ELECTRICAL MACHINE- II
[2EEPC2003]
LECTURE NOTES
B. TECH II YEAR – IV SEM (2024-25)

DEPARTMENT OF ELECTRICAL ENGINEERING
MODERN ENGINEERING
&
MANAGEMENT STUDIES

A.C. Generator

Difference betn D.C. generator & Alternator:-

It is seen that in case of d.c. generator, basically the nature of Induced emf in armature conductor is alternating type and by the help of commutator we we converted to d.c..

If commutator is removed from d.c. generator and induced emf is tapped from armature directly, than the nature of such emf will be alternatig, providing an a.c. "such a machine without commutator, is called alternator". emf to external ckt.

We know that Induced emf is basically the effect of the relative motion present betn the armature and field. So in case of d.c. generator the relative motion is achived by rotating the armature with con-stant field. But in case of alternator it is possible to have.

i) Rotating armature & stationary field.
ii) Rotating field & Stationary armature.

Key-point: Practically most of the ~~armature~~ alternator prefer rotating field type construction due to certain advantages.

Advantages of Rotating field over Rotating Armature:-

* As everywhere a.c. is used, the generation level of a.c. voltage is high as 11 KV to 33KV. This gets induced in the armature. for stationary armature large space can be provided to accomodate large number of conductor and the insulation.

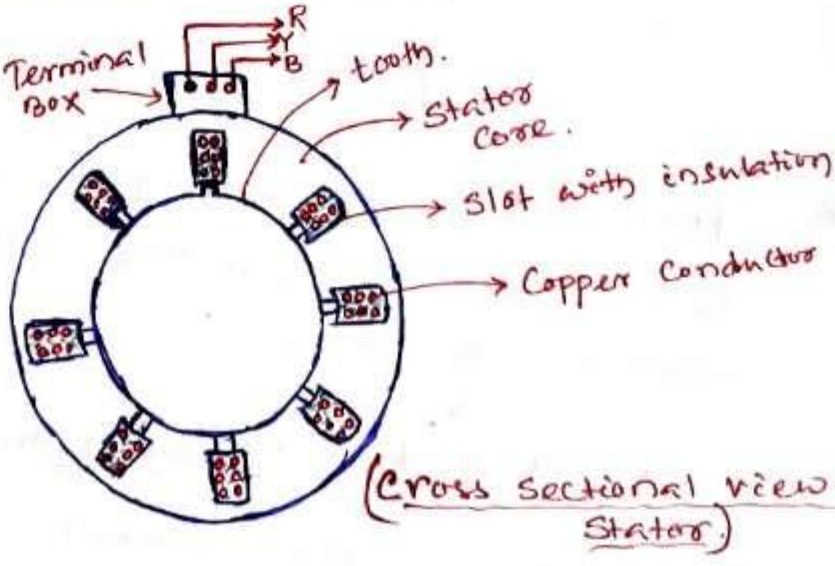
* To avoide electrical and mechanical stresses it is always better to protect high voltage wdg from centrifugal force caused due to rotation. Hence it is better to keep stationary armature.
* It is easier to collect large current at very high voltage from a stationary member
* Due to low voltage level on field side, the insulation required is less hence field system has very low inertia. So it is better to rotate low inertia system then high inertia. as efforts required is less.
* The ventilation arrangment for high voltage side can be improved if it is kept stationary.

Construction:-

In alternator the stationary winding is stator while rotating winding is rotor.

* So most of the alternator have stator as armature and rotor as field. in practice.

Stator:-



(Cross sectional view of Stator.)

The stator is a stationary armature. It consists of a core and the slots to hold the armature wdg simillar to the armature of a d.c. generator. The stator core uses a laminated construction, to reduce eddy current and hysteresis loss.

frame does not carry any flux and serves as the support to the core. ventilation is maintained with the help of holes in the frame.

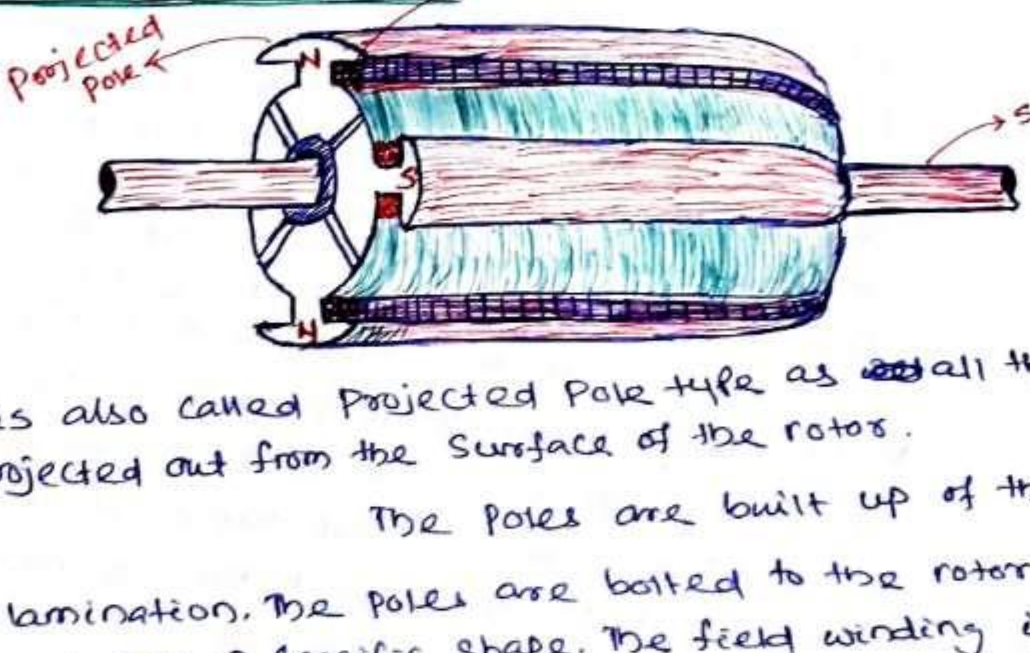
Rotor:-

There are two types of rotor in alternator.

i) Salient pole type.

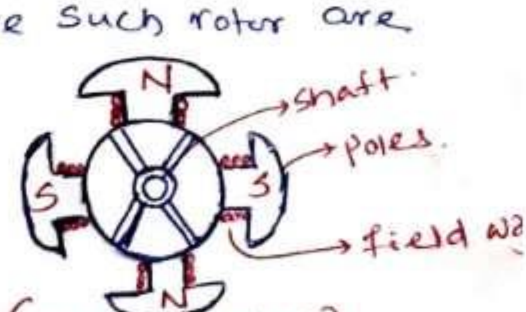
ii) smooth cylindrical type.

i) Salient pole type Rotor:-



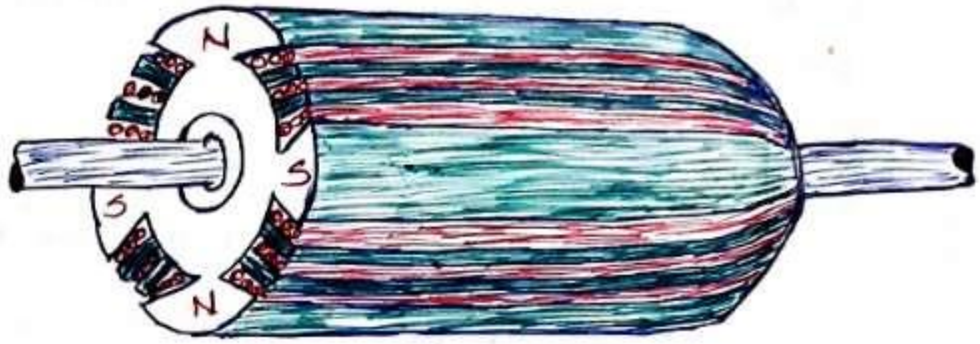
This is also called projected pole type as all the pole are projected out from the surface of the rotor. The poles are built up of thick steel lamination. The poles are bolted to the rotor. The pole faces are a specific shape. The field winding is provided, on the pole shoe.

These rotor have large diameter and small axial length. As the mechanical strength of the pole is less this is preffered for low speed alternator ranging from 125 r.p.m to 500 r.p.m. The primover preffered for low speed alternator to drive such rotor are generally water turbine.



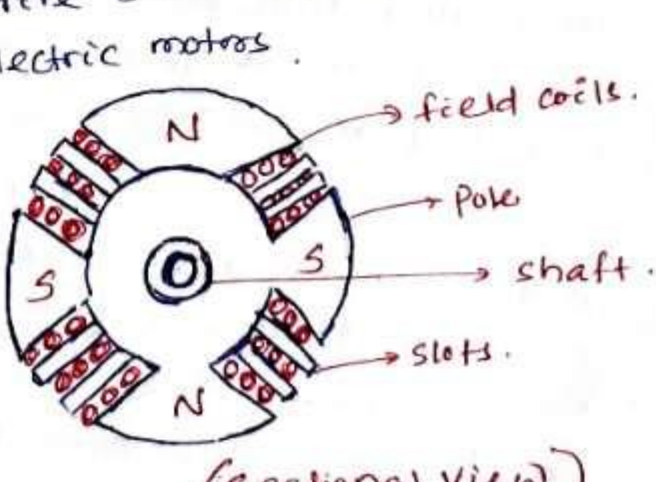
(sectional view)

ii) Smooth cylindrical type rotor.



This is also called non salient type or non-projected pole type rotor.

The rotor consists of smooth solid steel cylinder, having number of slots to accomodate the field coil. The unslotted portions of the cylinder itself act as the poles. The poles are not projecting out and the surface of the rotor is smooth which maintain uniform air gap betn stator and the rotor. These rotor have small diameter and large axial length. The main advantages of this type is that these are mechanically very strong and thus preffered for high speed alternator ranging betn 1500 to 3000 r.p.m. Such high speed alternator is called turbo-alternator. The prime mover used to drive such type of rotor are generally steam turbine, electric motors.



(sectional view)

Difference betⁿ Salient & non-salient pole type rotor

Salient pole	Non-Salient pole
* Poles are projecting out from the surface	* Poles are non projecting & unslotted portion acts as poles.
* Air-gap is non-uniform	* Air-gap is uniform.
* Diameter is high & short axial length	* Small Diameter & large axial length.
* Mechanically weak	* Mechanically strong.
* Preffered for low speed	* Preffered for high speed.
* Prime mover used are water turbine, I.C. engine	* Prime mover used are steam turbine, electric motor.
* Separate Damper way will be provided	* Separate Damper way is not necessary.

Note:- Working Principle of alternator is same as D.C. generator

EMF Equation of an alternator:-

Let ϕ = flux per pole in wb.

P = Number of poles.

N_s = Synchronous speed in r.p.m.

f = frequency of induced emf in Hz.

Z = total no. of conductor.

Z_{ph} = conductor per phase connected in series

$\therefore Z_{ph} = \frac{Z}{3}$ (as no. of Phases = 3)

Consider a single conductor placed in a slots.

$\therefore$ Average value of emf induced in a conductor

$= \frac{d\phi}{dt}$.

for one revolution

Total flux cut by conductor = $\phi \times P$.

time taken for one revolution = $\frac{60}{N_s}$.

$\therefore e_{avg}$ per conductor $= \frac{\phi P}{\left(\frac{60}{N_s}\right)} = \frac{\phi P N_s}{60}$ —— (1)

But we know that $f = \frac{PN_s}{120}$.

$\therefore \frac{PN_s}{60} = 2f$.

So equation(1) will be

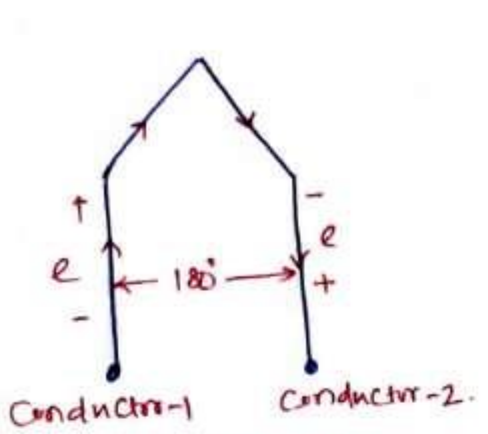
e_{avg} per conductor = $2f\phi$ volt.

Assuming full pitch winding for simplicity i.e. this conductor is connected to a conductor which is 180° electrical apart. So these two emf will try to set up a current in the same direction i.e. the two em are helping each other and hence resultant emf per tur will be twice the emf induced in a conductor.

$\therefore$ emf per turn $= 2 \times$ (emf per conductor)

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

$$= 4f\phi \text{ volt.}$$



Let T_{ph} be the total no. turns in series per phase connected wdg. Assuming concentrated wdg. net emf per phase will be algebric sum of the emf per ~~phase~~ turn.

$\therefore$ Average $E_{ph} = T_{ph} \times$ (Avarage emf per turn)

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

But in a.c. ckt RMS value is used for analysis.

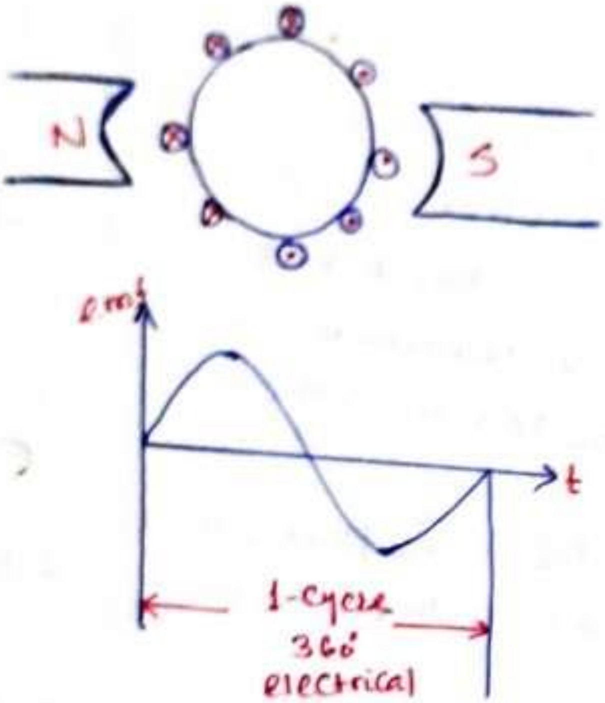
$$\therefore E_{ph}(r.m.s) = 1.11 \times E_{ph}(avg)$$

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

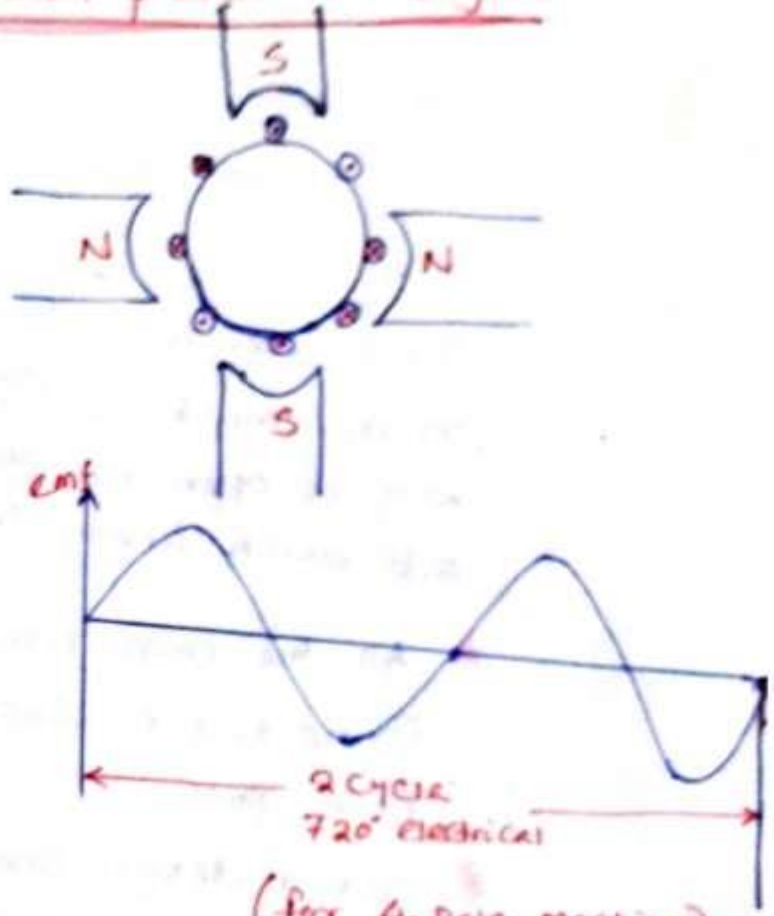
$$\boxed{E_{ph}(r.m.s) = 4.44\, \phi f\, T_{ph}.}$$

$$\left[\text{Where } T_{ph} = \frac{Z_{ph}}{2}\right]$$

Relation betⁿ Mechanical & Electrical Degree



(for 2-pole m/c)
(360° mechanical rotation)



(for 4-pole machine)
(360° mechanical rotation)

From the above two experiment we come to know that the degree electrical of induced emf i.e. number of cycles of the induced emf depends on the number of poles of an alternator.

So for 4 pole alternator, we can write.

360° mechanical = 720° electrical

$\Rightarrow$ 360° mechanical = $360° \times \frac{P}{2}$ electrical

i.e. 1° mechanical = $\left(\frac{P}{2}\right)^{\circ}$ electrical

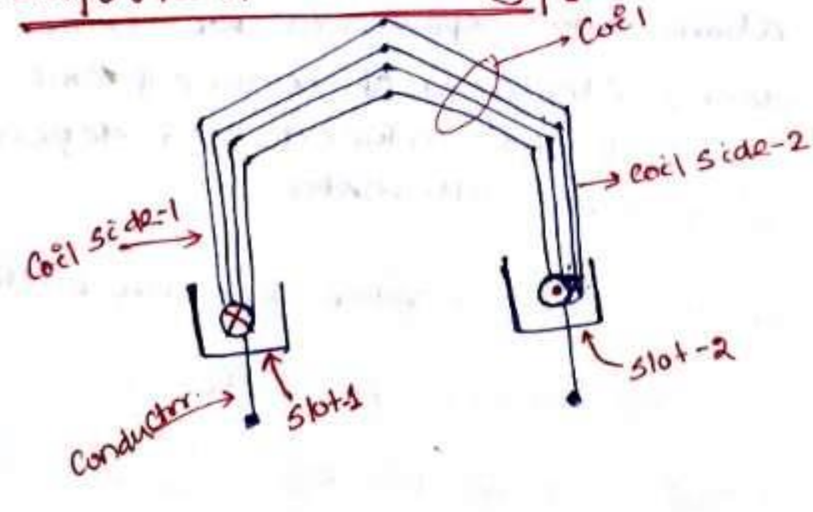
(where P = Number of Poles)

Armature Winding:-

Armature wdg of alternator is different from d.c. machine Beacuse in case of 3-Φ alternator it carry 3-sets of wdg in such a way that there exists a phase difference of 120° betn them. In d.c. machine wdg is closed but in alternator wdg is open i.e. six terminals are brought out which finally connected in star or Delta.

* All the coils used for one phase must be connected in such a way that their emf helps each other.
* overall design should be in such a way that the waveform of an Induced emf is almost sinusoidal in nature.

Important Terminology:-



Pole Pitch:-

It is the distance betn the two adjacent poles.

We have seen that 2-pole are responsible for 360° electrical of emf. 4-poles are responsible for 720° electrical and so on. So one pole is responsible for 180° electrical

* So 180° electrical is also called one pole pitch

Key point:- Generally number of slots under one pole which are responsible for 180° electrical are measured to specify the pole pitch.

Eg:- If there is 2-poles and 20 slots armature then under 1-pole there are $\frac{20}{2} = 10$ slots. So pole pitch is 9 or 180° electrical.

$$\therefore \boxed{\text{Pole pitch} = 180° \text{ electrical} = \text{slots/pole} = n.}$$

Slot Angle (β):-

The phase difference contributed by one slot in electrical degree is called slot angle (β).

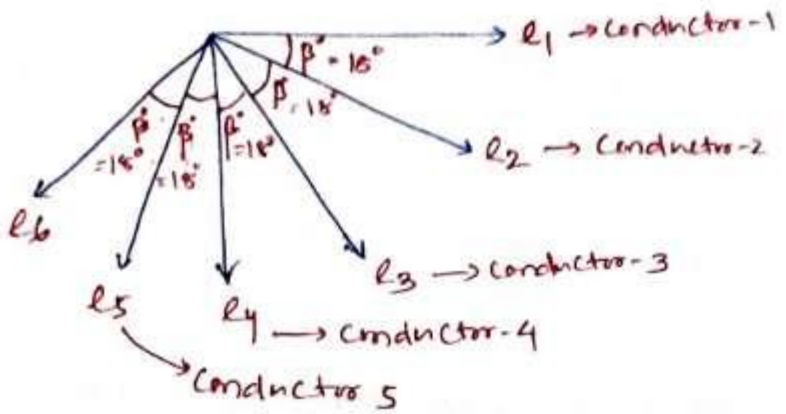
We know that

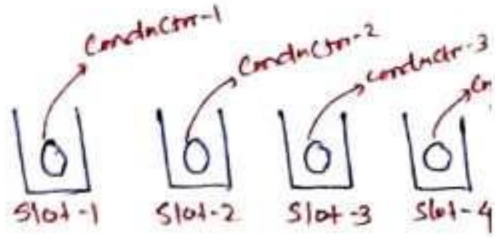
slots/pole contributed 180° electrical. notation is 'n'.

$$\therefore 1 \text{ slot angle} = \frac{180°}{n}.$$

$$\therefore \boxed{\beta = \frac{180°}{n}}.$$

Eg:- If slots per pole is 10 for 2-pole alternator. then $\beta = \frac{180°}{n} = \frac{180°}{10} = 18°$.





Types of Armature winding:-

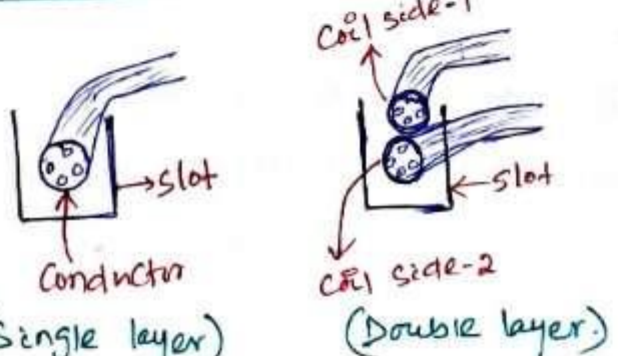
Armature wdg are classified as

i) single layer and double layer wdg.

ii) full pitch and short pitch wdg.

iii) Concentrated and distributed wdg.

i) Single layer and double layer wdg:-

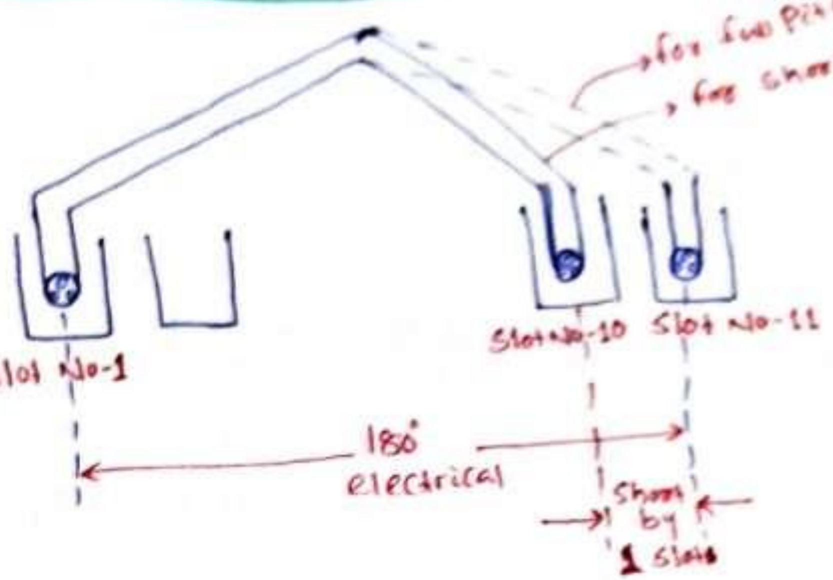


(Single layer) (Double layer)

If a ~~coil~~ slot consists only one coil side, winding is called single layer wdg. But if the slot consists of dual coil side winding, than it is called double layer winding as shown in fig.

* Practically double layer wdg is used becoz in single layer wdg a lot of space get wested in slots.

ii) full Pitch and Short pitch:-



If the coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from first slot i.e. 180° electrical, than this type of winding is said to be full pitch winding.

for example:- In 2 pole, 20 slots alternator.

Pole pitch $n = \frac{20}{2} = 10$ slots/pole.

So if coil side in slot no-1 is connected to coil side in slot no-11 are one pole pitch or 180° electrical apart. this coil is full pitch coil.

But if the coils are used in such a way that coil span is slightly less than a pole pitch i.e. less than 180° electrical, the coils are called short pitch coil or fractional pitch coil.

* practically the short pitched coil are used due to some advantages.
  * The coil length required is less. so less copper is required. Hence economical.
  * It eleminates high frequency harmonics

which distorts the sinusoidal nature of emf. Hence waveform is more sinusoidal.

* As high frequency is eleminated. So the eddy current and hysteresis loss also minimized. which increse the efficiency.

iii) Concentrated and Distributed wdg:-

If all conductors or coils belonging to a phase are placed in one slot under every pole is called Concentrated wdg.

Alternator is 3-phase. i.e. three different set of winding, each for a phase. So depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. It is denoted as 'm'.

$$m = \text{slots per pole per phase} = n/\text{number of phase}$$

$$\Rightarrow m = \frac{n}{3} \quad (3\text{-phase})$$

[for example:- In 18 slots, 2 pole alternator.

$$\text{slots per pole } 'n' = \frac{18}{2} = 9.$$

$$\text{and slots per pole per phase } 'm' = \frac{9}{3} = 3.$$

So we have 3 slots per pole per phase available. Now let 'x' number of conductor per phase are to be placed under one pole. If all 'x' conductors per phase are placed in one slot keeping remaining 2 slots empty is concentrated wdg.]

But if 'x' conductors per phase are distributed amongst the 3 slots per phase available under every pole, the wdg is called distributed wdg.

* Distributed wdg makes the waveform of the induced emf more sinusoidal in nature.
* In concentrated wdg due to large number of conductor per slot, heat dissipation is poor. So practically distributed wdg is used.

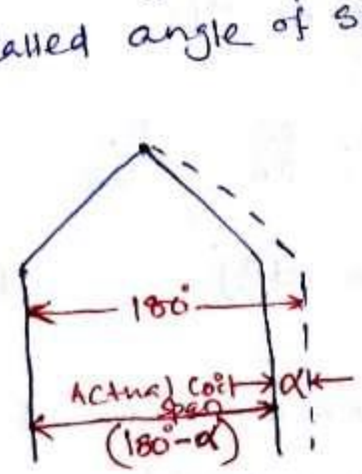
Note:- In practical field, generally double layer, shortpitched and distributed type armature wdg is preffered.

—x—

Pitch factor or Coil span factor (K_c):-

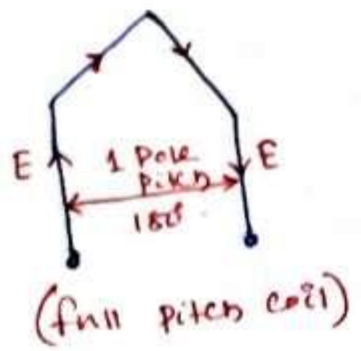
In practice short pitch coil are preferred. Short pitch coil is less than one pole pitch means less than 180°. The coils is generally shorted by one or two slote.

Note:- The angle by which coils are short pitched is called angle of short pitch denoted as 'α'.



α = Angle by which coils are short pitched.

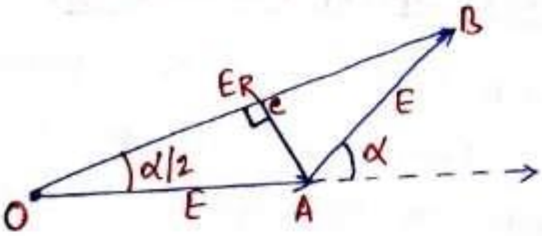
So $\alpha = 180° -$ Actual coil span.



Let 'E' be the induced emf in each coil side. If coil is full pitch coil, the induced emf in each coil side help each other. Hence the resultant emf across a coil will be algebric sum of the two.

$$E_R = E + E = 2E \longrightarrow \text{for full pitch.}$$

Now Coil is short-pitched by angle 'α',
so the two coil sides no longer in phase. Hence
the resultant emf is also no longer remain algebric
sum of two but become a Phasor sum. It is obvious
that E_R value is less than E_R in full pitch coil.



Draw AC perpendicular on OB bisecting OB.

$$\therefore \, l(OC) = \frac{E_R}{2} = l(CB)$$

and $\angle BOA = \alpha/2$.

$$\therefore \cos\left(\frac{\alpha}{2}\right) = \frac{OC}{OA} = \frac{E_R}{2E}.$$

$$\Rightarrow E_R = 2E\cos(\alpha/2) \longrightarrow \text{for short pitch.}$$

Now "the factor by which induced emf get reduced due to short pitching is known as Pitch factor or Coil span factor (K_c).

Mathmatically it is expressed as

$$K_C = \frac{E_R \text{ when coil is short pitch}}{E_R \text{ when coil is full pitch}}$$

$$\Rightarrow K_C = \frac{2E\cos(\alpha/2)}{2E}$$

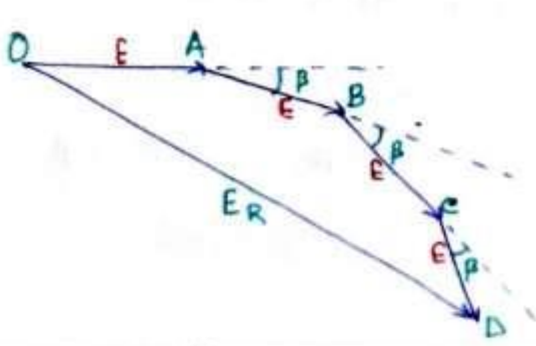
$$\Rightarrow \boxed{K_C = \cos\frac{\alpha}{2}}$$ $\alpha \rightarrow$ Angle of short pitch.

Distribution factor:-(K_d)

Similar to full pitch coil, concentrated winding is rarely used.

In concentrated type all coils are placed in a one slots under one pole. So induced emf in all coil will be in phase, hence resultant emf after connecting coils in series will be algebric sum of all the emf.

But in case of distributed wdg all the slots contain the coils, and there is a slot angle also(β). Though the magnitude of emf in each coil is same 'E'. and as slot angle 'β' exist betⁿ the coils, so there is a phase difference occurs to each other. Hence resultant emf will be phasor sum of them. So due to distributed wdg resultant emf decreases.

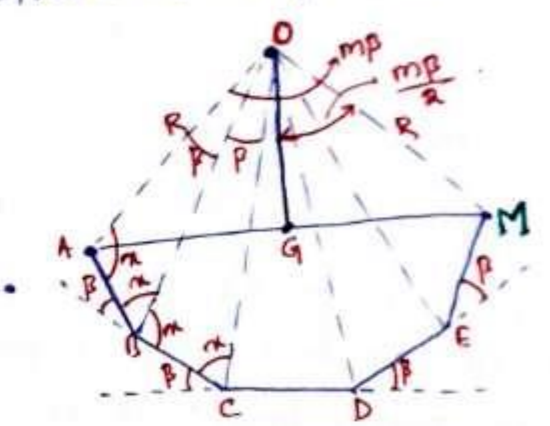


* "The factor by which there is a reduction in the emf due to distribution of coils is called Distribution factor as (K_d)."

Derivation of Distribution factor :- (K_d)

Let there are 'n' slots and 'm' slots/pole/phase so there is 'm' coils distributed under a pole/phase connected in series.

Let 'E' be the induced emf per coil then all the 'm' emf's induced in the coil will phase difference of $\beta = \frac{180°}{n}$.



AB, BC, CD, DE & EF → Represents emf per coil.
All the ends are joined at 'O' which is center of radius 'R'.

So $AB = BC = CD = EF = E$

Let the base angle be 'α'.

$\angle OAB = \angle OBA = \angle OBC = \angle OCB = \alpha$

and $\angle AOB = \angle BOC = COD = y$ (say)

Now consider AOB triangle

$2\alpha + y = 180°$ ——— (i)

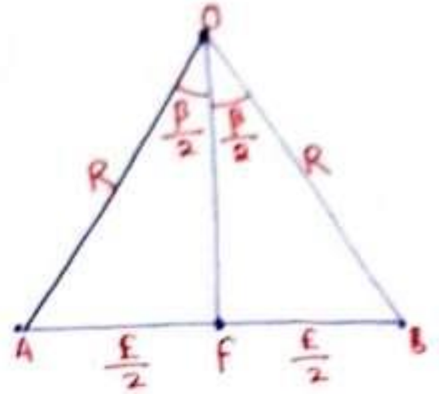
while $\angle OBA + \angle OBC + \beta = 180°$

i.e. $2\alpha + \beta = 180°$ ——— (ii)

Comparing eqn (1) & (4)

$$\gamma = \beta$$

So $\angle AOB = \angle BOC = \angle COD = \cdots = \beta$



If 'M' is the last point of the last phasor

so $\angle AOM = m \times \beta = m\beta$ and

$AM = E_R$ = Resultant of all the emf.

Now from the triangle AOB Δ

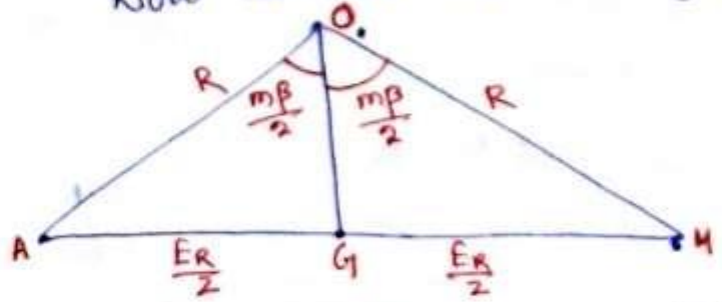
$l(AB) = E$ so $l(AF) = \frac{E}{2}$.

and $l(OA) = R$.

$$\therefore \sin\left(\frac{\beta}{2}\right) = \frac{AF}{OA} = \frac{E/2}{R}.$$

$$\Rightarrow E = 2R\sin\left(\frac{\beta}{2}\right). \quad \text{———— (3)}$$

Now consider the triangle OAM Δ from main fig.



$\angle AOG = \angle GOM = \frac{m\beta}{2}$.

& $l(AM) = E_R$, so

$l(AG) = \frac{E_R}{2}$.

$$\therefore \sin\left(\frac{m\beta}{2}\right) = \frac{AG}{OA} = \frac{E_R/2}{R}.$$

$\Rightarrow$ $\boxed{E_R = 2R \sin\left(\frac{m\beta}{2}\right)}$ → Resultant emf for distributed wdg

Now for concentrated wdg

$$E_R = m \times E.$$

from eqn ③, $E = 2R \sin\left(\frac{\beta}{2}\right)$

So $\boxed{E_R = 2mR \sin\frac{\beta}{2}}$ → Resultant emf for concentrated wdg

Now Distribution factor is defined as

$$K_d = \frac{E_R \text{ when coil is distributed}}{E_R \text{ when coil is concentrated}}$$

$$\Rightarrow K_d = \frac{2R \sin\left(\frac{m\beta}{2}\right)}{2mR \sin\left(\frac{\beta}{2}\right)}.$$

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

m = slots/pole/phase.

β = slots angle = $\frac{180°}{n}$.

n = slots per pole.

Generalized Eqn of EMF

When we consider full pitch, concentrated wdg.

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

But at the time of short pitch, distribution wdg

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

* for full pitch $K_c = 1$
* for concentrated wdg $K_d = 1$

Parameters of Armature Winding:-

There are three important parameter of armature winding.

i) Armature Resistance (R_a)

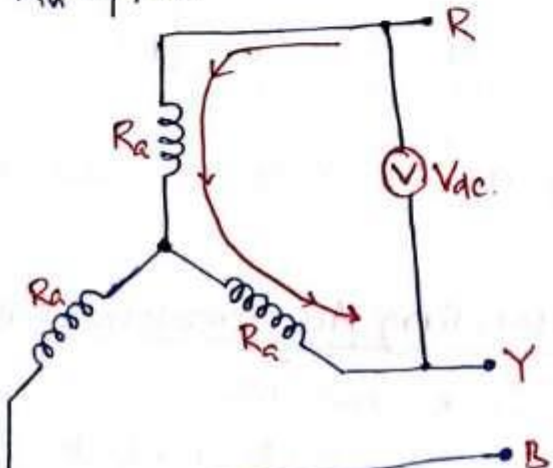
ii) Armature leakage reactance (X_L)

iii) Reactance corresponding to Armature reaction.

These three important parameter is help-ful to determine the Regulation of an alternator and drawing the equivalent ckt.

i) Armature Resistance(R_a):-

every armature wdg has its own resistance. the effective resistance is denoted as R_a Ω/ph.



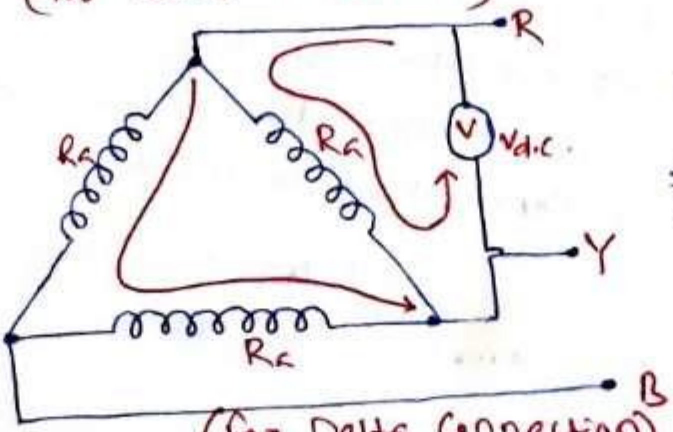
(for star connection)

To measure the armature resistance of a alternator we give the d.c. voltage to any two phase.

R_{RY} = Resistance betn R-Y terminal

$= R_a + R_a = 2R_a$.

$$\Rightarrow R_a = \frac{R_{RY}}{2} \; \Omega/ph$$



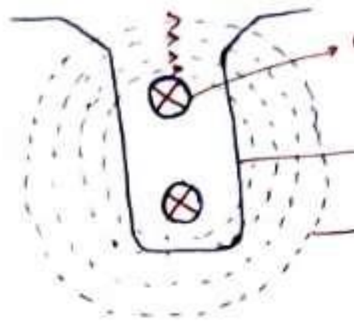
(for Delta Connection)

$R_{RY} = R_a \parallel 2R_a$ Ω/ph.

$\Rightarrow R_{RY} = \frac{2}{3} R_a$

$$\Rightarrow R_a = \frac{3}{2} R_{RY} \; \Omega/ph.$$

Armature Leakage Reactance:-



When armature carries a current. it produces its own flux. Some part of this flux completes its path through the air around the conductor itself. Such a flux is called leakage flux.

This leakage flux makes the armature wdg inductive in nature. So wdg possesses a wdg reactance in addition to the resistance.

So leakage reactance is given by

$$X_L = 2\pi f L \ \Omega/ph.$$

* It's value is much higher than armature resistance

Reactance Corresponding to Armature Reaction:-

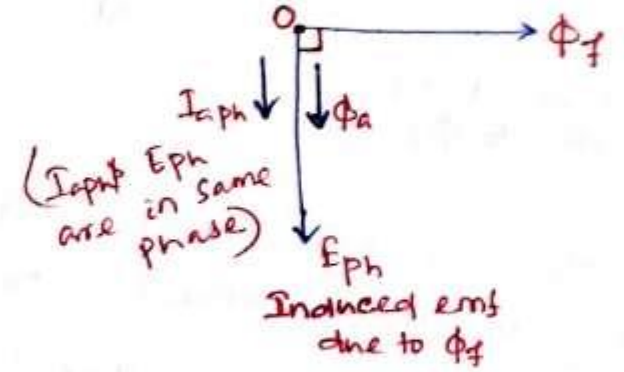
Due to armature flux and main flux armature reaction comes in to the picture. ~~but armature reaction also depends upon~~ The effect of the armature flux. not only depend upon the magnitude of current but also depend upon the nature of power factor of the load connected to load.

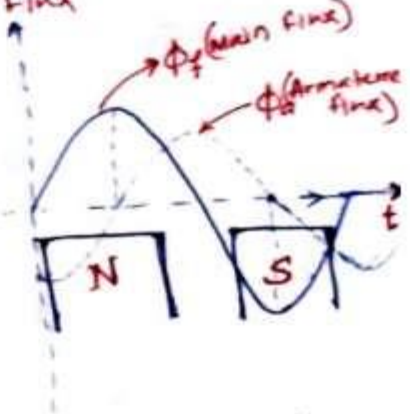
Let us see the effect of power factor on the armature reaction.

i) Unity P.f. Load:-

Consider a purely resistive load connected to the alternator, having unity power factor. i.e. Eph and Iph are in phase.

If 'ϕ_f' is the main flux produced by the field wdg responsible for producing Eph, than Eph lags ϕ_f by 90°.





Now current through armature I_a produces armature flux 'ϕ_a'. So ϕ_a and I_a are always in phase in same direction.

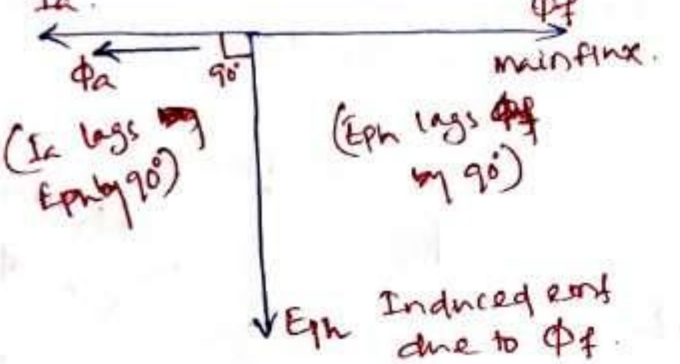
It is seen that there exist a phase difference of 90° betn ϕ_a and ϕ_f. from the waveform it is seen that the two fluxes opposes each other on the left half and assist each other at right half of each pole. Hence average flux is constant but its flux distribution gets distroted.

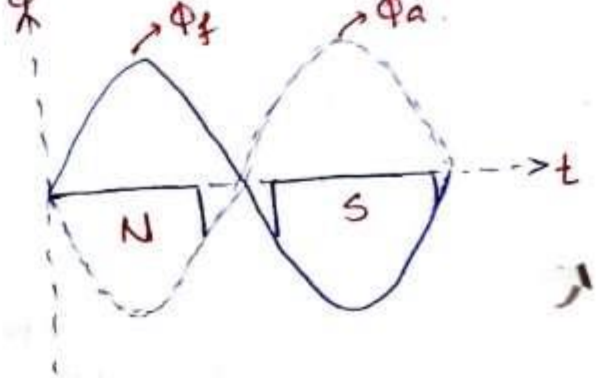
"Such distortion effect of armature reaction under unity P.f. is called Cross magnetising effect".

Due to this. small voltage drop will occure at the terminals of alternator.

ii) Zero Lagging P.f :-

Consider a pure Inductive load connected to the alternator having zero lagging P.f. This Indicates that I_a is lags by E_{ph} by 90°.



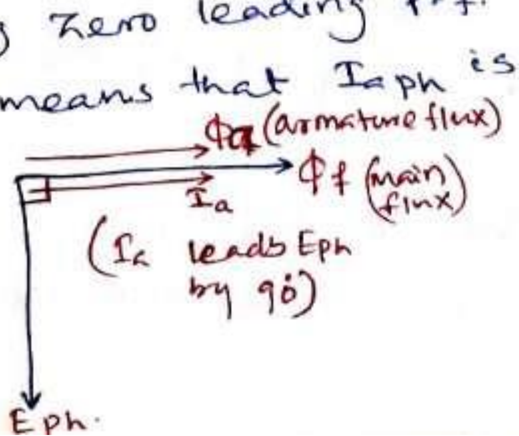


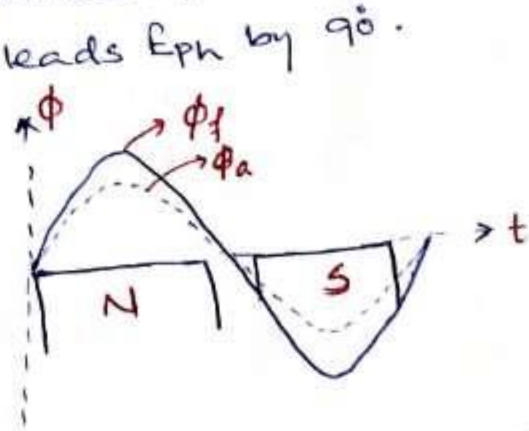
It is seen from phasor diagram that ϕ_f and ϕ_a are exactly in opposite direction to each other. "So armature flux tries to cancel the main flux. such an effect of armature reaction is called <u>demagnetising effect</u>."

As this effect causes reduction in the main flux, the terminal voltage drops. This drop is higher than unity P.f.

iii) Zero Leading P.f :-

Consider a Pure Capacitive load having zero leading P.f. connected to alternator this means that I_{aph} is leads E_{ph} by 90°.





It can be seen from the phasor diagram and waveform that the armature flux and the main flux are in the same direction. i.e. they are helping each other. This results in to the addition in main flux.

"Such an effect of armature reaction due to which armature flux assists field flux is called magnetising effect of armature reaction."

As this effect adds the flux to the main flux, greater emf gets induced in the armature

Armature Reaction Reactance (X_{ar}):-

We have seen that in inductive load demagnetising effect occurs. and generally practical loads are inductive in nature. due to this terminal voltage reduces. This drop is not across any physical element.

But to quantify the voltage drop due to armature reaction, armature reaction is assumed to have a fictitious reactance. This reactance is called Armature reaction Reactance (X_{ar}). and the drop is $I_a X_{ar}$.

Synchronous Reactance and Synchronous Impedance

The sum of the fictitious armature reaction reactance and the leakage reactance of the armature is called synchronous reactance of the alternator denoted as X_s.

So $$X_s = X_L + X_{ar} \ \Omega/Ph$$

Now it is possible to define Synchronous Impedance.

"By combining per phase value of synchronous reactance and armature resistance is called synchronous Impedance of alternator, denoted as 'Z_s'.

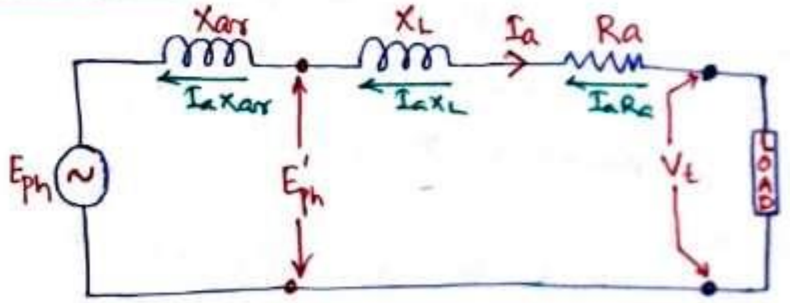
$$\text{So } Z_s = R_a + jX_s$$

$$\Rightarrow \boxed{|Z_s| = \sqrt{R_a^2 + (X_s)^2}\ \Omega/ph}$$

(Where $X_s = X_L + X_{ar}$)

* Generally Impedance of the wdg is constant for any machine. But in case of alternator, synchronous reactance is depends on load condition and powerfactor. So Z_s also varies with the load.

Equivalent Ckt of Alternator:-



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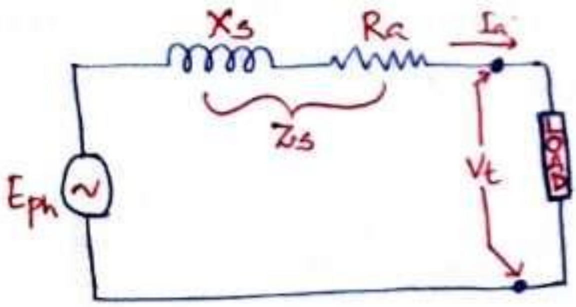


Here V_t is less than E_{ph} or E'_{ph}.

from the equivalent ckt.

$$\boxed{\bar{E}_{ph} = \bar{V}_{tph} + \bar{I}_a Z_s}$$ (Phasor sum)

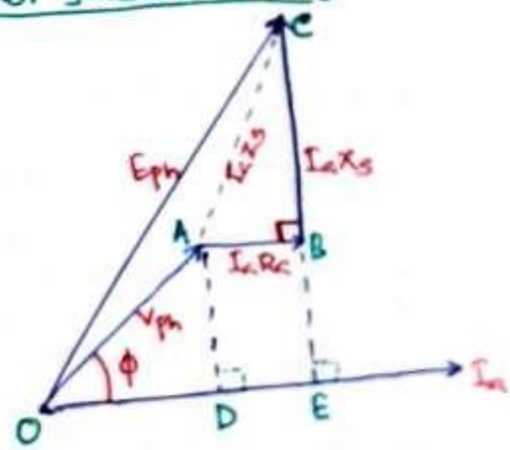
$\Rightarrow \boxed{\bar{E}_{ph} = \bar{V}_{ph} + \bar{I_a R_a} + \bar{I_a X_s}}$

This is called voltage equation of an alternator.

from this voltage equation we can draw the phasor diagram for various load power factor and establish the relationship betn E_{ph} and V_{ph}, in terms of armature current, i.e load current and the power factor $(\cos\phi)$.

Phasor Diagram

i) For lagging power factor load:-



$OD = V_{ph}\cos\phi$

$AD = BE = V_{ph} = V_{ph}\sin\phi.$

$DE = I_a R_a.$

Consider Δ OCE, we can write

$$(OC)^2 = (OE)^2 + (EC)^2$$

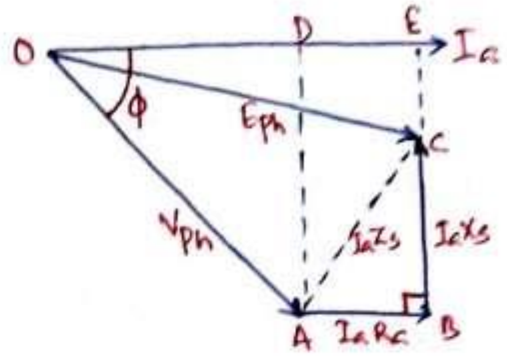
$$\Rightarrow (E_{ph})^2 = (OD + DE)^2 + (EB + BC)^2$$

$$\Rightarrow (E_{ph})^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2.$$

$$\Rightarrow \boxed{E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2}}$$

from this eqn Induced emf can be calculated.

ii) leading powerfactor :-



Considering ΔOAD

$$OD = V_{ph}\cos\phi$$
$$AD = BE = V_{ph}\sin\phi$$
$$DE = I_aR_a.$$

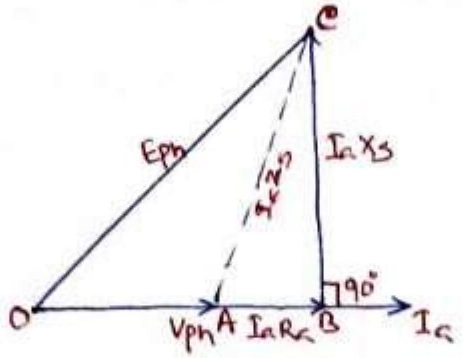
Now considering ΔOCE

$$(OC)^2 = (OE)^2 + (EC)^2$$
$$\Rightarrow (E_{ph})^2 = (OD+DE)^2 + (EC)^2$$
$$\Rightarrow (E_{ph})^2 = (OD+DE)^2 + (BE-BC)^2$$
$$\Rightarrow (E_{ph})^2 = (V_{ph}\cos\phi + I_aR_a)^2 + (V_{ph}\sin\phi - I_aX_s)^2$$
$$\Rightarrow \boxed{E_{ph} = \sqrt{(V_{ph}\cos\phi + I_aR_a)^2 + (V_{ph}\sin\phi - I_aX_s)^2}}$$

* Note:- for leading P.f. I_aX_s is negative where as for lagging P.f. I_aX_s is positive, this is beacuse Armature reaction is magnetising in case of leading P.f & demagnetising in case of lagging P.f.

iii) unity powerfactor :-

unity powerfactor means $\cos\phi = 1$. so $\phi = 0$ which means V_{ph} is in phase with I_a so phasor diagram is drawn as shown below



Considering ΔOBC,

$$(OC)^2 = (OB)^2 + (BC)^2$$

$$\Rightarrow (E_{ph})^2 = (OA + AB)^2 + (BC)^2$$

$$\Rightarrow (E_{ph})^2 = (V_{ph} + I_a R_a)^2 + (I_a X_s)^2$$

$$\Rightarrow \boxed{E_{ph} = \sqrt{(V_{ph} + I_a R_a)^2 + (I_a X_s)^2}}$$

* As $\cos\phi = 1$ & $\sin\phi = 0$, hence does not appear in the eqⁿ.

* Note:- So it is clear that V_{ph} is less than E_{ph} for lagging and unity p.f. due to demagnetising and cross magnetising effect where as V_{ph} is greater than E_{ph} in case of leading p.f. due to magnetise effect.

Thus in general, for any p.f. condition.

$$\boxed{(E_{ph})^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}$$

+ sign for lagging p.f.
− sign for leading p.f.

from this, we can now define the voltage regulation of an alternator.

Voltage Regulation of an Alternator:-

under the load condition, the terminal voltage is less than the induced emf E_{ph}. so if the load disconnected, V_{ph} is equal to E_{ph}, if flux and speed is maintained constant. This change in the terminal voltage is significant in defining the voltage regulation.

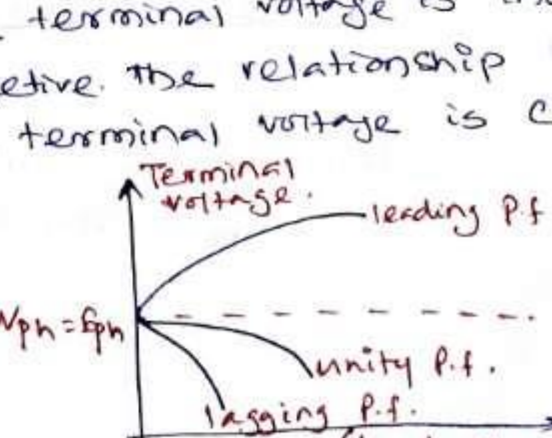
"The voltage regulation of an alternator is defined as the change in its terminal voltage when full load is removed, keeping field excitation and speed constant, devided by the rated terminal voltage"

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

E_{ph} = No load induced emf
V_{ph} = Rated terminal voltag

The value of the regulation not only depends on the load or load current but also depends on the load powerfactor.

for lagging and unity powerfactor there is always drop in the terminal voltage, hence regulation value is always positive. while the leading powerfactor, the terminal voltage is increases, hence Regulation is negetive. the relationship betn load current and the terminal voltage is called load characteristics.



(load characteristics)

Methods of Determining the Regulation :-

There are various method to determining the voltage regulation for small alternator it can be determined by direct loading test while for large capacity alternator it can be determined by synchronous impedance method.

i) Direct loading method.

ii) Synchronous Impedance method or EMF method.

iii) Ampere-turns method or MMF method.

iv) Zero powerfactor method or potier triangle method.

v) ASA Modification form of MMF method

vi) Two reaction theory.

i) Voltage Regulation by Direct Loading :

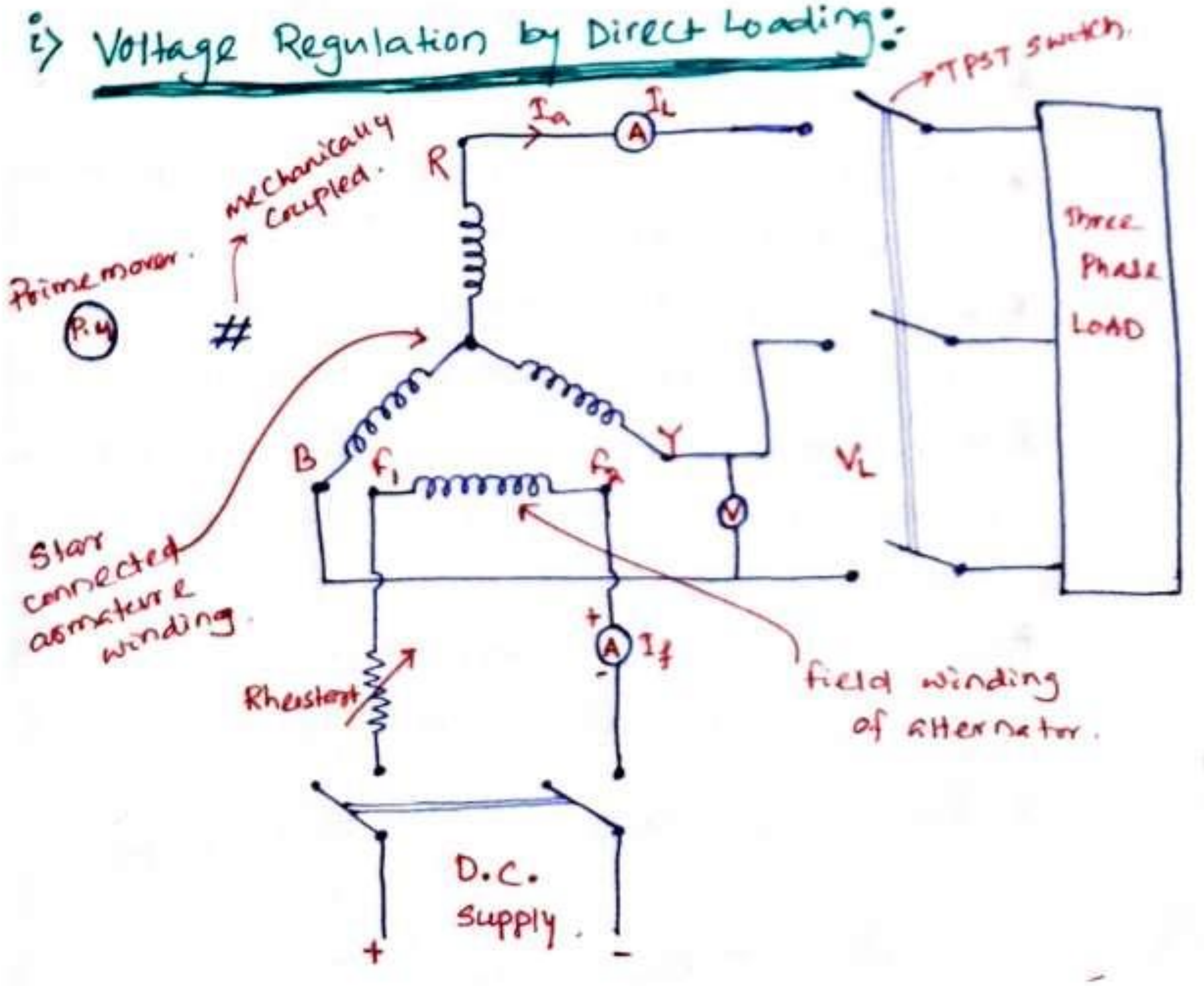


fig shows the ckt diagram for conducting the direct loading test. A star connected armature is to be connected to a three phase load by the help of TPST switch. The field winding is excited by separate d.c. supply. To control the flux i.e. the current through field winding, a rheostat is inserted in series with the field wdg.

Procedure :-

* The alternator is first driven at its synchronous speed N_s. 20

$$\text{Now} \quad E_{ph} \propto \phi$$

* By giving d.c. supply to field wdg, the field current is adjusted to adjust the flux, so that the rated voltage is available across the terminals. This can be observed on voltmeter.
* The load is then connected by means of TPST switch.
* The load is than increased, so that ammeter reads rated value of current.
* Again adjust the voltage to its rated value by means of field excitation using a rheostart connected (V_{ph})
* Then ~~through~~ throw off the entire load by the help of ~~tops~~ TPST switch, without changing the speed and the field excitation.
* Observe the voltmeter reading. This reading is the no load induced emf (E_{ph}).
* The rated voltage on full load is V_{ph}.

$$\text{Now} \quad \% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100.$$

*** Key Point:** But for high capacity alternator that much full load can not be directly connected to the alternator. Hence this method is only for small capacity alternator (Less than 5 KVA)

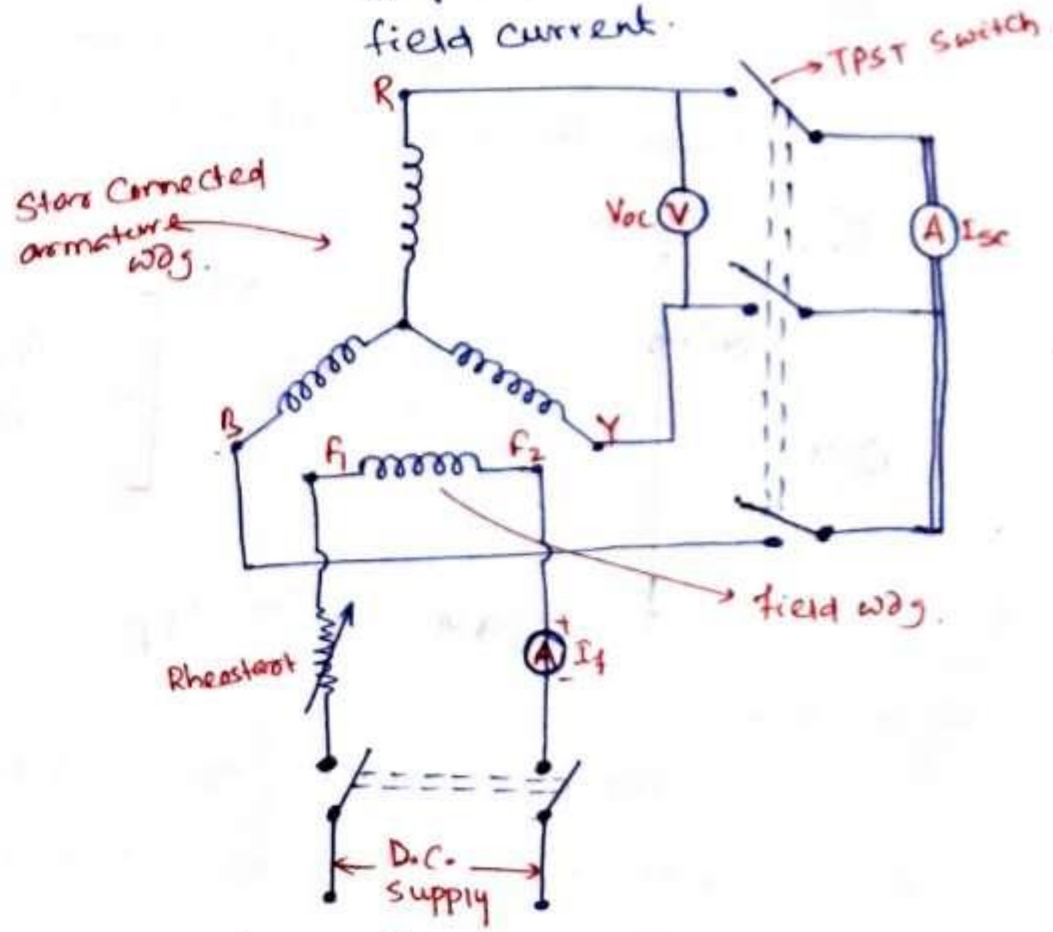
ii) Synchronous Impedance Method (Emf Method):-

Synchronous Impedance method requires following data to calculate the regulation

i) The armature resistance per phase (R_a)

ii) open ckt characteristics which is the graph of open ckt voltage against the field current

iii) short ckt characteristics which is the graph of short ckt current against the field current.



(ckt diagram)

Open ckt test:-

The procedure for open ckt test is as follows

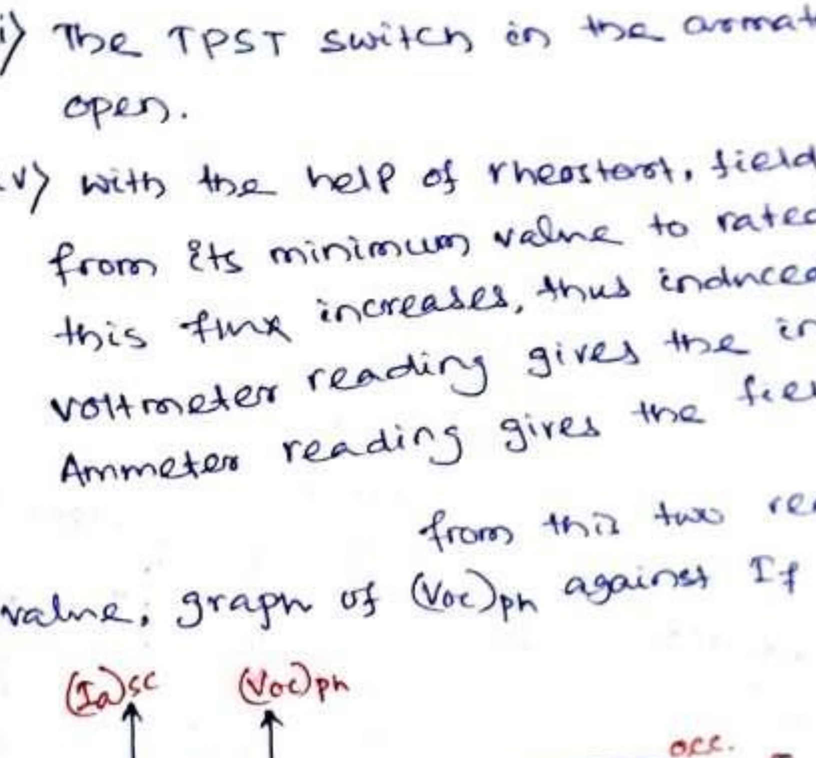
i) Start the prime mover and adjust the speed to synchronous speed.

ii) Keeping rheostat in the field ckt max. switch on the d.c. supply.

iii) The TPST switch in the armature ckt is kept open.

iv) with the help of rheostat, field current is varried from its minimum value to rated value. Due to this flux increases, thus induced emf increases. voltmeter reading gives the induced emf and Ammeter reading gives the field current.

from this two reading of varrious value, graph of $(V_{oc})_{ph}$ against I_f is plotted.



$$Z_s = \frac{(V_{oc})_{ph_1}}{(I_a)_{sc_1}} \Bigg|_{\text{when } I_f = 3A}$$

Short ckt test:-

After completing open ckt test

i) The field rheostat is brought to max. position, reducing field current to a minimum value.

ii) Close the TPST switch. ~~is closed.~~ As the ammeter has negligible resistance, the armature gets short ckted

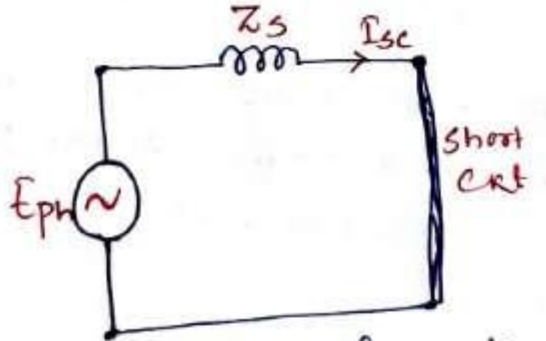
iii) Then the field excitation gradually increased till full load current is obtained through armature wdg. This can be observed on ammeter.

iv) Now for different value of I_f and I_{sc}, we can plot the graph of S.C.C.

Determination of 'Z_s' from OCC and SCC.

We know that 'Z_s' will change as load changes.

In short ckt test, external load impedance is zero. The short ckt armature current circulates against the impedance of the armature wdg which is 'Z_s'. The voltage responsible for driving this short ckt current is induced emf. This can be shown by the equivalent ckt

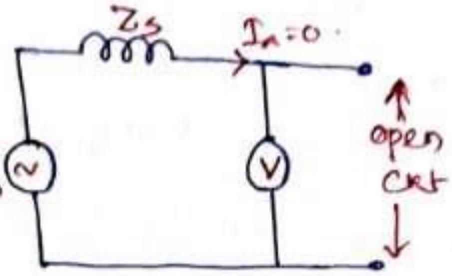


from the ckt.

$$Z_s = \frac{E_{ph}}{I_{asc}}.$$

I_{sc} is know, which can be observed on ammeter but internally induced emf can not observed in short ckt test becoz it will be zero. So to determining the 'Z_s' it is necessary to determine the value of E_{ph} from O.C.C.

The O.C.C. equivalent ckt will be.



It is clear from the equivalent ckt that as $I_a = 0$, the voltmeter reading $(V_{oc})_{ph}$ will be equal to internally induced emf (E_{ph}).

So $$Z_s = \left.\frac{(V_{oc})_{ph}}{(I_{asc})_{ph}}\right|_{\text{for same } I_f}$$

$$\Rightarrow Z_s = \left.\frac{\text{Phase emf on open ckt}}{\text{Phase current on short ckt}}\right|_{\text{for same excitation}}$$

Regulation Calculation:-

* The armature resistance can be measured by applying d.c. known voltage across the two terminals and measuring current. So value of R_a is also known.

Now $Z_s = \sqrt{(R_a)^2 + (X_s)^2}$

$$\Rightarrow X_s = \sqrt{(Z_s)^2 - (R_a)^2}\ \Omega/\text{ph}$$. Synchronous Reactance.

No load induced emf per phase

$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}$$

So $$\%\ \text{Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

Harmonics :-

In case of alternator, the voltage & current induced are having sinusoidal waveform. But practically we can not get sinusoidal waveform when such alternators are loaded. Such a non sinusoidal waveform is called complex wave.

By fourier transform, the complex waveform can be shown to be built of a series of sinusoidal wave whose frequency are integral multiple of the frequency of fundamental wave. These sinusoidal component are called harmonics of complex wave.

Consider a complex wave which is represented by

$$e = E_{1m}\sin(\omega t+\phi_1) + E_{2m}\sin(2\omega t+\phi_2) + E_{3m}\sin(3\omega t+\phi_3) + \dots E_{nm}\sin(n\omega t+\phi_n)$$

$E_{1m}\sin(\omega t+\phi_1)$ → Fundamental Component

$E_{nm}\sin(n\omega t+\phi_n)$ → nth Harmonic Component.

The complex wave containing fundamental component and even harmonics only is always unsymetrical about x-axies. where as fundamental component & odd harmonics is always symetrical about x-axies. And in case of alternator, the voltage generated is mostly symmetrical as the field system and coils are all symmetrical.

Effect of Harmonics on pitch & Distribution factor:

a. If the short pitch angle or chording angle is 'α' degree (electrical) for the fundamental wave, than its value for different harmonics are

for 3rd harmonics = 3α &

for 5th harmonics = 5α.

$\therefore K_C = \cos \alpha/2$ ⟶ for fundamental.

$= \cos 3\alpha/2$ ⟶ for 3rd Harmonics

$= \cos 5\alpha/2$ ⟶ for 5th harmonics.

b. for distribution factor.

$K_d = \frac{\sin(m\beta/2)}{m\sin(\beta/2)}$ ⟶ for fundamental

$= \frac{\sin(3m\beta/2)}{m\sin(3\beta/2)}$ ⟶ for 3rd harmon

$= \frac{\sin(5m\beta/2)}{m\sin(5\beta/2)}$ ⟶ for 5th harmon

c. frequency also changed. If fundamental frequency is 50 Hz, than.

for 3rd harmonics → $f_3 = 3\times50 = 150$ Hz.

for 5th harmonics → $f_5 = 5\times50 = 250$ Hz. etc.

Parallel operation of Two Alternator And Synchronization:- (20)

In utility system, there will be thousands of generator which have to be operated in parallel so that they will get interconnected by thousands of Kilometer of transmission line.

When number of generator are operating at same voltage and are require to be interconnected electrically, bus-bar are used as the common electrical component.

"Bus bar are nothing but copper rods which operated at constant voltage".

The process of switching of an alternator to another alternator or with a common bus-bar without any interruption is called synchronization.

or

It is the process of connecting two alternator in parallel without any interption.

Necessary condition of Synchronization/Parallel operation:-

i) The terminal voltage of incomming m/c must be same as that of busbar voltage

ii) The frequency must be same as that of incomming machine with bus-bar.

iii) The phase of alternator voltage must be identical with phase of bus-bar voltage.

from above three Condition, cond-1 is indicated by voltmeter, Cond-2 & 3 are indicated by Synchronizing lamp or synchroscope.

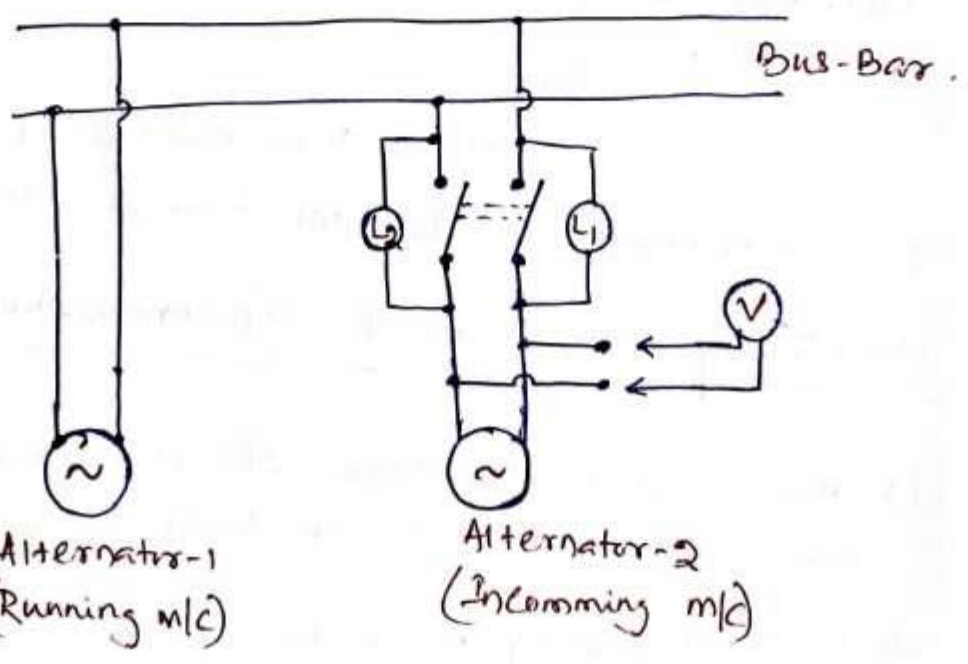
Note:- The violence of any of the above condn may Cause a Circulating current and power Surges, Due to this a undesirable electro-mechanical oscillation of rotor will occure.

Parallel operation of two Alternator:-

It can be done by two ways.

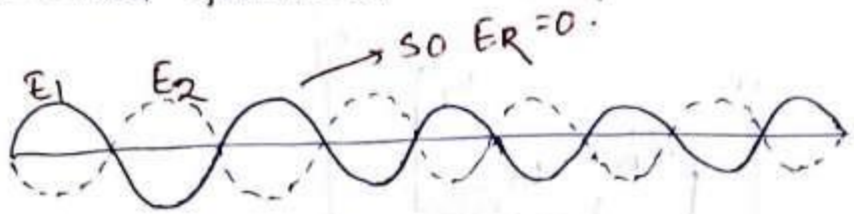
i) Dark lamp method.
ii) Bright lamp method.

i) Dark lamp method:-

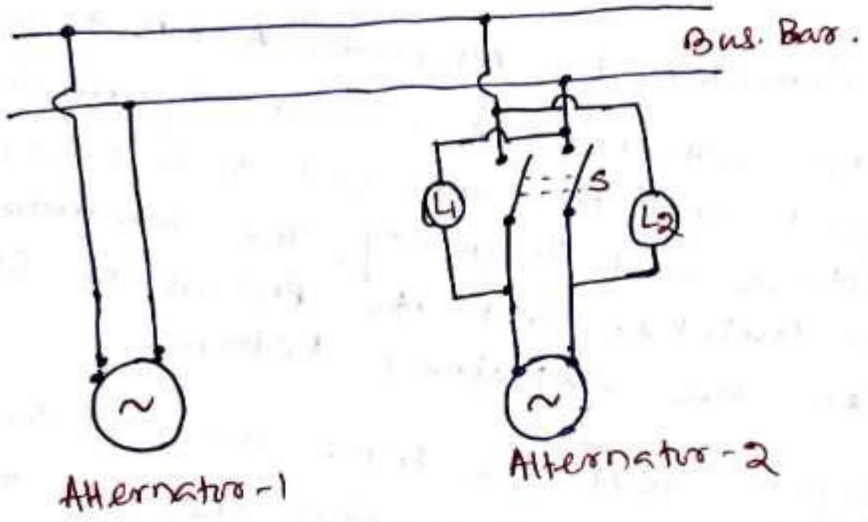


In this method, the lams are arranged as shown above fig. The alternator to be Synchronised, which Consists of two lamps connected across the switch terminal of Same Phase.

The lamps are connected in such a way that the Polarity and frequency of two m/c can be checked. When the frequency is exactly same and voltage is just phase opposition to each other, so no resultant emf, under this condⁿ lamp will not glow and at that moment, the switch is closed for parallel operation.

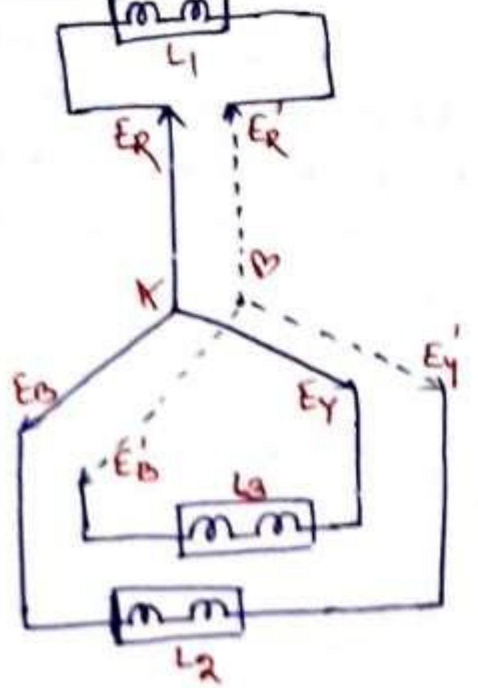


ii) <u>Bright lamp Method</u>:-



Since it is very difficult to judge the correct instant of zero voltage in lamps dark method. So this method is used for synchronizing of two alternator. This is more sharp and accurate method of synchronization because the lamps are much more sensitive to change in voltage at their maximum brightness than when they are dark.

Parallel operation of 3 phase Alternator:-



Consider two Alternator A & B to be synchronised. The alternator A is already running at synchronous speed and is connected to bus-bar of constant voltage and frequency. The alternator 'B' is connect to bus-bar and its process of synchronization can be explained below:

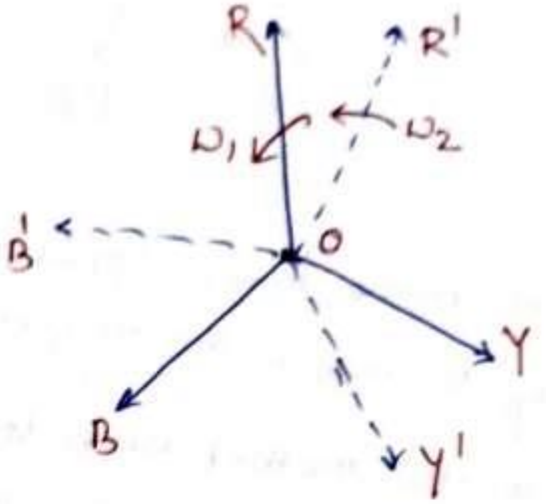
Step-1: start the prime mover of the m/c. Adjust its speed to a synchronous speed of m/c-B.

Step-2:- By adjusting the excitation to field by the help of rheostat, the induced emf of 'B' is equal to the induced emf of A.

Step-3: By varifying remaining condⁿ, the three lamps are used (L_1, L_2 & L_3) as shown above

Let the three bus bars voltage are represented by phasor OR, OY & OB rotating at a angular speed of ω rad/sec.

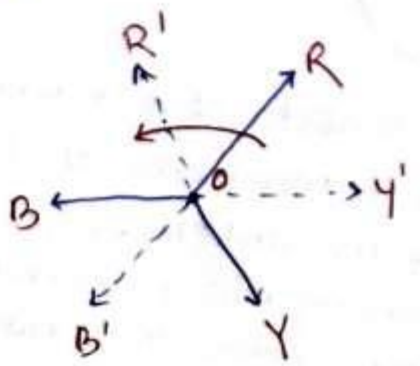
And the incomming m/c voltage are represented by OR', OY' & OB', rotating at ω_2 rad/sec.

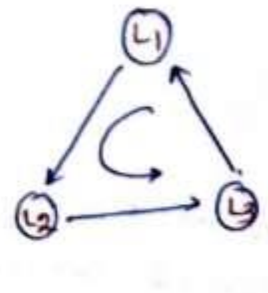


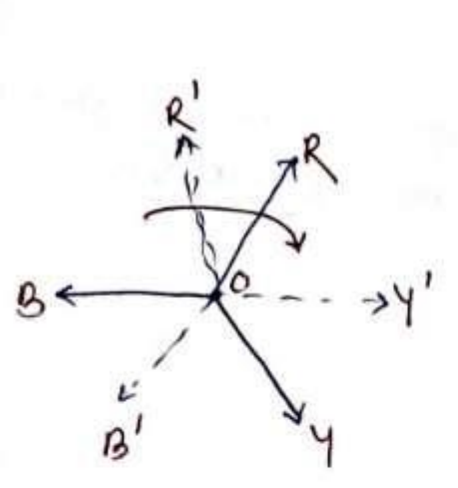
The Phasor sum $E_{RR'}$, joining the tips R & R' is voltage across lamp pair L_1. Similarly $E_{YB'}$ and $E_{BY'}$ are voltage across lamp L_2 & L_3 respectively.

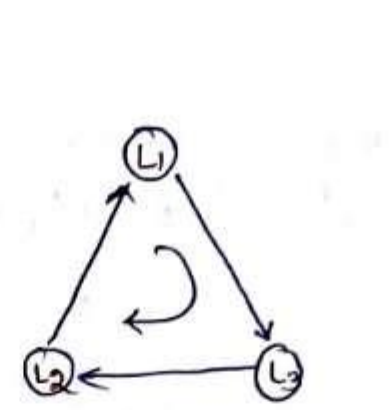
If there is difference betⁿ two frequencies, due to different in speed, the lamp will become dark and bright in a sequence. This sequence tells whether incomming m/c frequency is less or greater than M/C-A.

The Sequence L_1, L_2, L_3 tells that M/C-B is faster, but the sequence L_3, L_2, L_1 tells that M/C-B is slower then m/C-A.







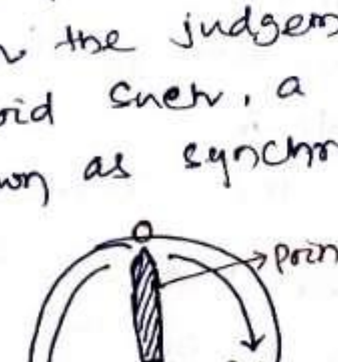


So the Prime mover speed can be adjust accordingly to match the frequency.

So in this method when lamp L_1 is dark and other two lamps L_2 & L_3 are equally bright, at that moment, synchronisation is done. So this method is called "Bright and Dark lamp" method.

Synchronization by Synchroscope:-

The lamp method is not accurate, since it depend on the judgement of the operator. Hence to avoid such, a accurate device is used is known as synchroscope.

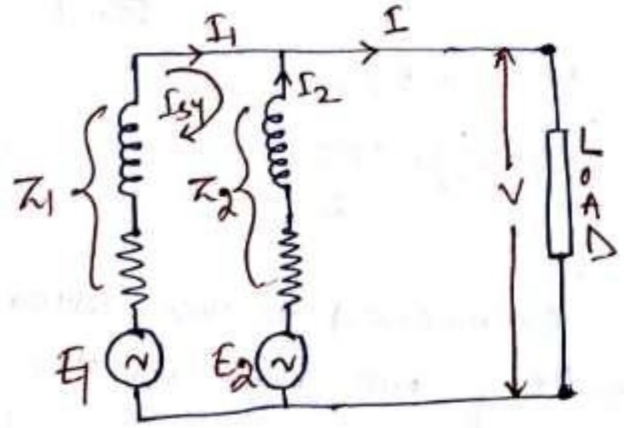


It consists of a rotating Pointer which indicate the exact movement of closing the switch. If Pointer rotates in anticlockwise direction it indicate that incomming m/c is running slow, where as clockwise rotation shows the fast. The rotation of Pointer is proportional to difference in two frequencies. When the Pointer is at vertical position.

The switch is to be closed and the two m/c are connected in parallel.

Distribution of load by parallel connected Alternator:-

Consider two identical alternator connected in parallel as shown below.



The terminal voltage 'v' is given by

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

or $\bar{V} = \bar{I}\bar{Z}$

Load current $I = I_1 + I_2$

from the above expression,

$$\bar{E}_1 = \bar{V} + \bar{I}_1\bar{Z}_1$$
$$= \bar{I}\bar{Z} + \bar{I}_1\bar{Z}_1 = (\bar{I}_1 + \bar{I}_2)\bar{Z} + \bar{I}_1\bar{Z}_1$$
$$= \bar{I}_1(\bar{Z} + \bar{Z}_1) + \bar{I}_2\bar{Z} \quad \text{—— (1)}$$

Similarly $E_2 = \bar{I}_2(\bar{Z} + \bar{Z}_2) + \bar{I}_1\bar{Z}$ —— (2)

Solving eqn (1) & (2), we can get

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

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

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

& $$V = \bar{I}\bar{Z} = \frac{E_1 Z_2 + E_2 Z_1}{(Z_1 + Z_2) + \frac{Z_1 Z_2}{Z}}.$$

If no load is connected to the alternator, only circulating current I_{sy} will flow in the ckt. This current is given by

$$\boxed{I_{sy} = \frac{\bar{E}_1 - \bar{E}_2}{\bar{Z}_1 + \bar{Z}_2}}$$

SYNCHRONOUS MOTOR

Simillar to d.c. Machine, there is no constructional difference betn Alternator and synchronous motor. If three Phase supply is given to the stator of a 3-ϕ Alternator, it can works as a motor. As it is driven at synchronous speed. it is called synchronous motor.

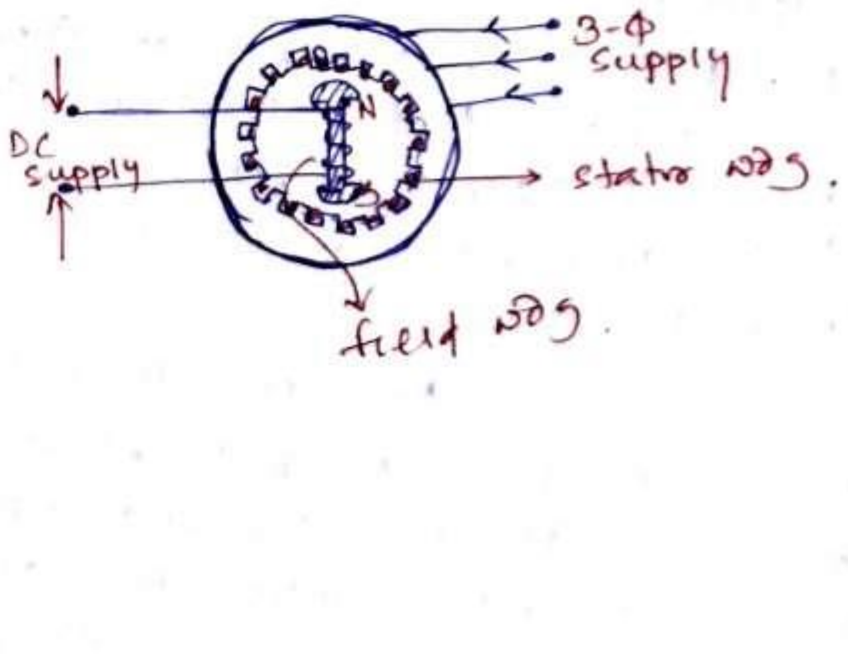
Construction of S.M:-

Simillar to ~~Alternator~~ d.c. machine, there is no Constructional difference betn Alternator & S.M.

It has two main parts.

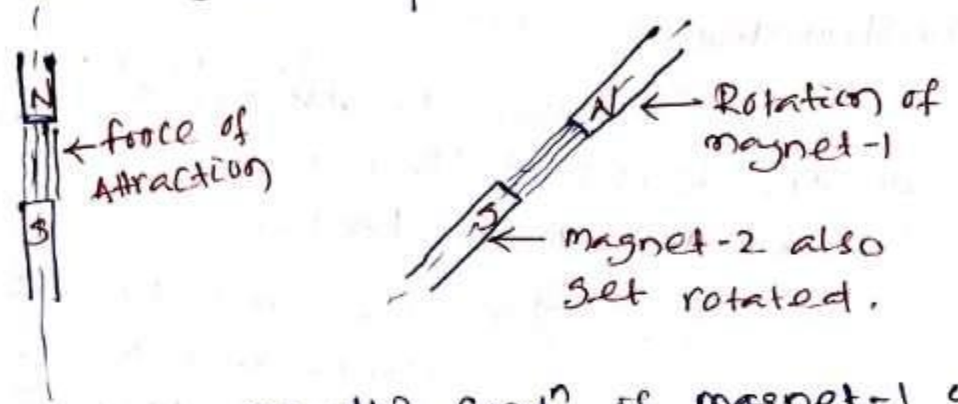
i) Stator :- It consisting of a star or Delta Connected wdg. This is excited by 3-ϕ A.C. supply.

ii) Rotor :- Rotor is field wdg. Practically most of the S.M. use Salient Pole type. The field wdg is excited by Separate d.c. supply.



Principle of operation :-

Synchronous motor works on the Principle of magnetic locking. When two unlike Pole are brought near to each other, & if magnet are strong. There exist a tremendous force of attraction betn those poles. In such Condn, the two magnets are said to be magnetically locked.

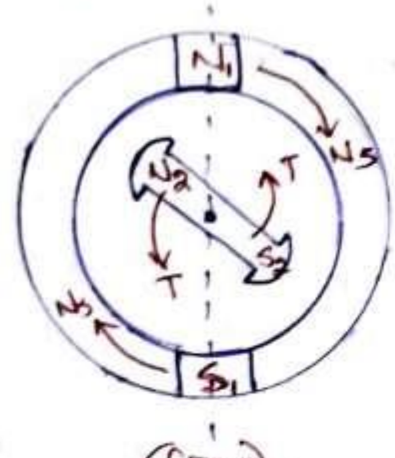


In this Condn if magnet-1 will rotate, than magnet-2 also rotated is the same direction along with this due to magnetic locking.

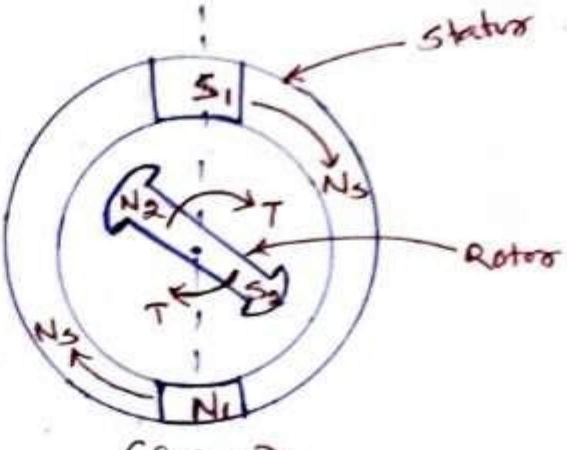
In S.M. Motor, we give the 3-Φ supply to stator wdg & Produces a rotating magnet field which is rotated at Synchronous Speed. So it creates N & S Pole in Stator. Let there is two poles N_1 & S_1. Now we give the d.c supply to the rotor, and it will also creates two poles Let N_2 & S_2.

Now one magnet is rotating at Ns having poles N_1 & S_1 while at Start, rotor is stationary i.e. second magnet is N_2 & S_2. if somehow, the unlike Pole N_1 & S_2 or S_1 & N_2 are brought near to each other, the magnetic locking is get establish betn stator & rotor Poles. As the stator poles are rotating, the rotor poles are also rotate in same direction.

Why synchronous motor is not self starting:-



(fig-1)



(fig-2)

Consider an instant when two poles are at such a position where stator magnetic axis is vertical as shown above.

At this instant, rotor poles are arbitrarily positioned as shown.

At this instant, rotor is stationary and unlike poles are try to attract each other. Due to this, rotor is subjected to an instantaneous torque in anticlockwise direction as shown in fig-1.

But stator poles are rotating very fast i.e. at a speed of Ns r.p.m. Due to inertia before rotor rotates, the stator pole changes their position. Consider an instant, half a period, where stator poles are reversed but due to inertia, rotor poles are unable to rotate. This is shown in fig-2.

At this instant, due to unlike pole try to attract each other, the rotor will try to rotate in clockwise direction. But before this stator poles again changes and rotor will not able to rotate. Hence it is not self starting.

Procedure to start a synchronous motor:-

The general procedure to start a S.M. are

i) Give a 3-φ AC supply to stator wdg. It will produce rotating magnetic field at Ns r.p.m.

ii) Then drive the rotor by some external means like diesel engine in the direction of r.m.f. at a speed of near to or equal to synchronous speed (Ns).

iii) Switch ON the d.c. supply given to the rotor which will produce rotor poles.

iv) At a particular instant, both the field gets magnetically locked. The stator field pulls rotor field in to synchronism. Then the external device is removed. But the rotor will continue to rotate at a speed of Ns due to magnetic locking.

Method of starting the synchronous motor:-

The various method to start the S.M. are

i) using pony motor.

ii) using Damper wdg.

iii) As a slip ring I.M.

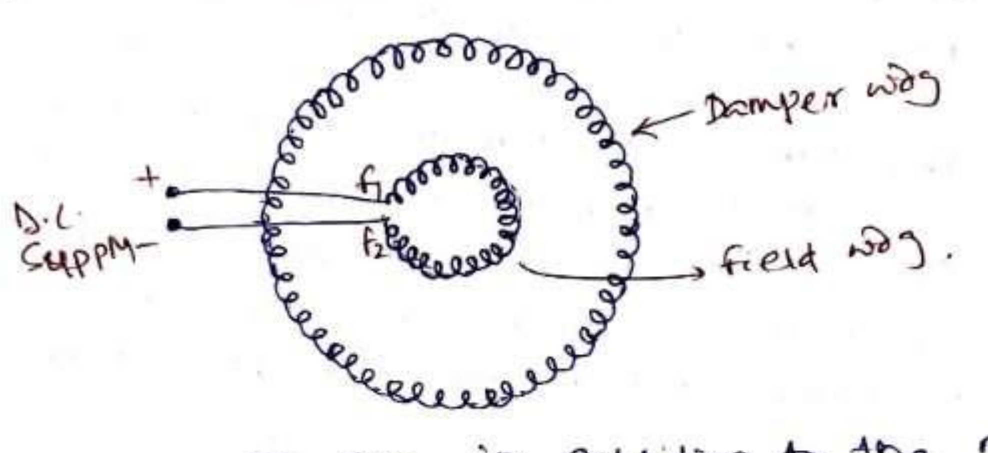
iv) using small d.c. machine couple to it.

i) Using pony motor:-

In this method, the rotor is brought in to synchronous speed with the help of some external device like small induction motor.

such an external device is called Pony motors.
once the rotor attains the Synchro-
-nous speed. the d.c. excitation to the rotor is
switched ON. once the synchronizing is establish,
Pony motor is decoupled.

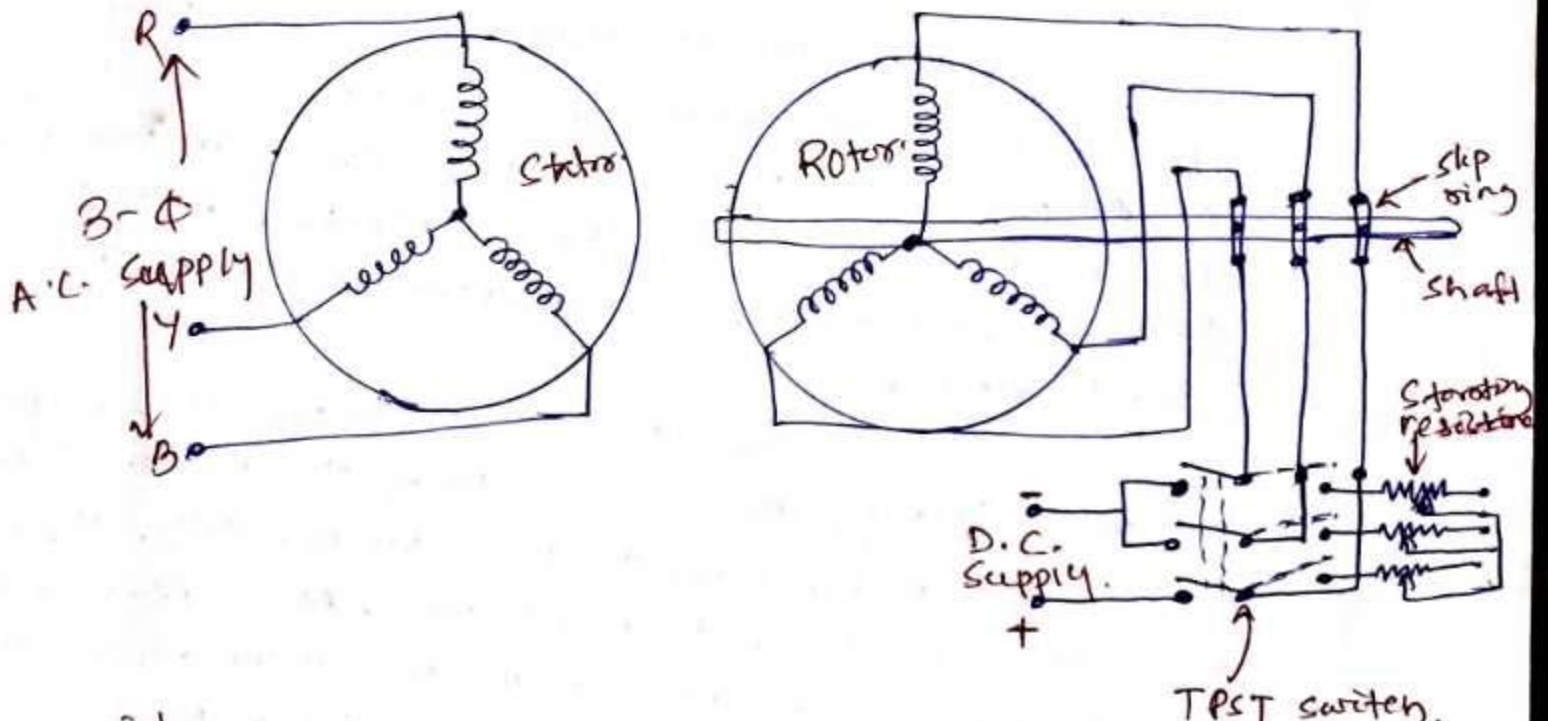
ii) Using Damper winding:-



In S.M. in addition to the normal
field wdg, a additional winding consisting
of copper bars placed in the slotes in the pole
faces. the bars are short circuited with the
help of end rings. such a additional wdg is
called damper wdg.
So once the Stator is excited
by 3-ϕ supply, the S.M. starts to rotate like
a Induction motor due to the damper wdg. then
d.c. supply is given to field wdg. At a perticular
instant motor gets pulled in to synchronizing and
starts rotating at a synchronous speed. As rotor
rotates in synchronous speed, the relative motion
betn damper wdg & rotating magnetic field is zero.
Hence when motor is running as synchronous
motor, there can not be any induced emf in damper
winding. So damper wdg only active on starting
condn.

iii) <u>As a slip ring I.M</u> :-

The above method does not provide high starting torque. so to achive this, instead of shorting the damper wdg, it is designed to to form a 3-Φ star or Delta connected wdg. The three ends are brought out through slip ring. An external rheostat is connected in series with rotor ckt. so when stator is excited, the motor starts as a slip ring induction motor and due to the resistance added in the rotor provided the high starting torque. The resistance is then gradually cut-off, when rotor gathers speed. when motor pulled in to synchronising, d.c. excitation is provided to rotor and it will run as synchronous motor.



iv) <u>Using small d.c. machine</u> :

Many times, a large S.M. are provided with coupled with d.c. machine. This machine is used as a d.c. motor to rotate the S.M. at a synchronous speed. then the excitation is given to rotor wdg. once the motor runs as a S.M. the same d.c. motor acts as a d.c. generator called exciter

Concept of load Angle(δ):-

When a d.c. motor or Induction motor is loaded the speed decreases. But in case of synchronous motor, speed always constant.

In d.c. motor, armature develops an emf after motoring action, which opposes the supply voltage, is called back emf. E_b.

$$\text{So} \quad I_a = \frac{V - E_b}{R_a} \quad \text{wher} \quad E_b = \frac{\phi Z N P}{60 A}.$$

In S.M. also, once rotor starts at synchronous speed, an emf is induced in stator which oppoes the supply voltage. This emf is also called back emf E_{bph} in synchronous motor. Here

$$\boxed{E_{bph} = 4.44\, K_c K_d \phi f T_{ph}} \quad \text{or}$$

$$E_{bph} \propto \phi .$$

As speed is constant, the frequency also constant so magnitude of back emf controlled by changing the flux 'ϕ' produced by rotor.

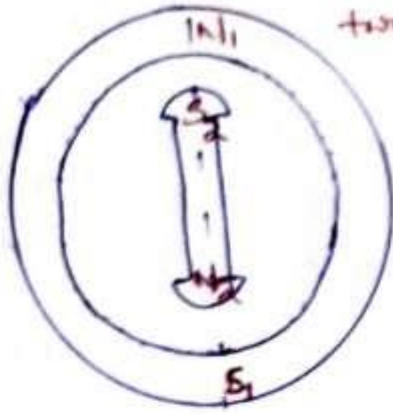
Like d.c. motor Here also

$$\boxed{I_{aph} = \frac{V_{ph} - E_{bph}}{Z_s}}$$

(Here vector addition)

In Ideal condition, i.e. at no losses condⁿ

$V_{ph} = E_{bph}$.



Under this condition, the magnetic locking betⁿ stator and rotor in such a way that the magnetic axis of both coincide with each other. This is said to be ideal condⁿ.

The phasor diagram for this condⁿ is

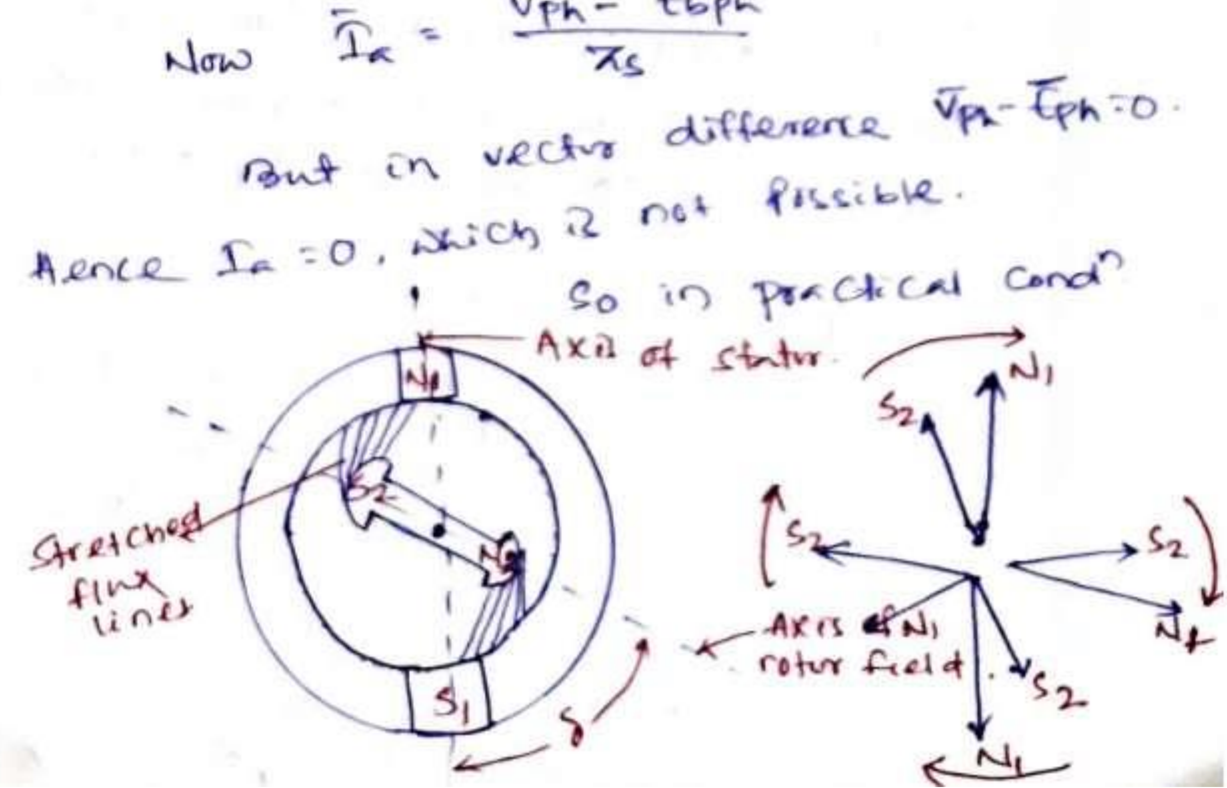
$|E_{bph}| = |V_{ph}|$

Now $\bar{I}_a = \dfrac{\bar{V}_{ph} - \bar{E}_{bph}}{X_s}$

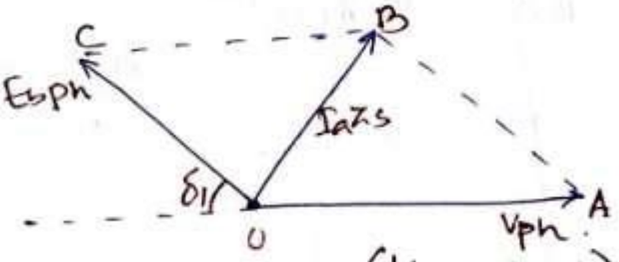
But in vector difference $\bar{V}_{ph} - \bar{E}_{ph} = 0$.

Hence $I_a = 0$, which is not possible.

So in practical condⁿ



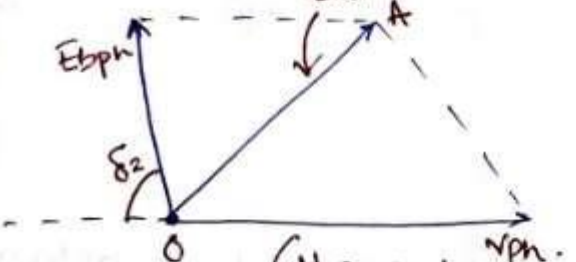
Due to various losses, the magnetic locking exist betn stator & rotor but in such a way that their exists a small angle difference betn the axes. This angle is called load angle, power angle, coupling angle, torque angle or angle of retardation & denoted as 'δ'.



(Light load)

$\bar{V}_{ph} - \bar{E}_{bph} = \overline{I_a Z_s}$

$\therefore OB = \overline{I_a Z_s} = \bar{E}_{Rph}$



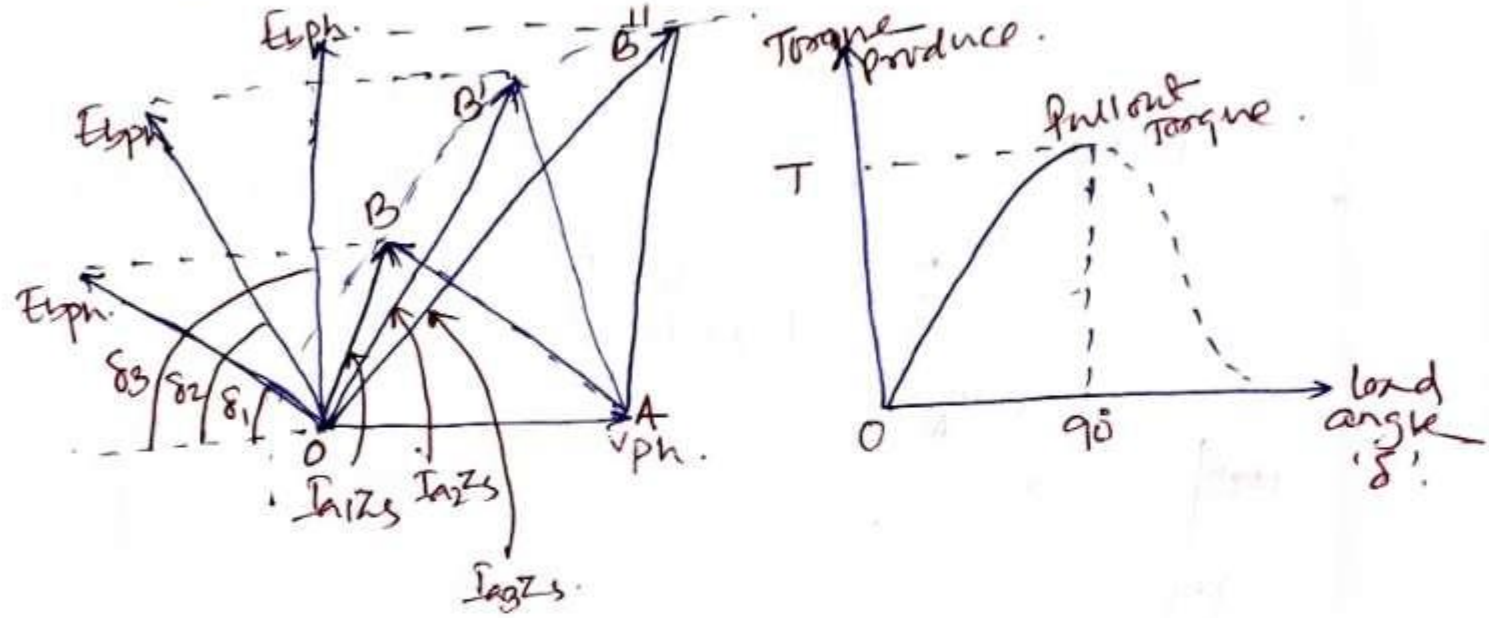
(Heavy load)

Effect of varying load with constant excitation:-

As Ebph depends on flux, for constant excitation Ebph also constant. for constant excitation, if load is varied then δ keeps on changing. Due to which $\overline{V_{ph}} - \bar{E}_{bph} = \bar{E}_{Rph} = \bar{I}_{aph} \bar{Z}_s$ also changes. As δ increases $I_{aph} Z_s$ increases and motor draws more current.

So from above discussion, it is clear that on no load, current drawn by the motor is very small as δ is small.

As load increases, rotor magnetic axis starts retarding i.e. load angle 'δ' increases. As δ increases This weakens the force maintaining the magnetic locking, though torque produce by the motor increases. As δ reaches up to 90° electrical, flux lines get broken & motor stops.



Effect of varying Excitation with Constant Load.

We have Seen that with constant excitation with load changes, current drawn by the motor increases.

But if excitation i.e. field current is changed keeping load constant, S.M. reacts by changing its powerfactor of operation.

At start, consider normal excitation motor drawing certain current Ia & the power factor is lagging. Now when excitation is change, so Eb also changes but the power input is constant as load constant.

Now $P_{in} = \sqrt{3} V_L I_L \cos\phi = 3 V_{ph} I_{ph} \cos\phi$.
Most of the time voltage applied to the motor is constant. Hence for constant power input as V_{ph} is constant, $I_{aph} \cos\phi$ remain constant.

i) UNDER EXCITATION:-

The motor is said to be under excited, if field excitation is such a way that $E_b < V$. under such condition, the current I_a lags behind V, so that powerfactor is lagging. as shown in fig-(1). Since $E_b < V$, the net voltage E_r decreases & turn clockwise. As angle 'θ' betn E_r & I_a is constant, therefore phasor I_a also turns clockwise. consequently, the motor has a lagging P.f.

ii) NORMAL EXCITATION:-

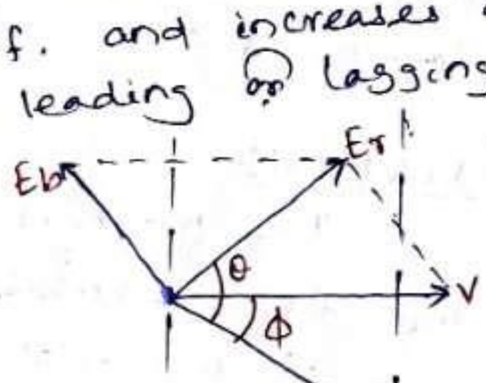
The motor is said to be normally excited, if the field excitation in such a way that $E_b = V$. as shown in fig-2. Note that the effect of increasing excitation is turn the phasor E_r and hence I_a in the anti clockwise direction. i.e. phasor I_a comes closer to phasor 'V'. therefore P.f. increasing through still lagging. Since input power is unchanged the stator current I_a must decrease with increase in P.f.

Suppose the field excitation is increased until the current I_a is in phase with the applied voltage 'V', making the P.f. of the S.M. unity. as shown in fig-3. for a given load at unity p.f., the resultant Er & Ia is minimum.

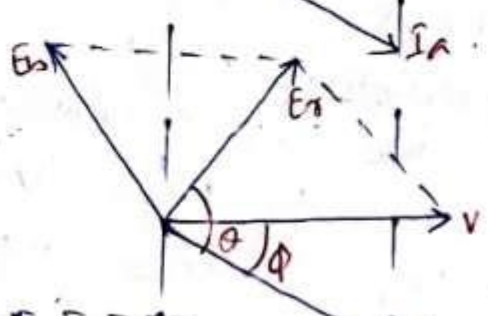
iii) OVER EXCITATION :-

The motor is said to be over excited, if field excitation is such a way that Eb > V. under such condition Ia leads V and the motor power factor is leading as shown in fig-4. Note that Er and hence Ia further turn anticlock wise from normal excitation position.

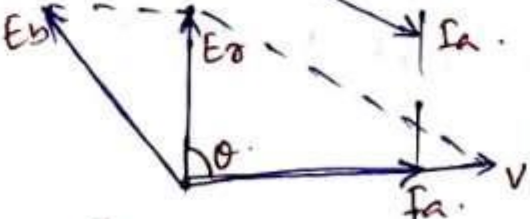
From the above discussion, it is conclude that if the excitation is increases with constant load, the p.f. also increases. Note that armature current Ia is minimum at unity p.f. and increases as the p.f. becomes poor, either leading or lagging.



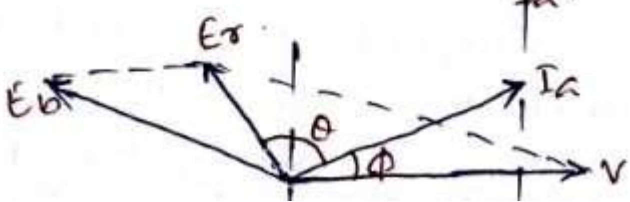
(fig-1) under excitation. (Eb < V)



(fig-2) Normal excitation. (Eb = V)



(fig-3) unity p.f. (Eb > V)



(fig-4) over excitation (Eb > V)

Torque & Power Develop in S.M.

Net input to S.M. is the 3-ϕ input to stator

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

$$\Rightarrow P_{in} = 3(\text{per phase power}) = 3 \times V_{ph} \times I_{ph} \times \cos\phi$$

Now in stator, due to its resistance Ra/phase there are stator Cu. loss

$$\therefore \text{Total stator Cu. loss} = 3 \times (I_{aph})^2 \times R_a .$$

The remaining power is converted to the mechanical power, called gross mechanical power developed by the motor denoted as P_m.

$$\therefore P_M = P_{in} - \text{Stator Cu. loss.}$$

In d.c. motor, gross mechanical power developed is $E_b \times I_a$. Similarly in S.M. the electrical equivalent of gross mechanical power developed is given by

$$P_m = 3 \times E_{bph} \times I_{aph} \times \cos(E_{bph} \wedge I_{aph})$$

For lagging p.f. $\rightarrow E_{bph} \wedge I_{aph} = \phi - \delta$

for leading p.f $\rightarrow E_{bph} \wedge I_{aph} = \phi + \delta$

for unity p.f $\rightarrow E_{bph} \wedge I_{aph} = \delta$ ..

So in general.

$$\boxed{P_m = 3 E_{bph} I_{aph} \cos(\phi \pm \delta)}$$

$+ \rightarrow$ for leading
$- \rightarrow$ for lagging.

Now in mechanical point of view.

$$P = T \times \omega$$

$$\Rightarrow P_m = T_g \times \frac{2\pi N_s}{60}$$

$$\Rightarrow T_g = \frac{P_m \times 60}{2\pi N_s} \text{ N-m.}$$

$$\Rightarrow \boxed{T_g = 9.55 \frac{P_m}{N_s} \text{ N-m}}$$

Mechanical power developed by Motor:-

(Neglecting Ra)

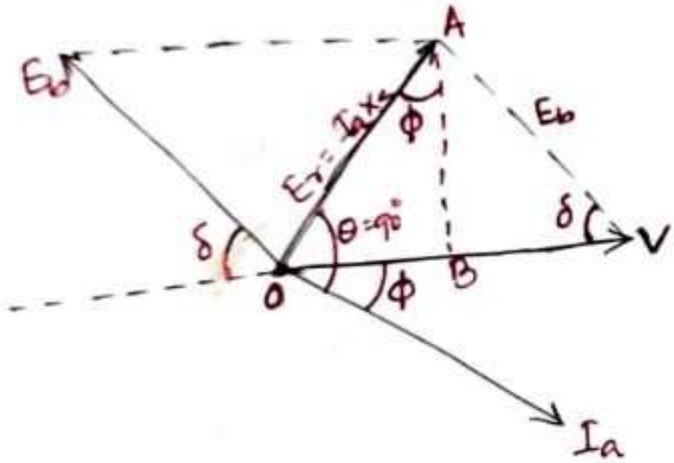


fig. shows the phasor diagram for under-excited S.M. driving a mechanical load. Since armature resistance is assumed to be zero, and hence $\theta = 90°$.

So $\tan\theta = \frac{X_s}{R_a} = \infty$

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

since R_a is zero, so stator Cu. Loss ($I_a^2 R_a$) will be zero. Hence input power is equal to the mechanical power 'P_m' developed by the motor.

$$\therefore P_m = V I_a \cos\phi \text{ ——— (i)}$$

Now from phasor diagram.

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

Also $AB = E_b \sin\delta$

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

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

Now substituting the value of $I_a \cos\phi$ in eqn (1)

$$\therefore \boxed{P_m = \frac{V E_b}{X_s} \sin\delta} \longrightarrow \text{Per Phase.}$$

$$= \frac{3 V E_b}{X_s} \sin\delta \longrightarrow \text{for 3-phase.}$$

It is clear from the above relation that mechanical power with torque angle, and its max. value reached when $\delta = 90^\circ$.

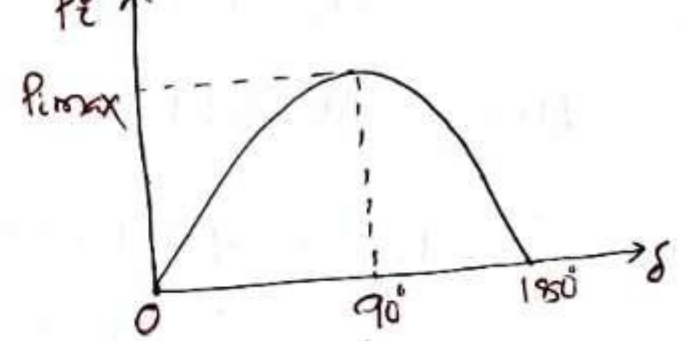
$$\boxed{\therefore P_{max} = \frac{V E_b}{X_s}}$$

Power Angle Characteristics:-

We know that

$$P_m = P_i = \frac{E_b \cdot V}{X_s} \sin\delta$$

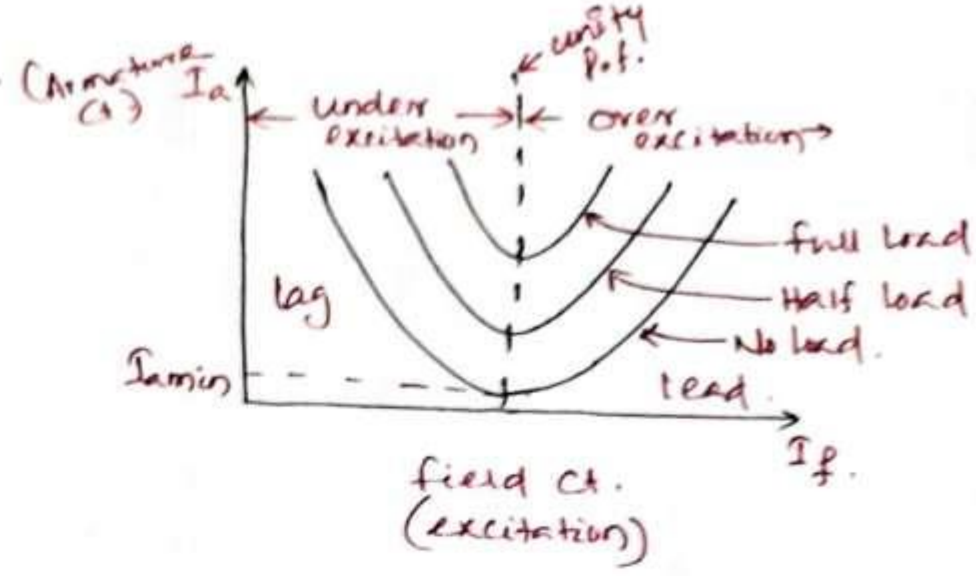
The relationship betn 'Pi' and 'δ' is known as Power angle characteristics, of the Machine.



The max. power occurs at $\delta = 90°$. Beyond this Point, the machine falls out of Step and losses Synchronism. The machine is normally operated at δ much less than 90°.

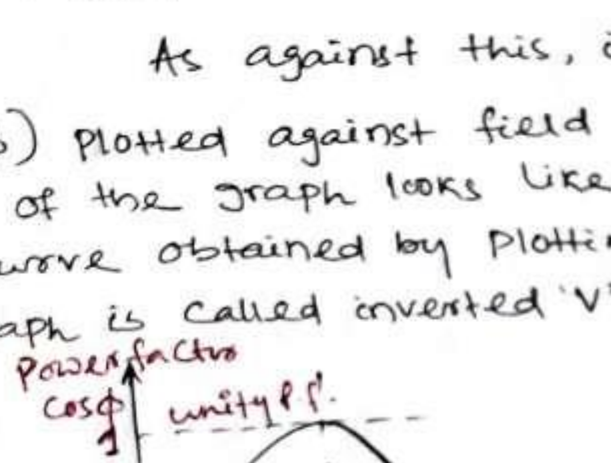
Effect of Excitation on Armature current & power factor:-

We know that if excitation is varied from very low (under excitation) to very high (over excitation) value, than Ia decreases up to unity Powerfactor and than again increases. But initially current is lagging and than it is leading. This can be ploted as shown betn Ia & If.



The shape of this plot looks like an english alphabet 'V'. Such curve is called V-curve.

As against this, if the power factor ($\cos\phi$) plotted against field current (I_f), than the shape of the graph looks like an inverted 'V'. Such curve obtained by plotting p.f. against If. This graph is called inverted 'V' curve.



Hunting in Synchronous Motor:-

It is seen that, when S.M. is on no load, the stator & rotor poles axis almost coinside with each other.

But when motor is loaded, the rotor pole axis falls back with respect to stator. If the load is suddenly changed by a large amount, the rotor tries to retard to takes new equilibrium position. But due to inertia of the rotor, It can not achive, its final position instantaneously. This will produce more torque than what it is demanded. This will try to reduce the load angle. ~~x~~ rotor swings in other direction.

Such oscillation of the rotor about its new equilibrium position, due to sudden application or removal of load is called Hunting of synchronous motor.

Due to hunting, 'δ' changes with constant excitation, Hence current drawn by the motor changes, ~~so~~ which may cause problem to the other appliences connected to the same line. the changes in armature current not desirable.

Function of Damper winding:-

The damper wdg is prodvided in the pole faces. When rotor starts oscillates, a relative motion betn damper winding and rotating magnetic field is created. Due to this emf gets induced in the Damper winding. According to Lenz's law the direction of induced emf is always so as to oppose the cause producing it. The cause is hunting. So such induced emf oppose the hunting. Thus hunting is minimized due to damper winding.

1 Application of Synchronous motor.

Due to constant Speed Characteristics, S.M. is used in machine tools, motor generator sets, synchronous clock, stroboscopic device, timing device, compressors, fan & blowers, Centrifugal Pump, vacume Pump, Pulp grinder, textile mills, Paper mills, rolling mills, cement mills etc.

By adjusting the excitation, the S.M. Can also used for power factor improvement in transmission line.

The disadvantages of S.M. are high cost, necessity of frequent maintenance, and need a d.c. excitation source and a auxilary device or extra winding to make it self starting.

- x -

:Induction Motor:- ①

In whole over world 80% a.c. motor are 3-Phase Induction motor. It is beacuse of its some special advantages. The advantages are

i) Self starting property.

ii) No need fro starting device.

iii) higher power factor.

iv) Good speed regulation.

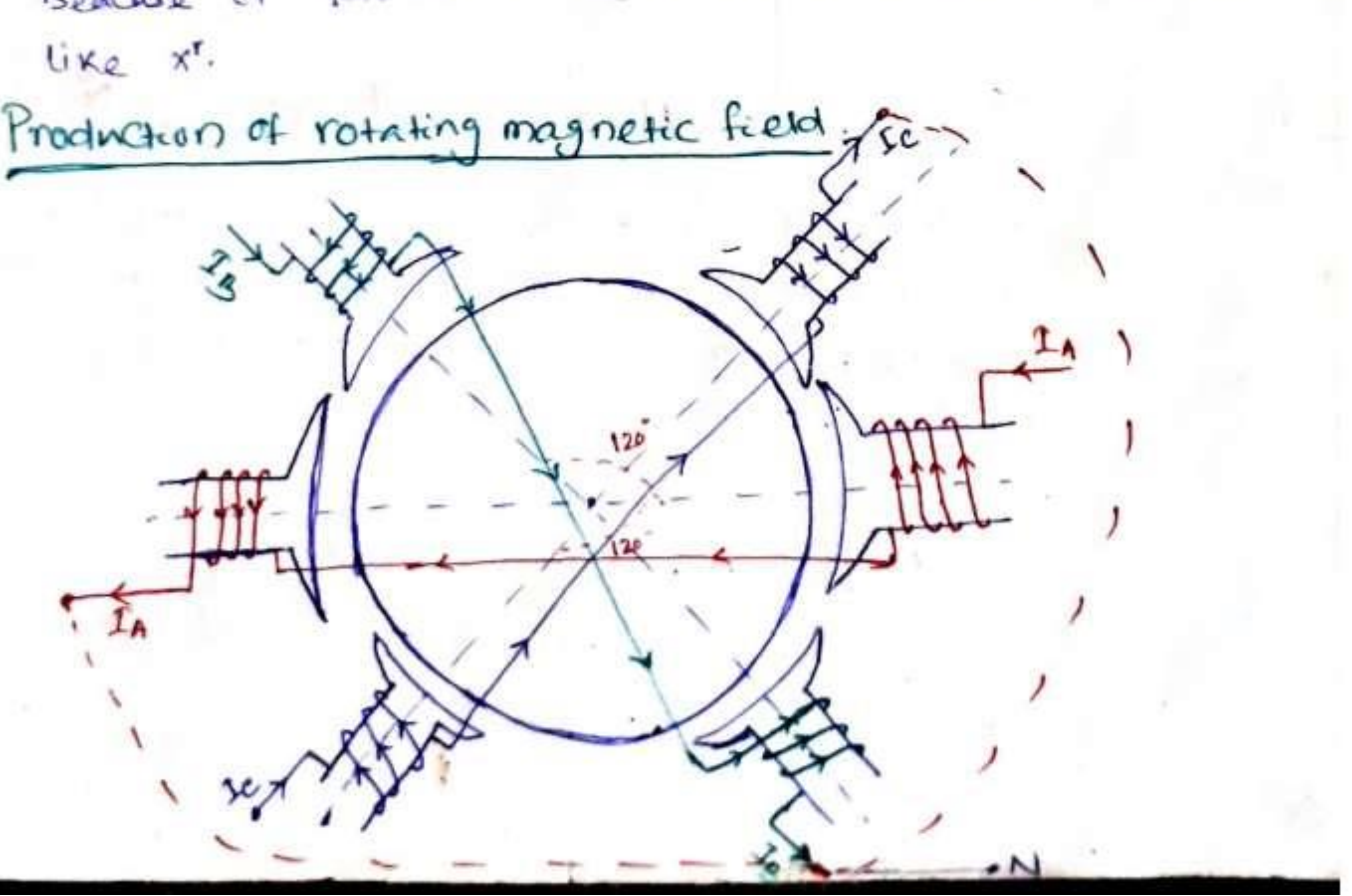
The working principle of 3-phase Induc[tion] motor is based on the production of rotating magnetic field.

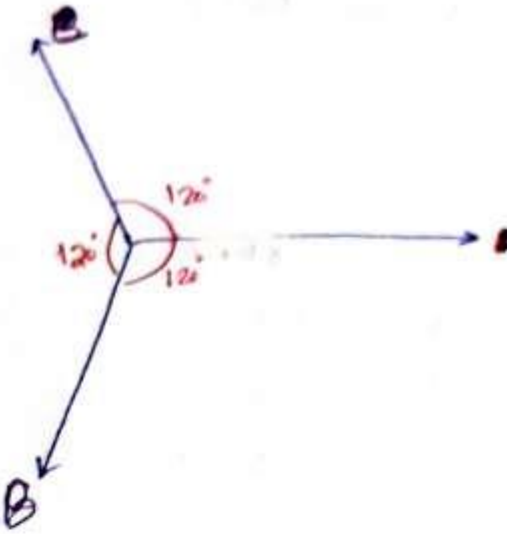
X^r → Electrical domain → magnetic domain → Electrical domain.

I.M. → Electrical domain → magnetic domain → Mechanical domain or Electrical domain.

So a 3-phase I.M. is also called rotating transformer Beacuse it oparate on the principle of mutual Induction like x^r.

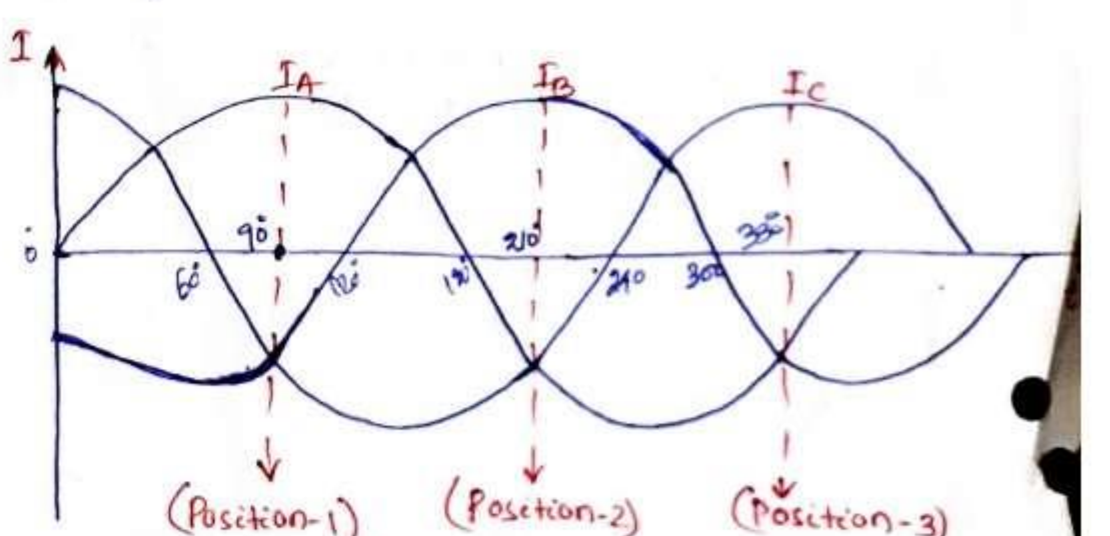
Production of rotating magnetic field.





$$\Phi_A = \Phi_m \sin \omega t$$
$$\Phi_B = \Phi_m \sin(\omega t - 120^\circ)$$
$$\Phi_C = \Phi_m \sin(\omega t - 240^\circ)$$

In this above figure, we give the 3-phase supply to the stator of an I.M. Here each phase contain 2-pole & each phase is placed 120° apart to each other. Now we give the 3-phase supply (I_A, I_B, & I_C) which is sinosoidal in nature.

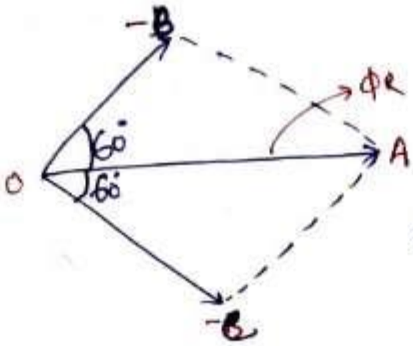


In this 3-phase waveform we will consider three critical position (Position-1, 2, & 3) and we will see what happened to magnetic field flux when time increases in the stator field.

Position-1

At Position-1, Current I_A is max. & +ve direction
Current I_B is Phase -ve & half
Current I_C is phase -ve & half.

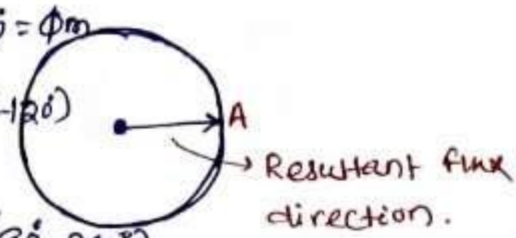
$\underline{\theta = 90^\circ}$



$\phi_A = \phi_m \sin 90^\circ = \phi_m$

$\phi_y = \phi_m \sin(90^\circ - 120^\circ)$
$= -\frac{\phi_m}{2}$

$\phi_z = \phi_m \sin(90^\circ - 240^\circ)$
$= -\frac{\phi_m}{2}$



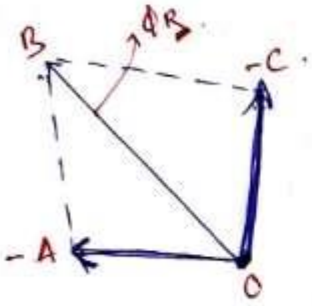
$\therefore \phi_R = \phi_m + \frac{\phi_m}{2}\cos 60^\circ + \frac{\phi_m}{2}\cos 60^\circ$

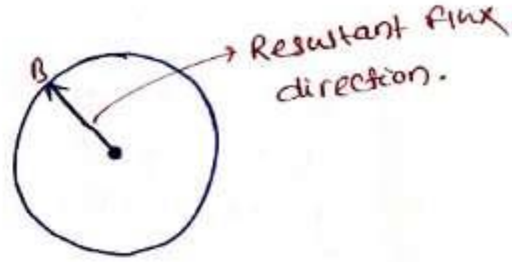
$\boxed{\phi_R = 1.5\,\phi_m}$

Position-2:-

In Position-2

Current I_B is max. & +ve direction.
Current I_A is half & -ve Phase
Current I_C is half & -ve Phase.

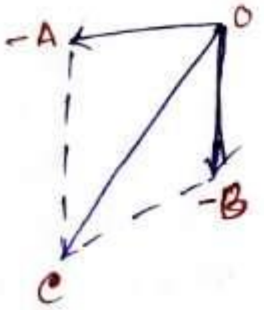


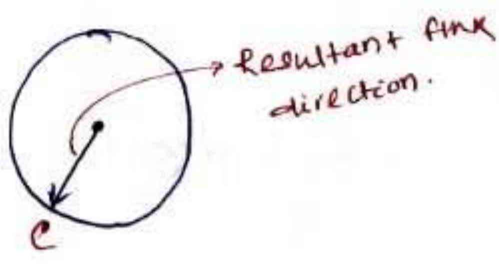


Position-3:-

In this position

Current I_C is max. & +ve direction
Current I_A is -ve phase & half.
Current I_B is -ve phase & half.





So from the above three experiment, we conclude that as time progress, the flux place is changing i.e. it creates it own rotating magnetic field.

In this way a rotating magnetic field is created which is rotates in a synchronous speed denoted as Ns.

Principle of oparation :-

The IM rotates as same principle of d.c. motor called lorentz's force. When the rotating magnetic field (Ns) cuts the rotor conductor and as the rotor conductor are short ckted at both ends a current induced in that conductor which has own magnetic field. Due to this a force is created when generates a torque & this torque helps to rotate the rotor in the same direction of Ns. i.e. rotor speed Nr follows the Ns. So there is a relative speed difference betn them.

When rotor is at standstill, the speed difference is high but when rotor starts to rotate, the relative speed difference decreases, due to this emf is also decreases. Hence due to decrease the emf the rotor current decreases. there by reducing torque of the rotor. so as the torque of the rotor decreases, the rotor speed slow down & it does not catch up the speed of field flux. This difference is called slip.

Slip (S) :-

We have seen that rotor rotates in the same direction as that of rotational magnetic flux in stator. But in steady state attains a speed less than the synchronous speed.

The difference betn the two speed i.e. synchronous speed (R.M.F) 'N_s' and rotor speed 'N_r' is called Slip speed.

So Slip of Induction motor can be defined as "the difference betn synchronous speed (N_s) and actual speed of rotor (N_r)".

Thus $\boxed{S = \frac{N_s - N_r}{N_s}}$ ——— ①

% slip is expressed as

$$\% S = \frac{N_s - N_r}{N_s} \times 100 \text{ ——— (ii)}.$$

from equ ①

$$S = \frac{N_s - N_r}{N_s}$$

$$\Rightarrow S N_s = N_s - N_r.$$

$$\Rightarrow \boxed{N_r = N_s(1-S)}$$

→ Actual Speed of rotor interm of Slip.

<u>At Stand-Still condition</u>, $N_r = 0$

So $0 = N_s(1-S)$.

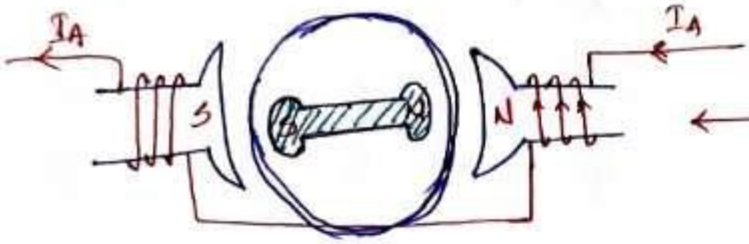
$$\Rightarrow S = \frac{N_s}{N_s} = 1.$$

$$\Rightarrow \boxed{S = 1}$$

<u>when $N_r = N_s$</u>, (not possible in case of I.M.)

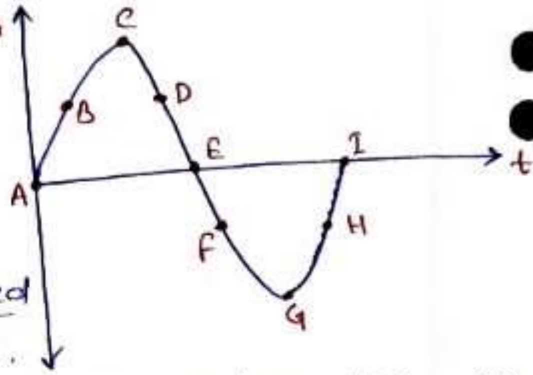
$$\boxed{S = 0}$$

Speed of Rotational Magnetic field:-



← 2 Pole/Phase.

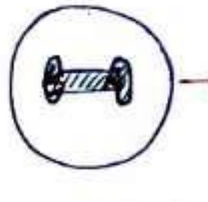
Consider any one phase wound with 2-pole. Let its a imaginary dumbled in the rotor. we give the sinosodal wave form to coil-A.



At Position 'A', Here the flux density is zero, b'coz $I_A = 0$. So MMF (NI) = 0. The imaginary dumbled represents the magnitude of flux.

So at position-A, the imaginary dumbled looks like as below fig.

→ Position A, E, I



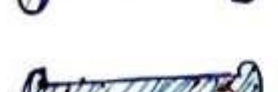
→ Position. B, D

→ Position-C.

As the magnitude of I_A increses, the dumbled size or magnitude of flux also increases. & at point 'C' it increses to its max. value. These are the dumbled position in case of. +ve half cycle.

Now on -ve half cycle also same but the dumbled changes its Polarity.

→ for +ve half cycle.



→ for -ve half cycle.

So from above experiment, we conclude that the the imaginary dumbled rotates 180° per half cycle. So for full cycle, it rotates 360°.

So in 'T' sec dumbled rotates 1-revolution.
1 sec. dumbled rotates $\frac{1}{T}$ revolution.
in 60 sec. dumbled rotates $\frac{60}{T}$ revolution

So speed of dumbled.

$$N_s = \frac{60}{T} = 60f \text{ r.p.m. per no. of pole pair}$$

$$\text{So } N_s = \frac{60f}{\text{no. of pole pair}}.$$

$$\Rightarrow N_s = \frac{60f}{P/2} = \frac{120f}{P}.$$

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

This speed of rotating magnetic field is called synchronous speed.

Construction of I.M:-

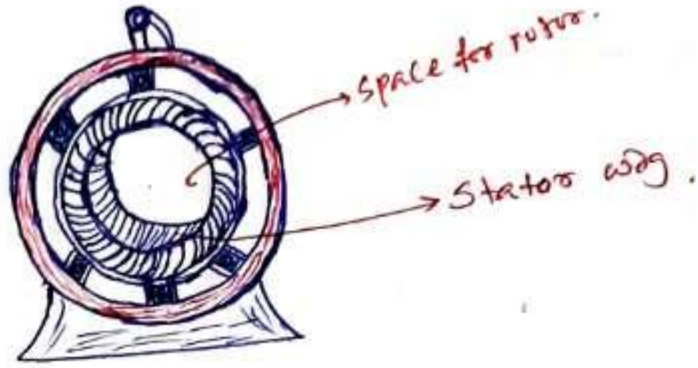
Basically, the I.M. consists of two main parts.

i) The part consisting 3-phase wdg which is stationary called stator.

ii) The part which rotates & connected to the mechanical load through shaft called rotor.

i) stator:-

It consists of a steel frame which encloses a hollow, cylindrical core made up of thin lamination of silicon steel to reduce hysteresis and eddy current losses. A number of evenly spaced slots are provided on the inner periphery of the lamination



The insulated conductors are placed in the stator Slots and are suitably connected to form a ~~[illegible]~~ 3-phase star or delta connected ckt. The 3-Phase stator wdg is wound for a definite number of poles as per requirement of speed.

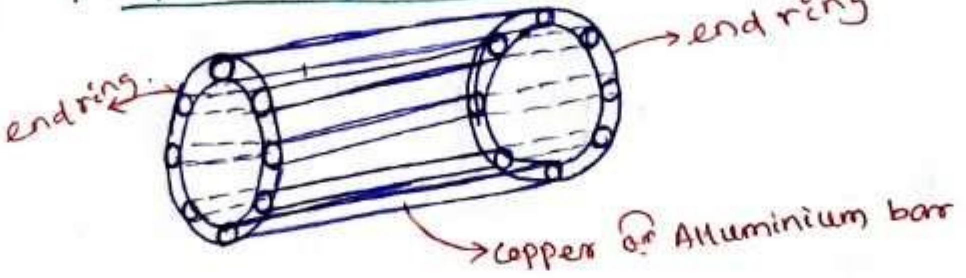
* Greater numer of poles, means lesser speed. & vice-versa.

ii) Rotor :-

The rotor is placed inside the stator. The rotor core is also laminated in construction and uses cast iron. It is cylindrical with slots on its periphery. There are two types of rotor construction which are used for induction motor are,

i) Squiral cage rotor ii) slip-ring or wound rotor.

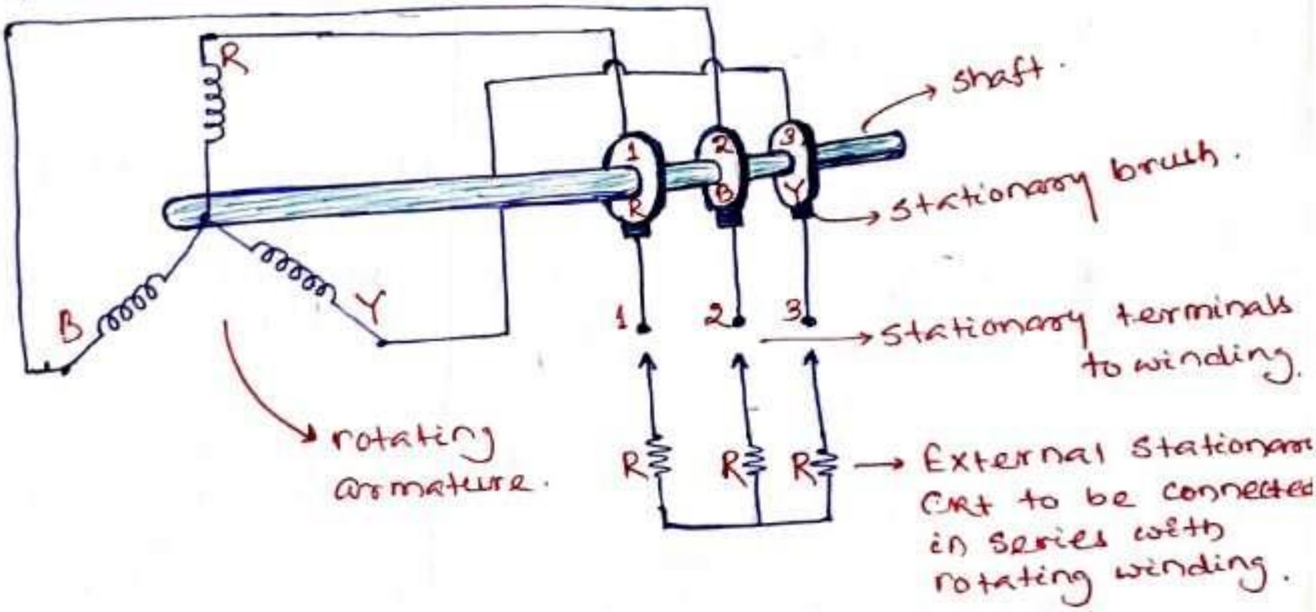
i) Squiral-cage rotor :-



The rotor core is cylindrical & slotted. The rotor consists of uninsulated copper or alluminium bars called rotor conductors. The bars are placed in the slots. The bars are permanently [illegible] end with the help of conducting copper ring called end ring. The entire structure looks like a cage, forming a closed electrical ckt. so this rotor is called squiral cage rotor.

As the bars are permanently shorted to each other through end ring, the entire rotor is also called short ckted rotor.

ii) Slip ring Rotor or wound rotor:-



In this type of construction, rotor winding is exactly similar to the stator. The rotor carries a three phase star or Delta connected, distributed wdg. wound for same number of poles as that of stator. The three ends of three phase wdg available after connecting the wdg in star or delta are permanently connected to the slip rings. The slip rings are mounted on the same shaft. We have seen that slip rings are used to connected external stationary ckt to the internal rotating ckt.

In this way, the value of rotor resistance per phase can be controlled. This helps us to control some of the important characteristics of the motor like starting torque, speed etc

Comparison of squiral cage & wound rotor

Slip ring rotor	Squiral-cage rotor
* Rotor consists of 3-phase 1ϕ wdg.	* Rotor consists of copper bar
* Resistance can be added externally	* Resistance can not be added
* Slip ring & brushes are present	* Slip ring & brushes are absent.
* Rotor are costly.	* Rotor are cheap
* Only 5% of Induction motor in industry uses slip ring rotor.	* Very common, about 95% uses.
* High starting torque can be obtained	* Modarrate starting torque which can not be controlled.
* Rotor cu. loss is high so efficiency is low.	* Rotor cu. loss is less, so efficiency is high.
* Used for lifts, hoists, cranes elevators, compressor etc	* Used for lathes, drilling machine, fans, blowers, water pumps, grinder, printing m/c etc.

Speed of Rotational Magnetic field (N_s)

We know that

1° mechanical = 1° electrical for 2 poles

But 1° mechanical = $\left(\frac{P}{2}\right)$ electrical for more than 2 poles

Let speed of Rotation of R.M.F. be N rpm. So in one second it will complete (N/60) revolution. That is $\frac{N}{60} \times \frac{P}{2}$ cycle per second.

$\therefore f = \text{frequency} = \text{cycle/sec.} = \frac{NP}{120}$

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

Effect of Slip on Rotor Parrameter :-

In case of X^r the frequency is same for Primary as well as Secondary also. But Induction motor Secondary parr (rotor) is a rotating part. When rotor is at standstill i.e. $N_r = 0$, slip = 1 and hence stator frequency is same as rotor frequency But when rotor gathers speed. induction motor has Some slip corresponding to speed N. Due to this Some parameter also get affected. these parameter are

i) Rotor frequency. ii) magnitude of rotor induced emf iii) Rotor reactance iv) Rotor Power factor v) Rotor current

i) Effect on Rotor frequency :-

At starting $N_r = 0$, $S = 1$. so

frequency of stator = frequency of rotor.

But when rotor rotates some speed, the relative speed difference decreases and hence emf also. If f_r is the rotor frequency in running condition at slip speed $(N_s - N_r)$, then there exist a fixed relation betn $N_s - N_r$, f_r and P.

$$N_s - N_r = \frac{120 f_r}{P} \quad \text{(rotor pole = stator pole)} \quad \text{—— (I)}$$

we know that the speed of rotating magnetic field is

$$N_s = \frac{120 f}{P} \quad \text{—— (II)}$$

Now deviding equ (I) to (II).

$$\frac{N_s - N_r}{N_s} = \frac{(120 f_r / P)}{(120 f / P)}$$

But we know that

$$S = \frac{N_s - N_r}{N_s}.$$

$$\Rightarrow S = \frac{f_r}{f}.$$

$$\Rightarrow \boxed{f_r = Sf}.$$

Thus frequency of rotor induced emf in running condition is slip times the supply frequency.

ii) Effect on magnitude of rotor Induced emf:-

We have seen that

when $N_r = 0$, $S = 1$, At this Condition relative speed is maximum & hence max. emf gets induced in the rotor. Let this emf be

E_2 = Rotor induced emf at standstill condition.

As rotor gains speed, the relative speed decreases and hence emf also decreases. Let

E_{2r} = Rotor induced emf at running Condⁿ.

Now $E_2 \propto N_s$ while $E_{2r} \propto N_s - N_r$.

Dividing the two proportionality equation.

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

$$\Rightarrow \frac{E_{2r}}{E_2} = S.$$

$$\Rightarrow \boxed{E_{2r} = S E_2}$$

Thus magnitude of induced emf in the rotor also reduces by slip times the magnitude of induced emf at standstill

iii) Effect on Rotor Resistance and Reactance:-

The rotor winding has its own resistance and Inductance. In general, let

R_2 = Rotor resistance | Phase at standstill

X_2 = Rotor reactance | Phase at standstill

We know that Resistance is independent of frequency but reactance is depend on frequency i.e. rotor frequency.

In running condition $f_r = Sf$.

X_{2r} = reactance | Phase at running condition

$X_{2r} = 2\pi f_r L_2$ (L_2 = inductance of rotor)

$$\Rightarrow X_{2r} = 2\pi (Sf) L_2$$

$$\Rightarrow X_{2r} = S \cdot (2\pi f L_2)$$

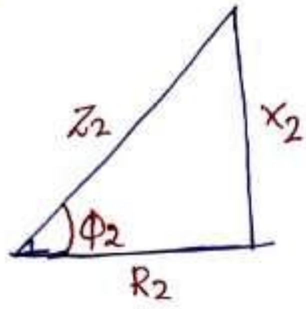
$$\Rightarrow \boxed{X_{2r} = S \cdot X_2}$$

Hence impedance will be

$$\begin{cases} Z_2 = \sqrt{R_2^2 + X_2^2}\ \Omega \text{ | Phase} \rightarrow \text{At standstill.} \\ Z_{2r} = \sqrt{R_2^2 + (SX_2)^2}\ \Omega \text{ | Phase} \rightarrow \text{At running.} \end{cases}$$

iv) Effect on Rotor power factor:-

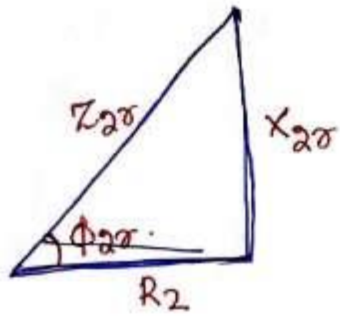
At standstill, the impedance triangle of rotor will be.



$\cos \phi_2$ = Rotor Powerfactor on standstill.

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

But at running condition, the impeda triangle will be.



$$X_{2r} = S \cdot X_2$$
$$Z_{2r} = \sqrt{R_2^2 + (SX_2)^2}$$

$\cos \phi_{2r}$ = Rotor Powerfactor on running.

$$\Rightarrow \cos \phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Note:- As rotor winding is inductive, the rotor p.f. is always inductive in nature.

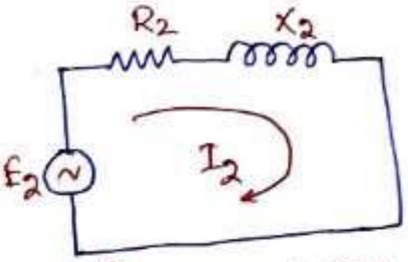
v) Effect on Rotor Current :-

Let I_2 = rotor current at standstill.

The rotor current depend upon E_2 (emf) and impedance (Z_2) per phase.

$$\therefore \quad I_2 = \frac{E_2}{Z_2}.$$

$$\Rightarrow I_2 = \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \text{ A}.$$



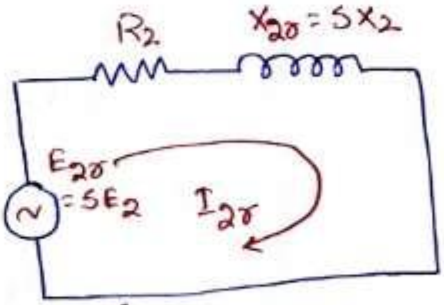
(Equivalent Ckt of rotor at Standstill)

Let I_{2r} = rotor current at running condition.

At running condition

$$I_{2r} = \frac{E_{2r}}{Z_{2r}}.$$

$$\Rightarrow \boxed{I_{2r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}}$$



(Equivalent Ckt of rotor at running)

Note :- * ϕ_{2r} is angle betn E_{2r} and I_{2r}, which decides p.f. at runing condition.

* ϕ_2 is angle betn E_2 & I_2 which decides p.f. at standstill condition.

Torque Equation:-

The torque produced in the I.M. depends on following factors

i) The part of rotating magnetic field (ϕ) which reacts with rotor and is responsible to produced induced emf on rotor (E_{2r})

ii) Magnitude of rotor current (I_{2r})

iii) The powerfactor of rotor ckt in running cond. ($\cos\phi_{2r}$)

So $\boxed{T \propto \phi I_{2r} \cos\phi_{2r}}$ ——— ①

The flux produced by stator is proportional to E_1

i.e. $\phi \propto E_1$ ——— ②

while E_1 & E_2 are related to each other through turns ratio (like x^r)

i.e. $\frac{E_2}{E_1} = K$ ——— ③

So by using eqn ② & ③, we can write

$E_2 \propto \phi$.

So in eqn ①, ϕ can be replaced by E_2.

$\therefore T \propto E_2 I_{2r} \cos\phi_{2r}$ ——— ④.

while $I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{S E_2}{\sqrt{R_2^2 + (S X_2)^2}}$

and $\cos\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (S X_2)^2}}$.

So Equation (4) will be

$$T \propto E_2 \cdot \frac{S E_2}{\sqrt{R_2^2 + (S X_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (S X_2)^2}}$$

$$\Rightarrow T \propto \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2} \quad N\text{-}M$$

$$\Rightarrow T = \frac{K S E_2^2 R_2}{R_2^2 + (S X_2)^2}.$$

(K = Proportionality constant)

$\Rightarrow K = \frac{3}{2\pi n_s}$ (for 3-Phase I.M)

$$\therefore \boxed{T = \frac{3}{2\pi n_s} \cdot \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}}$$

$n_s \rightarrow$ Synchronous Speed in r.ps.

$\Rightarrow \left(n_s = \frac{N_s}{60}\right)$.

Starting torque :- (T_{st})

At Starting of I.M.

$N_r = 0$, slip $= 1$, So putting these value in above eqn.

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

from the above, we can conclude that by changing the value of R_2, we can control the starting torque of an Induction motor which is applicable in case of slip ring Induction motor. Where external resistance can be added.

Condition of Max. Starting torque:-

Generally stator supply voltage E_1 is constant, that means E_2 is also constant.

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

$$\Rightarrow T_{st} = \frac{K R_2}{R_2^2 + X_2^2} \quad (E_2 \text{ is constant})$$

Starting torque will be max. when $\frac{dT_{st}}{dR_2} = 0$.

$$\therefore \frac{d}{dR_2}\left(\frac{K R_2}{R_2^2 + X_2^2}\right) = 0.$$

$$\Rightarrow K\left[\frac{1}{(R_2^2 + X_2^2)} - \frac{R_2(2R_2)}{(R_2^2 + X_2^2)^2}\right] = 0.$$

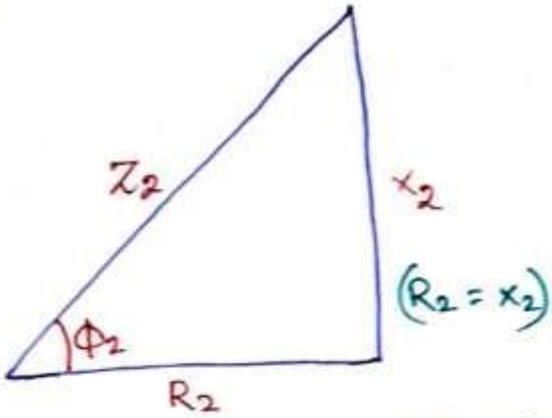
$$\Rightarrow \frac{1}{R_2^2 + X_2^2} = \frac{R_2(2R_2)}{(R_2^2 + X_2^2)^2}.$$

$$\Rightarrow R_2^2 + X_2^2 = 2R_2^2.$$

$$\Rightarrow \boxed{R_2 = X_2}$$

So starting torque will be max. when

Rotor resistance/phase = standstill rotor reactance/phase



As $R_2 = X_2$

So $\phi_2 = 45^\circ$.

i.e. $\cos\phi_2 = 45^\circ$ i.e. 0.707 lagging in this cond^n.

Effect of change in supply voltage on starting torque

Generally the supply voltage V or E_1 is constant. But if it varies, then starting torque will change.

We know that

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

Since $E_2 \propto E_1$ or V

$$\text{So } T_{st} = \frac{K V^2 R_2}{R_2^2 + X_2^2}.$$

$$\Rightarrow \boxed{T_{st} \propto V^2}$$

Note :- So starting torque is very sensitive to supply voltage. If drop of 10% supply voltage will decrease the starting torque by about 20%.

Condition for Max. Torque:- (T_m) (Running cond^n)

We know that

$$T = \frac{K S E_2^2 R_2}{R_2^2 + (S X_2)^2} = \frac{3}{2\pi n_s} \cdot \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

As E_1 is constant E_2 also constant. Similarly R_2, X_2 and n_s are constant for I.M.

So only one parameter which control the torque is slip.

Mathmatically for max. torque we can write

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

$$\Rightarrow \frac{dT}{ds} = \frac{(K S E_2^2 R_2) \cdot \frac{d}{ds}(R_2^2 + S^2 X_2^2) - (R_2^2 + S^2 X_2^2) \frac{d}{ds}(K S E_2^2 R_2)}{R_2^2 + S^2 X_2^2} = 0$$

$$\Rightarrow K S E_2^2 R_2 (2 S X_2^2) - (R_2^2 + S^2 X_2^2)(K E_2^2 R_2) = 0.$$

$$\Rightarrow 2K S^2 X_2^2 E_2^2 R_2 - R_2^2 K E_2^2 R_2 - K S^2 X_2^2 E_2^2 R_2 = 0.$$

$$\Rightarrow K S^2 X_2^2 E_2^2 R_2 - R_2^2 K E_2^2 R_2 = 0.$$

$$\Rightarrow K E_2^2 R_2 (S^2 X_2^2 - R_2^2) = 0.$$

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

$$\Rightarrow S^2 = \frac{R_2^2}{X_2^2}$$

$\Rightarrow s = \frac{R_2}{X_2}$. (neglecting negetive slip)

At max. torque, the slip is denoted as S_M.

$$\therefore \boxed{S_M = \frac{R_2}{X_2}} \longrightarrow \text{this is the cond}^n \text{ for max. torque.}$$

Magnitude of Max. Torque:-

max. torque is

$$T_M = \frac{K S_M E_2^2 R_2}{R_2^2 + (S_M X_2)^2}.$$

Putting the value of $S_M = \frac{R_2}{X_2}$.

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

$$\Rightarrow T_M = \frac{K E_2^2 \cdot R_2^2 \cdot \left(\frac{1}{X_2}\right)}{R_2^2 + R_2^2}$$

$$\Rightarrow T_M = \frac{K E_2^2 \cdot R_2^2 \cdot \left(\frac{1}{X_2}\right)}{2R_2^2}$$

$$\Rightarrow \boxed{T_M = \frac{K E_2^2}{2X_2}}$$

from the above expression, we can observed that

* max. torque is inversly proportional to rotor reactance
* It is directly proportional to induced emf at stand still

* The most interesting observation is, "The max. torque is not depend on rotor resistance 'R_2''." But the slip at which it occurs i.e. speed at which it occurs depends on the value of rotor resistance 'R_2''.

Torque - Slip Charactaristics:-

(Squiral - Cage - rotor)

As the I.M. is loaded from no load to full load, it's speed decreases, hence slip increases. Due to increased load, motor has to produce more torque to satisfy the load demand. the torque is depend upon the slip. as explin earlier.

The curve ploting betn ~~torq~~ torque against slip from $S=1$ to $S=0$ is called torque-slip charactaristics.

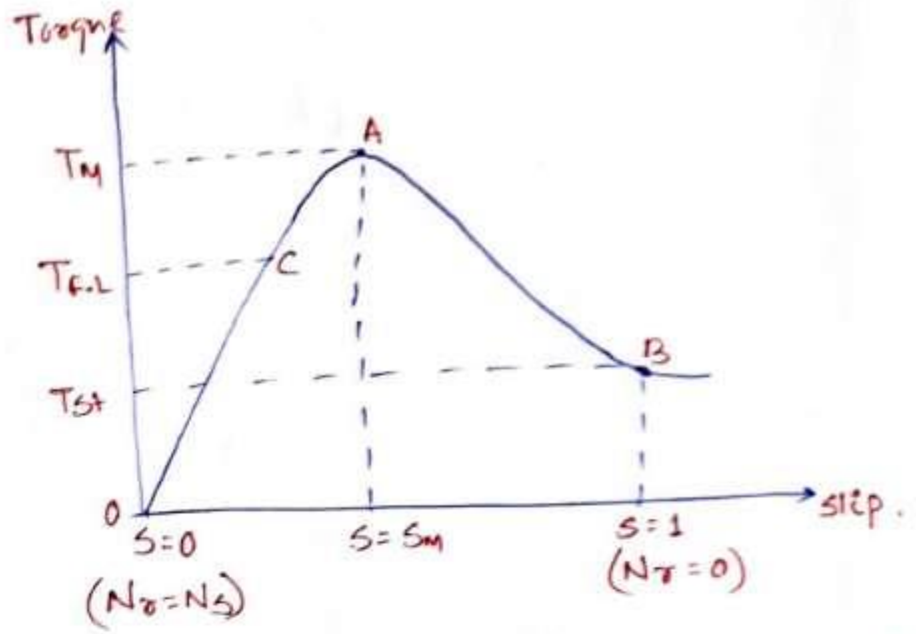
We know that

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

As supply voltage is constant, so E_2 also constant.

$$\therefore T \propto \frac{S R_2}{R_2^2 + (S X_2)^2}.$$

Now to Judge the nature of torque-slip charactaristics, Let us devide the slip range (s=0 & s=1) in to two parts and analyse them independently.



S_M → slip at max. Torque.

OA → stable region.
AB → unstable region.

i) <u>low slip region</u>:-

In low slip region, 'S' is very small. Due to this $(SX_2)^2$ is also too small as comparred to R_2^2. So it can be neglected.

$$\text{So} \quad T \propto \frac{SR_2}{R_2^2}.$$

$$\Rightarrow \boxed{T \propto S} \quad (\text{As } R_2 \text{ is constant})$$

Hence in low slip region torque is directly proportional to slip.

So as load increases, speed decreases and slip increases. so torque increases.

Hence the graph is straight line in nature (line OA) which is called stable region.

ii) High - slip region :-

In this region slip is high i.e. Slip value is approaching to 1.

Here we can assumed that R_2^2 is very small as compared to $(sX_2)^2$.

$$\text{So } T \propto \frac{sR_2}{(sX_2)^2}$$

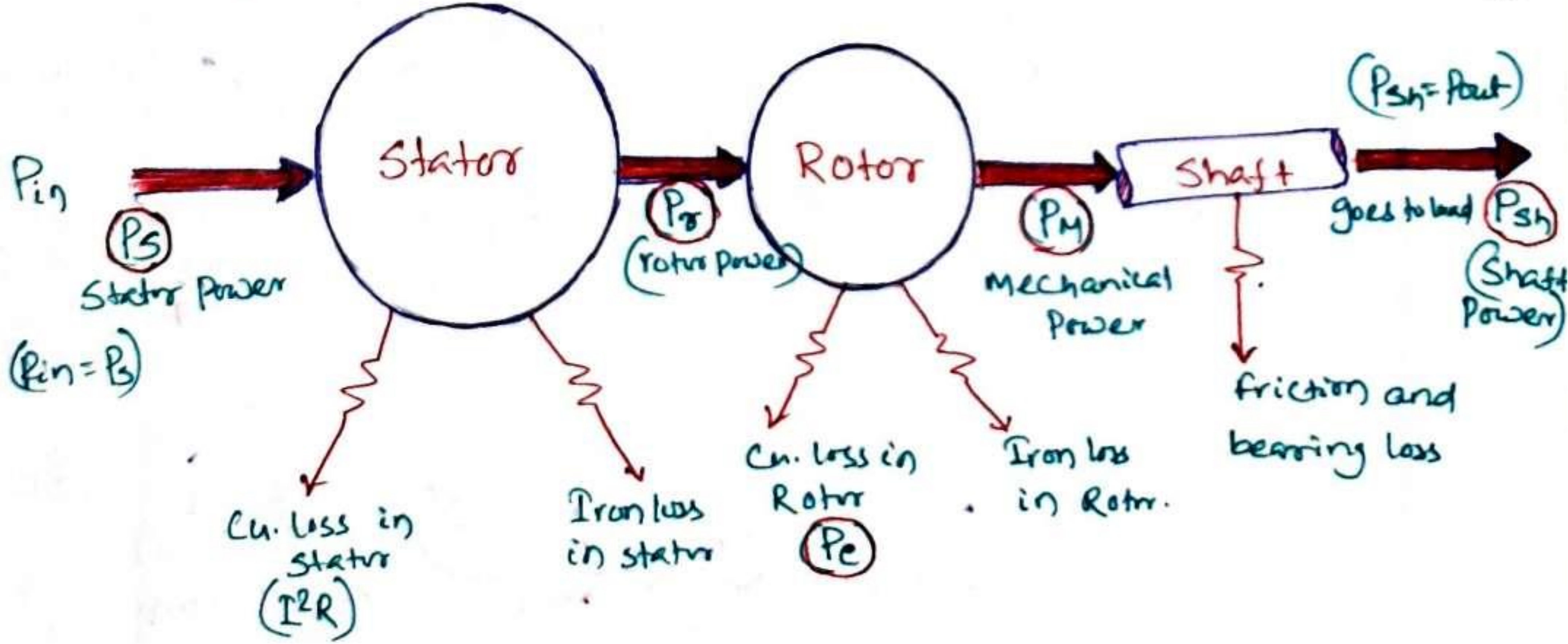
$$\Rightarrow T \propto \frac{sR_2}{s^2 X_2^2}$$

$$\Rightarrow \boxed{T \propto \frac{1}{s}}$$ (As R_2 & X_2 are constant)

So in high region torque is inversly proportional to slip. Hence its nature is like reactangular hyparabola (line AB). This region is also called unstable region.

– x –

Power-stages in an I.M:-



The three phase supply given to the Stator is the net electrical input to the motor. This is nothing but the Stator Power (P_S). The part of the power is utilised to supply the losses in the stator which are stator Cu. loss and stator Iron loss. The remaining power is delivered to the rotor magnetically through air-gap. is called rotor power (P_r).

So $P_r = P_s$ - stator loss (Core + Copper)

The rotor is not able to convert its entire input to mechanical as it has self iron and copper loss. In rotor iron loss is very small as compared to copper loss. So iron loss is negligible. So only copper loss is there denoted as 'P_c'.

→ (I.at running cond?)

So Rotor Cu. loss $P_c = 3 \times I_{2r}^2 \times R_2$ → for 3-phase

After supplying these losses, the remaining part of 'P_r' is converted in to mechanical power developed by the motor denoted as (P_m).

So $P_M = P_r - P_c$

Now this power, motor tries to deliver to the load connected to shaft. But during the mechanical transmission, the part of P_M is goes to losses due to friction and windage.

So $P_{out} = P_M$ - Mechanical losses

→ This power is the final output to the load.

So Rotor efficiency (η_r) = $\frac{\text{Rotor output}}{\text{Rotor input}} = \frac{P_M}{P_r}$.

and Net motor efficiency (η_M) = $\frac{\text{Motor output}}{\text{Motor input}} = \frac{P_{out}}{P_{in}} = \frac{P_{sh}}{P_s}$

Relation Betn Rotor Input, Rotor output and Rotor Cu. loss (P_r, P_M, P_c)

$P_r \rightarrow$ Rotor Input

$P_M \rightarrow$ Rotor output

$P_C \rightarrow$ Rotor Cu. loss.

Let T = Gross torque developed by motor in N-m

We know that

$$P = T \times \omega$$

ω = angular speed = $\frac{2\pi N_s}{60}$

Now input to the rotor (P_r) is from stator side through rotating magnetic field which is rotating at synchronous speed (N_s).

$$\text{So } P_r = T \times \omega_s.$$

$$\Rightarrow P_r = T \times \frac{2\pi N_s}{60} \quad \text{——— (1)}$$

Rotor tries to deliver this torque to the load. So rotor output is gross mechanical power (P_m). and torque 'T'.

So $P_M = T \times \omega_r$ (Here $\omega_r \neq \omega_s$)

$$\Rightarrow P_M = T \times \frac{2\pi N_r}{60} \quad \text{———— (2)}$$

The difference betn P_r and P_M is rotor Cu. loss (P_c)

So $P_c = P_r - P_M$

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

$$\Rightarrow P_c = T \times \frac{2\pi}{60}(N_s - N_r) \quad \text{———— (3)}$$

Now deviding eqn (3) by eqn (1)

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

$$\Rightarrow \frac{P_c}{P_r} = \frac{N_s - N_r}{N_s} = S.$$

$$\Rightarrow \frac{P_c}{P_r} = S$$

$\Rightarrow$ **Rotor Cu. loss (P_c) = S × Rotor input (P_r)** ———— (4)

Now $P_r - P_c = P_M$

$$\Rightarrow P_r - SP_r = P_M.$$

$$\Rightarrow P_r(1 - S) = P_M$$

$$\Rightarrow \boxed{\frac{P_M}{P_r} = (1 - S)} \quad \text{———— (5)}$$

So from eqn ④ and ⑤, the relationship can be expressed in form of ratio is

$$\boxed{P_r : P_c : P_M = 1 : s : 1-s}$$

$$\boxed{\frac{P_c}{P_M} = \frac{s}{1-s}} \qquad \boxed{\frac{P_r}{P_c} = \frac{1}{s}} \qquad \boxed{\frac{P_r}{P_m} = \frac{1}{1-s}}$$

— x —

Torque Ratio:-

The Performance of the motor is sometimes expressed in terms of comparision of various torque.

i) Full load and max. Torque Ratio:-

In general

$$T \alpha \frac{S E_2^2 R_2}{R_2^2+(S X_2)^2}.$$

Let S_f = full load slip

& S_m = Slip for max. torque T_m

$$\therefore \quad T_{F.L.} \alpha \frac{S_f E_2^2 R_2}{R_2^2+(S_f X_2)^2}$$

$$\& \quad T_m \alpha \frac{S_m E_2^2 R_2}{R_2^2+(S_m X_2)^2}$$

$$\therefore \quad \frac{T_{f.L.}}{T_m} = \frac{S_f E_2^2 R_2}{R_2^2+(S_f X_2)^2} \times \frac{R_2^2+(S_m X_2)^2}{S_m E_2^2 R_2}.$$

$$\Rightarrow \frac{T_{F.L}}{T_m} = \frac{S_f}{S_m} \times \frac{R_2^2+(S_m X_2)^2}{R_2^2+(S_f X_2)^2}.$$

Dividing both numerator and denominator by X_2^2

$$\frac{T_{FL}}{T_m} = \frac{S_f}{S_m} \times \frac{\left(\frac{R_2^2}{X_2^2}+S_m^2\right)}{\left(\frac{R_2^2}{X_2^2}+S_f^2\right)}.$$

$$= \frac{S_f \times a\, S_m^2}{S_m \times (S_m^2+S_f^2)} \Rightarrow \boxed{\frac{T_{f.L.}}{T_m} = \frac{a S_f S_m}{(S_m^2+S_f^2)}}$$

iii) <u>Starting Torque & maximum Torque :-</u>

We know that

$$T_{st} = \frac{E_2^2 R_2}{R_2^2 + X_2^2}.$$

While for T_m, $S = S_m$

$$\therefore T_m = \frac{S_m E_2^2 R_2}{R_2^2 + (S_m X_2)^2}$$

$$\therefore \frac{T_{st}}{T_m} = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{R_2^2 + (S_m X_2)^2}{S_m E_2^2 R_2}.$$

$$= \frac{R_2^2 + (S_m X_2)^2}{S_m [R_2^2 + X_2^2]}$$

Dividing both numerator & denominator by X_2^2, we get

$$\therefore \frac{T_{st}}{T_m} = \frac{\left(\frac{R_2^2}{X_2^2} + S_m\right)}{S_m\left(\frac{R_2^2}{X_2^2} + 1\right)}$$

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

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

iii) Starting Torque and f.l. Torque :-

we know that

$$T_{st} = \frac{E_2^2 R_2}{R_2^2 + X_2^2}.$$

and full load torque

$$T_{F.L} = \frac{S_f E_2^2 R_2}{R_2^2 + (S_f X_2)^2} \quad \text{at } S = S_f.$$

$$\therefore \frac{T_{st}}{T_{FL}} = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{R_2^2 + (S_f X_2)^2}{S_f E_2^2 R_2}.$$

$$= \frac{R_2^2 + (S_f X_2)^2}{S_f (R_2^2 + X_2^2)}.$$

Deviding both numarator and Denominator by X_2^2

$$\therefore \frac{T_{st}}{T_{FL}} = \frac{\frac{R_2^2}{X_2^2} + S_f^2}{S_f \left(\frac{R_2^2}{X_2^2} + 1\right)}$$

$$\Rightarrow \boxed{\frac{T_{st}}{T_{FL}} = \frac{S_m^2 + S_f^2}{S_f (S_m + 1)}}$$

Problem:-

In a 4 Pole, 3-ϕ, 50Hz induction motor Calculate, the frequency of the rotor current

i) at standstill.

ii) Motor is running at 500 rpm in same direction as field.

iii) Motor is running at 500 rpm in opposite direction as field.

iv) motor is running at 2000 rpm in same direction as field.

Soln:- We know that

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

i) At standstill:-

$N_r = 0$

$$\text{Here slip} = \frac{N_s - N_r}{N_s} = \frac{N_s - 0}{N_s} = 1$$

$\therefore$ Rotor frequency $f_r = sf = 1 \times 50\text{Hz} = 50\text{Hz}$.

ii) Motor runs at 500 rpm as the same direction of field.

$$\text{Here slip } s = \frac{1500 - 500}{1500} = \frac{1000}{1500} = 0.66$$

motoring operation.

$\therefore$ Rotor frequency $f_r = sf = 0.66 \times 50 = 33.33\text{Hz}$

iii) Motor runs at 500 rpm but in opposite direction

$$\text{Here slip } s = \frac{1500 - (-500)}{1500} = \frac{2000}{1500} = 1.33$$

Breaking operation

iv) <u>Motor runs at 2000 rpm in same direction</u>

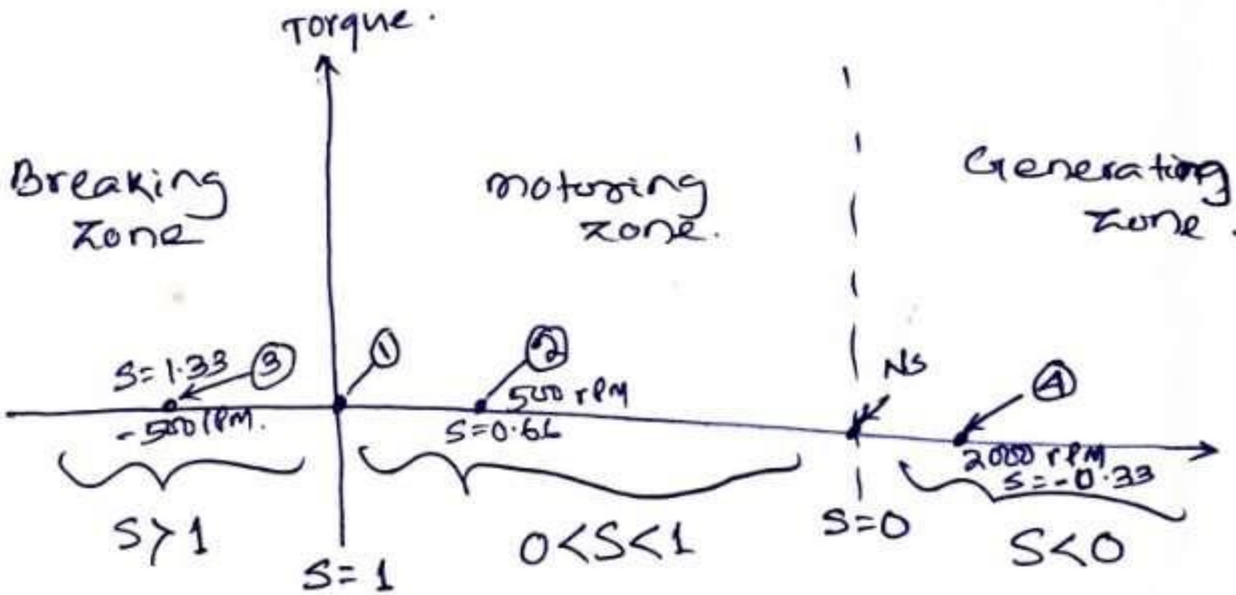
$N_s = 1500$ rpm.

$N_r = 2000$ rpm.

Here slip $= \frac{N_s - N_r}{N_s} = \frac{1500 - 2000}{1500} = -0.33$

Generating mode.

$\therefore f_r = sf = -0.33 \times 50 = -16.66$ Hz.



Method of Starting of I.M.

Necessity of Starter:-

In a 3-ϕ I.M., the magnitude of an induced emf in the rotor ckt depends on slip and this induced emf effectively decides the magnitude of the rotor current.

$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

But at start, slip is max., so induced emf is very large, so the current also and this current is 5 to 8 times the full load current which may damage the motor winding like short ckt condition of X^r.

So to reduce the induced emf starter is used. Simillarlly such sudden inrush current causes large line voltage drop. Thus other appliances connected to the same line may affect their working.

Types of Starter:-

The various types of starters are

i) Stator resistance starter.

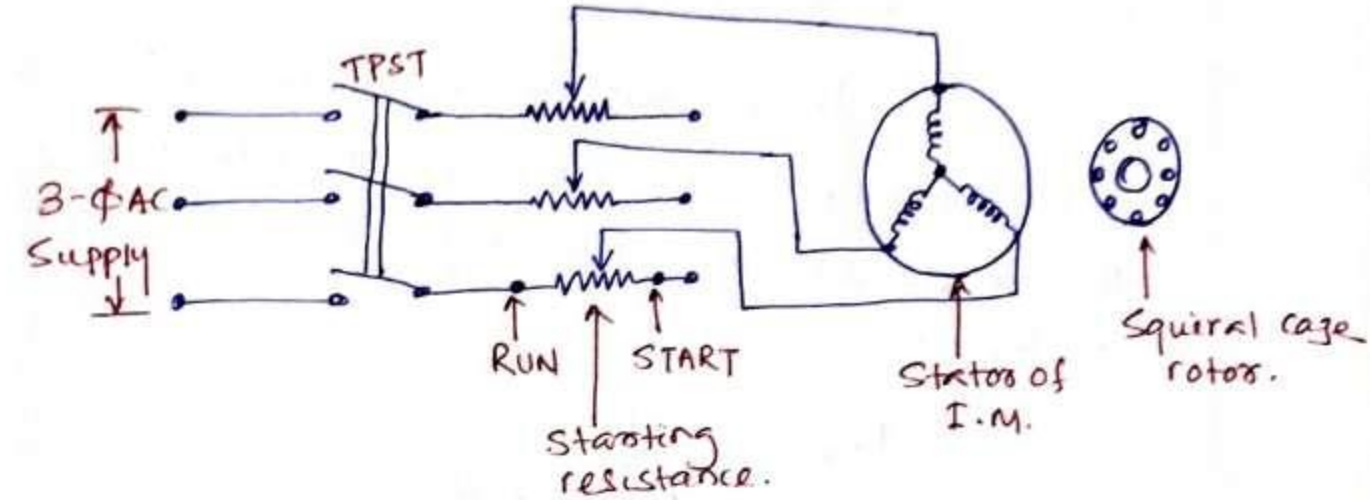
ii) Auto transformer starter

iii) Star - Delta Starter.

iv) Rotor resistance Starter.

v) Direct on line Starter.

i) <u>Stator Resistance Starter :-</u>

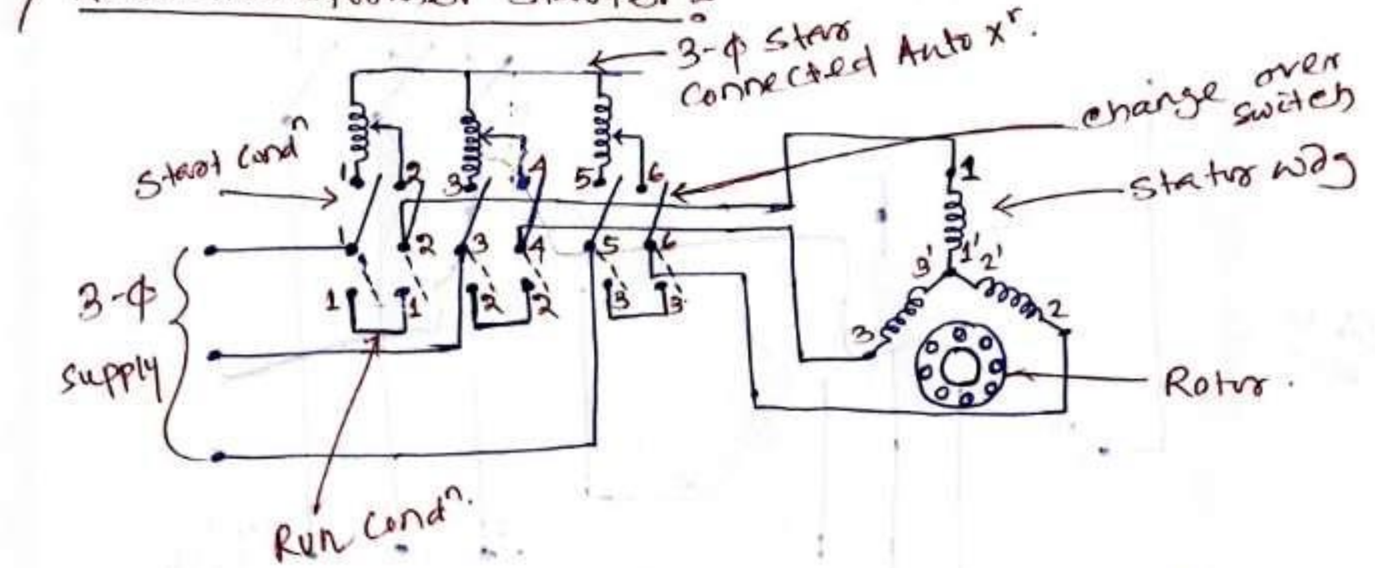


In order to apply the reduced voltage to the Starter, three resistance are added in series with each phase of Stator winding. Initially the resistance are kept maximum. Due to this large voltage will drop across the resistance. Hence it reduces the high Starting current.

When the motor starts running the resistances ares gradually cut-off from the ~~Starter~~ Stator Ckt. When it is entirely removed, than ratted voltage will applied to Stator and motor run in normal Speed.

The Starter is Simple in Constructn and cheap. It can be used for both Star or Delta ~~Starter~~. Stator. But there are large power loss due to resistances.

ii) Auto-transformer Starter :-

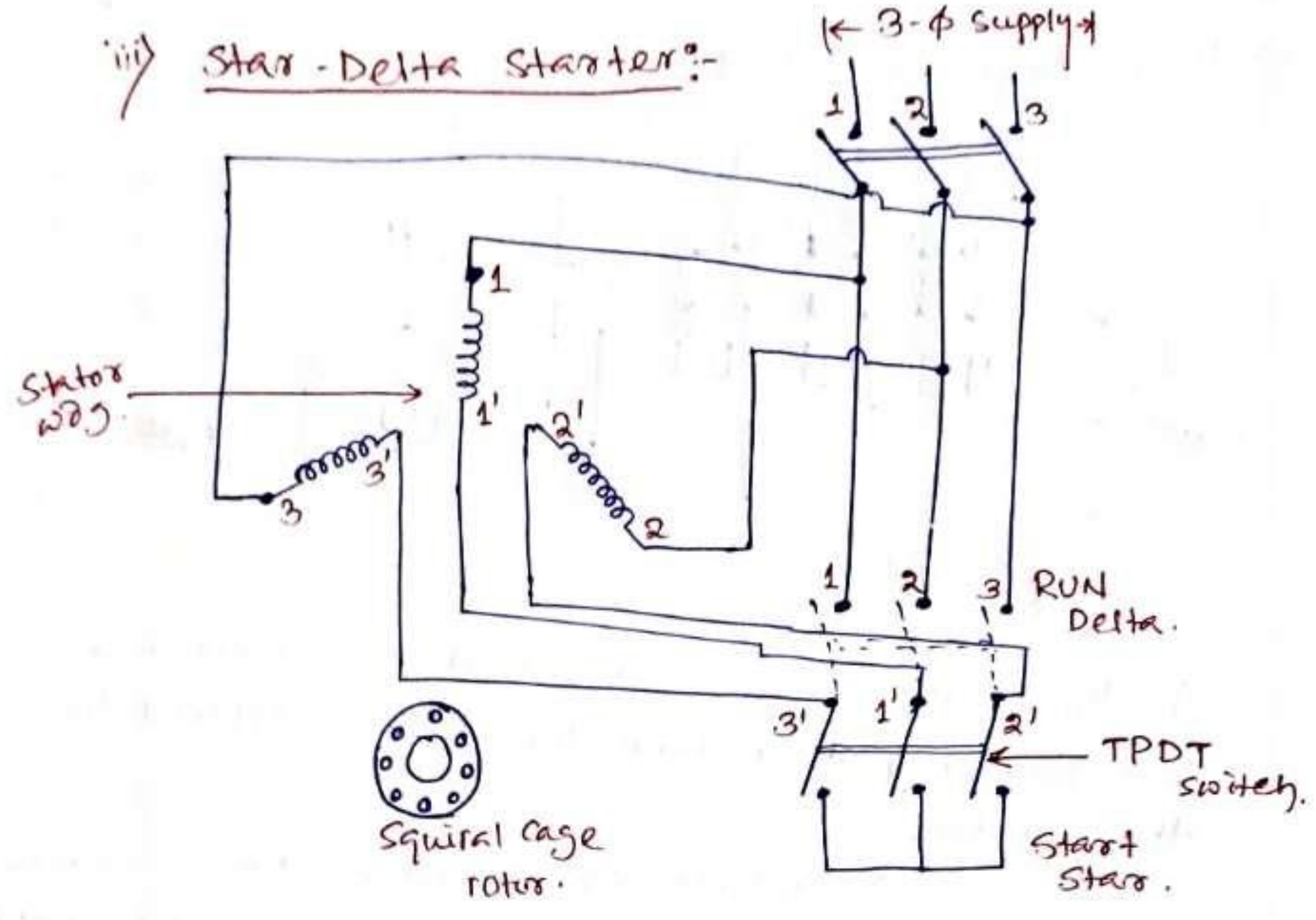


A three phase star connected auto transformer can be used to reduce the voltage applied to the stator.

It consists of a suitable change over switch. When the switch is in start position, the stator winding is supplied with reduced voltage. This can be controlled by tappings provided with a auto transformer. When the motor gathers 80% of the normal speed, the change over switch is thrown in to run position and the motor runs with ratted voltage at normal speed. Changing of switch is done automatically by using relay.

In this type power loss is very less at starting. It can be used for both star or Delta connected stator wdg. But it is expensive than stator resistance starter.

iii) Star - Delta Starter:-

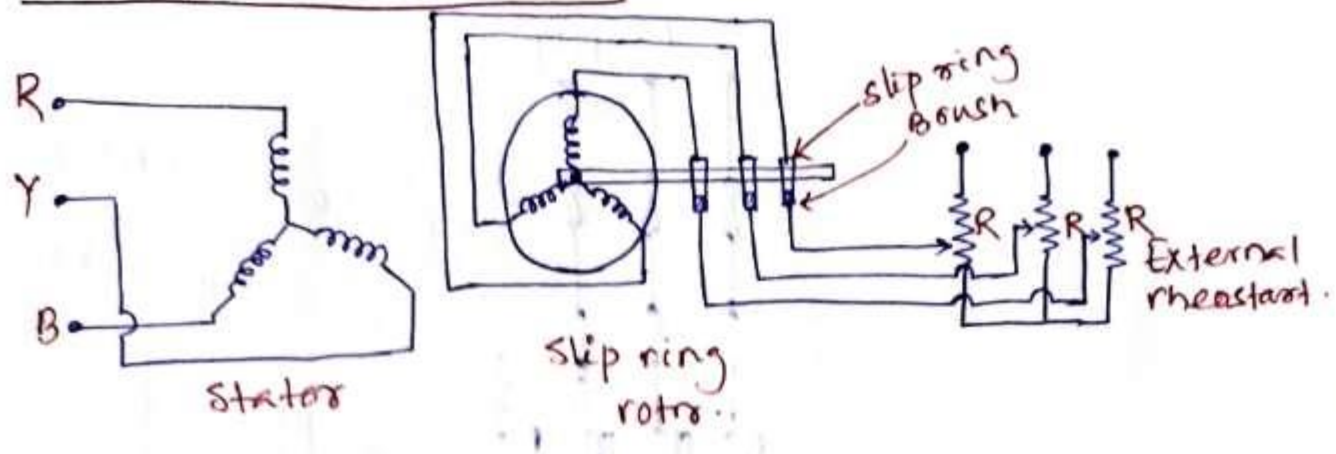


This is the cheapest starter of all and hence used very commonly for I.M. It uses Tripple pole Double through (TPDT) switch. The switch is connects the Stator wdg in star at start. Hence Per phase voltage get reduced by the factor $\frac{1}{\sqrt{3}}$. Due to this reduced voltage starting current is limitted.

When the switch is thrown to other side the wdg get connected in delta. So it gets normal ratted voltage. The wdg are connected in Delta when motor gathers sufficient speed.

The cheapest of all and maintanance free operation are two important advantages of this starter.

iv) Rotor Resistance Starter :-

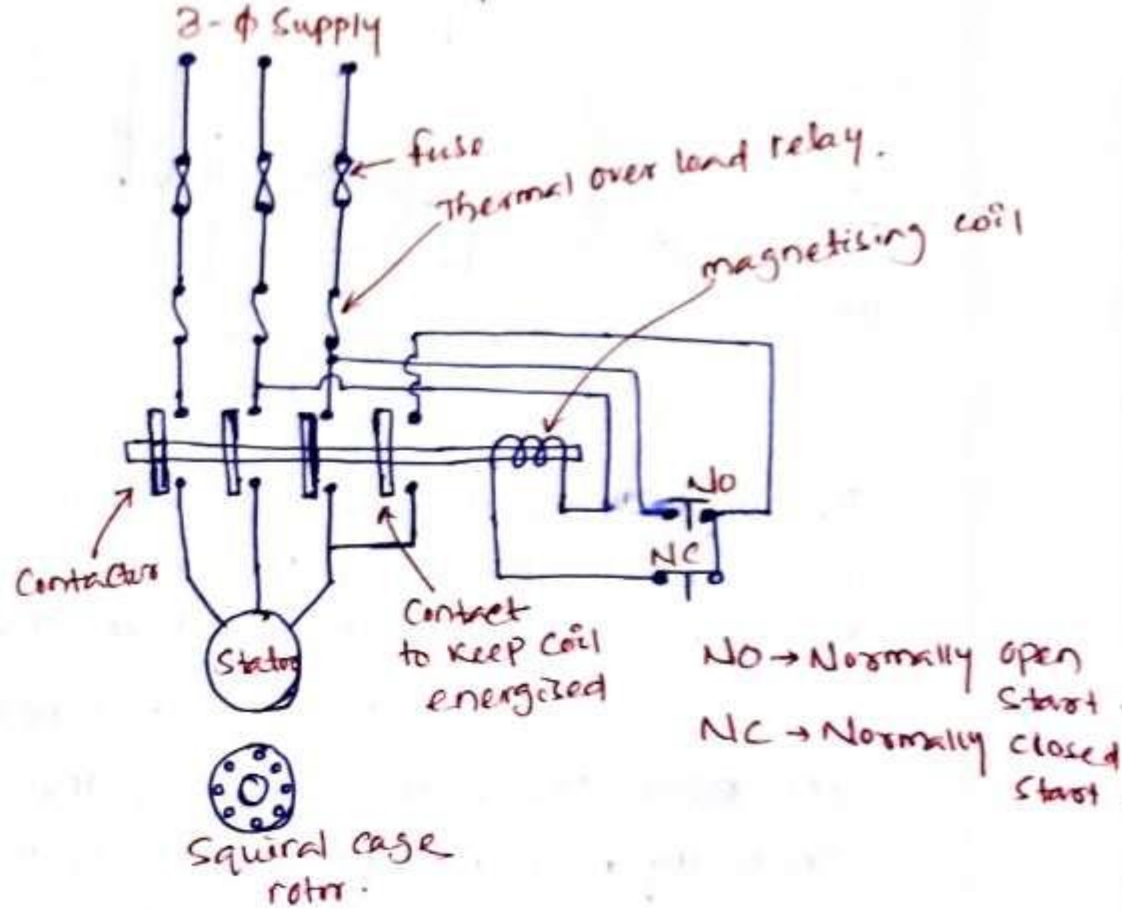


To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor ckt at start

The external resistance is inserted in each phase of rotor wdg through slip ring. Initially max. resistance is in the ckt. As motor gathers speed, the resistance is gradually cut-off.

The main advantages is its limit the current at starting and as the rotor resistance increases, the starting torque also increses. Its main disadvantages is it only used in slip ring induction motor.

v) Direct on line Starter (D.O.L)



In case of Small capacity motor having rating less than 5 HP, the starting current is not very high and such motor can withstand such starting current. Such motors use a type of starter which is used to connect stator directly to the supply without any reduction in voltage. Hence the starter is known as Direct on line starter.

It is used beacuse it protects the motor from various severe abnormal condition like over loading, low voltage, single phasing etc.

The NO contact is normally open & NC is normally closed. At start, NO is pushed for friction of second due to which coil get energized and attracts the contactor.

So stator get directly supply. The additional contact Provided, ensure that as long as supply is ON, the coil sets supply and keeps contact in ON Position. When NC is Pressed, the coil ckt get opened due to which coil get de-energised and motor gets Switched off from the supply.

— x —

Speed Control:-

A 3-phase I.M. is practically a constant speed motor like a d.c. shunt motor. But in case of 3-ϕ I.M. is very difficult to achive Smooth speed control.

We know that

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

from this expression, it can be seen that, the speed of I.M. can be changed either by changing synchronous speed (N_s) or by changing slip (s).

Simillarly

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

So as the parameter like R_2, E_2 are changed, than keep the torque constant for constant load condition.

Thus speed of the I.M. can be controlled by basically two methods.

i) from stator side &

ii) from Rotor side.

from stator side. it includes following method.

- i) Supply frequency Control, called V/f Control
- ii) Supply voltage control.
- iii) Controlling number of stator poles
- iv) Adding Rheostats in stator Ckt.

from Rotor side, it includes

- i) Adding external resistance in rotor ckt.
- ii) Cascade control
- iii) Injecting slip frequency voltage in to rotor Ckt.

i) Supply frequency control or V/f Control:-

The Synchronous Speed is given by

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

Thus by controlling the supply frequency smoothly, the synchronous speed can be controlled over a wide range. This gives smooth speed control of an I.M.

But the expression for the air gap flux is

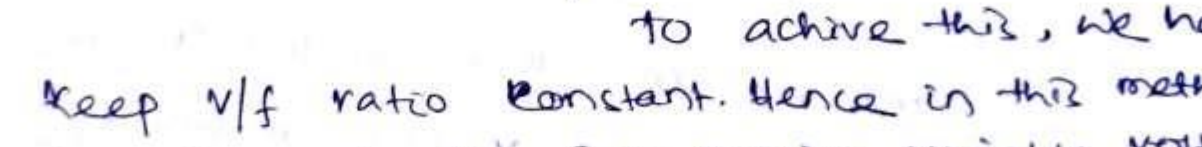
$$\phi_g = \frac{1}{4.44 K_1 T_{ph_1}}\left(\frac{V}{f}\right)$$

This is according to emf eqn of x^r.

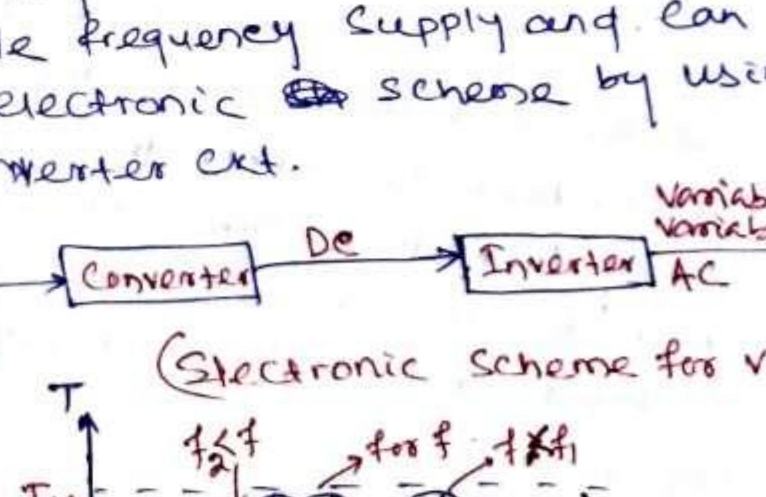
Where
K_1 = Stator wdg constant.
T_{ph1} = Stator turns per phase
V = Supply voltage
f = Supply frequency.

It can be seen that if the frequency changed, the air gap flux also gets affected. This may result in to saturation of stator and rotor cores. Such saturation leads to the sharp increse in the no load current of the motor. Hence it is necessary to maintain air gap flux constant when supply freqnecy changes.

To achive this, we have to keep V/f ratio constant. Hence in this method, the supply to the I.M. require variable voltage, variable frequency supply and can be achived by a electronic scheme by using converter and inverter ckt.



(Electronic scheme for V/f control)



[Torque-slip characteristics with variable f & constant (V/f)]

Its main disadvantages of this method is that, the Supply obtained Can not be used for other device. Hence a individual Scheme for a Separate motor is required which makes it costly.

ii) Supply voltage control:-

We know that

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

Now E_2, the rotor induced emf at Stand Still depends on the supply voltage 'V'.

$$E_2 \propto V$$

and we know that, at low Slip region

$$T \propto sV^2 \text{ (for constant } R_2\text{)}$$

Now if Supply voltage is reduced below ratted value, the torque also decreases. But to supply the Same load, it is necessary to produce Same torque, hence value of Slip must be increases. To Slip increase, motor reacts by running a lower Speed, to decrease the Supply voltage.

But in this method, due to reduction in voltage, current drawn by motor increases. Large change in voltage for small change in Speed is required is the biggest disadvantages, so it is rarely used only for motor driving fan load type.

iii) Controlling Number of Poles:-

In this method, insteed of one wdg, two separate stator wdg are placed in stator core. slots only but the wdg are placed in stator slots only but are electrically isolated from each other. Each wdg is devided in to coils to which pole changing with consequent poles, facility is provided.

By using switching arrangment two speed can be achived. The various limitation of this method are

i) It is applied only for squiral cage I.M.

ii) Smooth speed control is not possible.

iii) Two different stator wdg is required which increases the cost of motor.

iv) Complicated from the design point of view.

iv) Adding External resistance to Rotor ckt:-

We know that

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

for low slip region, $(sX_2)^2 << R_2$, and can neglected. So

$$T \propto \frac{sR_2}{(R_2)^2} \Rightarrow T \propto \frac{s}{R_2}.$$

Thus if the rotor resistance is increased, the torque produced decreases. But when the load of the motor is same, motor has to supply same torque. So motor reacts by increasing its slip to compensate decrese in torque due to R_2

So due to additional rotor resistance. Speed of motor decreases. Thus by increasing rotor resistance R_2' Speed below the normal value can be achived and also starting torque will increse.

But its limitations are

i) large speed change are not possible due to large cu. loss in rotor.

ii) It is only used for slip ring I.M.

iii) Speed above the normal speed can not be obtained.

iv) due to large power loss, efficiency is low.

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Enclousers and plugging - of I.M :-

Motor enclosures not only holds the motor component but also protects the internal components from moisture and containments. The degree of protection depends on the enclosure type. In addition, the type of enclouser affects the motor cooling. There are two catagories of enclousers

i) open type.

ii) Totally enclosed type.

i) Open type Enclousers :-

Open enclosures permits cooling air to flow through the motor. Fan blades are attached to the rotor moves air to the motor. This type enclouser should be used in environment free from contaminates.

ii) Totally enclosed type :-

In some application, the air surrounding the motor contains corrosive or harmful element which can damage the internal parts of motor. Totally enclosed type limits the flow of air in to the motor, but is not airtight. However, a seal at the point where the shaft passes through the housing prevents water, dust and other foreign matter from entering the motor along the shaft.

Plugging of An Induction motor:-

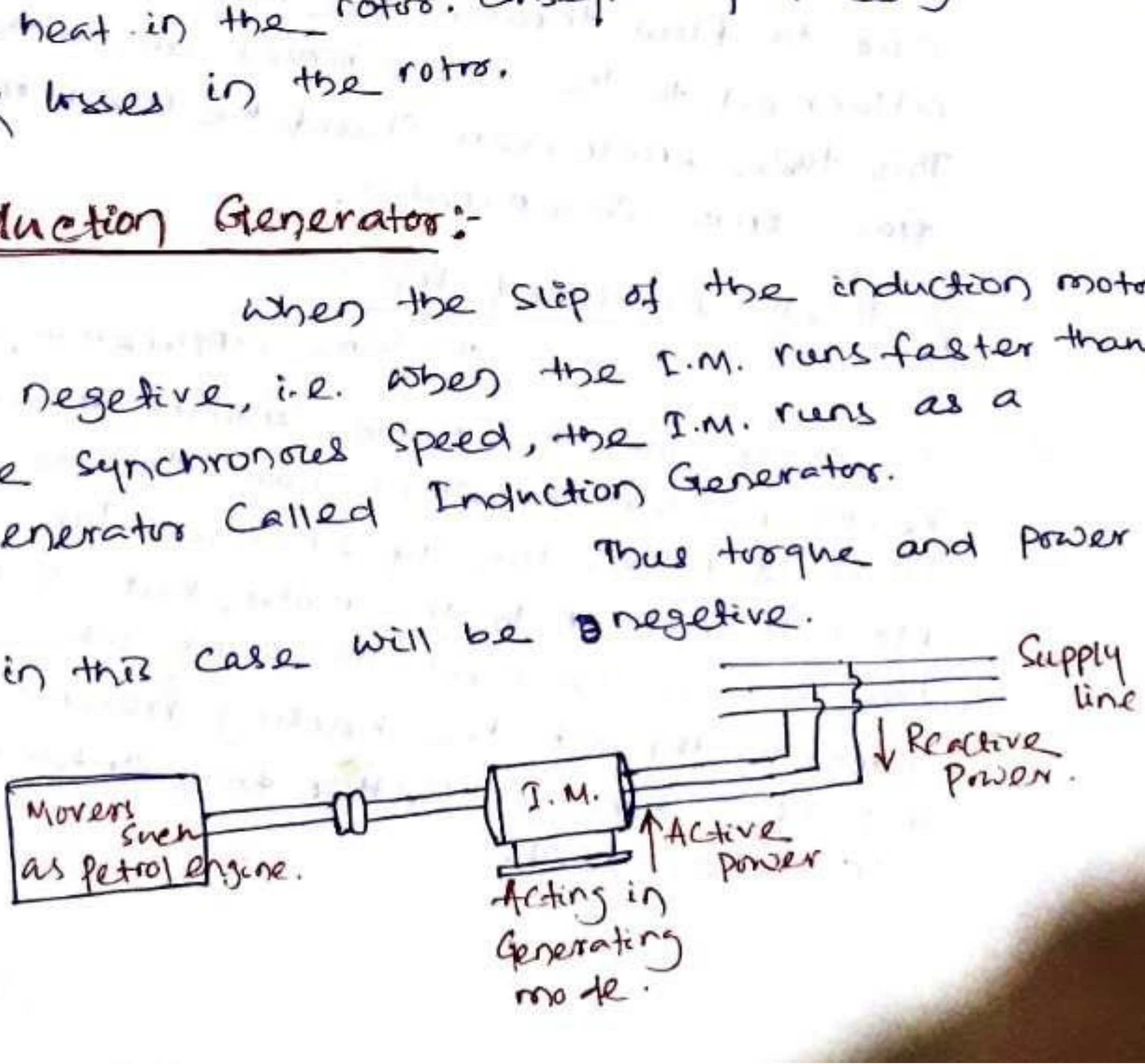
In some industrial application, it is desired to bring the running induction motor to a rapid stop. This can be done by simply interchanging the two stator leads. This process is called plugging.

When we interchange two stator leads the revolving field suddenly turns in the opposite direction to the rotor. During the plugging period, the motor acts as a brake. The mechanical power associated with the rotor is entirely dissipated as heat in the rotor. Consequently plugging produces I^2R losses in the rotor.

Induction Generator:-

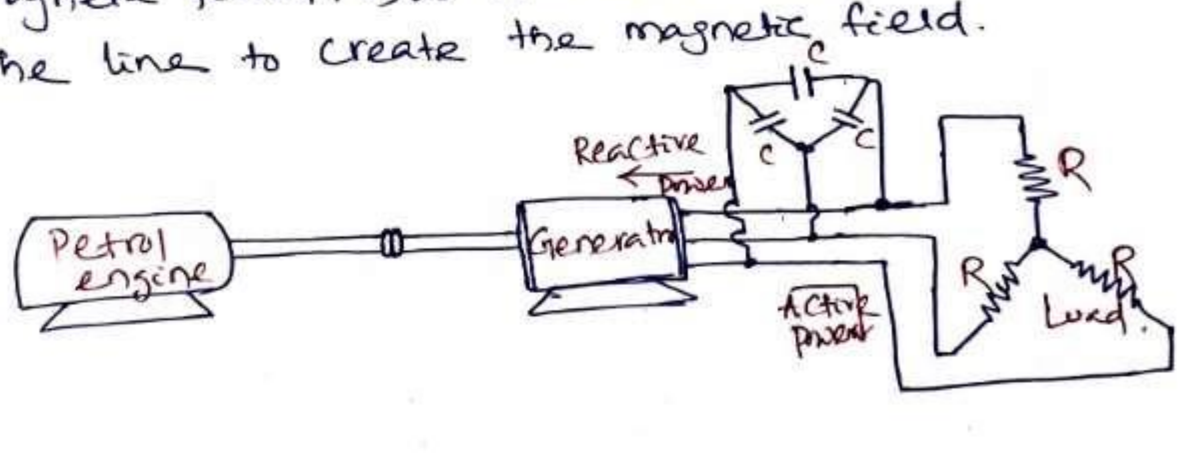
When the slip of the induction motor is negetive, i.e. when the I.M. runs faster than the synchronous speed, the I.M. runs as a generator called Induction Generator.

Thus torque and power in this case will be negetive.



In this fig. the I.M. is shown which is driven by a mover like Petrol engine. The motor is Supplied with electrical Power from 3-phase line When the motor speed exceeds the synchronous speed the active power is delivered by the motor and the corresponding mode of operation of motor is called generating mode.

The induction generator is not self exciting in the sense that supply must be maintained to act as a generator. Thus it must be operated with other generators which supplies exciting current of fixed frequency which is required for the production of rotating magnetic field. Thus it takes reactive power from the line to create the magnetic field.



Single Phase- Induction Motor.

Single Phase I.M. are usually used in domestice Purpose. Some of them are even fractional horse power rating, which are used in application like small toys, small fans, hair dryers etc.

Construction :-

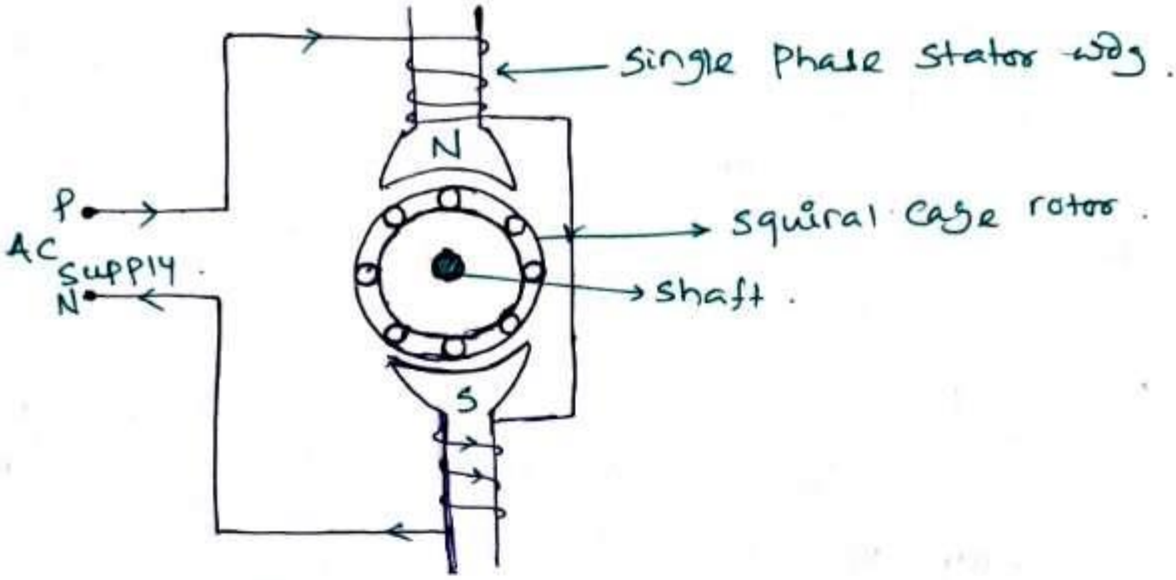
Similar to d.c. motor, 1-Φ I M has basically two main parts. The stationary part is stator while rotating part is rotor.

The stator is laminated constructi made up of stampings. The stampings are slotted in its peripheri to carry the stator winding or main wdg. This is excited by single phase a.c. supply. The stator wdg is wound for certain definite number of poles means when excited by single phase a.c. supply, stator produces the magnetic field which creates the effect of certain definite number of poles. The synchronous speed is denoted as Ns and is given by

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

The induction motor never rotates with the synchronous speed but rotates at a speed of slightly less than synchronous speed.

The Rotor construction is same squirral-cage type which consists of uninsulated copper or alluminium bars.

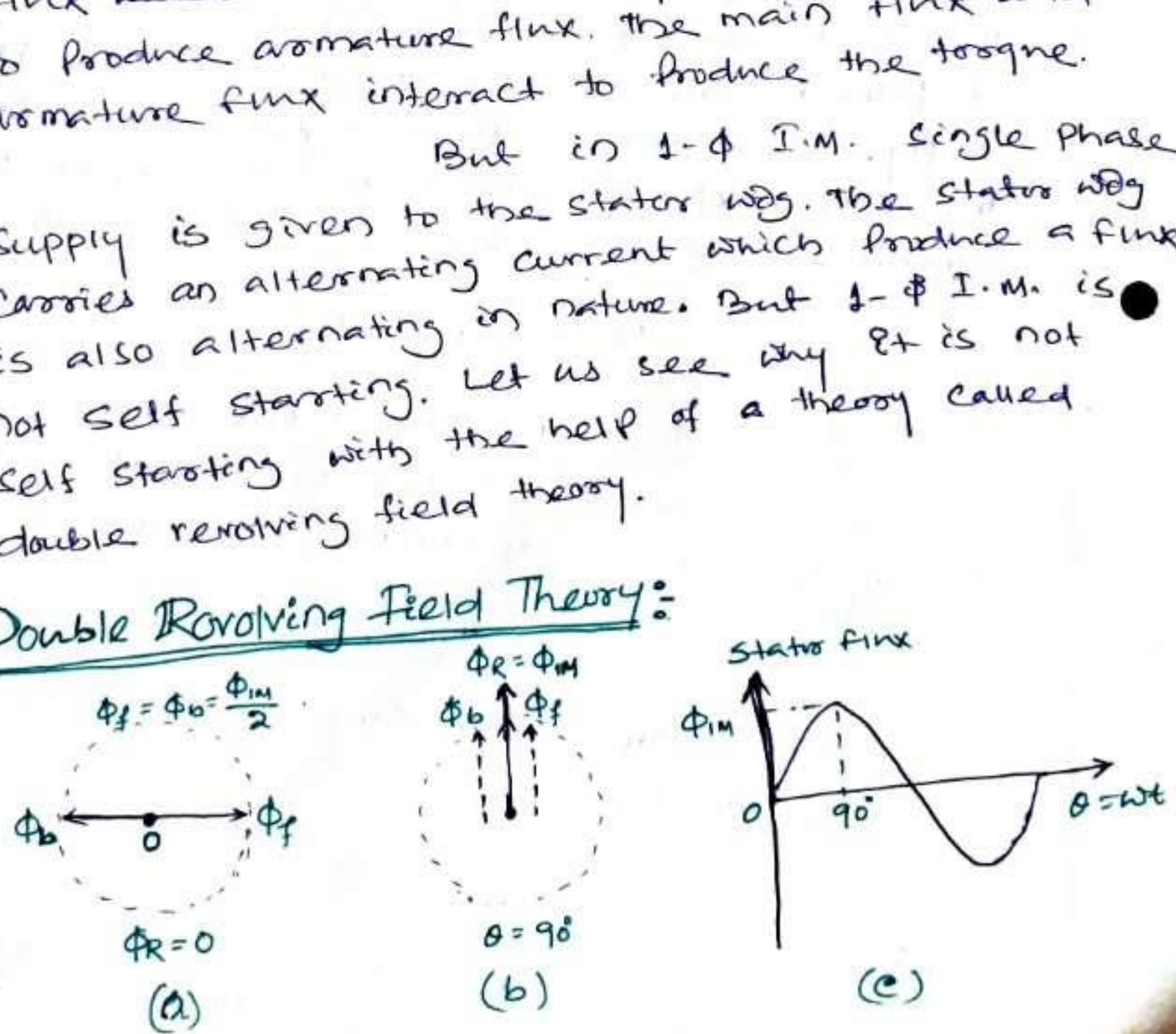


Working Principle:-

for Motoring action, there must exist two fluxes which interact with each other to produce the torque. In d.c. motor field wdg produce the main flux while d.c. supply gives to armature to produce armature flux. The main flux and armature flux interact to produce the torque.

But in 1-ϕ I.M. single phase supply is given to the stator wdg. The stator wdg carries an alternating current which produce a flux is also alternating in nature. But 1-ϕ I.M. is not self starting. Let us see why it is not self starting with the help of a theory called double revolving field theory.

Double Rovolving Field Theory:-



"According to this theory, any alternating quantity can be resolved in to two rotating component which rotate in opposite direction and each having magnitude as half of the max. magnitude of the alternating quantity."

In case of 1-ϕ I.M. the stator wdg produces an alternating magnetic field having max. magnitude of ϕ_{1M}. So according to double revolving field theory, consider two component having magnitude $\phi_{1M}/2$, rotating in opposite direction at a synchronous speed 'N_s'.

Let ϕ_f → forward component rotating in anticlockwise direction.

& ϕ_b → Backward component rotating in clockwise direction.

The resultant of these two is the original stator flux.

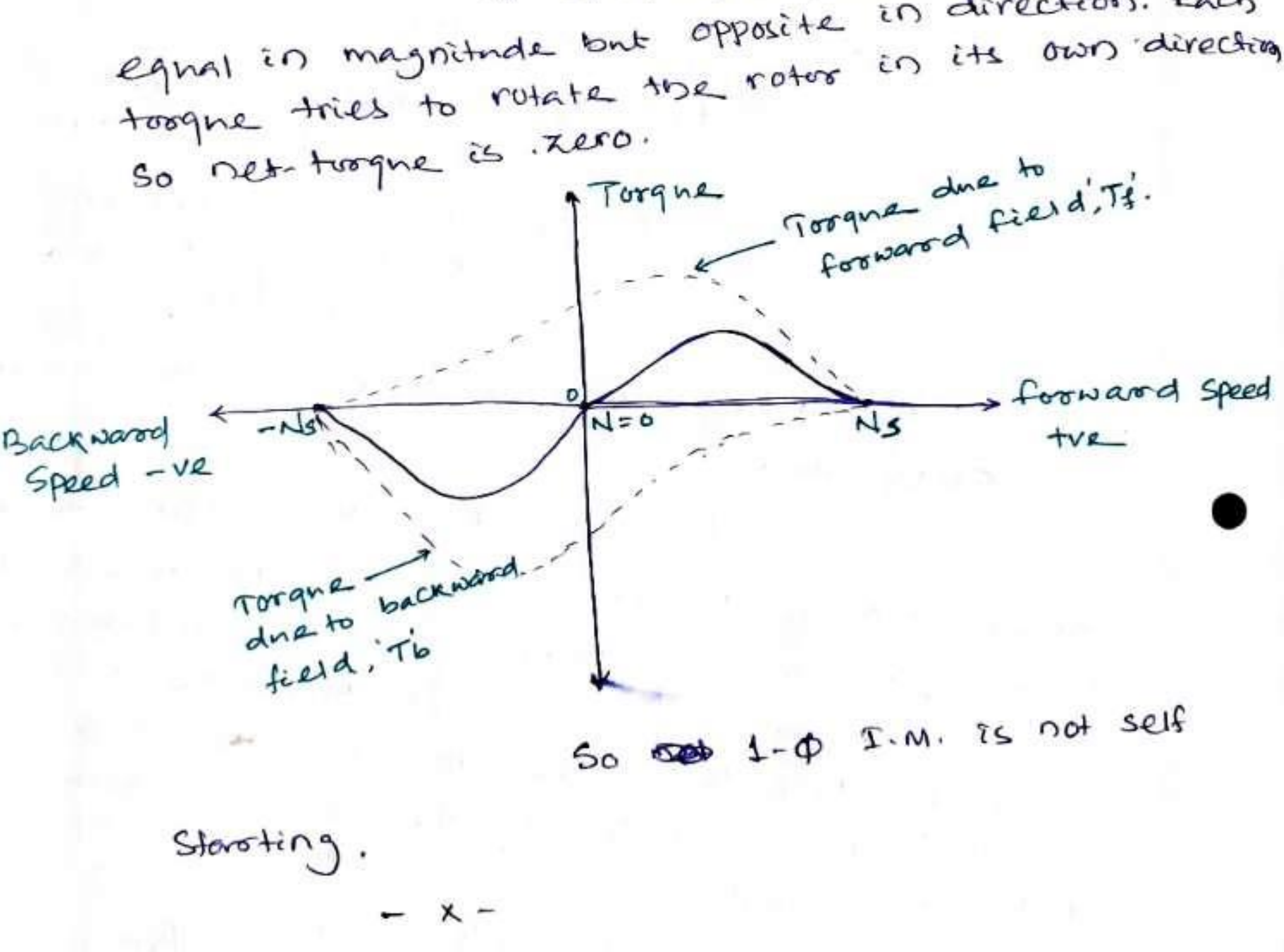
At start both the components are shown opposite to each other. Thus the resultant flux $\phi_R = 0$. This is nothing but the instantaneous value of stator flux at start. After 90° as shown in fig(b), both the fluxes pointing in same direction. Hence Resultant ϕ_R is the algebric sum of the magnitude of two component.

$$\text{So} \quad \phi_R = \left(\frac{\phi_{1M}}{2} + \frac{\phi_{1M}}{2}\right) = \phi_{1M}.$$

This is nothing but the instantaneous value of stator flux at $\theta = 90°$. Thus continious rotation of two component gives the original alternating stator flux.

Both the components are rotating and hence cut by the rotor conductors. Due to this emf gets induced in rotor which circulates rotor current. The rotor current produces a rotor flux. This flux interacts with forward component ϕ_f to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component ϕ_b to produce a torque in the clockwise direction. If anticlockwise torque is +ve then clockwise torque is negative.

At start these two torque are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. So net torque is zero.



So 1-ϕ I.M. is not self starting.

– x –

Types of 1-ϕ I.M.

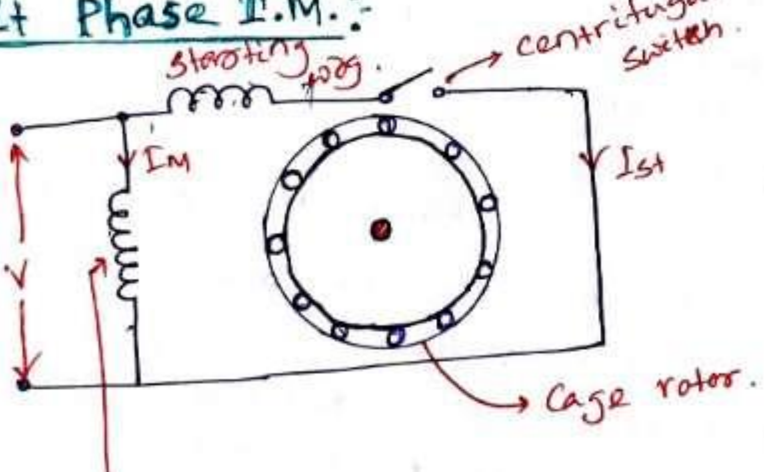
In practice some arrangment is Provided in the single-Phase I.M. so that the stator flux produced becomes rotating type rather than alternating type, which rotates in one perticular direction only. Thus depending upon the methods of producing rotating stator magnetic flux, the single phase i.m. are Classified as

i> Split Phase I.M.

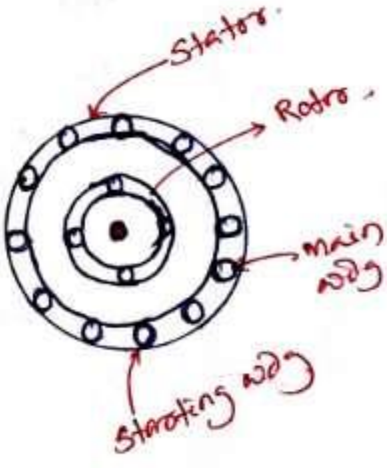
ii> Capacitor Start Capacitor Run I.M.

iii> Shaded Pole I.M.

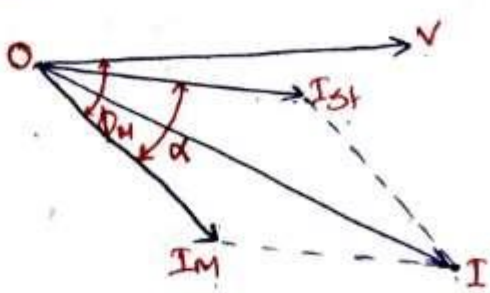
i> Split Phase I.M.:-



(Ckt diagram)



(Representation)



(Phasor Diagram)

This type of motor has 1-ϕ stator wdg called main winding, in addition to this stator carries one more winding called auxilary wdg or starting wdg. The auxilary winding carries a series resistor such that its impedance is highly resistive in nature. But the main winding is inductive in nature.

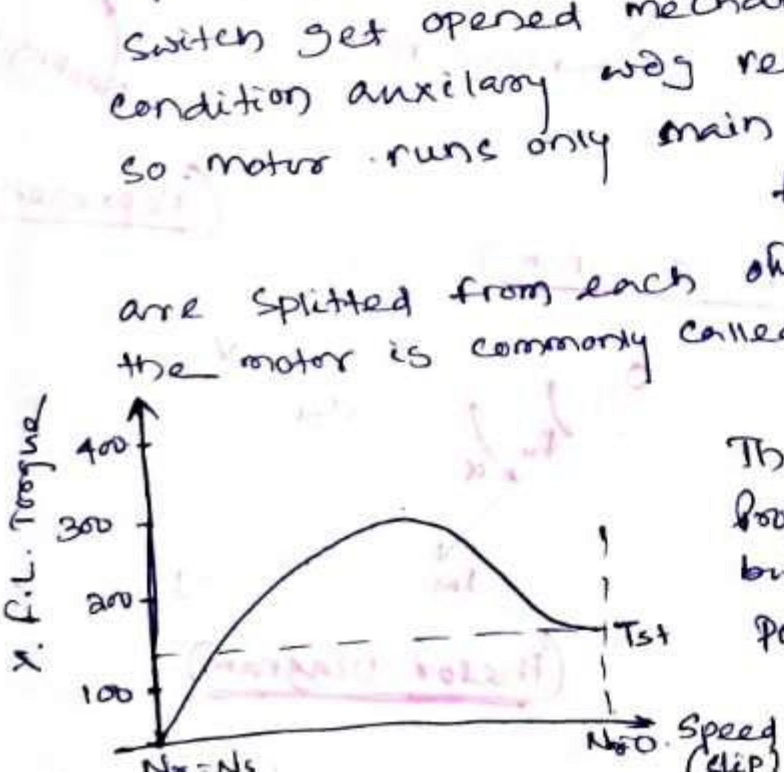
Let I_m = Current through main wdg

I_{st} = current through auxilary wdg.

As main wdg is inductive, current 'I_m' lags voltage 'V' by a large angle 'ϕ_m' while I_{st} is almost in phase in 'V' as it is highly resistive. Thus there exist a phase difference of 'α' betn the two current and hence the two flux. Due to this, starting torque, which acts only in one direction is produced.

When motor gathers a speed up to 75 to 80% of synchronous speed, centrifugal switch get opened mechanically and in running condition auxilary wdg remains out of the ckt. so motor runs only main wdg.

As the current I_m and I_{st} are splitted from each other by angle 'α' at start, the motor is commonly called split phase motor.



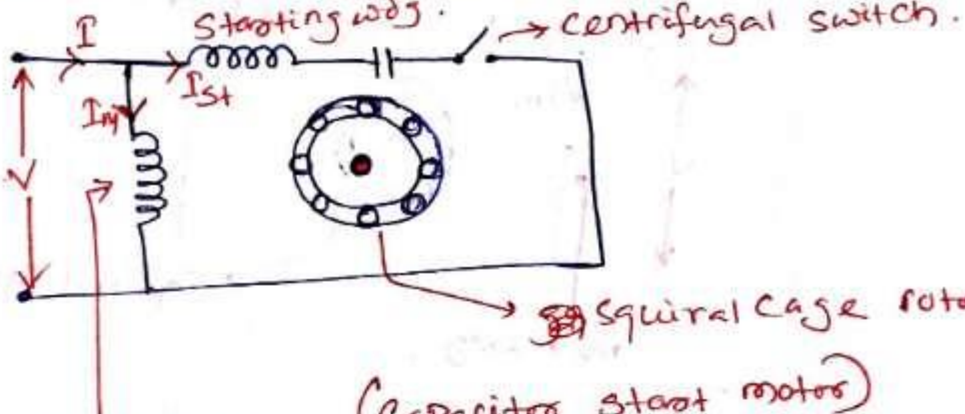
The starting torque Tst is proportional to the split angle 'α' but split phase motor has poor starting torque.

The direction of rotation can be reversed by reversing the terminals of either main or auxilary wdg.

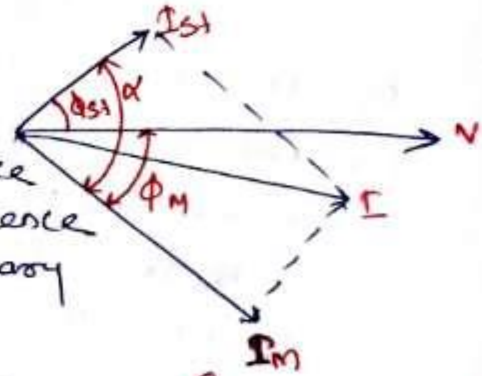
Application:-

As it has low starting torque, so these are used for low load like fans, blowers, grinder, centrifugal pump, whashing machine, office equipment. These are available in the range of 1/20 to 1/2 kw

Capacitor Start Capacitor Run Induction Motor:-



(Capacitor start motor)



(Phasor digram)

The construction of this type motor is similar to the resistance split phase type. The only difference is that in series with auxilary wdg the capacitor is connected.

Depending upon the capacitor in ckt permanently or is disconnected from the ckt using centrifugal switch, these motors are classified as

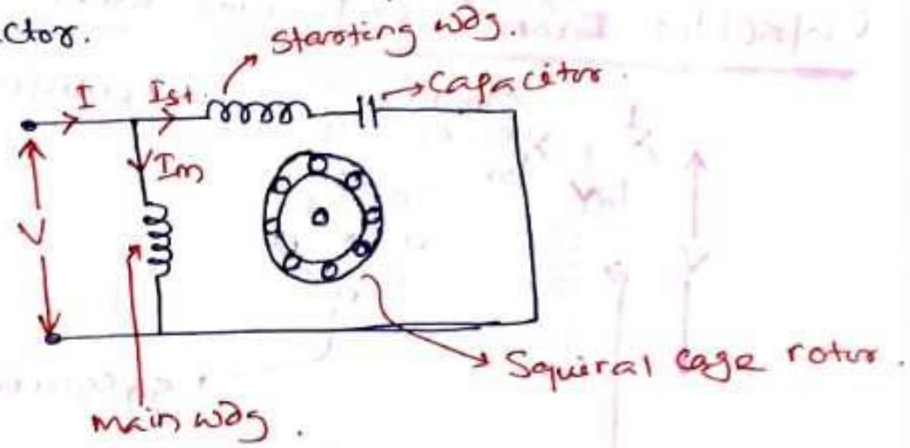
i) Capacitor start motor

ii) capacitor start capacitor run motor.

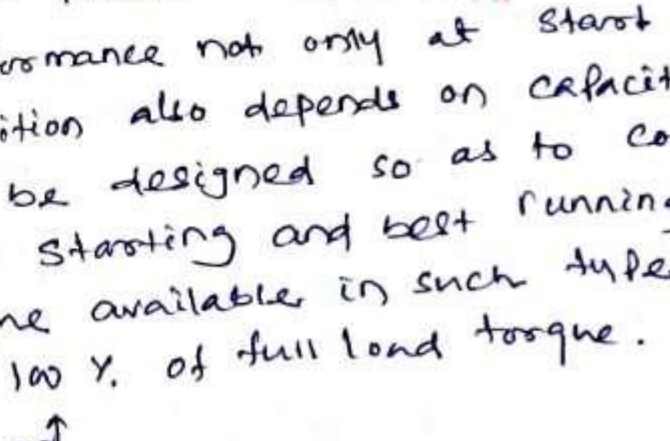
In Capacitor Start motor, the capacitive ckt draws a leading current, this feature used in this type of motor to increase the split phase angle 'α' betn two current Im an Ist. The starting torgue is proporti to 'α' and hence such motor poodnce very high starting torgne.

When speed approaches to 75 to 80% of synchronous speed, the starting wdg get disconnected due to oparation of centrifugal switch.

But in case of capacitor start. Capacitor run motor, there is no centrifugal switch and capacitor remain parmanently in the ckt. This improves the powerfactor.



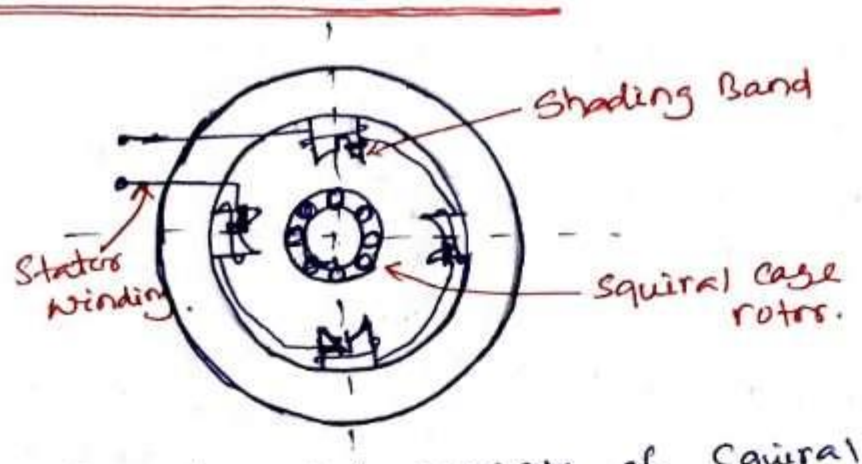
The phasor diagram is same as before. The performance not only at start but in running condition also depends on capacitor 'c' hence its value is to be designed so as to compromise bet^n best starting and best running cond^n. best starting available in such type of motor. so starting torgue is about 50 to 100 % of full load torque.

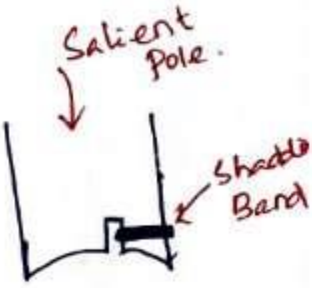


Application:-

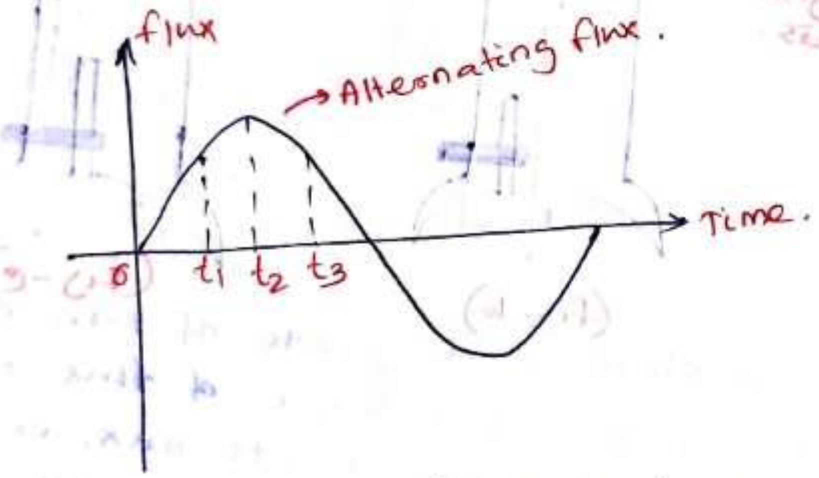
As these motor have high starting torgue hence used in compressors, conveyors, grinder, fan. refrigeratros, air conditioner etc.

Shaded Pole Induction Motor.





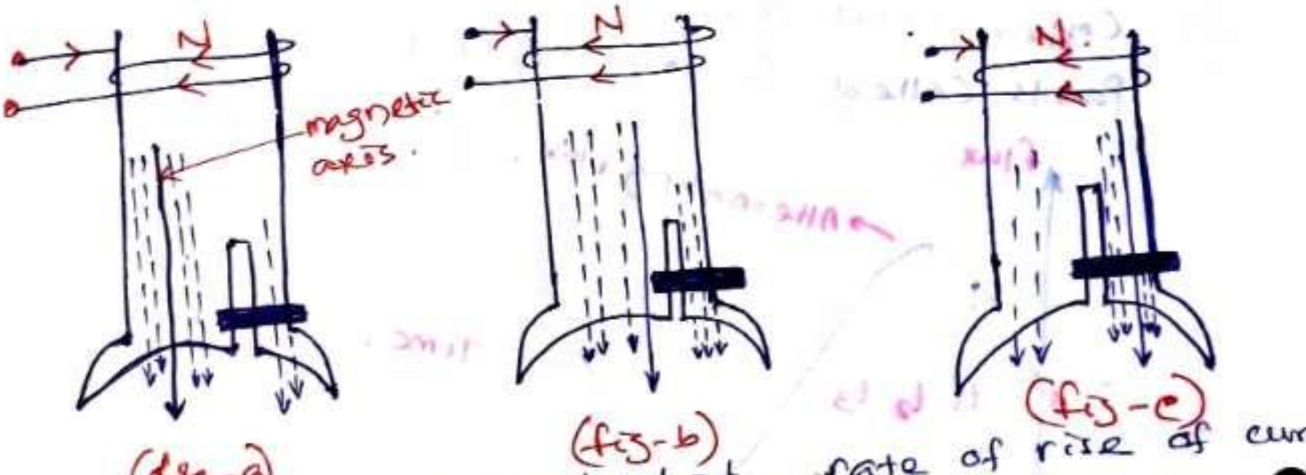
This type of motor consists of Squiral cage rotor and Stator consists of Salient Pole i.e. Projected Poles. The Poles are Shaded i.e. each Pole Carries a Copper band one one of its unequally devided parts called Sadding band.



When 1-ϕ a.c. Supply is given to the Stator wdg, due to shadding Provided to the Poles a rotating magnetic field is generated.

The current Carried by the stator wdg is alternating and Produces alternating flux. The distribution of this flux in the Pole area is greatly influenced by the role of copper shadding band. Consider the three instant t_1, t_2 & t_3 during first half cycle of flux.

At instant $t = t_1$, rate of rise of current and hence the flux is very high. Due to the x^r action large emf gets induced in the copper shadding band. This producing its own flux. According to lenz's law, the direction of this current is so as to oppose the cause i.e. rise in current. Hence shadding rings flux is opposes the main flux. Hence there is crowding of flux in non shaded part while weakning of flux in shaded part. overal magnetic axis shifts in non-shaded part as shown in fig (a)



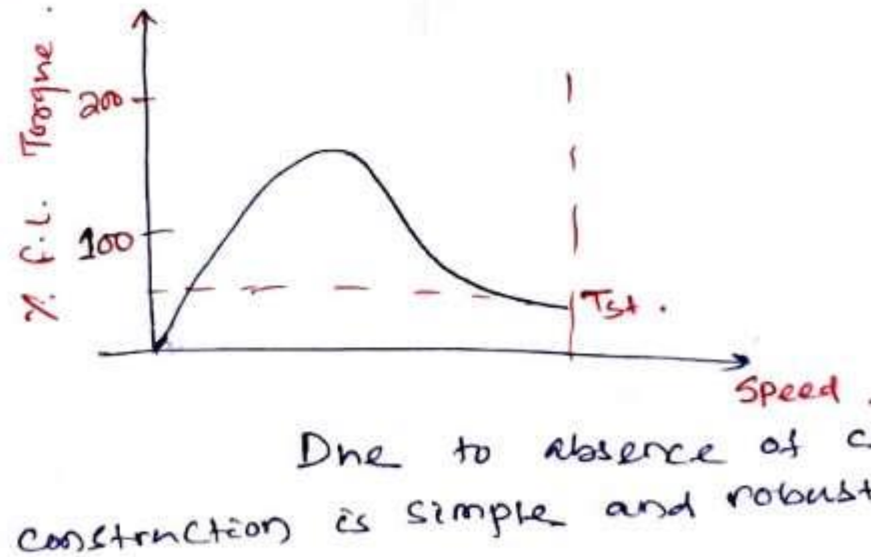
(fig-a) (fig-b) (fig-c)

At instant $t = t_2$, rate of rise of current is [illegible]
of change of flux is
and hence, the rate of change of flux its max. value. So
zero as flux almost reaches to its max. value. So
$\frac{d\phi}{dt} = 0$. Hence there is very little induced emf in
the shading ring. Hence shadding ring flux is also
negligible, hardly affecting the distribution of the
main flux. Hence the main flux distribution is
uniform and magnetic axies lies at the center
of the pole face as shown above (fig. b)

At instant $t = t_3$, the current and the flux is decreasing. The rate of decrese is high which again induces a very large

emf in the shadding ring which produces its own flux.
Now direction of the flux produced by the shaded
ring ~~which produces its own flux. shows direction of the flux produced by the shaded ring~~ oppose the cause
which is decrease the flux. So it oppose the decrease
in flux means its direction is same as that of
main flux, strengthening it. So there is crowding
of flux in the shaded part as compared to non-
shaded part. Due to this the magnetic axis shifts
to the middle of the shaded part of the pole.
This is shown in fig-(C).

This sequence keeps on repeating for negative half cycle too. Consequently this produces an effect of rotating magnetic field. Due to this motor produces the starting torque. The starting torque is low which is about 40 to 50% of f.l. torque



Due to absence of centrifugal switch the construction is simple and robust, but there is some limitation.

1. Low power factor.
2. Due to I^2R, copper loss in shadding righ is high
3. Speed reversal is very difficult. To achive this the additional set of shadding ring is required.

iv) The size and power rating of these motor is very small. These motor are usually in range of 1/300 to 1/20 KW.

Application :-

Small fans, toy motors, advertising displays, film projector, record players, gramophones, hair dries, photo copying machine etc.

* For Permanent Capacitor Motor → Paper Capacitor

* for Capacitor Start, Capacitor run motor → Start - Electrolytic Capacitor.
Run - Paper Capacitor

Commutator Motor.

Single Phase Series Motor
or
Universal Motor.

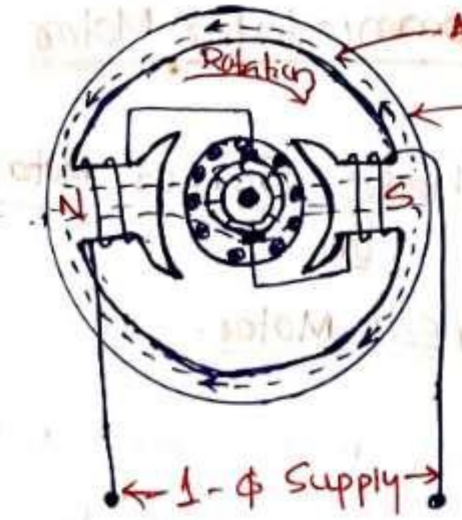
A d.c. series motor will rotate in the same direction regardless of the polarity of the supply. A d.c. series motor also operate on A.C. supply, then it is called A.C. series motor. But some changes will be required. These are.

i) The entire magnetic ckt is laminated in order to reduce the eddy current loss. Hence A.C. series motor are more expensive.

ii) The series field wdg uses as few turns as possible to reduce the reactance of the field wdg. This reduces the voltage drop across field.

iii) A high field flux is obtained by using a low reluctance magnetic ckt.

iv) To reduce the sparking at commutator a high resistance leads are connected to the commutator segment.



Construction:-

The Construction of A.C. Series motor is very much simillar to d.c. series motor except the above changes. Such motor can operate both A.C. & d.c. and resulting torque-speed characteristics about the same. Hence such motor is also Called universal motor.

Operation:-

When motor is connected to A.C. supply, The same alternating current flow through field & Armature wdg. The field wdg produces an alternating flux that reacts with the current flowing in the armature to produce a torque. It may be noted that no rotating flux is produced in this type of machine. The principle of operation is same as d.c. series motor.

Characteristics:-

i) The Speed increases to a high value with a decrease in load.

ii) It has high starting torque.

iii) At full load, P.f. is about 90%.

Application:- i) high speed vacume cleaner ii) sewing mach iii) electric shavers iv) drills v) m/c tools etc

Repulsion Motor:-

Repulsion motor are 1-ϕ Commutator motor, and are following three types.

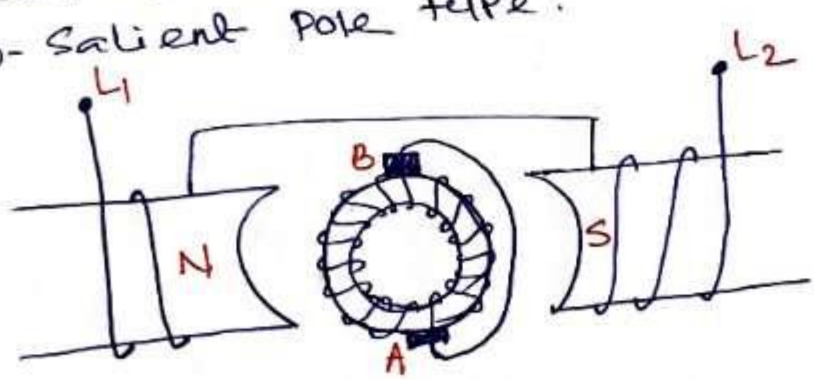
i) Plain repulsion motor.

ii) Repulsion start Induction motor.

iii) Repulsion Induction motor.

i) Plain Repulsion motor:-

A repulsion motor is simillar to A.C. Series motor except that, the brushes are not connected to supply but are short circuited. and the field structure are non-salient pole type.



Construction:- The field of stator wdg is wound like the main wdg of a split-phase motor. and is connected directly to 1-ϕ supply. The short-circuited brushes effectively makes rotor in to a type of squiral cage.

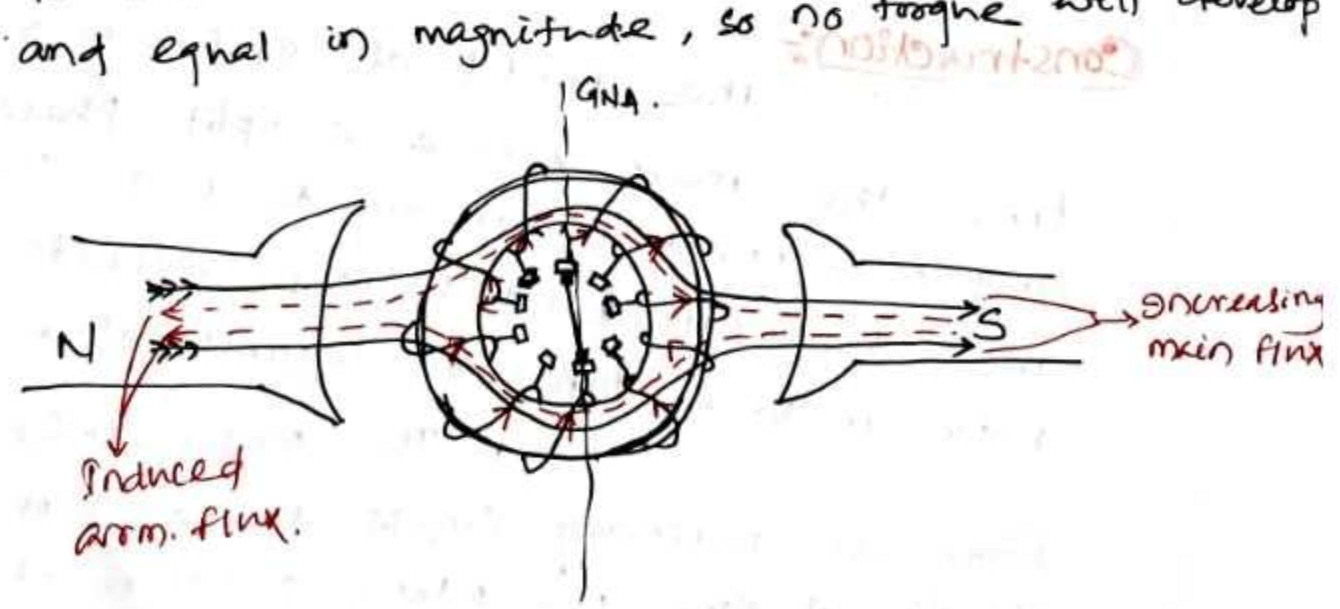
The major difficulties with an ordinary single-phase I.M. is low starting torque. By using a commutator motor with brushes short ckted, it is possible to vary the starting torque by changing the brush axis.

Principle of operation:-

fig. shows the schematic diagram of Repulsion motor.

Now consider two pole repulsion motor with brushes placed at right angle to the main field pole (i.e. Stator)

When a 1-φ a.c. is fed to Stator wdg, an alternating field will be produced. Let at this particular moment, the alternating ct. is passing through its +ve half & increasing in magnitude. So it will set up a magnetic flux of increasing nature which acts from north to South. This increasing flux will produce an emf in the armature wdg & set up a flux in opposite direction to Stator flux, according to Lenz's law. As both the fluxes are opposite to each other and equal in magnitude, so no torque will develop



If now the brushes are placed midway betn the field poles. which is made for the same moment of time as in the previous case, a clockwise Ct. will flow through the brushes in the upper half of armature wdg and anti-clockwise in lower half of the wdg. This current will produce equal & opposite torque, so rotor will not rotate.

Now suppose, the brushes are placed at a perticular angle 'α' to the field axies. At this position the main field flux & armature induced flux is in same direction. so net torque will be in one direction & motor will rotate.

Since the rotor of this motor possesses high resistance due to a.c. armature wdg, its starting current is low. However it has high starting torque & therefore started on load. Therefore it is used in lifts, cranes etc.

- x -

ii) Repulsion Start, Induction Motor :-

The construction of this motor is similar to an ordinary repulsion motor but an arrangement is provided in its rotor so that, the commutator segments are short circuited after the motor speeds up. For this purpose a spring type centrifugal device is fitted inside the commutator segments

When ac 1-ϕ supply is fed to the stator wdg, the motor starts as a plain repulsion motor, giving high starting torque. When the speed reaches a pre-determin value, the spring of the centrifugal device expands, & short ckted all commutator segment and the motor operates as a ordinary induction motor. Hence the motor named so.

This motor used at such places, where it required to have high starting torque & constant speed as in lathes, sawmills, water pumps etc.

(iii) Repulsion Induction Motor :-

The Stator of the Repulsion induction motor has only one winding but the rotor has two distinct wdg such as commutator wdg, Similiar to d.c. armature & a low resistance & high reactance squiral cage winding. The two winding are housed in separate slots as in the case of double squiral cage I.M. The armature wdg is done in upper slots and its connection are braught to the commutator segments. The squiral cage wdg is made of copper bars and is placed deep in slots which are short circuited by copper rings.

At the time of starting, the squiral cage wdg will be practically uneffective due to high frequency of the induced ct. & hence have high reactance. Therefore motor starts as a repulsion motor giving high starting torque. As the motor speeds up, the current lowers down & frequency of the rotor reactance of squiral cage thus reducing the squiral cage wdg becomes effective & now the squiral cage wdg in producing torque.

This motor is also a constant speed motor, having high starting torque. Thus it is suitable for machine tools, pumps, blowers, mixing machines etc.

Special Electrical Machine.

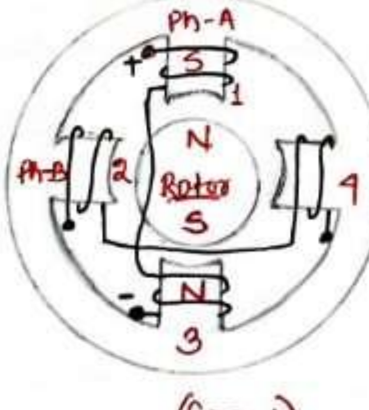
Principle:-

Stepper motor are also known as Stepping motor or step motor. A stepper motor is an electromagnetic motor, that rotates by a specific number of degree in response to an input electrical signal. Typical step size are 2°, 2.5°, 7.5° & 15° for each electrical pulse. Note that there is no continuous energy conversion, so that rotor does not rotate continiously.

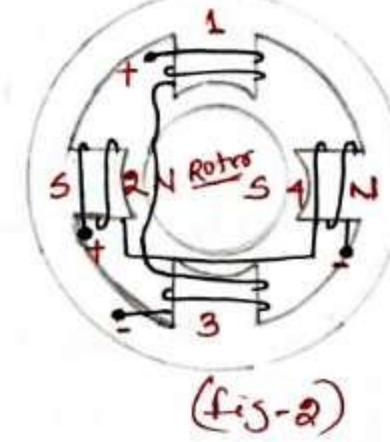
Stepper motor are ~~two~~ three types

i) Permanate-magnet (PM) Stepper motor
ii) Variable-Reluctance (VR) Stepper motor
iii) Hybrid Stepper motor.

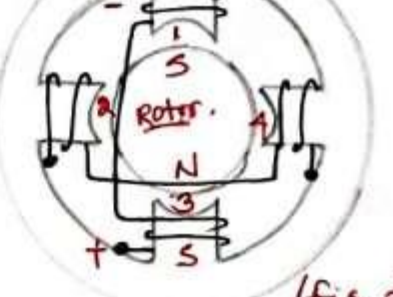
i) Permanate-Magnet Stepper motor:-



(fig-1)



(fig-2)



(fig-3)

Construction :-

The Stator of a PM stepper motor is composed of steel lamination and carries stator wdg. The stator winding is energised from a d.c source to create two or more stator pole. The rotor of the motor is a Permanent magnet, made of high-retentivity steel alloy. The rotor has even no. of pole.

Operation :-

For this stepper motor as shown in fig. no. of rotor poles $N_r = 2$, & no. of phases $m = 2$.

$$\therefore \text{Step angle}, \alpha = \frac{360^\circ}{m N_r} = \frac{360^\circ}{2 \times 2} = 90^\circ / \text{step}.$$

→ When only Phase-A winding is excited by a constant ct. (fig-i), stator tooth '1' become South pole & tooth-3 become North Pole. This makes the north pole & South pole of roto. align with Stator as shown in fig-(i). The rotor will remain locked in this Position as long as Phase-A is energised.

→ If Phase-A is de-energised, & Phase-B is energised as shown in fig-(ii), stator tooth become South Pole. As a result, north Pole of rotor align with South Pole of ~~Rotor~~ Stator. Thus the rotor is displaced 90° in the anticlockwise direction.

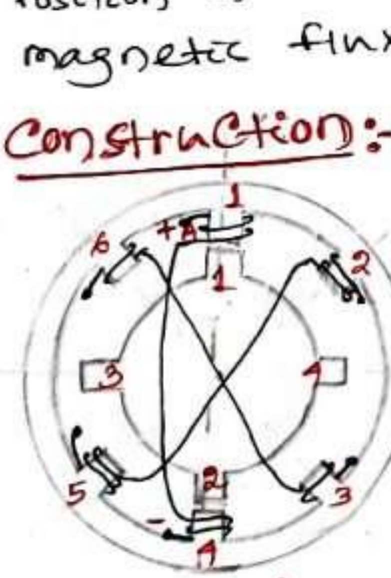
→ If Phase-B is de-energised & Phase-A is excited with reverse current as shown in fig-(iii) i.e. opposite to case-1. the rotor will further rotate 90° in anticlockwise direction. Now the north pole of PM motor align with the stator tooth 3.

This is the way in which P.M. stepper motor rotate.

ii) Variable Reluctance (VR) Stepper motor:-

The VR Stepper motor operate on the same principle as the reluctance motor that is, when a piece of feromagnetic material free to rotate, is placed in a magnetic field, torque acts on the material to bring it to the position of minimum reluctance to the path of magnetic flux.

Construction:-



(fig-(i))

fig-(ii)

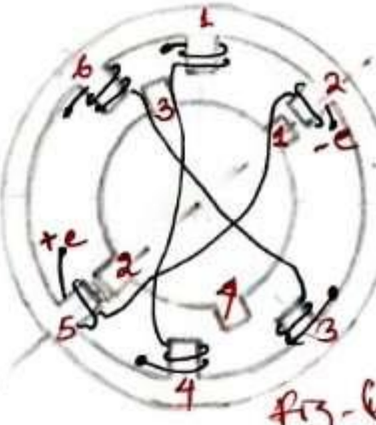


fig-(iii)

The stator construction of a VR stepper motor is the same as that of a PM stepper motor. The rotor is made of soft steel with teeth & slots. For this VR stepper motor as shown in fig.

$$\text{Step angle}, \alpha = \frac{N_s - N_r}{N_s N_r} \times 360^\circ$$

$$= \frac{6-4}{6 \times 4} \times 360^\circ = 30^\circ/\text{step}.$$

Operation :-

When the phase wdg is energised, the rotor teeth will align with the energised stator poles.

→ fig-(i) shows the position of the rotor when Phase-A is energised with a constant current. As long as Phase-A is energised, the rotor will be held stationary. Note that in this condition, the rotor teeth 1 & 2 are aligned with the energised stator teeth 1 & 4. The step angle $\alpha = 0^\circ$

→ When phase A is switched off & Phase-B is energised, the rotor will turn 30° clockwise so that the rotor teeth 3 & 4 allign with the energised stator teeth 6 & 3. as shown in fig(2)

→ The effect of de-energising phase 'B' and energising phase 'C' as shown in fig-(3). In this circuit, the rotor has further moved 30° clockwise, so that the rotor teeth 1 & 2 align with energised stator teeth 2 & 5

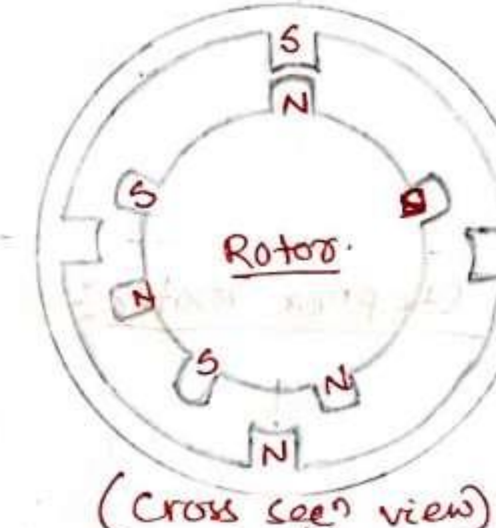
→ After the rotor has displaced 60° from its starting point, the step sequence completed one cycle.

The direction of rotation will be reversed if the switching sequence is in the order of. A, C & B.

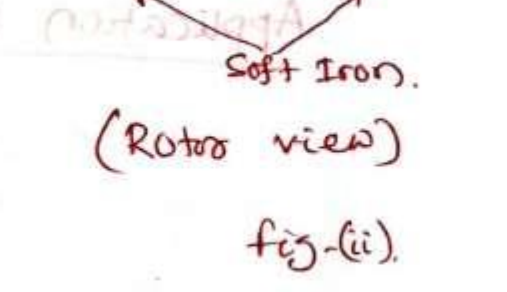
iii) Hybrid Stepper Motor :-

As the name, hybrid mean mixed. i.e. It combines the feature of the PM & VR stepper motor. The torque developed by this motor is greater then that of PM & VR type.

Construction :-



(Cross seen view)
fig.(i)



(Rotor view)
fig.(ii).

fig. Shows the basic construction of hybrid stepper motor. the stator construction is Similar to that of a VR & PM motor. the rotor of the hybrid stepper motor consists of two identical stacks of soft iron as well as Permanate magnet as shown in fig.(ii).

Operation:-

The operating mode of the hybrid stepper motor is very similar to that of a PM or VR stepper motor. The phase windings are energized in proper sequence & the rotor rotates in step.

The step angle, $\alpha = \frac{90^\circ}{N_r}$ in degree.

It may be noted that a hybrid stepper motor operates under the combined principle of the permanent magnet & variable reluctance stepper motor. Therefore the hybrid stepper motor develops both excitation torque & reluctance torque. Consequently, the resultant torque develops by the hybrid stepper motor is greater than that of the PM & VR stepper motor.

Application of Stepper motor:-

The stepper motor is used where step angle is required. like.

i) moving the arm of robot.

ii) paper mill

iii) Rolling mill

iv) packing industry.

v) Clock. etc.

vii) **Bushing:-**

Porcelain bushings are cleaned & examined for cracks and chips. very slight chips may be ignored but any serious damage will require replacement.

The others maintenance Proced are viii) oil sampling.

ix) oil testing.

x) oil treatment.

xi) Paint work.

xii) Internal inspection.

xiii) opening of x^r.

xiv) Removal of cover.

xv) cores & coil.

xvi) Inspection.

xvii) Retanking.