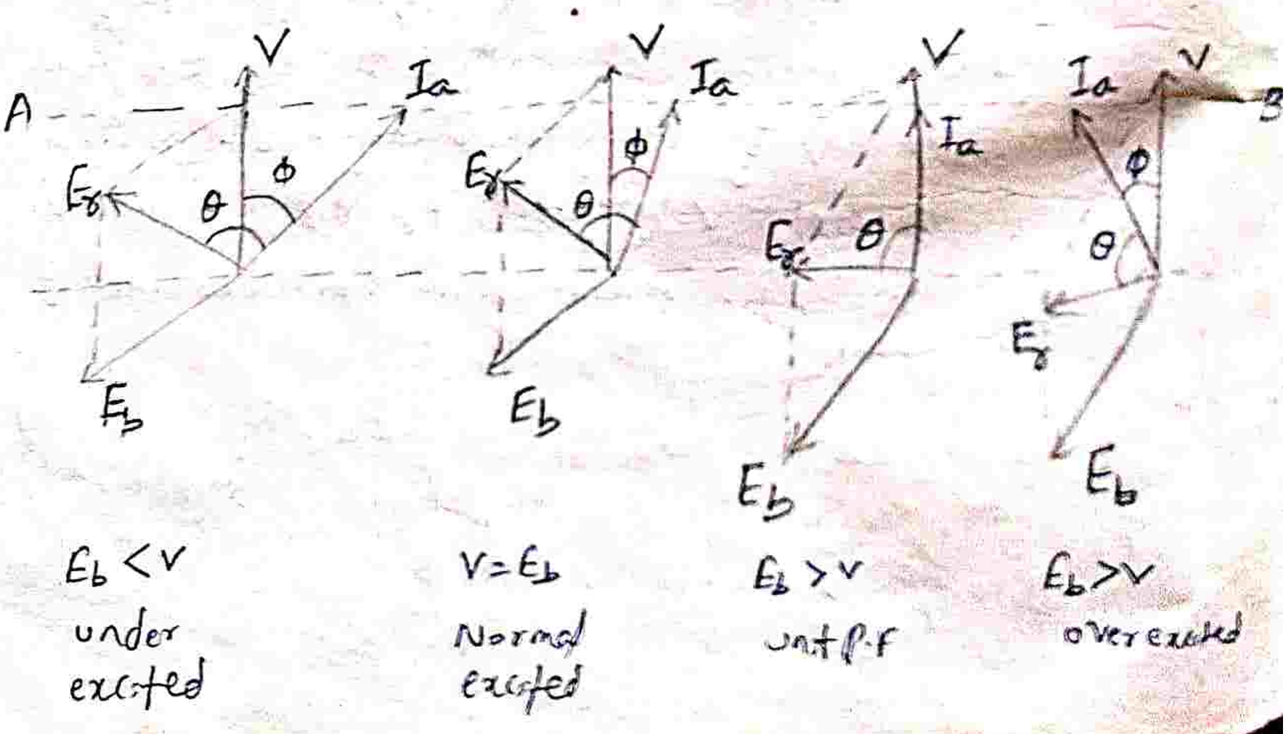
$= E_b I_a \cos(\delta - \phi)$

Synchronous motor with varying excitation at constant load

Consider a synchronous motor having a fixed supply voltage and driving a constant load. Since the load and speed is constant, the power input to the motor $(= 3 V I_a \cos\phi)$ is also constant. This means that in phase component $I_a \cos\phi$ is also remains constant.

If the field excitation is changed, then the backemf E_b will also changes. Therefore the phase position of I_a w.r.t V will change and p.f of the motor changes.

The fig shown below shows the phasor diagram of synchronous motor for different value of field excitation.



Under excitation =>

The motor is said to be under ~~excitation~~ excited if the field excitation is such that $E_b < V$.
Since $E_b < V$, the net voltage E_r is decreased and it turns clockwise. As angle between E_r and I_a ($\theta = 90°$) is constant thus phasor I_a turns clockwise. Thus current I_a lags behind the supply voltage as shown in fig. Therefore the motor has lagging power factor.

Normal excitation =>

The motor is said to be normally excited if $E_b = V$. Thus the net voltage E_r and hence I_a turns anticlockwise direction. The current phasor I_a has come closer to V. Therefore p.f increases but still it lagging. Since input power $= 3VI_a\cos\phi$ is constant, the stator current I_a must decrease to increase the p.f.

Suppose the field excitation is increased until the current I_a is in phase with V. Thus the p.f of synch. motor is unity. Therefore for a given load at unity p.f. the resultant E_r and I_a are minimum.

Over excitation => The motor is said to be over excited if $E_b > V$. In this condition E_r and I_a further turns anticlockwise direction. Therefore I_a leads V and the motor has leading p.f.

Different types of torque =>

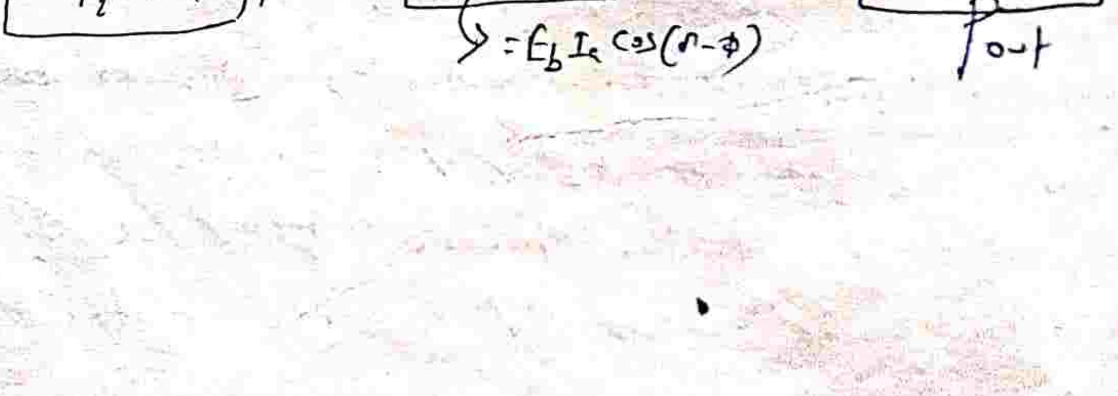
Starting torque => It is the torque developed by the motor when full voltage is applied to the stator winding.

Running torque => The torque developed by the motor under running conditions are known as running torque.

Pull-in torque => A synchronous motor is started as a induction motor till it 2 to 5% below the synchronous speed. When excitation is switched on, the rotor pulls into step with synchronously rotating field. So the amount of torque at which the motor pulls into step is called pull in torque.

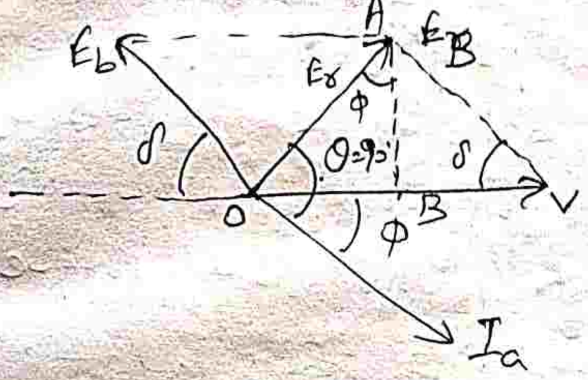
Pull out torque => As explained earlier.

Power flow in a synchronous motor =>



mechanical power developed by motor ⇒

Consider an under excited synchronous motor whose phasor diagram is shown below



Since $R_a << X_s$ thus $\theta = 90°$.

I/p power/phase = $V I_a \cos\phi$ ...

Since R_a is neglected, therefore stator cu loss is zero.

Thus mech. power developed P_m = I/p Power/phase

$$\Rightarrow P_m = V I_a \cos\phi \quad \ldots (i)$$

Now $AB = E_r \cos\phi = I_a X_s \cos\phi$

Also $AB = E_b \sin\delta$.

Thus $I_a X_s \cos\phi = E_b \sin\delta$

$$\Rightarrow I_a \cos\phi = \frac{E_b \sin\delta}{X_s}$$

Substituting this value in eq (i)

$$P_m = V \times \frac{E_b \sin\delta}{X_s} \quad \ldots \text{per phase}$$

The mech. power will increases with torque angle δ and it becomes maximum at $\delta = 90°$.

$$\therefore P_{max} = \frac{V E_b}{X_s} \quad \ldots \text{per phase}$$

$$= \frac{3 V E_b}{X_s} \quad \text{for 3 phase}$$

Hunting ⇒ When a synchronous motor is used for driving a varying load, then hunting is produced.

When a synchronous motor is loaded such as compressor or pumps etc, its rotor poles falls slightly behind the stator poles by an angle α. When load is increased, this angle also increases so as to produce more torque to cope with this load. If there is a sudden decrease in load then the motor will immediately advanced to new value of α. In this process the rotor starts oscillating about its new position. If the time period is more then the amplitude of these oscillation will be more and it will pulls out from synchronism.

Hunting is prevented by providing damper bars (i.e. squirrel cage windings) in the rotor. These damper bars consists of short circuited copper bar embedded in the pole faces of the ~~field~~ rotor poles. The oscillatory motion produces eddy current in the rotor which flows in such a way to suppress these oscillation.

Application of synchronous motor ⇒

(1) Power factor correction ⇒ overexcited synchronous motor are widely used for improving the power factor of those power system which employs large number of induction motor.

(2) Constant speed application ⇒ Due to their high efficiency and high speed it is well suited for constant speed device such as centrifugal pump, blower, rubber and paper mills etc.

(3) Voltage Regulation ⇒ By installing a synchronous motor with a field regulator, the voltage rise of a transmission line can be controlled. i.e it improve the voltage regulation of transmission line.

Effect of Excitation on Armature Current and Power Factor ⇒

If the field excitation is such that the rotor current produces all the required flux, then no reactive power is needed in the stator. Thus the motor operates at unity p.f.

If the motor is underexcited, then the deficit in flux is given by the stator. Thus the motor will draws reactive power to provide the remaining flux. Hence it operates at lagging p.f.

If the motor is over excited then the excess flux is counterbalanced in the stator. Thus instead of absorving reactive power, the stator delivers reactive power to the 3 ϕ line. Hence it operates at leading P.F.

Single phase Series motor or A.C Series motor ⇒

Single phase commutator motor →
- Series motor
- Universal motor
- Repulsion motor
- Repulsion induction motor

A.C Series motor ⇒

If an ordinary d.c. series motor is connected to an a.c supply, then it will rotate and exerts unidirectional torque, because the current flowing both in armature and field reverses at the same time. But the performance will not be satisfactory due to the following reason.

(a) the alternating flux will create excessive eddy current losses in the yoke and it becomes extremely heated.

(b) There is a considerable sparking between the brushes and commutator when the motor is used on a.c supply. Because high voltage and current are induced in the short ckted armature coils during their commutation period.

(c) Power factor is low because of high inductance of the field and armature ckt.

Thus by proper modification a d.c series motor is made to operate on a.c supply.

The eddy current losses has been reduced by laminating the entire magnetic ckt. The power factor has been improved by reducing the magnitude of the reactance of the field and armature winding. So that the number of turns of the field winding is reduced.

The sparking which is produced between the brushes and commutator can be eliminated by using high resistance leads to connect the coils to the commutator segments.

Operation => When the motor is connected to an a.c supply, the same alternating current flows through the field and armature winding. The field winding produces alternating flux ϕ and it reacts with the armature current to produce a torque. Since both armature current and flux reverses simultaneously, then the torque always acts in the same direction.

Application => For fractional h.p A.c series motor. It has high speed and large starting torque. Therefore it is used in

high-speed vacuum cleaner

sewing machine.

machine tools etc.

Universal motor =>

A universal motor is defined as that motor which operate both on d.c and a.c at same speed and output. It is a smaller version of a.c series motor (5 to 150w). It has high starting torque and variable speed characteristics.

Universal motor are manufactured in two types. ① concentrated pole, non compensated type (low power rating)
(2) Distributed field compensated type (high " ")

① Concentrated pole type =>

It has two salient poles and its whole magnetic path is laminated. It has a laminated core having either straight or skewed slots and a commutator to which the leads of the armature winding are connected.

② Distributed field type =>

It has a stator core similar to that of a split phase motor. Here compensating winding is used to ~~react~~ reduced the reactance voltage present in the armature when motor runs on a.c supply. This voltage is due to alternating flux by transformer action.

Operation => This motor develops unidirectional torque whether they operate on a.c or d.c supply. It works on the principle of a current carrying conductor placed in a magnetic field experiences a force.

Single phase Repulsion motor =>

A repulsion motor is similar to an a.c Series motor. But in this Case brushes are not connected to supply but are short circuited. Therefore the current are induced in the armature conductor by transformer action. In a repulsion motor the field structure are of non-Salient pole type.

Consider a 2 pole Salient pole motor with the magnetic axis vertical as shown in fig 1

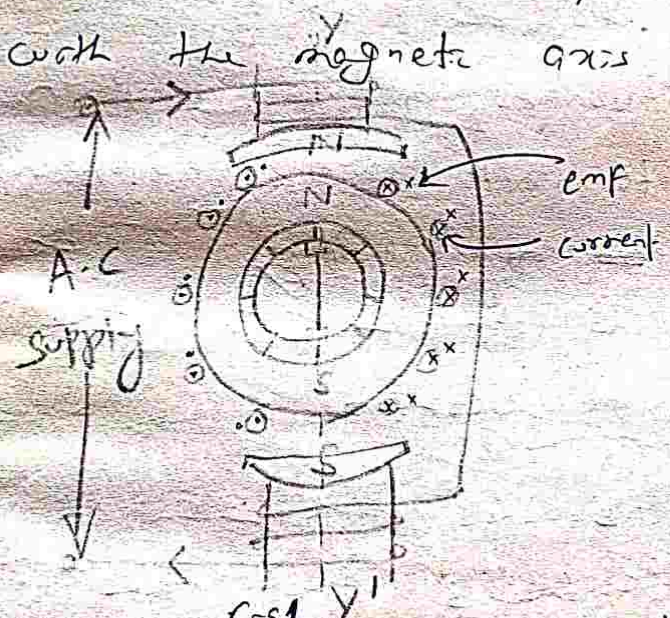


Fig 1

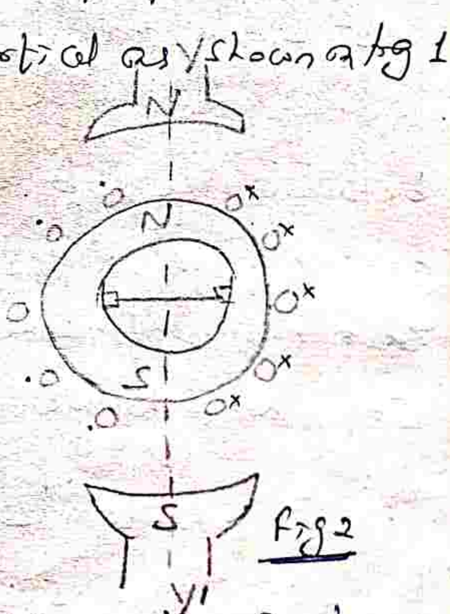


Fig 2

Suppose that the alternating current produces N pole at top and S pole at bottom of the stator winding. Therefore alternating flux will be produced in the stator winding which will induces an emf in the armature conductor by transformer action. The direction of this induced emf can be found by Lenz's law and is shown in fig 1. But the direction of induced current in the armature conductor will depends upon the position of the short circuited brush.

If the brush axis is parallel with the magnetic axis of the main field pole, then the direction of induced current is shown by dots and arrow as shown in fig 1. Thus the armature will become an electromagnet with N pole at the top and S pole at the bottom. Therefore the two forces of repulsion on top and bottom acts along YY' and thus No ~~torque~~ torque will be developed.

If the brushes are shifted 90° as shown in fig 2, then the voltage induced in the armature conductors in each path between the brush terminals will neutralise each other. Hence ~~no~~ net voltage will be zero thus there is no armature current. So No torque will be developed.

Now if the brushes are set in position as shown in fig 3, then the induced voltage in conductors a and b opposes the voltage in other conductor lying above brush axis. Similarly induced voltage in conductor c and d opposes the voltage in other conductors lying below brush axis. Therefore a net voltage will be induced between the brush terminal which will produce armature current. Thus the armature will again become an electromagnet and develops its own N and S Poles as shown in fig 4.

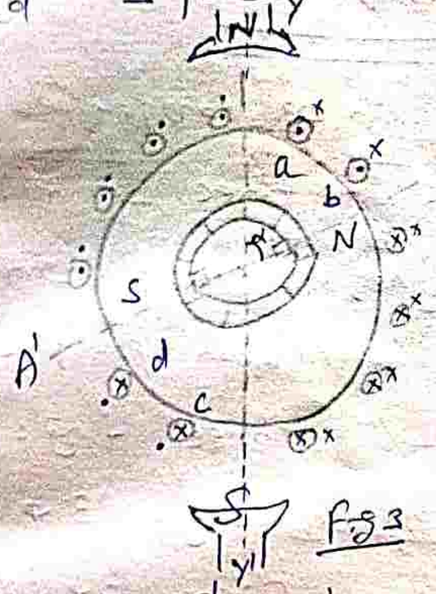


Fig 3

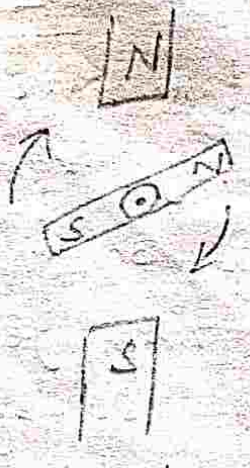


Fig 4

Hence due to repulsion between the rotor poles and main field poles, the rotor will rotate in clockwise direction. If the brushes are shifted in anticlockwise direction, then the net torque developed will also in anti-clockwise direction.

Thus a Repulsion motor is made to operate in either direction depending upon the direction of brush shift.

It has high starting torque (about 350%) and moderate starting current (3 to 4 time I_{Fl})