Lecturer Notes

on

Energy Conversion-II

5th Semester

Submitted By:

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HOD

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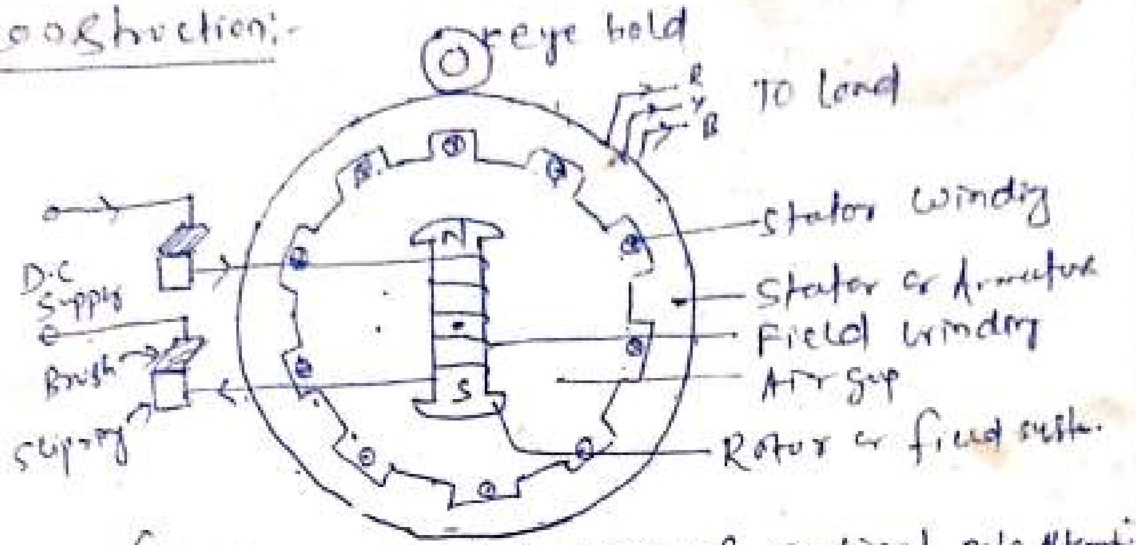
Module I

Synchronous machines:-

3-ϕ Alternators:- The electrical device which generates alternating current is known as alternator or A.C generator.

Construction:-



Cross sectional view of Salient pole Alternator

The m/c is consists of stator and rotor with an air gap in between.

Stator:- It is the stationary part of the m/c. It is also called armature. Its shape is cylindrical. The stator core is made of sillicon steel laminations in order to reduce eddy current loss. It is slotted at the inner periphary to house the conductor. The stator carries 3-ϕ winding which is always star connected.

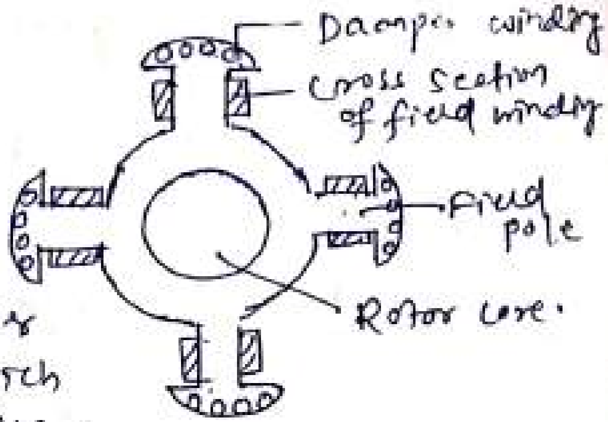
Rotor:- It is the rotating part of the m/c. It is also called field system. There are two types of rotors.

(i) Salient pole type.
(ii) Smooth cylindrical type.

According to the type of rotor the name comes for the alternator.

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

① Salient pole type:-

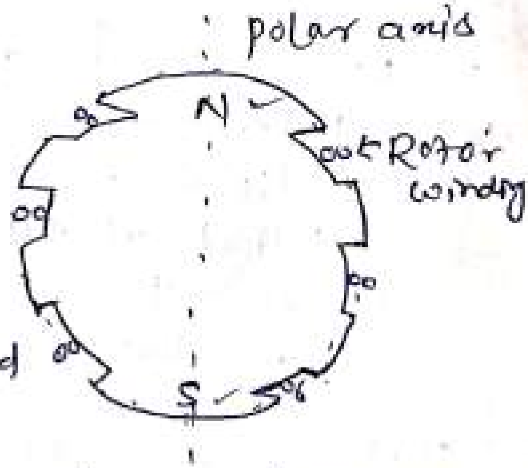


The term salient pole means projected pole. This type of rotor used in Low and medium speed alternators. The primemover used is water turbine which gives speed 50 to 500 rpm. In order to get frequency 50HZ, the no. of pole is 12 to 120. Due to low speed such m/c are characterised by large diameter and small length.

The damper winding is provided in pole shoe to reduce the oscillation and to increase stability. Since each slot carries one conductor this winding is also called squirrel cage winding. The damper bars are nothing but heavy copper rods.

Since water turbine is used as primemover this type m/c is also called hydroelectric generator.

② cylindrical pole type:-



This type of rotor is used for large alternators. The rotor structure is cylindrical. From the entire periphery $\frac{2}{3}$ rd portion is slotted and rest $\frac{1}{3}$ rd portion is left for poles.

The primemover used is steam turbine which gives high speed 3000 rpm. In order to get frequency 50HZ, the no. of poles is always 2. Due to high speed, such m/c are characterised by small diameter and large length.

As steam turbine is used as primemover, This type of m/c is also called turbo alternator.

Working principle:-

When D.C. supply is given to the rotor winding of an alternator, it produces north pole and south poles. The rotor produces a steady flux in the air gap. The rotor is rotated by a prime mover at a particular speed. When the rotor rotates the stator conductors are cut by the magnetic flux. Hence an emf is induced in the armature conductors by the Faraday's laws of electro-magnetic induction. The emf induced in the armature conductor is alternating in nature since the conductor alternatively see north and south poles. The frequency of the emf induced depends on the number of poles and the speed at which the m/c is driven.

Advantages of stationary armature and rotating field:-

1. Since armature is stationary, the load ckt can be directly connected to it without slip rings and brushes.
2. As the armature is stationary, it is easy to provide winding insulation for high voltage.
3. Since weight of rotor is less as compair to stator high speed can be achieved.
4. The rotor of an alternator requires an exciter for which voltage rating is less and hence that needs less insulation.
5. Only two slip rings and two brushes are required to give d.c. supply to the field system.

EMF Equation:-

Let Z = No. of conductr/ph, T = No. of turns/ph.
P = No. of poles. N = Speed in rpm
f = Frequency K_p = pitch factr
ϕ = Flux per pole K_d = Distribution factr.

According to Faraday's law of electromagnetic induction, the average emf induced in a conductor is the rate of change of flux linkages

Consider one revolution of rotor

$N - 1\,min$
$1 - \frac{1}{N}\,min$
$= \frac{60}{N}\,sec$

i.e. in $\frac{60}{N}$ sec each stator conductr cuts flux $P\phi$ wb

Average emf induced/conductr/phase $= \frac{d\phi}{dt} = \frac{P\phi}{\left(\frac{60}{N}\right)}$

$$= \frac{P\phi N}{60} = \frac{P\phi}{60} \times \frac{120f}{P} = 2f\phi$$

~~Average~~ emf induced for Z conductr/phase $= 2f\phi Z$

$$= 2f\phi(2T) \quad (\because Z = 2T)$$

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

Rms value of induced emf/phase = Form factr × Average value

$$= 1.11 \times 4f\phi T = 4.44 f\phi T$$

The above equation is valid, if the winding is full pitched and concentrated. But practically it does not happen. Since the winding may be short pitched and always distributed, pitch factr and distributed factr are to be considered.

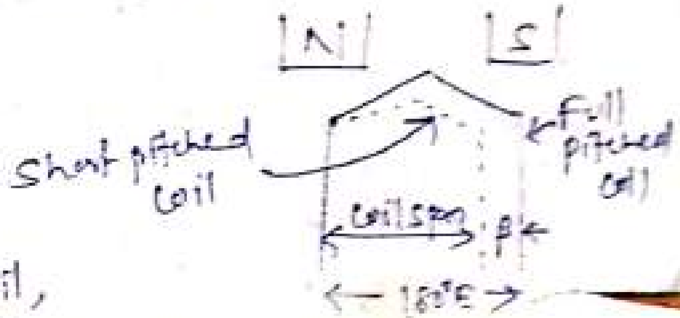
∴ Rms value of induced emf/phase

$$\boxed{E_{rms} = 4.44 f\phi T K_p K_d} \text{ volt.}$$

Pole pitch:- One pole pitch is the space corresponding to the axis of a north pole to the axis of next south pole. One pole pitch is defined as 180° Electrical.

Coil pitch or coil span

If one conductor of the coil comes under the slot below the north pole and other conductor of the same coil comes under south pole such a coil is called full pitched coil. Coil span or coil pitch of a full pitched coil is equal to 180° Electrical.



Sometimes the coil is short pitched or short chorded.

For a short pitched coil,

Coil pitch or coil span is less than 180° E.

If β is the chording angle, coil span is $(180° - \beta)$

Slots/pole (S')

$$S' = \frac{\text{No. of slots}(S)}{\text{No. of poles}(P)}$$

$$S' = \frac{S}{P}$$

Slots/pole/phase (m)

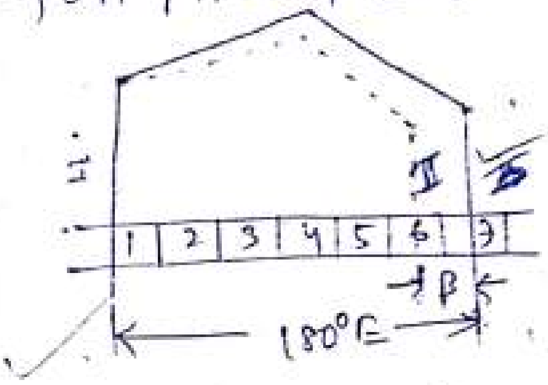
$$m = \frac{\text{slots/pole}}{\text{No. of phases}}$$

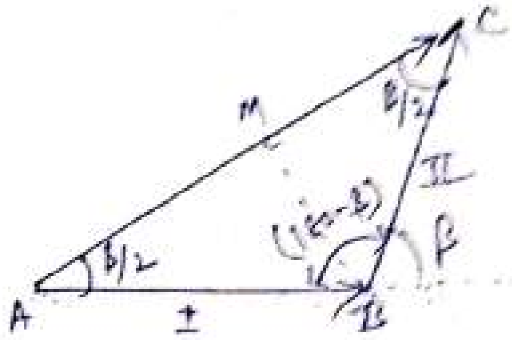
$$m = \frac{S'}{\text{phases}}, \quad m = \frac{S'}{1} \text{ for } 1\text{-}\phi \text{ M/c}$$

$$m = \frac{S'}{3} \text{ for } 3\text{-}\phi \text{ M/c}$$

Chording factor (K_c) or pitch factor (K_p)

It is defined as the ratio of induced emf in a short chorded coil to the induced emf in a full pitched coil.





In a practical alternator the coils are short pitched to reduce harmonics and to save the copper.

Let us consider a M/C with 6 slots/pole. of conductor One of the coil starts in slot number 1, the other conductor of the same coil ends in slot no. 7 since slot per pole is 6. This is true for a ~~full~~ full pitched coil.

In the case of a short pitched coil, the conductor 2 is wound through slot no. 6 or 5. This is called short chording. In the above figure short chording is done by one slot. In other ~~words~~ chording angle $\beta = 30°$, Coil span $= 180° - 30° = 150°$.

In the above vector diagram AB is the emf induced in coil side I, BC is the emf induced in the coil side II. AC is the resultant emf.

$$K_c = \frac{AC}{2AB}$$

$$K_c = \frac{2AM}{2AB} = \frac{AB\cos\beta/2}{AB} = \cos\beta/2$$

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

Slot angle:- Slot angle is defined as the ratio of 180° Electrical to no. of slots per pole.

Consider an alternator with 4 slots and two poles, $\alpha = 90°$

$$\alpha = 90° = 180°/(4/2)$$

In general $\alpha = \frac{180°E}{S'}$

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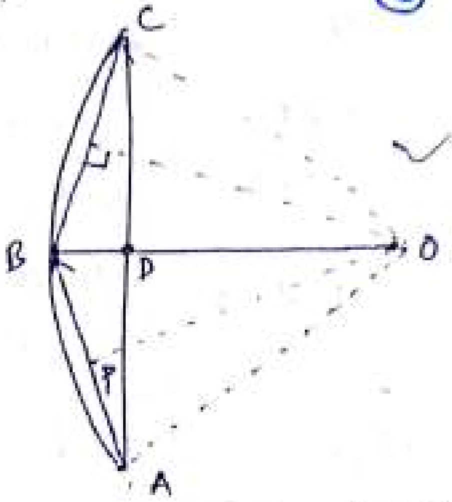
Distribution factor:- (K_d)



Coil one starts from slot no. 5 and ends at slot no. 8. Coil two starts at slot no. 6 and ends at slot no. 9. The armature has distributed winding throughout the stator. The conductors are distributed throughout the space of the stator. If all the conductors are bunched in one slot all the voltage vectors would be inphase. The total voltage would be mE if there are m no. of conductors. Practically the conductors are not bunched, they are distributed. The vectors are not inphase since their positions are different with respect to the rotor.

Distribution factor is defined as the ratio of emf induced in a distributed winding to the emf induced in a concentrated winding. In other words K_d is defined as the ratio of vector sum of voltages to the scalar sum of voltages.

Let us consider an alternator with 12 no of slots. Let the no. of poles be 2. Consider a 3-φ alternator.

$$S' = \frac{S}{P} = \frac{12}{2} = 6, \quad \alpha = \frac{180}{6} = 30° \quad (\because S' = 6)$$

$$m = \text{slots/pole/phase} = \frac{S'}{\text{phases}} = \frac{6}{3} = 2$$

Let us consider one conductor per slot. Therefore there are two conductors / pole / phase for the above M/c.

AB is the voltage in one conductor and BC is the voltage induced in the next conductor. AC is the resultant voltage.

$$K_d = \frac{AC}{2AB} = \frac{\text{vector sum}}{\text{Arithmetic sum}}$$

$$= \frac{2AD}{2\cdot 2AP} = \frac{OA\sin 30}{2OA\sin 15} = \frac{\sin 2\times(30/2)}{2\sin(30/2)}.$$

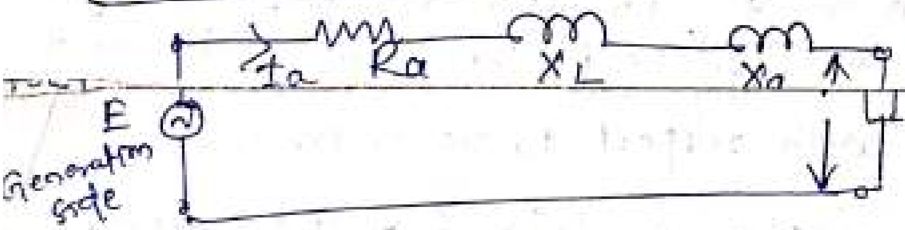
$$\boxed{K_d = \frac{\sin m\alpha/2}{m\sin\alpha/2}}$$

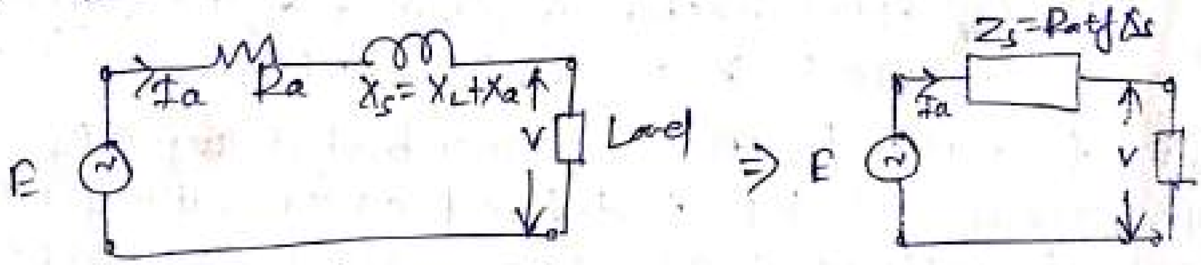
Alternator on Load:-

Factors affecting the terminal voltage:-

When the alternator is loaded, at its terminals certain voltage drop occurs due to flow of current through the winding and presence of armature resistance (R_a) armature leakage reactance (X_L) and armature reaction reactance (X_a)

Equivalent Circuit:-





Synchronous reactance:- (X_s)

The algebric sum of leakage reactance and armature reaction reactance is called synchronous reactance.

$$\boxed{X_s = X_L + X_a}\ \Omega$$

Synchronous Impedance:- (Z_s)

The vector sum of armature resistance and synchronous reactance is called synchronous Impedance

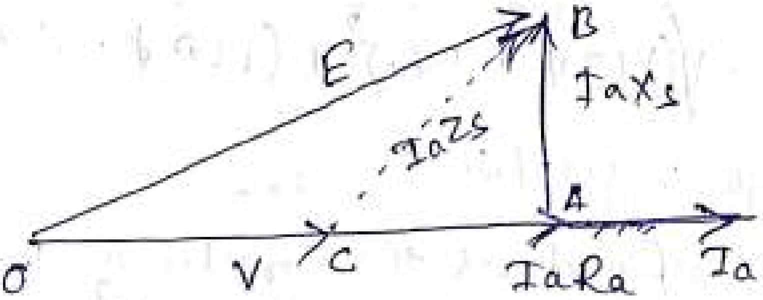
$$\boxed{Z_s = R_a + jX_s}\ \Omega$$

③ · ...tor diagram:- (Taking current as reference)

When there is no load, the terminal voltage is maximum and it's equal to no load induced emf (E_0).

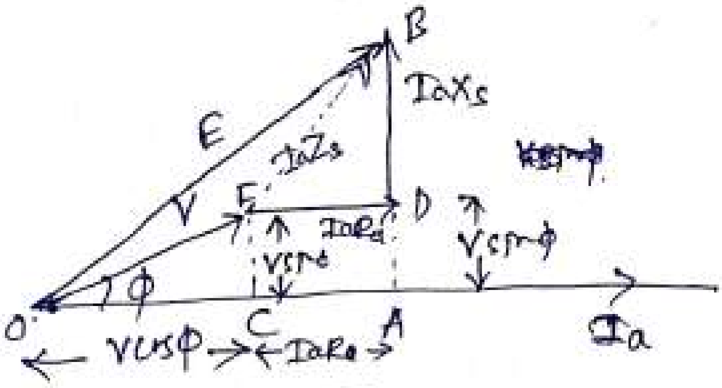
Case-I For resistive load:- (Unity p.f)

$$E = V + I_a Z_s$$
$$= V + I_a(R_a + jX_s)$$



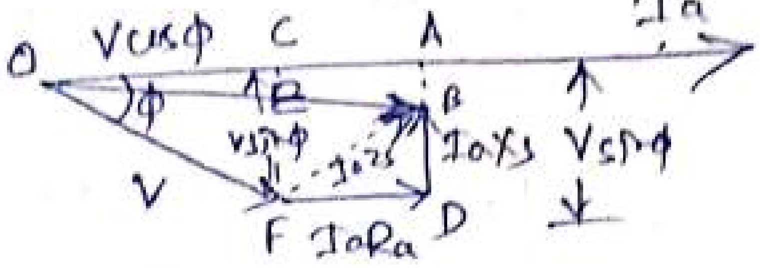
$$OB = \sqrt{OA^2 + AB^2}$$
$$= \sqrt{(OC + CA)^2 + AB^2}$$
$$E = \sqrt{(V + I_a R_a)^2 + (I_a X_s)^2} \text{ volt}$$

Case-II For inductive load:- (lag p.f)



$$OB = \sqrt{OA^2 + AB^2}$$
$$= \sqrt{(OC + CA)^2 + (AD + DB)^2}$$
$$E = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2} \text{ volt}$$

Case-III For capacitive load:- (Lead p.f)



$$OB = \sqrt{OA^2 + AB^2}$$
$$= \sqrt{(OC + CA)^2 + (AD - BD)^2}$$
$$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2} \text{ volt.}$$

Voltage regulation :-

It is defined as the ratio of the difference in terminal voltage from no load to full load to the terminal voltage on load. Always it is expressed in percentage.

∴ percentage regulation, $\boxed{\%R = \frac{E-V}{V}} \times 100$.

where E = Terminal voltage on no load

V = " " on load.

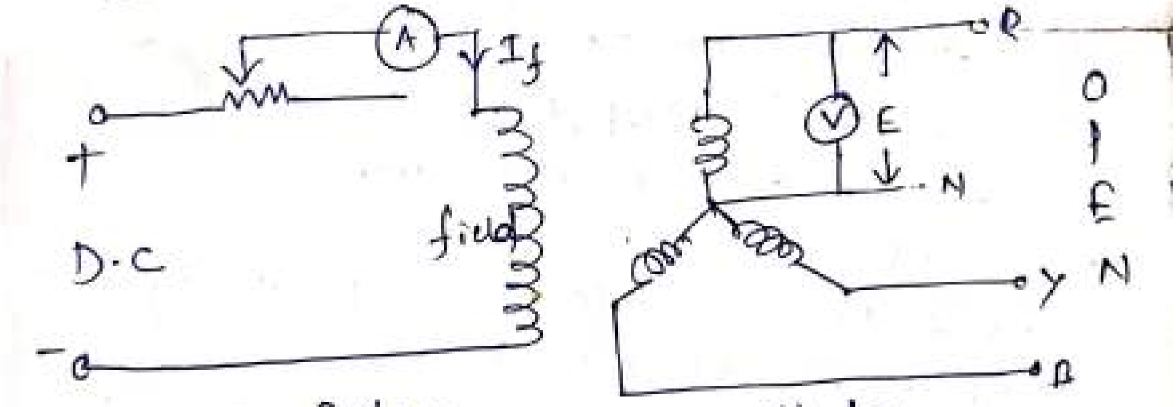
Calculation of Regulation using synchronous impedance method or EMF method:-

It is an indirect method to used to determine the voltage regulation. This method requires
① Armature resistance
② open circuit characteristics (O.C.C) and
③ short circuit characteristics (S.C.C)

① Armature resistance

Armature resistance per phase can be measured by voltmeter ammeter method or by using an ohm meter. Rac is taken as 1.6 time Rdc due to skin effect.

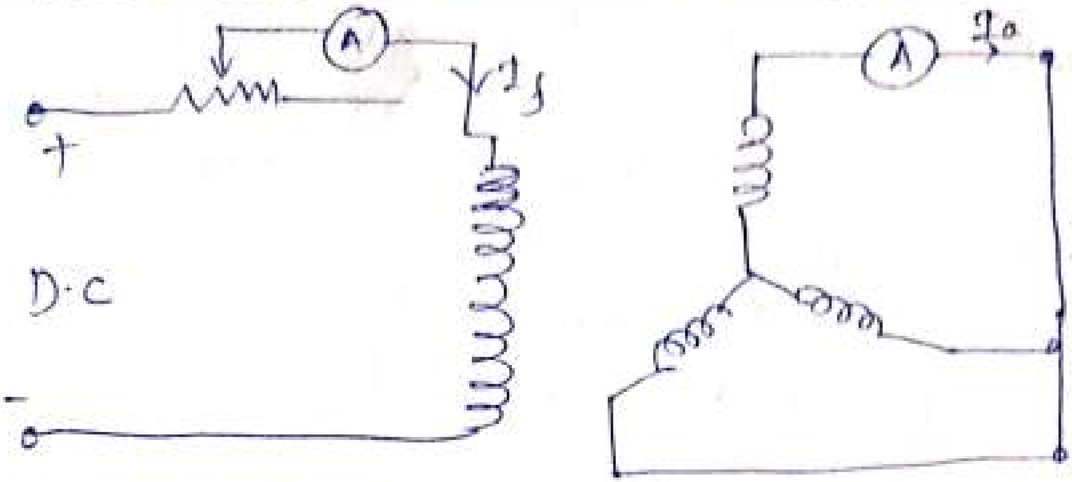
② open circuit characteristics (O.C.C):-



Rotor Stator

OCC of an alternator is a curve of open circuit voltage as a function of field current when m/c is running at synchronous speed. This curve is experimentally obtained with the armature terminals open circuited. The reading of voltmeter and ammeter are noted for various values of field currents. The graph is plotted with field current (I_f) on x-axis and open circuit voltage (E) on y-axis.

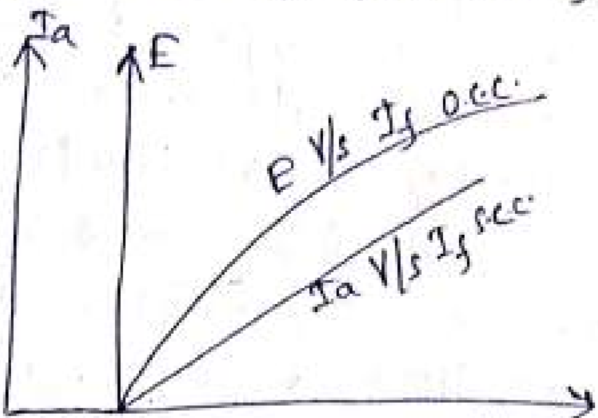
③ Short Circuit Characteristics:- (S.C.C)



In this test the armature terminals of the synchronous m/c are short circuited through an ammeter. The generator is driven at synchronous speed. The field current is initially zero and then raised slowly till the armature current reaches rated current. The readings of ammeters in field and armature circuits are noted. The graph is plotted with field current on x-axis and armature current on y-axis. On short circuit the whole emf generated is used to circulate current through the shorted armature. Therefore,

synchronous impedance = $\frac{\text{open cut voltage/ph}}{\text{Short cut current/ph}}$ for the same field curr.

~~$Z_s = \frac{E}{I_{sc}}$~~ $Z_s = \frac{E}{I_{sc}}$ | for same I_f



(Characteristic)

Armature resistance R_a can be measured by using voltmeter, ammeter method

Synchronous reactance $X_s = \sqrt{Z_s^2 - R^2}$

Terminal voltage on no load

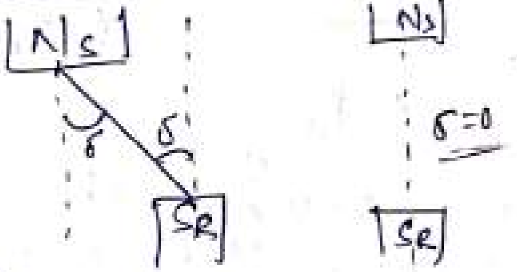
$$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi \pm I_aX_s)^2}$$

$$\% \text{ Regulation} = \frac{E - V}{V} \times 100$$

Short circuit ratio

It is defined as the ratio of field current required to produce rated voltage on open circuit to the field current required to circulate rated current on short circuit.

Power angle of an alternator (δ)



Power angle δ represents the change in relative position between the rotor and resultant pole axis. The value of δ is proportional to load power.

Armature Reaction at various p.f load

(i) at unity pf

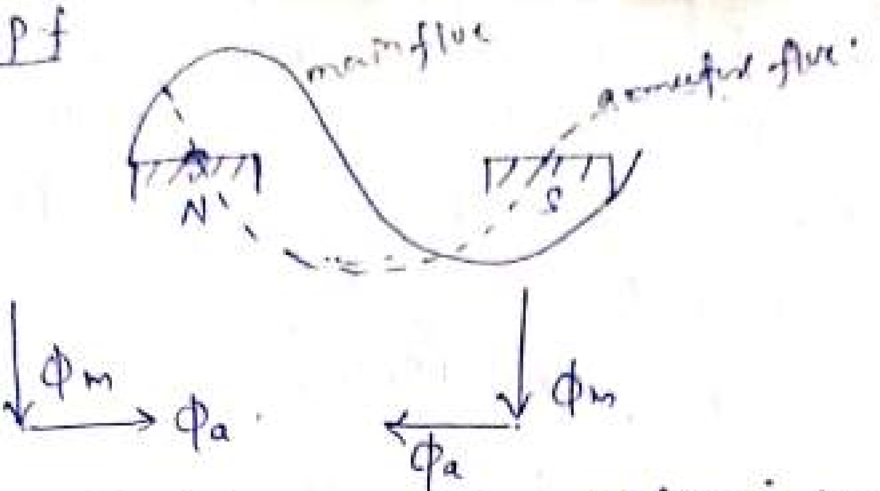
(ii) at 0 p.f (lag)

(iii) at 0 p.f (lead)

The armature flux opposes field flux which is known as armature reaction.

In case of alternator the p.f of the load has a considerable effect upon the armature reaction

(i) unity p.f

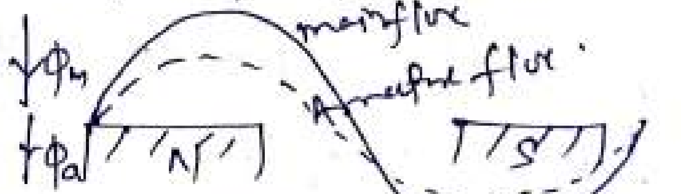


In this case the armature reaction is cross magnetising. The angle between main flux and armature flux is 90°. Due to cross magnetising effect the field pole distorted (disturbed) but terminal voltage of alternator does not change.

(ii) zero p.f (lag)

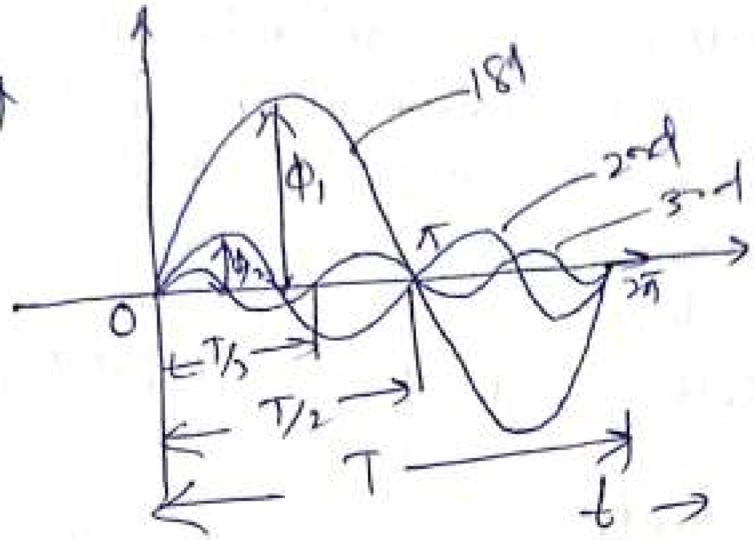
In this case the armature reaction is demagnetising. The armature flux whose wave form has moved backward by 90° is in direct opposition to the main flux. The field is Demagnetised and main flux reduced as induced emf decrease terminal voltage of alternator decreases.

(iii) zero p.f (lead)



In this case the armature reaction is magnetising. The armature flux whose wave form has moved forward by 90° is in phase with the main flux wave form. This results added flux. Since induced emf increases the terminal voltage of alternator increases.

Effect of harmonics and its elimination



The harmonics are produced due to variation in flux. The harmonic can be considered up to nth order. As the order of harmonics increases, magnitude of flux and time period are decreased proportionately but frequency value increases accordingly.

(i) **Flux** $\phi_1 = \phi$, $\phi_3 = \frac{\phi}{3}$, $\phi_5 = \frac{\phi}{5}$ etc.

(ii) **Time period**

for 1st harmonic $T_1 = T$

for 3rd " $T_3 = \frac{T}{3}$

for 5th " $T_5 = \frac{T}{5}$

(iii) **Frequency:-**

for 1st harmonics $f_1 = f$

for 3rd " $f_3 = 3f$

for 5th harmonic $f_5 = 5f$ etc.

(iv) Every alternating wave form contain the wave form of different harmonics. But even harmonic wave form does not cause effect on the winding. In this case the resultant emf is calculated as given below

Resultant emf $E_{rm} = \sqrt{E_1^2 + E_3^2 + E_5^2 + \dots}$

(v) <u>pitch factor</u>

For 1st harmonics $K_{p_1} = \cos\frac{\beta}{2}$

For 3rd " $K_{p_3} = \cos\frac{3\beta}{2}$

For 5th " $K_{p_5} = \cos\frac{5\beta}{2}$

(vi) <u>Distribution factor</u>

For 1st harm $K_{d_1} = \frac{\sin m\alpha/2}{m \sin \alpha/2}$

For 3rd " $K_{d_3} = \frac{\sin m3\alpha/2}{m \sin 3\alpha/2}$

For 5th " $K_{d_5} = \frac{\sin m5\alpha/2}{m \sin 5\alpha/2}$

... synchronous generator has 9 slots/pole. If
(1) ... coil spans 8 slots. What is the value of pitch factor

$\frac{S}{P} = 9$, coil span $= 8$ slots $\quad K_p = ?$

Slots/pole, $\frac{S}{P} = 9$ for full pitch coil

given coil span $= 8$ slots

for 9 slots $= 180°$ E

for 1 slots $= \frac{180°}{9} = 20°$ E

∴ chording angle, $\beta = 20°$

$$K_p = \cos\frac{\beta}{2} = \cos\frac{20}{2} = 0.9848.$$

(2) A 3-Φ, 16 pole alternator has a Y connected winding with 144 slots and 10 conductors per slots the flux per pole is 0.03wb. Sine distributed and the speed is 375 RPM. Find the frequency, phase and line emf. Assume full pitch coil.

3-Φ, $P = 16$ Y connected, $S = 144$, $Z_s = 10$, $\phi_m = 0.03$wb

$N = 375$ rpm $\quad K_p = 1 \qquad f, E_{ph}, E_L$

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

$$m = \frac{S}{\text{phase}} = \frac{144/16}{3} = 3$$

$$\alpha = \frac{180°}{S'} = \frac{180}{(144/16)} = 20°$$

$$K_d = \frac{\sin m\alpha/2}{m\sin\alpha/2} = \frac{\sin 3\left(\frac{20}{2}\right)}{3\sin\frac{20}{2}} = 0.96$$

$$Z = Z_s \times S = 10 \times 144 = 1440$$

$$T_{ph} = \frac{Z}{2 \times 3} = \frac{1440}{2 \times 3} = 240.$$

$$E_{ph} = 4.44 f \phi_m T_{ph} K_p K_d \text{ volt}.$$

$$= 4.44 \times 50 \times 0.03 \times 240 \times 1 \times 0.96 = 1534.46\text{ V}$$

$$E_L = \sqrt{3} E_{ph}$$

$$= \sqrt{3} \times 1534.48 = 2657.78 \text{ volt}.$$

parallel operation of Alternators:-

Need for parallel operation

In modern power system alternators are operated in parallel to supply the total load. The need for parallel operation arises due to the following reasons

(i) Total load requirement cannot be met by a single alternator.

(ii) parallel operation increases reliability of electric supply. An outage of one alternator will not cause total power losses to the load.

(iii) If alternators are operating in parallel, one or more of them can be shut down for preventive maintenance turn by turn.

(iv) parallel operation of alternators leads to economy in operating costs. The less efficient machines can be shut down when the load required is less.

Condition for parallel operation:-

The following conditions must be fulfilled before an incoming alternator can be put in parallel with the bus bars.

(i) The terminal voltage of the incoming alternator must be the same as that of bus bars.

(ii) The frequency of incoming alternator must be the same as that of bus bars

(iii) The phase of the voltage of incoming alternator must be identical with the phase of the bus bar voltage, with respect to external circuit i.e. opposite in phase with respect to the local circuit through the armature and the bus bars.

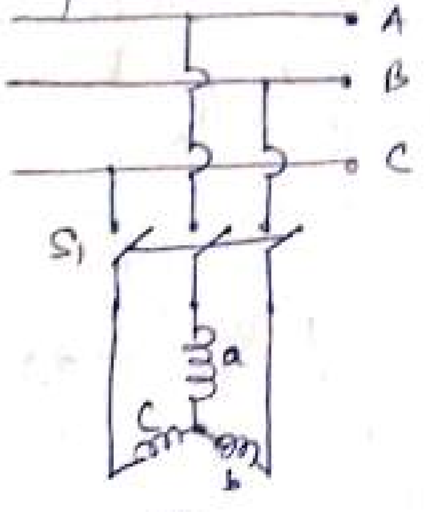
(iv) The phase sequence of the voltage of incoming alternators must be the same as that of bus bar voltage.

The condition of same phase sequence is checked by the phasing out test during the commissioning of alternators. The remaining three conditions have to be checked each time the alternator is to be put in parallel with bus bars

Synchronising:

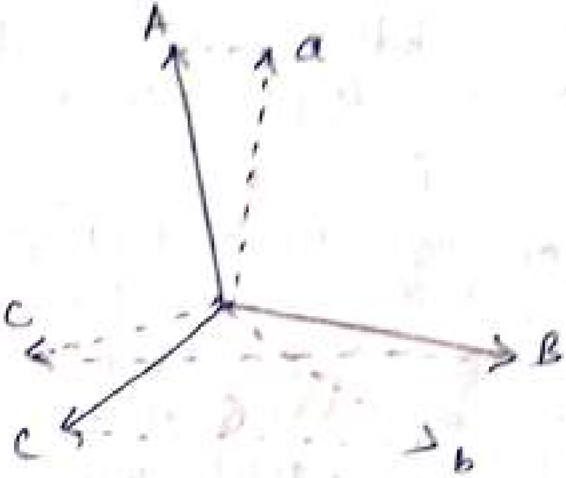
• To avoid severe shock to the incoming and existing alternators, a definite procedure known as synchronising procedure has to be followed.

Figure show an alternator G_1 to be put in parallel with bus bars.



G_1

Alternator in parallel with bus bar



voltages of bus bar and incoming alternator.

The conditions of correct phase sequence has already been checked at the time of initial commissioning of G_1. The remaining three conditions (i.e. equal voltages equal frequency and same phase) have to be checked before S_1 can be closed.

First of all the field current of G_1 is adjusted so that the terminal voltage of G_1 is equal to busbars voltage. Then the speed of G_1 is adjusted, so that its frequency is slightly higher than the bus-bar frequency. [All alternators have a reverse power relay connected to them. If the frequency of G_1 is less than system frequency, it will start drawing power from the system as soon as it is put in parallel. This will cause the reverse power relay to trip.]

Fig shows the line to neutral voltages a b c of the incoming alternator G_1 and the line to neutral voltage of A, B, C of the bus bar. [As the two frequencies are not exactly equal, these two sets phasors change phase with respect to each other at $2\pi(\Delta f)$ rad/sec, where Δf is the difference in frequencies]. The exact instant of switching is when-the two systems are inphase. This is done by using a synchroscope. A synchronoscope is an instrument which measures the phase difference between voltage of one of the phases (say a) of incoming alternator G, and the corresponding phase (i.e A) of bus bar. The dial of synchronoscope shows 0° (i.e. in phase) at the top and 180° at the bottom. The switch S_1 is closed when synchronoscope indicates zero phase difference.

Before the use of synchronoscope became common, the instant of switching was determined by two bright and one dark lamp method. For this purpose one lamp is connected across aA, one across bC and one across BC. It is seen from fig, that when the voltages are in phase, lamp across aA is dark, while the other two lamps are equally bright. Since the voltage across each lamp can be twice the system voltage the should have a voltage rating of twice the system voltage. For modern generators operating at 11kv, the synchronoscope (or the lamps) have to be connected through potential transformer. For large generators use in power plant systems the process of synchronising is automated using a computer.

SYNCHRONOUS MOTOR

1.0 COMPARISON BETWEEN SYNCHRONOUS AND INDUCTION MOTOR

Induction Motor	Synchronous Motor
1. It runs at a speed less than synchronous speed.	1. It runs only at synchronous speed.
2. 3-phase induction motor is self starting.	2. This is not self starting.
3. It always operates at lagging p.f.	3. It can be operated at any p.f.
4. It requires ac supply only.	4. It requires both ac and dc supplies.
5. Design and construction are simpler.	5. Design and construction are complicated.
6. Less cost.	6. Cost is more.
7. Performance of this motor is very much affected by the fluctuations in the supply voltage.	7. Performance is not affected by the fluctuations in the applied voltage.

2.0 PRINCIPLE OF OPERATION

The disadvantage ~~to~~ of synchronous motor is that it is not self starting. When a 3-phase balanced voltage is applied to a synchronous motor, a rotating magnetic field (RMF) of constant ~~magnetic field~~ magnitude and rotating at synchronous speed (N_s) is produced. This RMF can be assumed as two poles rotating in clockwise direction at synchronous speed.

Fig.1 shows the stator poles N_s and S_s. During the first half period, the stator has N_s at the top and S_s at the bottom With the rotor poles shown in Fig.1, a repulsive force is produced. The rotor tends to rotate in anticlockwira direction.

During the next half period, the stator has S_s at the top and N_s at the bottom. With this poles as shown in Fig.2, an attractive force is produced. The rotor tends to rotate in clockwise direction.

Thus the rotor is subjected to quickly reversing torque. The rotor can not respond to this torque because of the large inertia. Hence synchronous motor is not self starting.

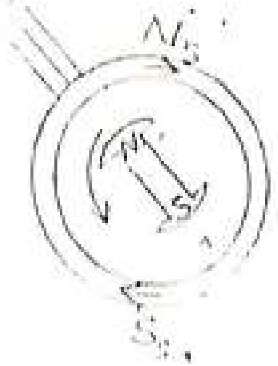


FIG. 1

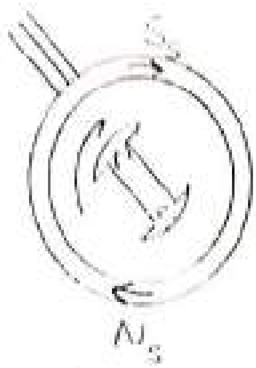


FIG. 2

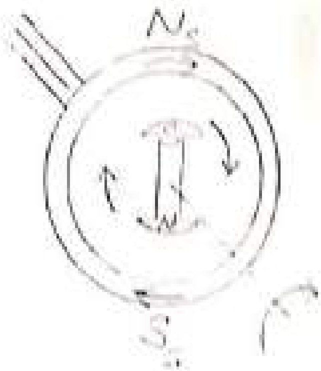


FIG. 3

If the rotor poles are also rotated at synchronous speed, as shown in Fig.3, rotor poles interchange their position by the time the stator poles change. The rotor poles are attracted by the stator poles and they move together. Thus the synchronous motor works on the principle of magnetic locking.

MOTOR ON LOAD

(Significance of load angle)

The stator and rotor poles run at synchronous speed since they are magnetically locked. In an ideal motor the axes of rotor and stator poles concide on no load. But, when the motor is loaddd, there is a small phase angle difference between them. This angle is known as load angle or torque angle. As the load on the motor is increased, the rotor falls back by a larger angle, but it still countinues to run synchronously.

The mechanical power developed is approximately equal to $\frac{VE}{X_s} \sin\alpha$. Where α is the load angle. Increase in load demands an increase in the mechanical power developed. As the load on the motor increases, the load angle increases. For α between 0 to 90, the mechanical power developed increases with the increase in the α . But, beyond 90, the mechanical power developed decreases. Hence the rotor becomes unstable. The synchronism will be lost. The rotor pulls out of step.

MOTOR WITH CONSTANT MECHANICAL LOAD & VARIABLE EXCITATION

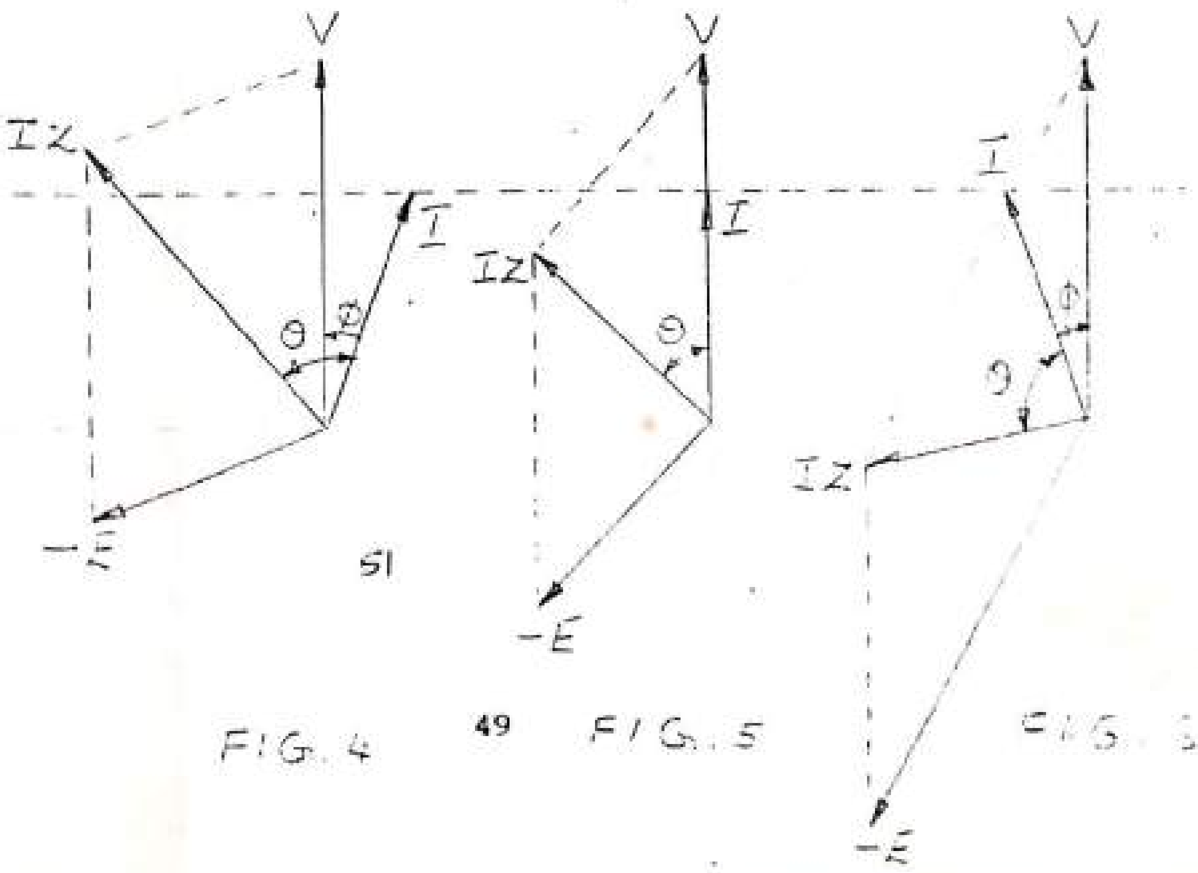


FIG. 4 FIG. 5 FIG. 6

Consider a synchronous motor operating on constant mechanical load. If the emf E is equal to the terminal voltage V, the corresponding excitation is called 100% excitation. If it is below 100%, the machine is said to be under excited and for above 100%, it is over excited.

The phasor diagram of under excited synchronous motor is shown in Fig.4. The resultant voltage Er is obtained by adding the vectorsV and -E. The vector I lags IZ vector by an angle Θ. From Fig.4, it can be seen that the current vector lags the voltage vector by a large angle Ø. Hence the p.f will be lower. Thus the under excited synchronous motor operates at lagging p.f.

The excitation is adjusted such that the EMF is slightly greater than the terminal voltage as shown in Fig.5. The emf is such that the current vector lags IZ vector by Θ or the current vector coincides with the voltage vector. Thus by adjusting the excitation, the synchronous motor can be operated at unity p.f. The current at unity p.f will be minimum.

The phasor diagram of over excited synchronous motor is shown in Fig.6. The IZ vector is pulled downwards and the current vector will be on the left side of voltage vector (or) the current vector leads the voltage vector. Thus a over excited synchronous motor operates at leading p.f. The locus of extremity of current vector is a straight line since the real component $I \cos \phi$ is constant. This is constant because the mech load is constant.

SYNCHRONOUS CONDENSER

An over excited condenser takes leading current like a capacitor and hence it is called synchronous condenser or synchronous capacitor. Thus the synchronous motor is useful in improving the power factor of a system since its own power factor can be varied. In an industry having several induction motors, one synchronous motor can be used to improve the overall power factor of the system as shown in Fig.7. The phasor diagram of the synchronous condenser is shown in Fig.6. The current taken by the synchronous capacitor must be equal to the reactive current drawn by the induction motor to raise the p.f to unity.

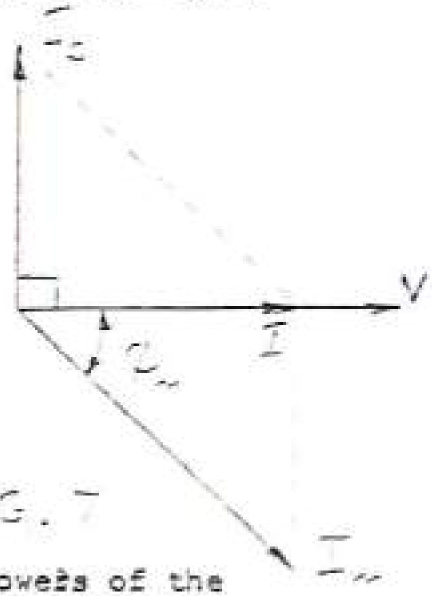


FIG. 7

$$\tan \phi = \frac{P_1 \tan \phi_1 - P_2 \tan \phi_2}{P_1 + P_2}$$

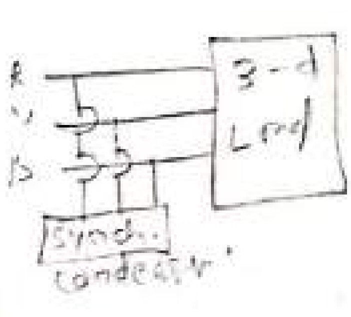
P_1 & Q_1 are the total real and reactive powers of the induction motors.

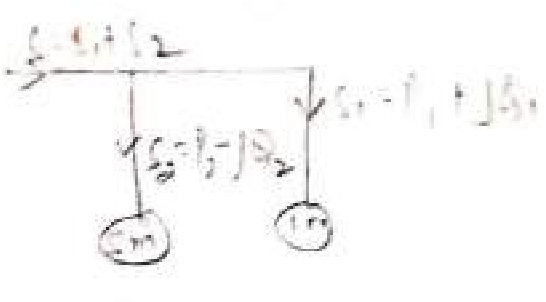
P_2 & Q_2 are the real and reactive powers of the synchronous motor.

ϕ_1 is pf angle of induction motor (lagging) ϕ_2 is pf angle of synchronous motor (leading)

ϕ is the overall power factor angle.

$\tan \phi$ & ϕ can be obtained from the above equation. $\cos \phi$ is the over all pf of the system.





④

VEE AND INVERTED VEE CURVES

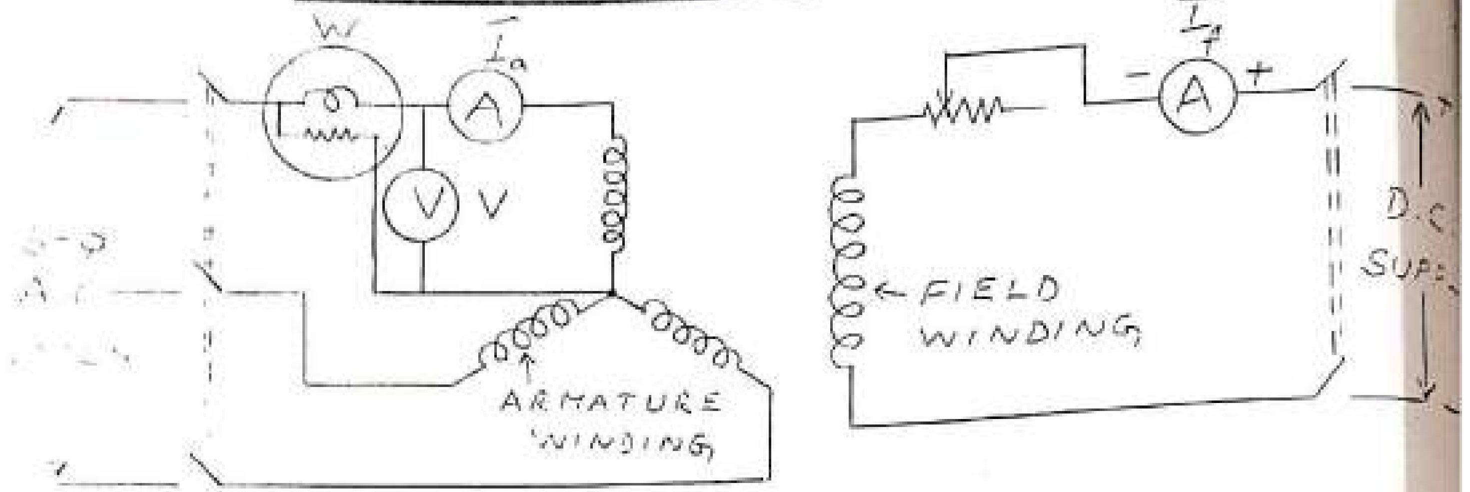
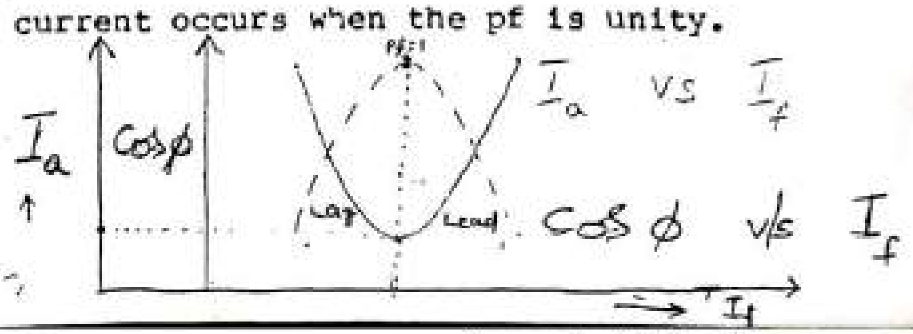


FIG. 8

The circuit for obtaining vee and inverted vee curves is shown in Fig.8. The three phase ac supply is given to the armature winding. The dc supply is given to the field winding. The watt meter on the ac side indicates the input power. Ammeter on ac side indicates armature current. Ammeter on dc side indicates field current. By varying the field current, note down the readings in the tabular column shown below:

S.No.	I_f	I_a	V	W	pf = W/VI

The graph with field current V/S armature current with constant input power is known as vee curve. The graph with field current V/S p.f for the same input power is known as inverted vee curve. They are shown in Fig.9. From Fig.9, it can be noted that the armature current varies with excitation current (Field current). From the vee curve we see that the current has large value for low and high values of field current. The power factor also varies between a wide range. The variation of p.f with field current looks like an inverted V curve. It can be seen that the minimum armature current occurs when the pf is unity.



STARTING METHODS OF SYNCHRONOUS MOTOR

Synchronous motor is not self starting. The various methods of starting are

1. Pony motor starting
2. Indu ction starting

Pony Motor Starting: Pony motor means a small motor. A small dc motor or induction motor may be coupled mechanically to the synchronous motor for starting. If the dc supply is available, dc motor is used, otherwise induction motor can be used. At the time of starting, the pony motor drives the synchronous motor till synchronous speed. Later it is disconnected.

Indu ction Starting: The damper winding provided on the rotor acts as a squirrel cage rotor. This is because the damper bars placed in the slots on polefaces are short circuited by copper rings. At the time of starting, the dc supply is not given to the field winding. When ac supply is given to the stator, the motor starts as a squirrel cage induction motor. When the motor rotates at its maximum speed, the dc supply is given to the field. Now the rotor and stator poles get interlocked with each other and the motor now runs as a synchronous motor. At synchronous speed, the emf induced in the damper winding is zero. Hence the effect of damper winding is not there at synchronous speed.

During the starting, the field winding is also cut by rotating magnetic field. A dangerously high voltage may be induced in the field winding. One of the methods to limit this high voltage is to short circuit the field winding through a resistance during starting. The applied ac voltage may also be reduced to reduce the flux and induced voltage in the field winding.

HUNTING

Momentary speed fluctuations of motor due to change of load is called hunting or phase swinging. When the load on the motor increases the angle α increases. Let us assume that the motor is operating on full load and the corresponding load angle is α_4 as shown in Fig.10. If the load on the motor is suddenly reduced to half full load, the angle between stator and rotor poles change and rotor tries to attain its new balanced position at α_2. In doing so, the rotor due to its own inertia will move to α_1. At α_1, the mechanical power developed is not sufficient to meet the load. The rotor slows down inorder to produce necessary mechanical power. It passes beyond α_2 and reaches α_3. Now extra power developed by the motor is not needed by the load. Thus the rotor will oscillate about final stable position (α_2) and this osdillasion of rotor is known as hunting.

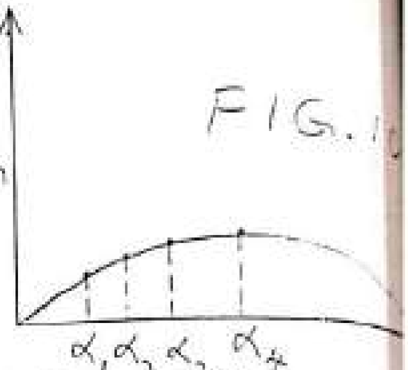
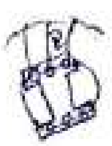


FIG.10

Hunting is reduced by using damper winding which is provided on the rotor. When hunting takes place, a difference in speed of rotor and RMF induces an emf in the damper bars. According to Lenz's law, this emf now acts in such way to reduce the difference between rotor speed and the synchronous speed. Thus the damper bars keep the rotor speed equal to the speed of RMF.



APPLICATIONS

1. They are used in power houses and in substations to improve the power factor.
2. There are used in big industries to improve the pf where many induction motor are installed.
3. Stroboscopic and timing devices
4. Rubber mills
5. Textile mills

ADVANTAGES

1. It is a constant speed motor
2. It can be operated at leading, lagging or unity power factor.
3. The efficiency is very high.

DISADVANTAGES

1. It is not self starting.
2. They are more costly and have complicated construction.
3. D.C supply is also needed.
4. The problem of hunting is present.

EMF Equation

From the vector diagram

$$E^2 = (V\cos\phi - IR)^2 + (V\sin\phi - I X_s)^2$$

$$E^2 = V^2\cos^2\phi + I^2R^2 - 2\,VIR\cos\phi$$

$$+\,V^2\sin^2\phi + I^2X_s^2 - 2\,VIX_s\sin\phi$$

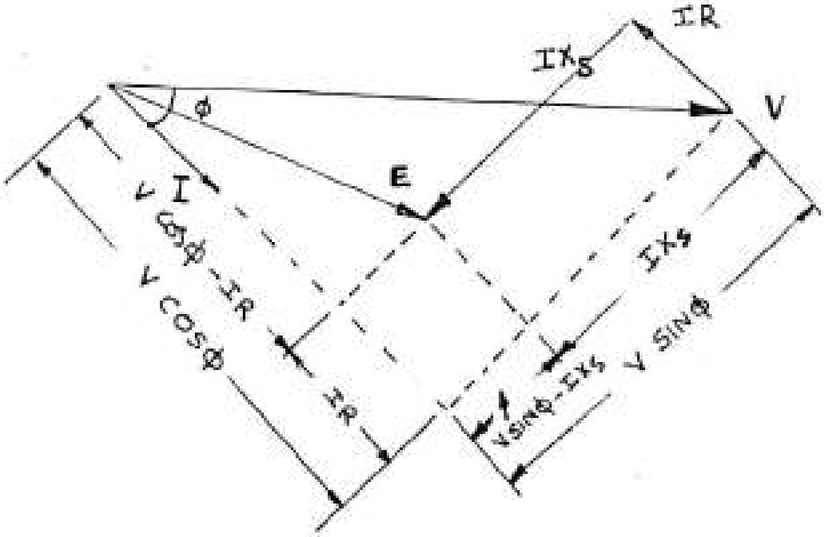
$$= V^2 + I^2(R^2 + X_s^2) - 2V\,I(R\cos\phi + X_s\sin\phi)$$

$$E^2 = V^2 + I^2Z_s^2 - 2\,V\,IZ\,(R/Z\cos\phi + X_s/Z\sin\phi)$$

$$= V^2 + E_r^2 - 2\,V\,IZ\,(\cos\theta\cos\phi + \sin\theta\sin\phi)$$

$$E^2 = V^2 + E_r^2 - 2\,VE_r\cos(\theta - \phi)$$

Where $E_r = IZ$



Electrical Power Input

Let

V - Applied voltage / phase

E - EMF induced / phase

I - Armature current / phase

R - Armature resistance / phase

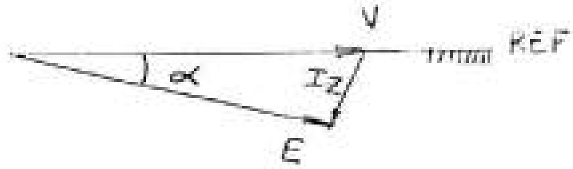
X_s - Synchronous reactance / phase

Z_s - Synchronous impedance / phase

α - Torque angle

θ - Impedance angle

ϕ - Power factor angle



Let us take voltage as reference vector

$$\dot{V} = V\underline{|0}$$
$$= V + j0$$
$$\dot{E} = E\underline{|-\alpha}$$
$$= E(\cos\alpha - j\sin\alpha)$$

$$I = \frac{\dot{V} - \dot{E}}{Z_s}$$

$$I = \frac{V - (E\cos\alpha - jE\sin\alpha)}{Z_s}$$

$$I = \frac{(V - E\cos\alpha) + jE\sin\alpha}{Z_s}$$

$$I = \frac{(V - E\cos\alpha) + jE\sin\alpha}{(R + jX_s)} \left(\frac{R - jXs}{(R - jX_s)}\right)$$

$$I = \frac{[(V - E\cos\alpha) + jE\sin\alpha]}{Z_s} \left(\frac{R - jXs}{Z_s}\right)$$

$$I = \frac{[(V - E\cos\alpha) + jE\sin\alpha]}{Z_s} (\cos\theta - j\sin\theta)$$

$$I = \frac{(V - E\cos\alpha)\cos\theta + E\sin\alpha\ \sin\phi + j\ \text{terms}}{Z_s}$$

Real power input = V x Real part of I

$$= \frac{V[V\cos\theta - E\cos\alpha\cos\theta + E\sin\alpha\sin\theta]}{Z_s}$$

$$= \frac{V^2\cos\theta - VE(\cos\alpha\cos\theta - \sin\alpha\sin\theta)}{Z_s}$$

$$\text{Power input / ph} = \frac{V^2\cos\theta - VE\cos(\theta + \alpha)}{Z_s}$$

Mechanical Power Output

Let

P_m - Mechanical power developed / phase

T - Torque developed / phase

V - Applied voltage / phase

E - EMF induced / phase

I - Armature current / phase

R - Armature resistance / phase

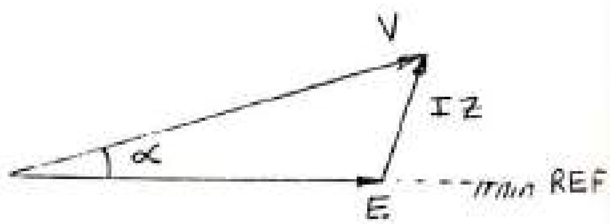
X_s - Synchronous reactance / phase

Z_s - Synchronous impedance / phase

α - Torque angle

θ - Impedance angle

ϕ - Power factor angle



In synchronous motor

$V = E + IZ$

multiply throughout with I

$VI = EI + I^2Z$

Real part of LHS = Real part of RHS

$VI\cos\phi$ = Real part of $EI + I^2R$

Input = Output + losses

Therefore mechanical power output is the real part of E I

Take EMF as reference vector

$P_m = R_e\{\dot{E}\,\dot{I}\}$

$= R_e\{E\angle 0 \; I\angle\gamma\}$

$= R_e\{EI\angle\gamma\}$

$= EI\cos\gamma$

$= E \times$ real part of I

$$\dot{E} = E\angle 0$$

$$\dot{V} = V(\cos\alpha + j\sin\alpha)$$

$$\dot{I} = \frac{\dot{V} - \dot{E}}{\dot{Z}}$$

$$\frac{V\cos\alpha + jV\sin\alpha - E}{Z} \times \frac{R - jX}{R - jX}$$

$$\frac{V\cos\alpha + jV\sin\alpha - E}{Z} (\cos\theta - j\sin\theta)$$

$$= \frac{V\cos\alpha\cos\theta + V\sin\alpha\sin\theta - E\cos\theta + j \text{ terms}}{Z_s}$$

$$= \frac{V\cos(\theta - \alpha) - E\cos\phi + j \text{ terms}}{Z_s}$$

Multiply the real part of current with E to get mechanical power developed

$$P_m = \frac{VE\cos(\theta - \alpha) - E^2\cos\theta}{Z_s}$$

<u>Condition for Maximum mechanical power developed.</u>

When load changes, torque angle changes. Condition for Maximum mechanical power developed is

$$\frac{dP_m}{d\alpha} = 0$$

$$\frac{VE\sin(\theta - \alpha)}{Z_s} = 0$$

$$\sin(\theta - \alpha) = 0$$

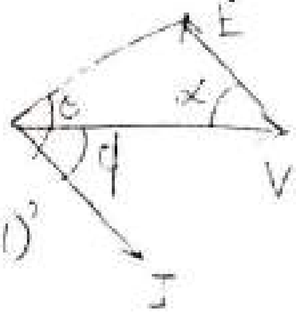
$$\theta - \alpha = 0$$

$$\theta = \alpha$$

Impedance angle = torque angle

Maximum mechanical power can be obtained by substituting $\theta = \alpha$ in the mechanical power expression

$$P_{m\,max} = \frac{VE - E^2\cos\theta}{Z_s}$$



$(IZ)^2 = V^2 + E^2 - 2VE\cos x$

$= (230.9)^2 + (230.9)^2 - 2(230.9)^2 \cos 8°$

$IZ = 32.3V$

$I = \frac{32.3}{2} = 16.15$ Amps $\left[Z = R + jX_s = 0 + 2 = 2\Omega \right]$

Another Method

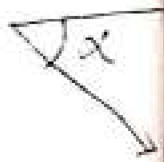
We know

$Z_s \angle \phi = \tan^{-1} \ldots$
$= \tan^{-1} \ldots$
$= 90°$

$I = \frac{V - E}{Z_s}$

$I = \frac{230.9\angle 0 - 230.9\angle -8°}{2\angle 90°}$

$= \frac{2.25 - j\,32.13}{2\angle 90°}$



$= \frac{32.21 \angle -85.99}{2\angle 90°}$

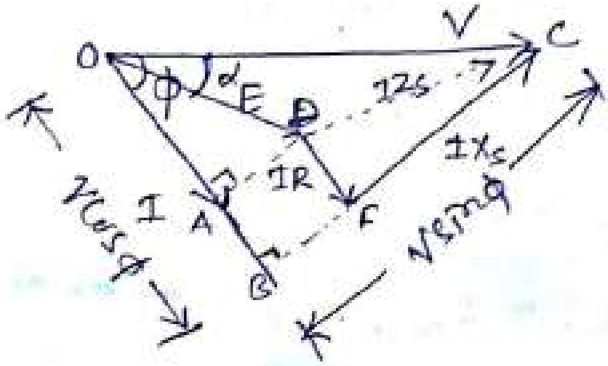
$I = 16.105$ Amps

Vector diagram :-

Considering under excitation ($E < V$) or lagging p.f.

For motor, $E_b = V - IZ_s$

$$V = E_b + IZ_s$$
$$= E_b + I(R + jX_s)$$
$$V = E_b + IR + jIX_s$$



- let E_b = Emf Induced in Stator due to field flux

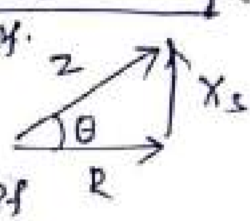
V = supply voltage to stator, volt.

Consider right angle tringle, OAD.

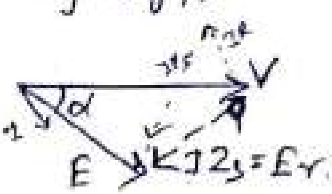
$$OD = \sqrt{OA^2 + AD^2}$$
$$= \sqrt{OA^2 + BF^2}$$
$$= \sqrt{(OB - AB)^2 + (BC - FC)^2}$$
$$E_b = \sqrt{(V\cos\phi - IR)^2 + (V\sin\phi - IX_s)^2}$$
$$E = \sqrt{(V\cos\phi - IR)^2 + (V\sin\phi \mp IX_s)^2}$$ − for Lag pf, + for Lead pf

Induced emf/phase in terms of impedance angle:-

$$E^2 = V^2 + E_r^2 - 2VE_r\cos(\theta \pm \phi)$$ (+ for Lead pf, − for Lag pf)

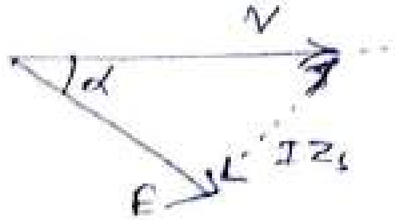


$$\overline{E_r} = \vec{V} - \vec{E}$$
$$= \overrightarrow{IZ_s}$$
= Resultant emf



Electrical power Input/phase or I/p to Stator/ph.

$$P_{in} = \frac{V^2\cos\theta - VE\cos(\theta+\alpha)}{Z_s}$$



$V \rightarrow$ Applied voltage/ph

$E \rightarrow$ EMF induced/ph

$I \rightarrow$ Armature current/ph

$R \rightarrow$ Armature Resistance/ph

$X_s \rightarrow$ Synchronous reactance/ph

$Z_s \rightarrow$ Synchronous Impedance/ph

$\alpha \rightarrow$ Load angle or torque angle

$\theta \rightarrow$ Impedance angle

$\phi \rightarrow$ power factor angle

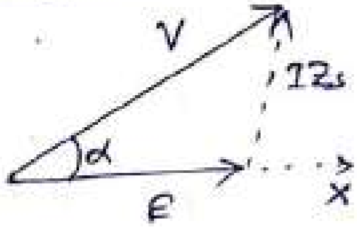
Condition for max^m power I/p :-

$$\frac{dP_{in}}{d\alpha} = 0 \Rightarrow \boxed{\alpha = \pi - \theta}$$

Note:- Load angle is always positive. Because due to increase in load, the rotor pole falls back the stator pole in anticlockwise direction.

Mechanical power developed per phase:-

$$P_m = \frac{VE\cos(\theta-\alpha) - E^2\cos\theta}{Z_s}$$



Condition for max^m mech. power

$$\frac{dP_m}{d\alpha} = 0 \Rightarrow \boxed{\alpha = \theta}$$

Load angle = Impedance angle.

max^m mech. power developed/ph

$$P_{m\,max} = \frac{VE - E^2\cos\theta}{Z_s}$$

Total Cu-loss in Stator :-

Total Stator Cu-loss for 3-ϕ = $3I^2R$ watt.

Hence, Cu-loss is independent of synchronous reactance.

Gross mech. power developed for 3-ϕ

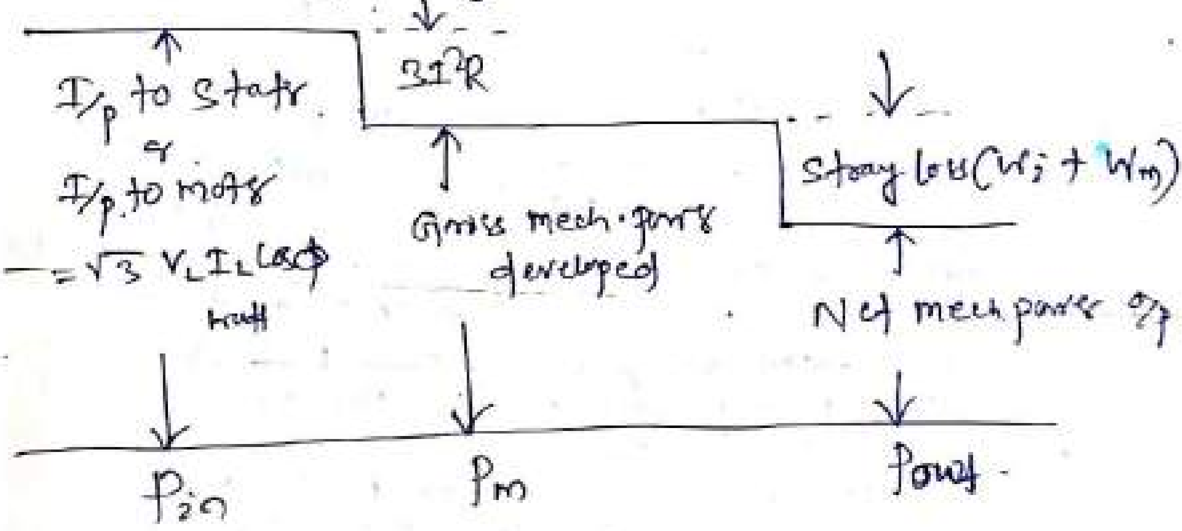
= Total Elect. power I/p for 3-ϕ

− total stator Cu-loss for 3-ϕ.

$$\boxed{P_m = P_{in} - 3I^2R} \text{ watt.}$$

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

Power stage diagram :-



Applications :-

① They are used in power houses and in substations to improve the power factor.

② They are used in big industries to improve the p.f. where many induction motor are installed.

③ Used in timing devices.

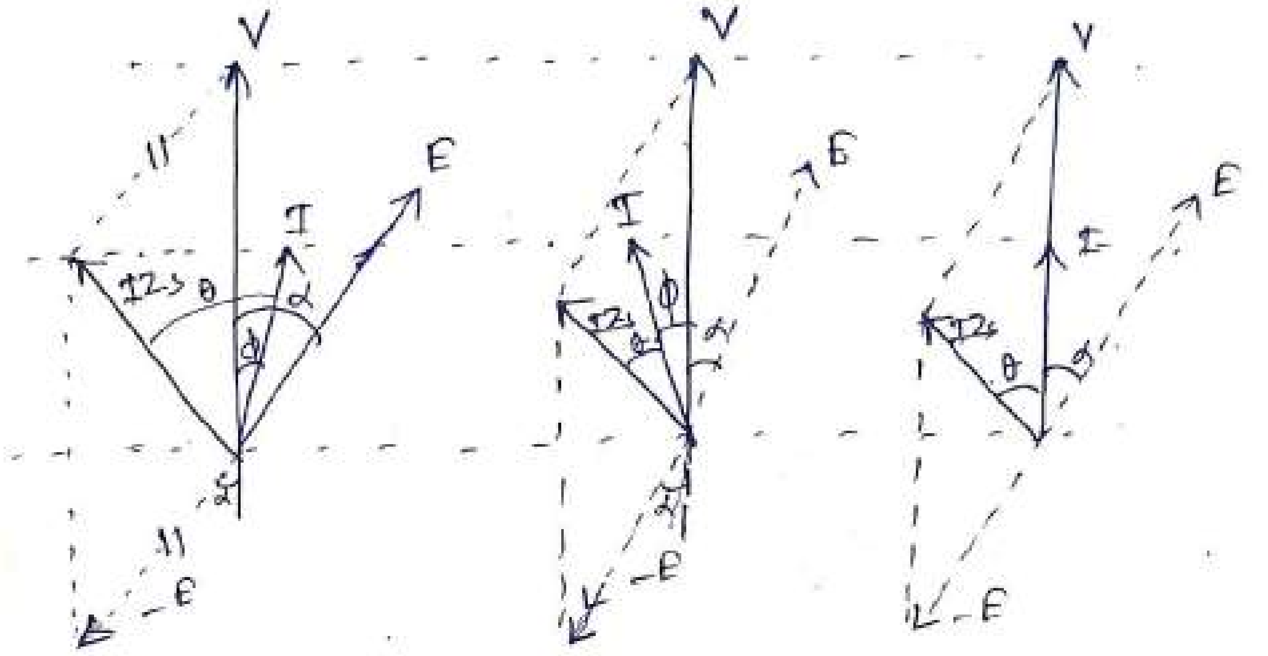
④ Rubber mills.

⑤ Textile mills.

$$\circledast \quad \frac{E_r}{\sin\delta} = \frac{E_b}{\sin(\theta \mp \phi)}$$

(− → lag pf, + → lead pf)

Effect of change of excitation with const. mech. load:



(I) E < V (Under excitation Lag. p.f)

(II) E > V (over excitation Lead p.f)

(III) E = 1.5 V Normal excitation unity p.f.

The vector diagrams are drawn for different excitation voltage (D.C voltage), for a constant mechanical load on the motor.

When excitation voltage is such that E < V, it is called under excitation. During such condition the motor is operated with lagging p.f as shown in fig (I).

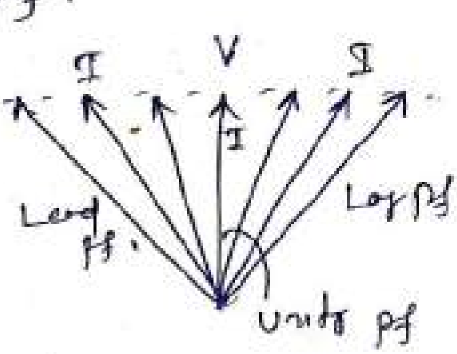
The excitation voltage is such that E > V, it is called over excitation. During such condition the motor draws current at leading p.f. This operation is known as synchronous condenser or synchronous capacitor.

When excitation is such that E is slightly more than V it is called normal excitation. During such condition the motor is operated at unity p.f.

Therefore a synchronous motor can be operated at lagging, leading and unity p.f.

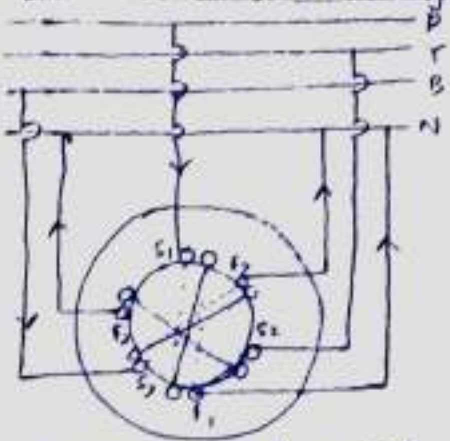
—x—

It is clear that under normal excitation current is minimum and gradually it increases for lagging and leading p.f during under and over excitation.

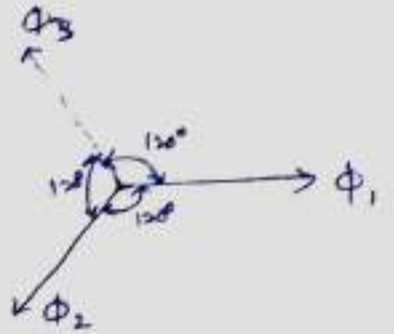


The locus (path) of the extremity of the current vector is a straight line, when the load is constant and excitation varies.

Production of rotating magnetic field (R.M.F)



(Stator with 3-φ winding)



When a 3-φ voltage is applied to a 3-φ winding spaced at 120° appart, a rotating magnetic field is produced. The resultant flux has magnitude 1.5 φm and it revolves in clockwise direction.

Let φ1, φ2 and φ3 are instantaneous fluxes in phasel 1,2&3 respectively. The flow of flux obey's sine law

$\phi_1 = \phi_m \sin\theta$ — (i), $\phi_2 = \phi_m \sin(\theta - 120°)$ — (ii), $\phi_3 = \phi_m \sin(\theta + 120°)$ — (iii)

where φm max value of flux in any one of the phases.

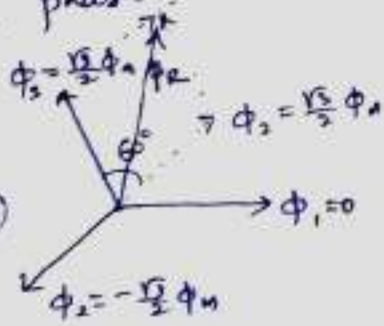
when θ = 0°

$\phi_1 = 0$

$\phi_2 = \phi_m \sin(-120°) = -\phi_m \sin 120° = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_3 = \phi_m \sin 120° = \frac{\sqrt{3}}{2}\phi_m$

$\phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60}{2}$, $\boxed{\phi_R = 1.5\phi_m}$ ($\cos 30 = \frac{\sqrt{3}}{2}$)



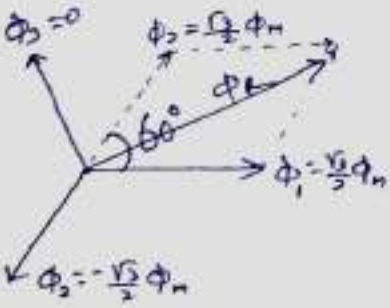
θ = 60°

$\phi_1 = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m$

$\phi_2 = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_3 = \phi_m \sin 180° = 0$

$\phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \times \cos\frac{60}{2}$, $\boxed{\phi_R = 1.5\phi_m}$



θ = 120°

$\phi_1 = \phi_m \sin 120° = \frac{\sqrt{3}}{2}\phi_m$

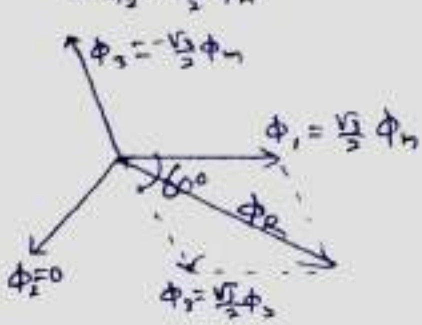
$\phi_2 = \phi_m \sin 0 = 0$

$\phi_3 = \phi_m \sin 240 = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60}{2}$

$= 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\phi_m$

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



<u>when $\theta = 180°$</u>

$\phi_1 = \phi_m \sin 180° = 0$

$\phi_2 = \phi_m \sin(180 - 120) = \frac{\sqrt{3}}{2}\phi_m$

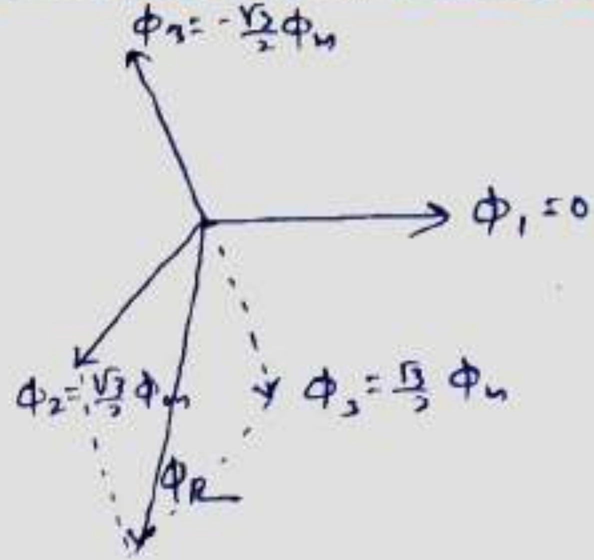
$\phi_3 = \phi_m \sin(180 + 120) = \phi_m \sin 300$

$= -\phi_m \sin 120 = -\frac{\sqrt{3}}{2}\phi_m$

$\therefore \phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60}{2}$

$= 2 \times \frac{\sqrt{3}}{2} \cdot \phi_m \times \frac{\sqrt{3}}{2} = 1.5\,\phi_m$

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



Hence it concludes that the resultant flux has a constant magnitude $1.5\phi_m$ and it rotates in clockwise direction.

Module-III

(1)

Polyphase induction motor:

An induction motor consists of two parts like stator and rotor. There is no electrical connection from the source to the rotor winding. The AC supply is given to stator and due to mutual induction voltage and current are developed in rotor. Hence the m/c is named as induction motor.

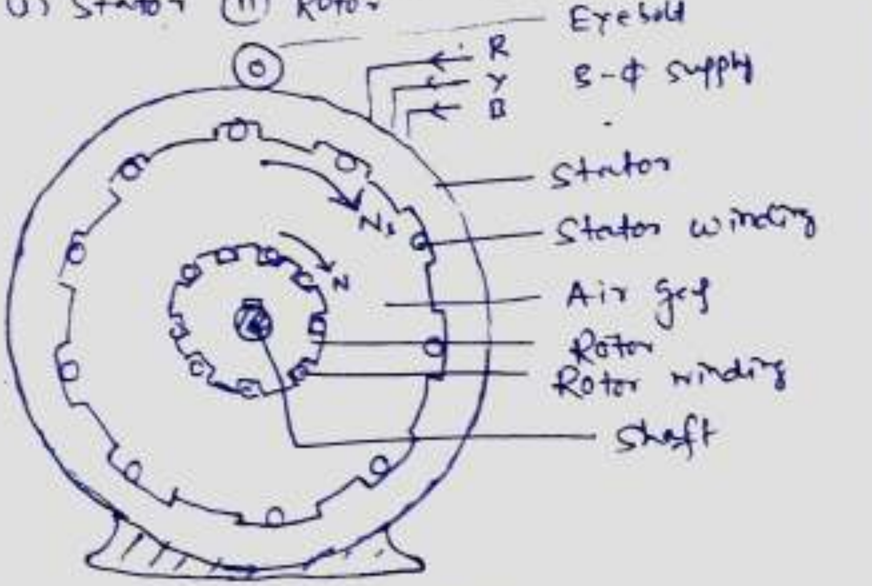
Advantages:-

(i) It has rugged and robbust construction.
(ii) It is self starting
(iii) Its cost is low.
(iv) It has sufficiently high efficiency
(v) It needs minimum maintenance.

Disadvantages:-

(i) speed decreases [redacted].
(ii) speed control is [redacted].
(iii) Starting torque is less than that of a dc shunt motor.

Construction - The main part of induction motor are (i) Stator (ii) Rotor.



(C.S view of 3-ϕ I.M)

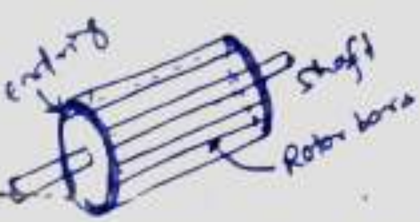
Stator - The core of Stator is made up of silicon steel laminations of 0.5mm thickness which are insulated by varnish coating. The stator carries 3 windings displaced in space by 120°. The stator windings are similar to windings provided for synchronous machines. The winding is wound for definite number of poles which is determined by the requirement of speed. Copper conductors are placed in the stator slots.

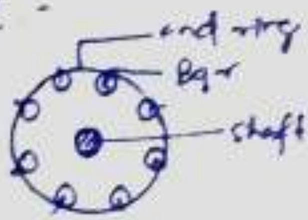
Rotor:- The two types of rotors are

(i) Squirrel cage type

(ii) Slip ring or phase wound type.

Squirrel cage rotor -





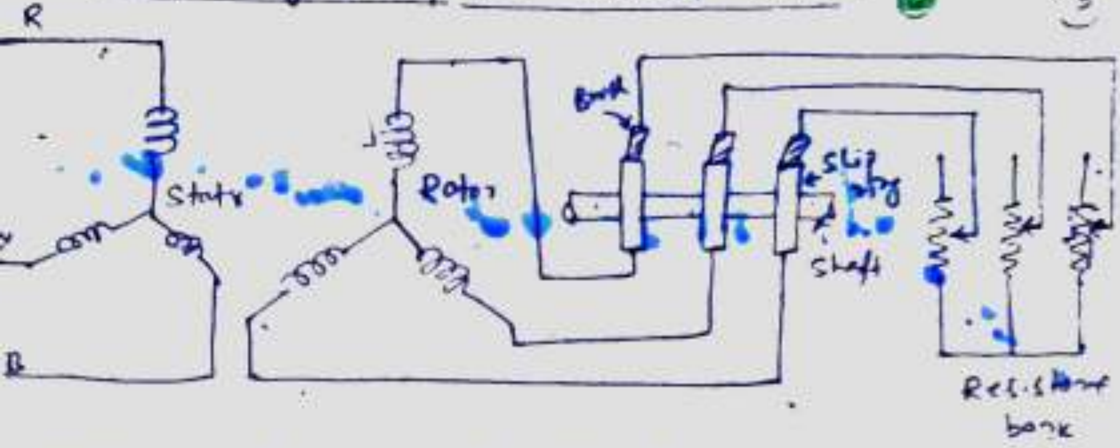
This rotor consists of a cylindrical laminated core having parallel slots for carrying the rotor bars. Rotor bars are made of copper or aluminium. The rotor bars are welded to the end rings on either sides. When the rotor bars are welded to end rings, it look like a squirrel cage. Hence it is called squirrel cage rotor. It is not possible to add any external resistance in series with rotor circuit, since rotor bars are welded to the end rings.

The starting torque depends upon rotor circuit resistance.

In small m/cs the rotor slots are taken parallel to shaft. But in large m/c the rotor slots are skewed in order to reduce magnetic hum(noise)

Slip speed :- The difference between (3)

(ii) Slip ring or phase wound rotor



The construction of this type of rotor is similar to stator construction. The rotor has three windings, displaced in space by 120°. The rotor is wound for same number of poles as the stator winding. The rotor windings are connected in star. The other three winding terminals are brought out and connected to three slip rings mounted on the shaft. The slip rings are insulated from the shaft. The slip rings and the brushes placed on them are stationary. A 3-ϕ star connected resistor bank is connected to the 3 brushes as shown in fig. Thus it is possible to add external resistance in series with rotor circuit due to the provision of brushes and slip rings. These rotors are costlier than squirrel cage rotors due to the complicated construction. But the starting torque of phase wound motor is much greater than that of squirrel cage motor.

Principle of operation :-

when a 3-ϕ balanced voltage is applied to stator winding, a Rotating magnetic field (RMF) rotating at synchronous speed is produced. RMF is i.e where magnitude is constant but the axis of field rotates in space. The RMF cuts the rotor conductors.

and an emf is induced in the rotor circuit by Faraday's law. The magnitude of induced emf is proportional to relative velocity between RMF and rotor. The emf in the rotor produce rotor current since the rotor conductors are closed. The current carrying rotor conductors kept in the RMF experience a force and the rotor rotates.

(4)

(*) The direction of rotation of rotor is given by Lenz's law. According to Lenz's law, the rotor rotates such as to oppose the very cause producing it. The cause of rotation is the relative velocity between RMF and rotor. Hence to reduce the relative speed, the rotor starts running in the same direction as that of RMF. The rotor tries to catch up RMF, but it can not. If the rotor rotates at synchronous speed, the relative speed, rotor emf, rotor current and torque are zero. The rotor decelerates and runs at a speed less than synchronous speed. Hence this motor is called asynchronous motor. The motor is called Induction motor since it works on Induction principle.

Relation between f_r & f

When the rotor is stationary, rotor frequency is equal to stator frequency. When the rotor starts moving the frequency depends upon slip speed and hence rotor frequency decreases.

Stator frequency or supply frequency, $f = \frac{PN_s}{120}$ Hz

Rotor frequency $f_r = \frac{P(N_s - N)}{120}$ Hz

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

$$\boxed{f_r = sf} \text{ Hz}$$

when $N = 0 \Rightarrow s = 1$, $f_r = f$

$= N_s$, $= 0$, $f_r = 0$

③ **Slip speed** :- The difference between ③ synchronous speed N_s and actual speed N is called slip speed. slip speed $= N_s - N$ rpm.

Slip :- It is defined as the ratio of slip speed to the synchronous speed. It is expressed in percentage.

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

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

$$S N_s = N_s - N$$

$$N = N_s - S N_s$$

Actual speed, $\boxed{N = N_s(1-S)}$ rpm.

when $N = 0 \Rightarrow S = 1$
$N = N_s \Rightarrow \ = 0$

(*) $f_r = S f$

$f_r \rightarrow$ Rotor frequency
$f \rightarrow$ stator "

$N = 0 \Rightarrow S = 1$, $f_r = f$
$= N_s$, $= 0$ $f_r = 0$

(*) $E_r = S E_2$

$E_r \rightarrow$ Rotor emf/ph at running condition.
$E_2 \rightarrow$ Rotor emf/ph at stand still.

$N = 0 \Rightarrow S = 1$, $E_r = E_2$
$= N_s$ $= 0$ $= 0$

(*) $X_r = S X_2$

$N = 0 \Rightarrow S = 1$, $X_r = X_2$
$= N_s$, $= 0$ $X_r = 0$

Torque developed by I.M :-

$$T = \frac{K S E_2^2 R_2}{R_2^2 + S^2 X_2^2} \qquad K = \frac{60}{2\pi N_s}$$

E_2 = Rotor emf/ph at stand still
X_2 = Rotor reactance/ph " "
R_2 = Rotor resistance/ph.

Starting torque or Stand still torque:-

The torque developed by the I·m at the instant of starting $T_{st} = \frac{KE_2^2 R_2}{R_2^2 + X_2^2}$ {put s = 1

For max^m starting torque, $\frac{dT_{st}}{dR_2} = 0$, rotor resistance is equal to rotor stand still reactance.

$$\boxed{R_2 = X_2}$$

Running torque:-

$$T_r = \frac{KSE_2^2 R_2}{R_2^2 + s^2 X_2^2}$$

For max^m running torque, $\frac{dT_r}{ds} = 0$, Rotor resistance is slip times rotor stand still reactance.

$$\boxed{R_2 = sX_2}$$

For max^m Running torque,

$$T_{r\,max} = \frac{KSE_2^2 \times sX_2}{s^2X_2^2 + s^2X_2^2}$$

$$= \frac{Ks^2E_2^2 X_2}{2s^2 X_2^2} = \frac{KE_2^2}{2X_2}$$

$$\boxed{T_{r\,max} = \frac{KE_2^2}{2X_2}}$$

max^m running torque is independent of rotor resistance.

Torque-slip characteristics of I·M:-

Running torque, $T_r = \frac{KSE_2^2 R_2}{R_2^2 + s^2 X_2^2}$

at $s = 0 \Rightarrow T_r = 0$

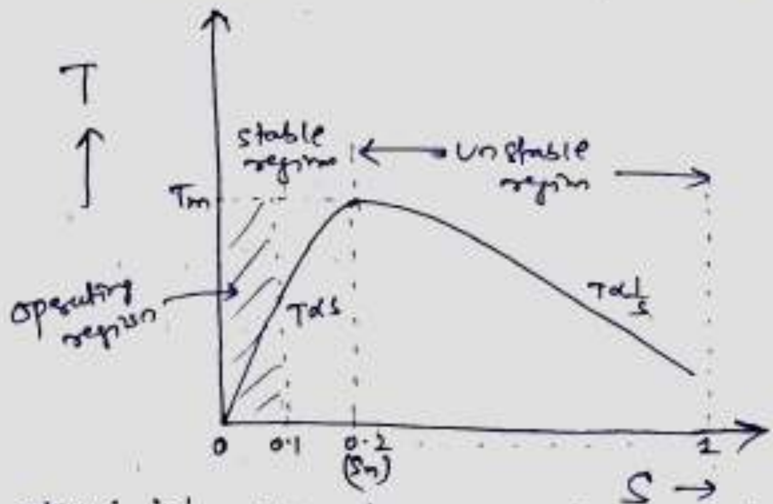
In stable region, (low slip) $R_2^2 \gg s^2X_2^2 \Rightarrow T_r = \frac{KSE_2^2 R_2}{R_2^2 + s^2X_2^2 \approx 0}$

$\Rightarrow \boxed{T_r \propto s}$ —— (1)

In unstable region, $s^2 x_2^2 \gg R_2^2$

(High slip) $T_r = \frac{K s E_2^2 R_2}{R_2^2 + s^2 x_2^2}$

$\Rightarrow \boxed{T_r \propto \frac{1}{s}}$ —— ② $\quad \uparrow S = \frac{(N_s - N\downarrow)}{N_s}\uparrow$



When the slip is '0' the torque is '0' from the torque equ.

In the stable region $s^2 x_2^2$ term is neglible as compared to R_2^2 due to low value of slip. Hence the torque is directly proportional to slip. So initial part of the graph is a straight line.

In unstable region the term R_2^2 is neglible as compared to $s^2 x_2^2$ due to higher value of slip. Therefore the torque is inversely proportional to slip. The curve during the unstable region is rectangular hyperbola. During unstable region the torque developed by the motor is reduced with the increase in load. Always increased load demands increase in torque developed by the motor. Hence this region is called unstable region.

Practically the I.M is operated with a slip of 0 to 10% as shown in the shaded portion of the graph.

Effect of rotor resistance:-

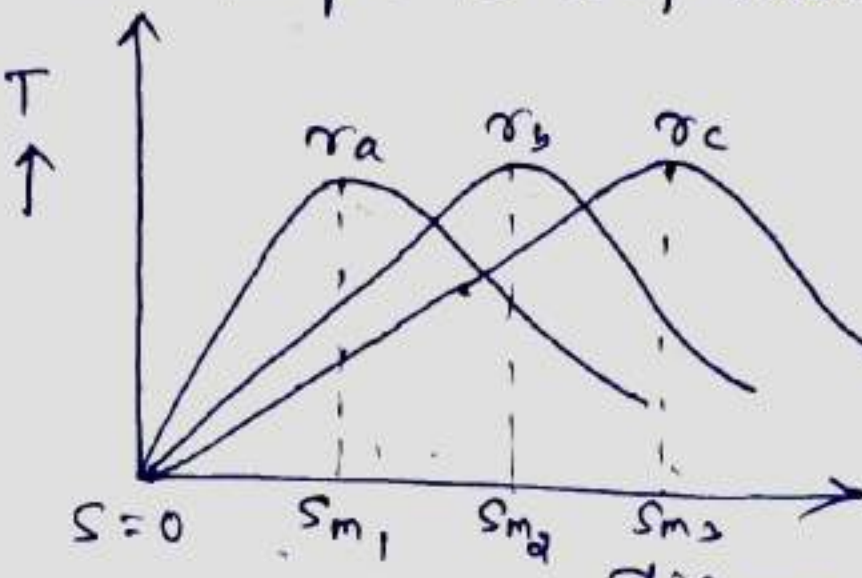
Consider the torque vs slip characteristics

$T \propto r_2$

$$T = \frac{K S E_2^2 r_2}{r_2^2 + (S X_2)^2}$$

$$T_{st} = \frac{K E_2^2 r_2}{r_2^2 + X_2^2}$$

$r_c > r_b > r_a$



From the characteristics the following observations can be made.

(i) The starting torque increases as the resistance of the rotor increases.

$$\boxed{T_{st} \propto \text{Rotor resistance}}$$

$$T_{st_3} > T_{st_2} > T_{st_1}$$

(ii) The slip corresponding to max^m torque increases as rotor resistance increases.

$$\boxed{S_{m_3} > S_{m_2} > S_{m_1}}$$

Relation between Rotor input, rotor output and rotor Cu. loss.

(3)

$$\frac{r_2}{s} = r_2\left(\frac{1}{s}\right) = r_2\left(\frac{1}{s} - 1 + 1\right)$$

$$= r_2\left[\frac{1-s}{s} + 1\right] = r_2\frac{(1-s)}{s} + r_2$$

$$\frac{r_2}{s} = r_2\frac{(1-s)}{s} + r_2$$

multiply throughout by I_r^2

$$I_r^2\frac{r_2}{s} = I_r^2 r_2\frac{(1-s)}{s} + I_r^2 r_2$$

In the above fig. is a R-L series circuit. In a series R-L circuit real power input is equal to the power consumed by the resistance in the circuit. Therefore $I_r^2\frac{r_2}{s}$ represents rotor input power per phase. $I_r^2 r_2$ is the rotor copper loss/phase. Therefore $I_r^2 r_2\frac{(1-s)}{s}$ is equal to gross mechanical power output per phase.

The resistance $r_2\frac{(1-s)}{s}$ represents the mechanical power developed.

Rotor power input = P_i

Rotor out put = P_0

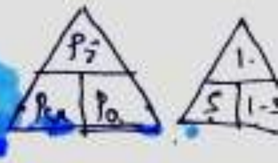
Rotor copper loss = P_{cu}.

$P_i = I_r^2 r_2/s$ W/ph

$P_0 = I_r^2 r_2(1-s)/s$ W/ph. $P_{cu} = I_r^2 r_2$ W/ph

$P_i : P_0 : P_{cu} = I_r^2 \frac{r_2}{s} : I_r^2 r_2 \frac{(1-s)}{s} : I_r^2 r_2$

multiply throughout by $s / I_r^2 r_2$



$P_i : P_0 : P_{cu} = 1 : (1-s) : s$.

$$\boxed{\frac{P_{cu}}{P_0} = \frac{s}{1-s}} \quad \boxed{\frac{P_0}{P_i} = (1-s)} \quad \boxed{\frac{P_{cu}}{P_i} = s}$$

Rotor copper loss = slip × rotor input.

Rotor iron loss is negligible since rotor frequency is very less.

Therefore Rotor input = Rotor output + Rotor cu-loss.

$$\frac{\text{Rotor cu-loss}}{\text{Rotor Input}} = s = \frac{P_i - P_0}{P_i} = \frac{\omega_s - \omega}{\omega_s}.$$

multiply and divide by T

$$\frac{P_i - P_0}{P_i} = \frac{T\omega_s - T\omega}{T\omega_s}$$

Comparing the term of LHS and RHS, mechanical power output is the product of T and ω (similar to D.C. motor). Rotor power input is the product of Torque and ω_s.

<u>Torque developed</u>:-

Let T = Gross torque in N-m/phase

P_i = Rotor input per phase

ω_s = Synchronous speed in radian per second.

s = Absolute value of slip

E_2 = Rotor emf/phase under stand still condition.

... induction motor.

r_2 = Rotor resistance per phase.

x_2 = Rotor reactance per phase under standstill condition.

I_r = Rotor current / phase under running condition.

E_r = Rotor emf / phase under running.

We know that $P_i : P_o : P_{cu} = 1 : (1-s) : s$

$$\frac{P_{cu}}{P_i} = s$$

$$sP_i = P_{cu}$$

$$sT\omega_s = I_r^2 r_2$$

Therefore $T = \dfrac{I_r^2 r_2}{s\omega_s}$

$$T = \frac{1}{s\omega_s}\left(E_r/Z_r\right)^2 r_2$$

$$T = \frac{1}{s\omega_s}\,\frac{s^2E_2^2}{r_2^2+s^2x_2^2}\,r_2$$

$$T = \frac{sE_2^2 r_2}{r_2^2+s^2x_2^2} \times \frac{1}{\omega_s} \quad N\text{-}m/\text{phase}.$$

$K = \dfrac{1}{\omega_s}$ or $K = \dfrac{60}{2\pi N_s}$

$$\boxed{T = \frac{K s E_2^2 r_2}{r_2^2+s^2x_2^2}} \quad N\text{-}m/ph$$

Condition for maxm Starting Torque:-

We know that, $T = \dfrac{KsE_2^2 r_2}{r_2^2 + s^2 x_2^2}$

maxm starting torque condition can be obtained by differentiating starting torque with respect to r_2.

This is because the starting torque can be varied by varying the resistance in the rotor circuit.

If $s = 1$, $T = T_{st}$

$$T_{st} = \frac{KE_2^2 r_2}{r_2^2 + x_2^2}$$

Condition for maxm starting torque $\dfrac{dT_{st}}{dr_2} = 0$

$$\frac{d}{dr_2}\left(\frac{KE_2^2 r_2}{r_2^2 + x_2^2}\right) = 0$$

$\dfrac{d}{dr_2}\left(\dfrac{u}{v}\right) = 0 \Rightarrow \dfrac{v\,du - u\,dv}{v^2} = 0$

$v\,du - u\,dv = 0$

$v\,du = u\,dv$

$$(r_2^2 + x_2^2)\,KE_2^2 = KE_2^2 r_2 \cdot 2r_2$$

$$r_2^2 + x_2^2 = 2r_2^2$$

$$r_2^2 = x_2^2$$

$$\boxed{r_2 = x_2}$$

Condition for maxm Torque under running:-

$$T = \frac{KsE_2^2 r_2}{r_2^2 + s^2 x_2^2}$$

When load on the motor varies speed varies and slip varies.

Condition for maxm torque,

$\dfrac{dT}{ds} = 0$, because slip is variable.

... induction motor.

(5) $\frac{dT}{ds} = 0$, because slip is variable. (4)

$$(r_2^2 + s^2 x_2^2) K E_2^2 r_2 = (K s E_2^2 r_2) 2s x_2^2$$

$$r_2^2 + s^2 x_2^2 = 2s^2 x_2^2$$

$$r_2^2 = s^2 x_2^2$$

$$\boxed{r_2 = s x_2}$$

If $s = s_m$, $T = T_m$

or if $r_2 = s x_2$, $T = T_m$

$$T_m = \frac{K s E_2^2 (s x_2)}{s^2 x_2^2 + s^2 x_2^2} = \frac{K s^2 E_2^2 x_2}{2 s^2 x_2^2}$$

$$\boxed{T_m = \frac{K E_2^2}{2 x_2}}$$

$$\boxed{T_{st} = \frac{K E_2^2 r_2}{r_2^2 + x_2^2}}$$

$S_m = r_2 / x_2$. Therefore Location of max^m torque point depends on the value of r_2. But magnitude of max^m torque is independent of r_2 since $T_{max} = \frac{K E_2^2}{2 x_2}$.

$$T - T_{sh} = T_l$$

multiply with ω

$(T - T_{sh}) \omega = T_l \omega$ where T = Gross torque

T_{sh} = Shaft torque or Load torque.

Gross rotor o/p − Net rotor o/p = mechanical losses.

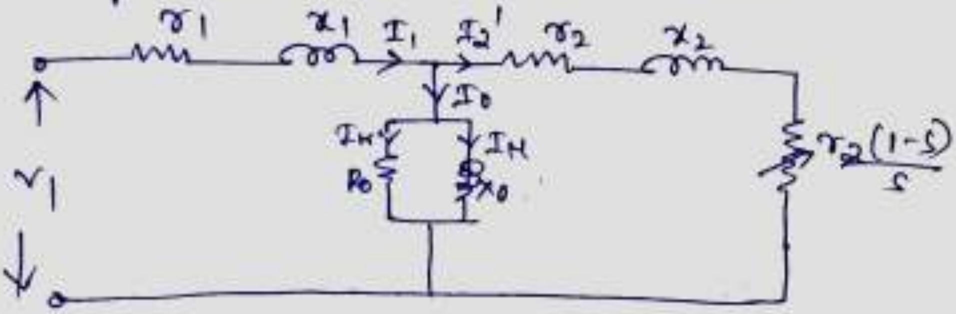
$T - T_{sh}$ = Torque lost due to friction and windage (T_l).

Representation of mechanical power developed in the Equivalent Circuit:-

The resistance $\frac{r_2}{s}$ in the equivalent circuit can be represented as follows.

$$\frac{r_2}{s} = \frac{r_2}{s}(1-s) + r_2 \quad \text{—} (1)$$

The equivalent circuit now becomes



multiplying eqn (1) by I_r^2, we get,

$$\frac{I_r^2 r_2}{s} = I_r^2 \frac{r_2(1-s)}{s} + I_r^2 r_2$$

where $\frac{I_r^2 r_2}{s}$ represent rotor input.

$I_r^2 r_2$ represents rotor losses

$I_r^2 \frac{r_2(1-s)}{s}$ represents the mechanical power developed.

$$P_m = I_r^2 r_2 \frac{(1-s)}{s}$$

mechanical power developed under standstill condition is $P_m = 0$ (because $s = 1$)

mechanical power developed when rotor runs at synchronous speed is

$$P_m = \infty \quad (\text{because } s = 0)$$

Ratios of torques:-

consider the following expression

Full load torque (T_{fl}), $T_{fl} = \frac{KsE_2^2 r_2}{r_2^2 + s^2 x_2^2}$ — (1)

Starting torque (T_{st}), $T_{st} = \frac{KE_2^2 r_2}{r_2^2 + x_2^2}$ — (2)

maximum torque (T_m), $T_m = \frac{KE_2^2}{2x_2}$ — (3)

(1) T_{st}/T_m

$$\frac{T_{st}}{T_m} = \frac{KE_2^2 r_2}{r_2^2 + x_2^2} \times \frac{2x_2}{KE_2^2} = \frac{2r_2 x_2}{r_2^2 + x_2^2}$$

dividing both Nr & Dr by x_2^2

$$\frac{T_{st}}{T_m} = \frac{2r_2 x_2 / x_2^2}{\frac{r_2^2}{x_2^2} + \frac{x_2^2}{x_2^2}} = \frac{2\, r_2/x_2}{\left(\frac{r_2}{x_2}\right)^2 + 1}$$

but $r_2/x_2 = S_m = a$ i.e. slip corresponding to maximum torque.

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

(2) T_{fl}/T_m

$$\frac{T_{fl}}{T_m} = \frac{KsE_2^2 r_2}{r_2^2 + s^2 x_2^2} \times \frac{2x_2}{KE_2^2} = \frac{2s r_2 x_2}{r_2^2 + s^2 x_2^2}$$

dividing both Nr & Dr by x_2^2

$$\frac{T_{fl}}{T_m} = \frac{2s r_2 x_2 / x_2^2}{\frac{r_2^2}{x_2^2} + \frac{s^2 x_2^2}{x_2^2}} = \frac{2s\, r_2/x_2}{\left(\frac{r_2}{x_2}\right)^2 + s^2}$$

but $r_2/r_1 = a$

$$\boxed{\frac{T_{fl}}{T_m} = \frac{2as}{a^2+s^2}}$$

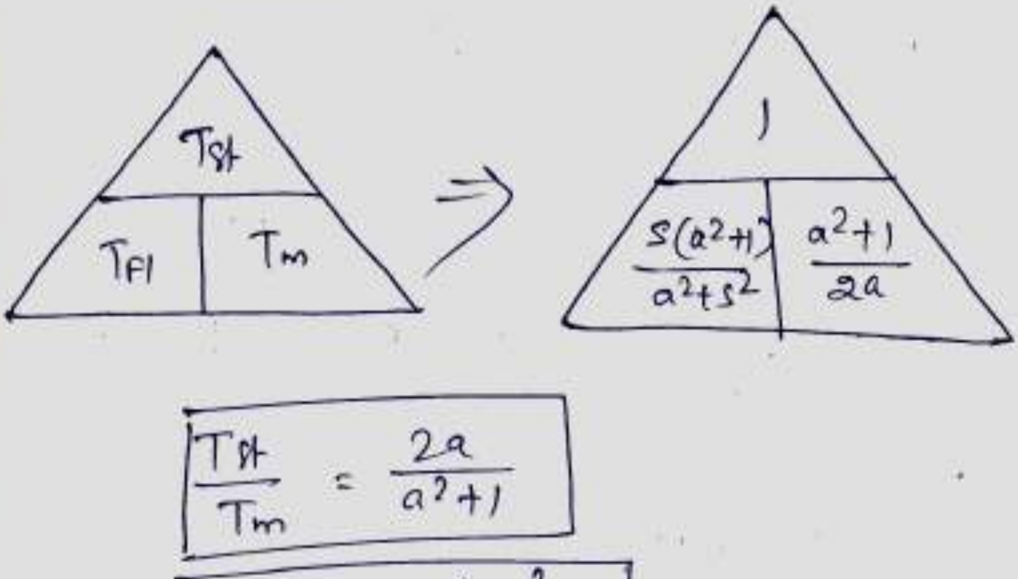
(3) T_{st}/T_{fl}

$$\frac{T_{st}}{T_{fl}} = \frac{T_{st}}{T_{fl}} \times \frac{T_m}{T_m}$$

$$= \left(\frac{T_{st}}{T_m}\right) \times \left(\frac{T_m}{T_{fl}}\right)$$

$$\frac{T_{st}}{T_{fl}} = \frac{2a}{a^2+1} \times \frac{a^2+s^2}{2as}$$

$$\boxed{\frac{T_{st}}{T_{fl}} = \frac{a^2+s^2}{s(a^2+1)}} \text{ or } \frac{T_{fl}}{T_{st}} = \frac{s(a^2+1)}{a^2+s^2}$$

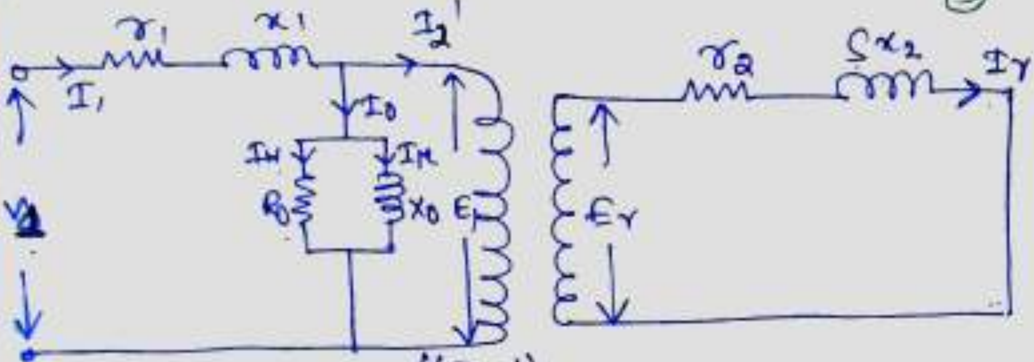


$$\boxed{\frac{T_{st}}{T_m} = \frac{2a}{a^2+1}}$$

$$\boxed{\frac{T_{st}}{T_{fl}} = \frac{a^2+s^2}{s(a^2+1)}}$$

$$\boxed{\frac{T_{fl}}{T_m} = \frac{2as}{a^2+s^2}}$$

Equivalent circuit of 3-Φ induction motor.



(fig-1)

$r_1 \rightarrow$ stator resistance

$x_1 \rightarrow$ stator leakage reactance.

$I_w \rightarrow$ wattfull component of no load current I_0

$I_\mu \rightarrow$ magnetizing component of no load current I_0

$X_0 \rightarrow$ pure inductance and $R_0 \rightarrow$ pure non inductive resistance.

$I_2' \rightarrow$ Reflected current

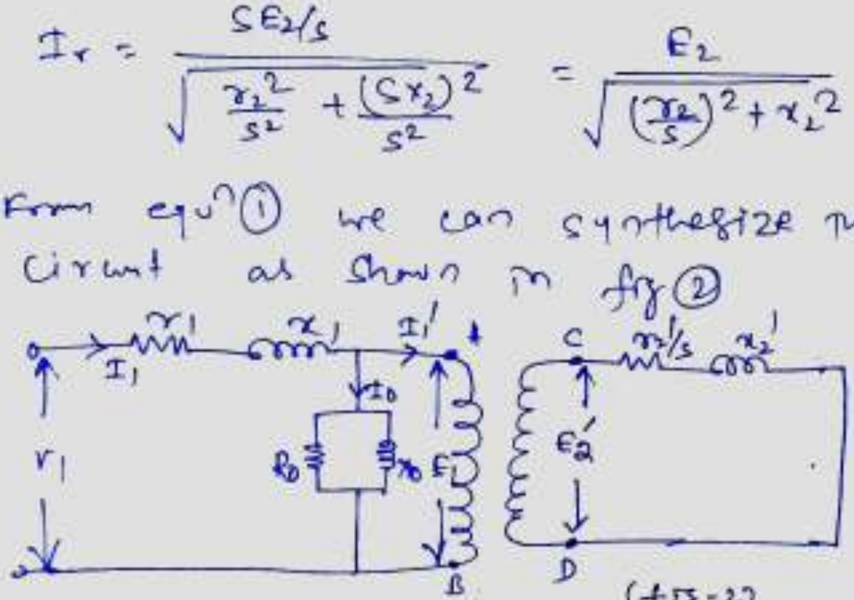
$I_r = \frac{E_r}{Z_r}$ & $I_2 = \frac{E_2}{Z_2}$

$$I_r = \frac{sE_2}{\sqrt{r_2^2 + (sx_2)^2}} \quad \text{or} \quad \left(I_2 = \frac{sE_2}{\sqrt{r_2^2 + (sx_2)^2}}\right)$$

Divide by s on both N_r & D_r

$$I_r = \frac{sE_2/s}{\sqrt{\frac{r_2^2}{s^2} + \frac{(sx_2)^2}{s^2}}} = \frac{E_2}{\sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} \quad \text{—(1)}$$

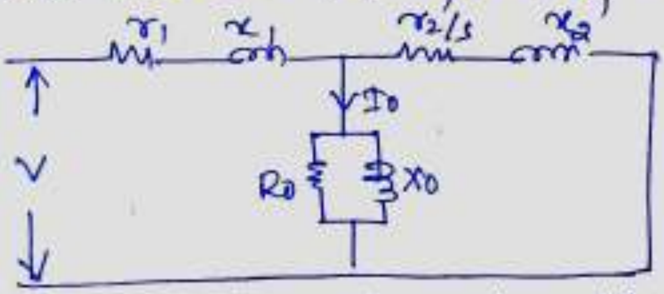
From equ^n (1) we can synthesize the motor circuit as shown in fig (2)



(fig-2)

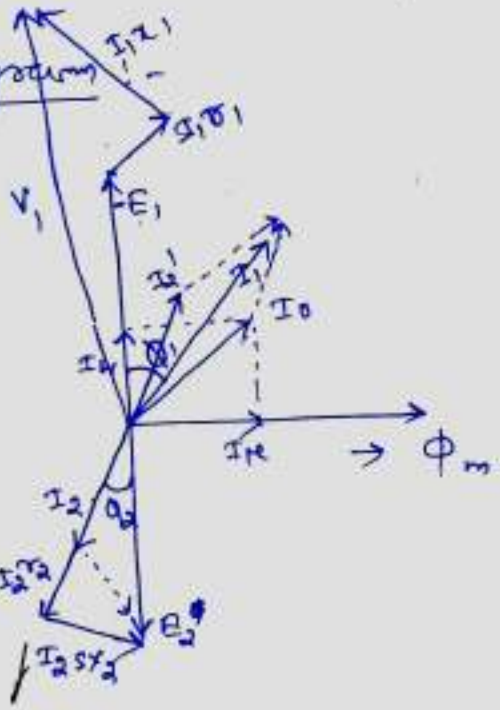
r_2', x_2' and E_2' are rotor resistance, rotor inductance and emf referred to stator circuit.

The point A and C, B and D are the same potential as $E_1 = E_2'$. Therefore they can be electrically connected in accordance with Steinmetz theorem. The resulting circuit obtained is,



(Exact equivalent ckt.)

Phasor diagram

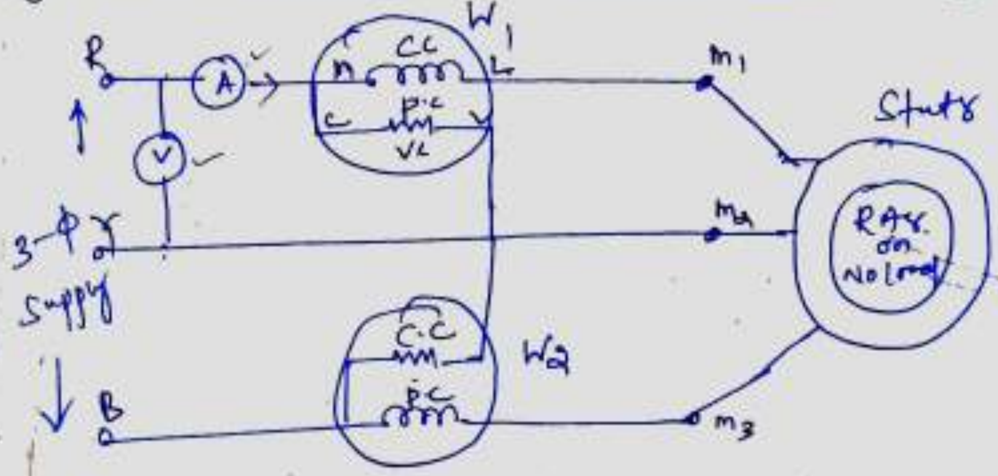


$$V_1 - I_1(r_1 + jx_1) = E_1$$

$$V_1 = E_1 + I_1(r_1 + jx_1)$$

(6)

Open circuit test or No-load test:-



The aim of this test is to determine the rotational and core-losses and constants R_0 and X_0 of the equivalent circuit. The stator is fed by 3-Φ rated voltage supply. The rotor is allowed to rotate freely without any external mechanical load on the shaft. The power input is measured by 2 wattmeter method. Since the motor is not supplying any load, the no load current is small and Cu-loss are negligible. The input is equal to mechanical and core losses. The no load power factor is low (less than 0.5) (because I_m is much larger than I_w). Therefore it is usually necessary to reverse the current coil or voltage coil connections of the wattmeter reading negative. In such a case the difference of wattmeter readings is input power W_0.

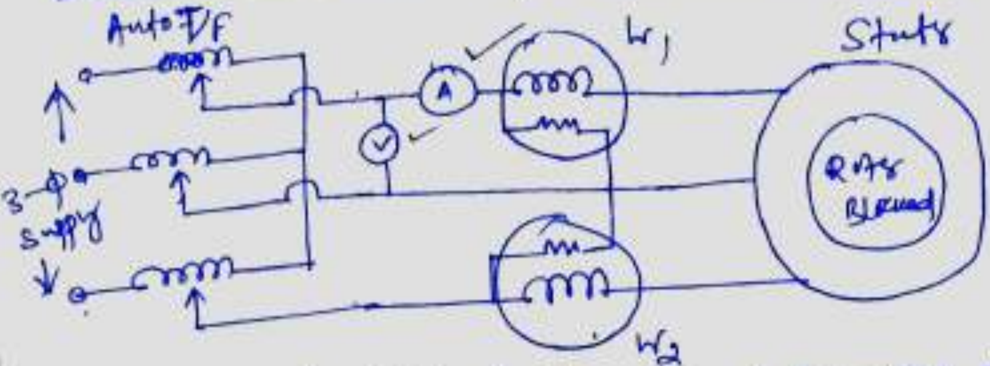
Let voltage and current per phase be V_0 & I_0. Then no load power factor $\cos\phi_0$ is

$$\cos\phi_0 = \frac{W_0}{3V_0 I_0} \qquad W_0 = 3V_0 I_0 \cos\phi_0$$

$$R_0 = \frac{V_0}{I_w} = \frac{V_0}{I_0\cos\phi_0}$$

$$X_0 = \frac{V_0}{I_\mu} = \frac{V_0}{I_0\sin\phi_0}$$

Short circuit test or Blocked Rotor test:-



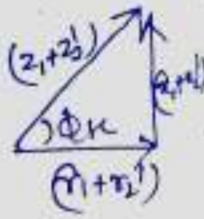
The aim of this test is to determine the winding resistance i.e. $(r_1 + r_2') = R_{01}$ and leakage reactance $(x_1 + x_2') = x_{01}$. It is similar to the short circuit test on a transformer. The motor of the rotor is blocked by a break. A low voltage 3-φ supply (obtained from a 3-φ auto-T/F) is applied to the stator. The magnitude of applied voltage is adjusted, so that the ammeter reads rated line current of stator. The power I/p is measured by the two wattmeters. (In this case the power factor is usually less than 0.5 and it may be necessary to reverse either current coil or potential coil connections of the wattmeter reading negative)

Let W_{sc} be the total power I/p and V_{sc} & I_{sc} be the per phase value of applied voltage and current.

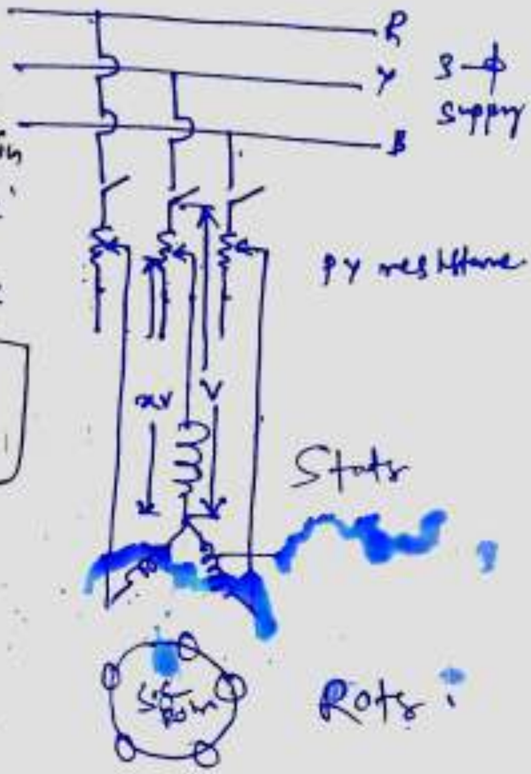
$$\cos\phi_{sc} = \frac{W_{sc}}{3 V_{sc} I_{sc}}$$

$$r_{01} = r_1 + r_2' = \frac{V_{sc}}{I_{sc}} \cos\phi_{sc}$$

$$x_{01} = x_1 + x_2' = \frac{V_{sc}}{I_{sc}} \sin\phi_{sc}$$



(2) Stator resistance Starter:-



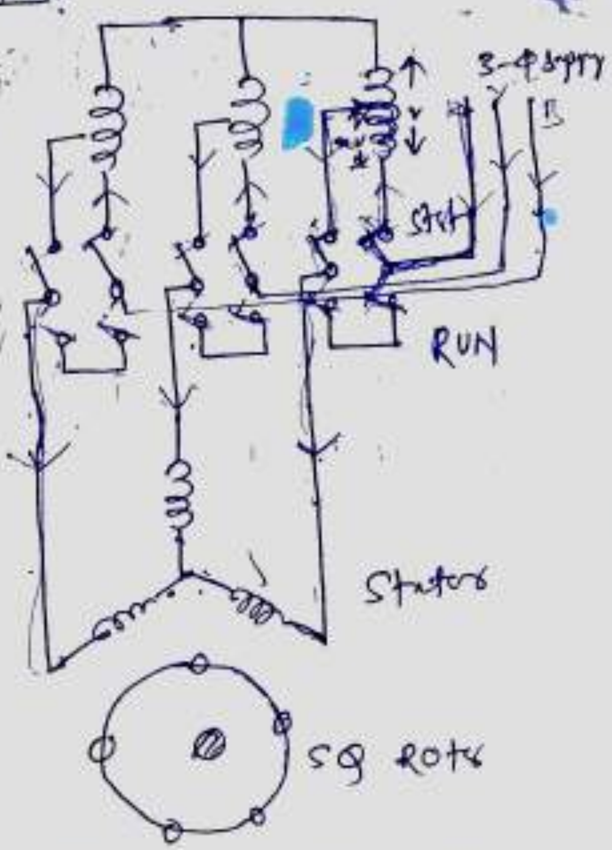
Let by using primary resistor the applied voltage/ph is reduced by a fraction 'x'

Starting current $I_{st} = x \cdot I_{sc}$

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

$x < 1$

(3) Autotransformer Starter



Starting current $I_{st} = K I_{sc}$

$K < 1$

$$\frac{T_{st}}{T_f} = K^2 \left(\frac{I_{sc}}{I_f}\right)^2 s_f$$

① **D.O.L Starter** at full load $T = T_f$

$I_2 = I_f$, $s = s_f$, $T_f \propto \frac{I_f^2}{s_f}$ — ⓑ

$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$

at starting $T = T_{st}$

$I_2 = I_{st} = I_{sc}$

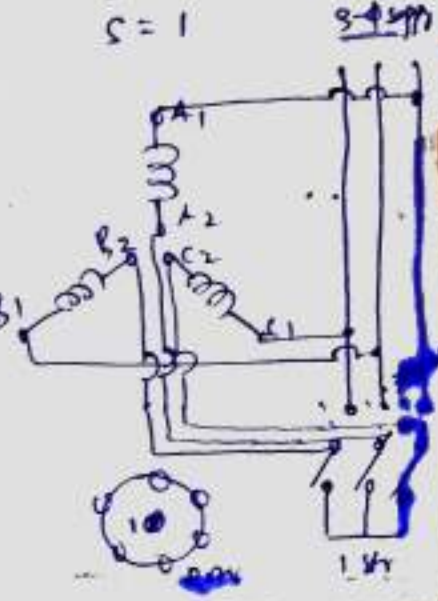
$s = 1$

$T_{st} \propto I_{st}^2$ — ⓐ

④ **Star-delta starter:-**

Starting current $I_{st} = \frac{1}{\sqrt{3}} I_{sc}$

$$\frac{T_{st}}{T_f} = \frac{1}{3}\left(\frac{I_{sc}}{I_f}\right)^2 s_f$$



(*)
$$\frac{T_{st}}{T_{fl}} = K^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

For DOL starter, $K = 1$

For Y-Δ starter, $K = \frac{1}{\sqrt{3}}$

For Auto T/F starter, $K = 0$ to 1 (tapping)

Losses

- Fixed losses
  - Core loss
  - Friction & windage loss
- Variable loss
  - Stator cu-loss
  - Rotor cu-loss

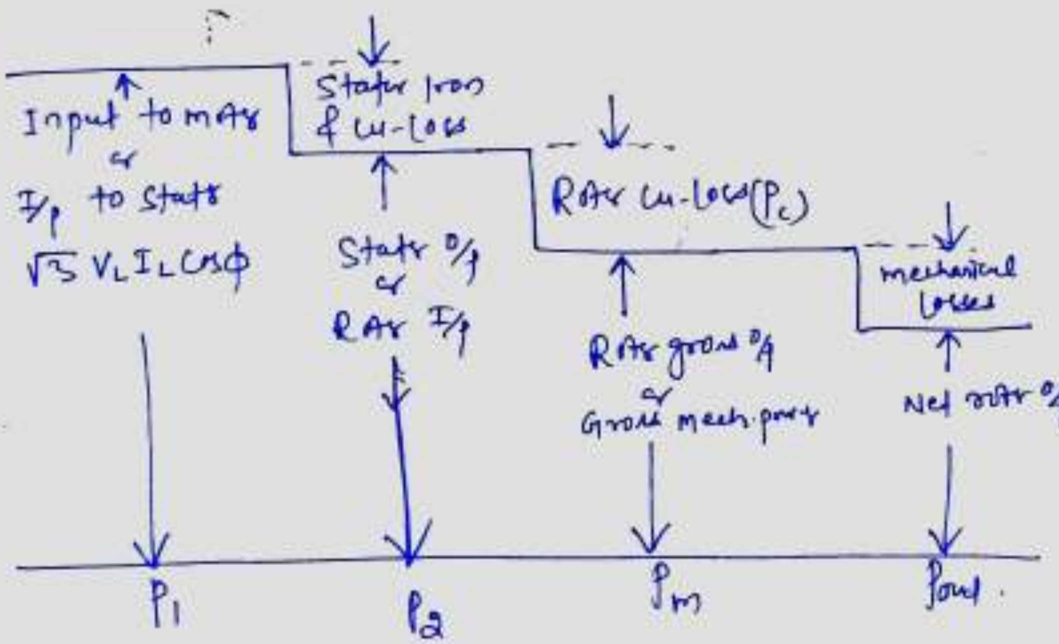
Efficiency:-

$$\eta = \frac{P_{sh}}{P_{sh} + P_f + P_{cu}} \times 100 \qquad \boxed{\eta = \frac{P_{out}}{P_{in}}}$$

$$\eta = \frac{P_{out}}{P_{out} + Loss}$$

$$\eta = \frac{P_{out} \text{ or } P_{sh}}{P_{out} \text{ or } P_{sh} + \text{Fixed Loss} + P_{cu}} \times 100$$

Power stages in an Induction motor :-



Note: since rotor frequency is very less in comparision with supply frequency, the iron loss becomes very less. Due to least amount of iron loss it is neglected in the motor.

Induction Generator:-

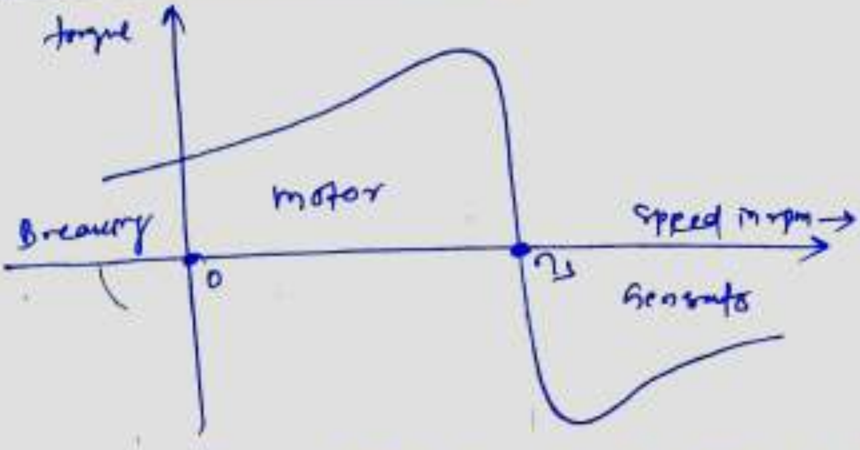


Figure shows the complete torque-speed curve of an induction m/c for all ranges of speed. If the m/c is driven at a speed greater than synchronous speed by a prime mover, the direction of induced torque reverses and it acts as an induction generator. As seen by the torque-speed curve, there is a maximum torque which can be induced when it is acting as a generator (Just as in motoring mode the max^m torque or pullout torque exists). If the prime mover applies a torque greater than this maximum value, the m/c will over speed.

The RMF in an IM is set up by the magnetising current drawn from the mains. Even when the speed of the m/c is above synchronous speed and it is acting as a generator, this magnetising current must be available. Thus an induction generator is not self ~~starting~~ exciting, but must be operated in parallel with another generator which can supply its magnetising current.

Cogging:- (Inter locking)

When no. of stator slots (or teeth) is equal to the no. of rotor slots (or teeth) the no. of poles produced in stator becomes equal to the no. of rotor poles. Hence the rotor interlocks magnetically with stator and the motor refuses to start.

Remedy:- No. of stator teeths > No. of rotor teeth

Crawling:-

The torque produced due to harmonic flux opposes the main field torque., so that the I.M runs at a speed less than the rated speed. This phenomena is called crawling.

Effect of harmonic

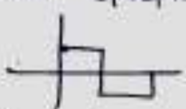
(i) Harmonic field is produced
(ii) Harmonic torque is developed
(iii) Noise is created.
(iv) voltage ripple (small waveform) are formed.

Remedies for harmonics

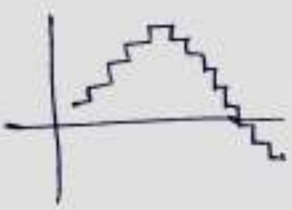
(i) By using integral slot winding (If $q = \frac{S_s}{m \times p} = \text{integer}$)
(ii) By using short pitch winding
(iii) By providing skewed slot
(iv) By increasing air gap length.

Harmonics < Time harmonics / Space harmonics (crawling)

Time harmonics:- o/p from power electronics inverters
e.g. inverter

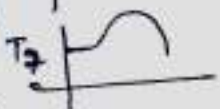


Space harmonics:- Flux wave form is never sine wave but it should be.



space between stator & rotor is not uniform.
∴ Flux wave form is distorted.
∴ we have space harmonic.

T_1 → Torque due to 1st harmonic.



T_7 → Torque due to 7th harmonic.

Torque produced by higher order harmonic is negligible.

T → Resultant torque

In Resultant torque there are two stable points. Cage motors have this kind of tendency of crawling. (i.e. IM is loaded it will be having speed, increases then decreases.

I.m running at $\frac{1}{7}$th of synchronous speed is called crawling.

Induction generator:-

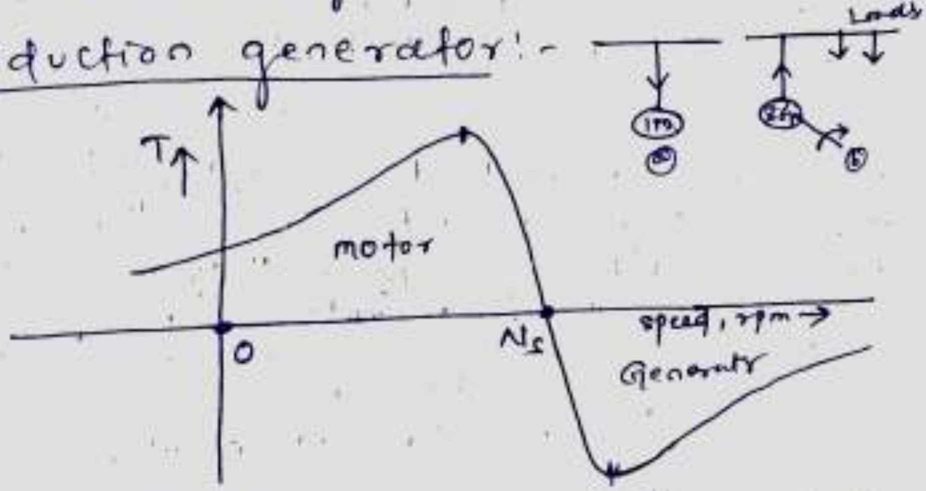


Figure shows the complete torque-speed curve of an [illegible] induction machine for all ranges of speed. If the m/c is driven at a speed greater than synchronous speed by a prime mover, the direction of induced torque reverses and it acts as an induction generator. As seen by the torque speed curve, there is a max^m torque, which can be induced when it is acting as a generator (just as in motoring mode the max^m torque or pull out torque exists) If prime mover applies a torque greater than this max^m value, the m/c will over speed.

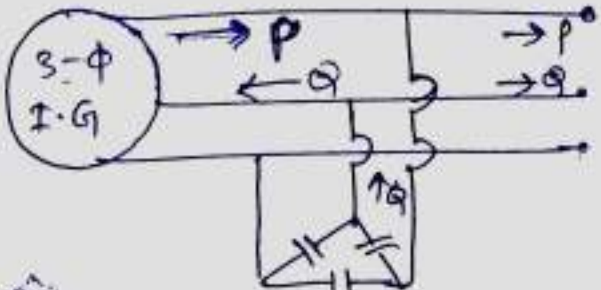
The rotating magnetic field in an I.M is set up by the magnetising current drawn from the mains. Even when the speed of the m/c is above synchronous speed and it is acting as a generator, this magnetising current must be available. Thus an Induction generator is not self-starting, but must be operated in parallel with another generator which can supply its magnetising current.

An Induction generator has many limitations. Since it does not have a field circuit, it can not produce reactive power. Rather it consumes reactive power because the magnetising current must be supplied to it. It can not control its output voltage. Normally the generators o/p voltage is maintained by the external power system connected ~~at~~ to it.

(*) Synchronous generator supplies both Reactive & active power.

(*) <u>Induction generators</u> gives active power but needs reactive power.

Isolated operation of Induction generator is not possible because it needs reactive power. We can do this if we use <u>capacitor bank</u>.



Capacitor bank.

Single Phase Induction Motor

The construction of this motor is almost similar to 3-ϕ Induction motor except that the stator is having a single phase winding. The rotor is similar to the rotor of a 3-ϕ squirrel cage induction motor. The rotor bars are short circuited by end rings. When 1-ϕ a.c. voltage is applied to the stator winding, an alternating flux is produced. During the positive half cycle, the flux induce a voltage in the rotor and the resulting current produce a torque. The rotor tends to rotate in one direction. During the negative half cycle, the torque produced tends to rotate the rotor in opposite direction. Because of the inertia of the rotor, the rotor cannot rotate in any direction. That is why the 1-ϕ induction motor is not self starting.

The working principle of 1-ϕ induction motor can be understood by using double field revolving theory.

DOUBLE FIELD REVOLVING THEORY

When the emf follows sine law, the flux follows co-sine law given by $\phi = \phi_m \cos wt$

We know that

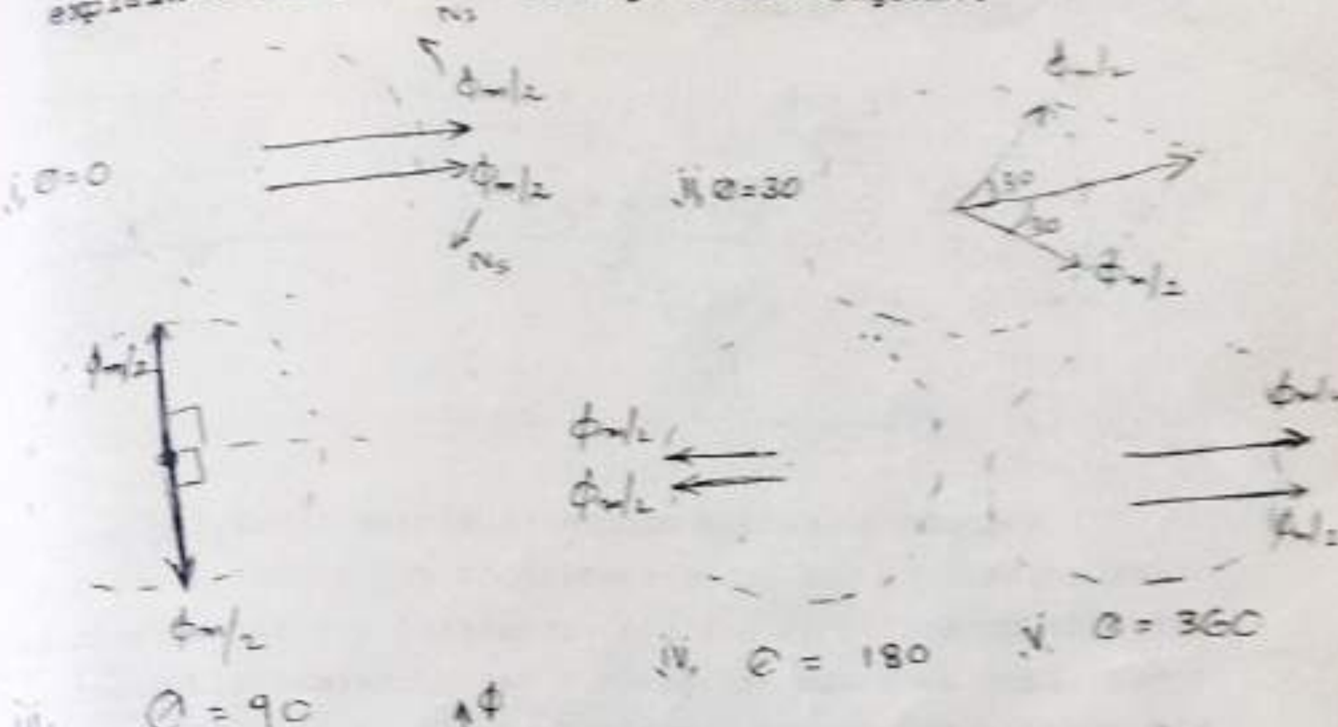
$$\cos wt = \frac{e^{jwt} + e^{-jwt}}{2}$$

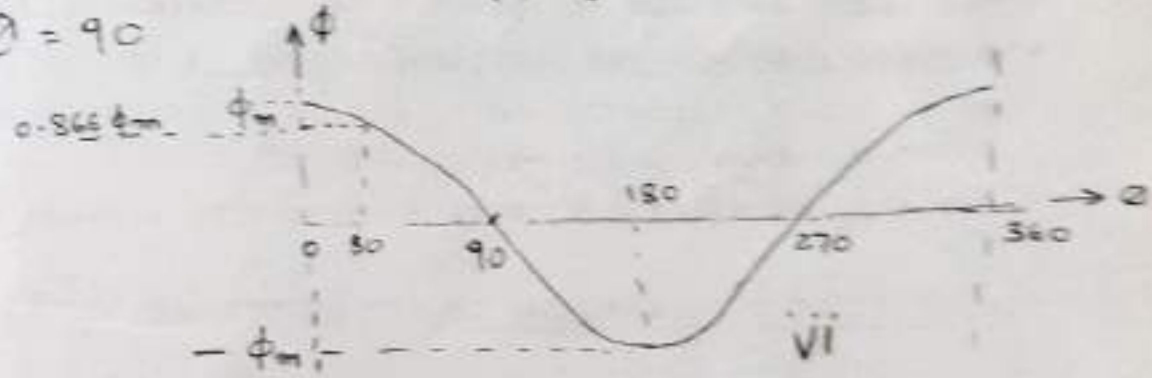
$$\phi = \phi_m \left(\frac{e^{jwt} + e^{-jwt}}{2}\right)$$

$$\phi = \frac{\phi_m}{2} e^{jwt} + \frac{\phi_m}{2} e^{-jwt} \quad \ldots$$

Hence an alternating flux can be represented by two rotating fluxes, each equal to half the value and each rotating synchronously in opposite direction.

The resultant flux at different values of θ are explained using the following vector diagrams.





When θ = 0, resultant flux = $\frac{\phi_m}{2} + \frac{\phi_m}{2} = \phi_m$ as shown in Fig.(i). When θ = 30, $\phi = 2 \times \frac{\phi_m}{2}$ Cos 30 = 0.866 ϕ_m as shown in Fig.(ii). At θ = 90, resultant flux is zero as shown in Fig.(iii). At θ = 180; $\phi = -\phi_m$ and θ = 360, $\phi = \phi_m$ as shown in Figs. (iv) and (v). The graph drawn with flux on y-axis and θ on x-axis is nothing but a cosinisoidal curve as shown in Fig.(vi).

If the actual speed of rotor is N RPM, then the slip with respect to forward rotating flux is S_f.

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

The backward rotating field rotates in a direction opposite to the direction of the rotor. Hence the speed should be taken as -N.

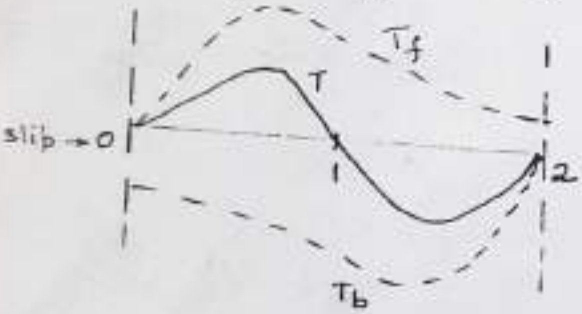
$$S_b = \frac{N_s - (-N)}{N_s} = \frac{N_s + N}{N_s}$$

$$= \frac{N_s + N - N_s + N_s}{N_s} = \frac{2 N_s - (N_s - N)}{N_s}$$

$$= 2 - \frac{N_s - N}{N_s}$$

$$S_b = 2 - S$$

Anticlockwise and clockwise fluxes revolving round the stator cut the rotor conductors and induce a voltage in the rotor. This voltage circulates a rotor current as the rotor is short circuited. The forward field produces forward torque and backward field produce backward torque. The resultant torque is the difference of T_f and T_b since T_f and T_b are in opposite directions.



We know that

Slip x rotor I.P. = rotor cu loss

$$S \times \frac{2 \pi N_s T}{60} = I_2^2 R_2$$

$$S \times T = \frac{60}{2 \pi N_2} I_2^2 R_2$$

$$T = \frac{K I_2^2 R_2}{S_f} \; ; \; T_f = \frac{K I_2^2 R_2}{S}$$

$$T_b = \frac{K I_2^2 R_2}{2 - S}$$

$$T = T_f - T_b = \frac{K I_2^2 R_2}{S} - \frac{K I_2^2 R_2}{2-S}$$

$$T = K I_2^2 R_2 \left(\frac{1}{S} - \frac{1}{(2-S)}\right) \quad \ldots (1)$$

At stand still condition, S = 1, sub. S = 1 in Eq.(1) $T_{st} = 0$. Thus the 1-Ø Induction motor is not self starting.

If the rotor is rotated in clockwise direction, S↓ and T_f↑ and T_b↓. Hence there is a resultant torque in clockwise direction. If the rotor is rotated in backward direction, there is a resultant torque in anticlockwise direction. The 1-Ø I.M. rotates in the direction in which it is made to rotate.

Types of Induction Motors

(1) Split phase resistance start induction motor.
(2) Split phase capacitor start induction motor.
(3) Permanent split capacitor induction motor.
(4) Shaded pole Motor.

1. Split Phase Resistance Start Induction Motor

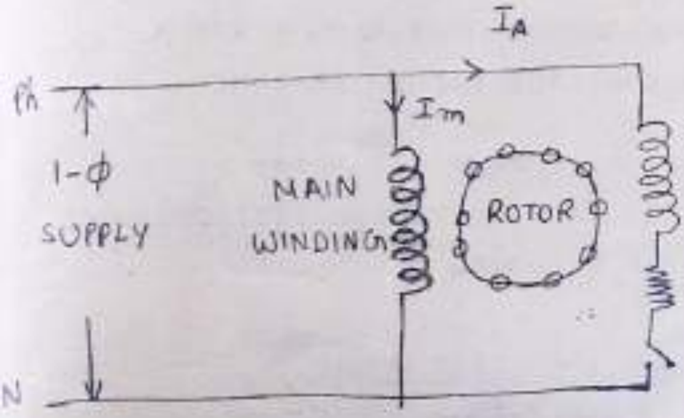


Fig (8)

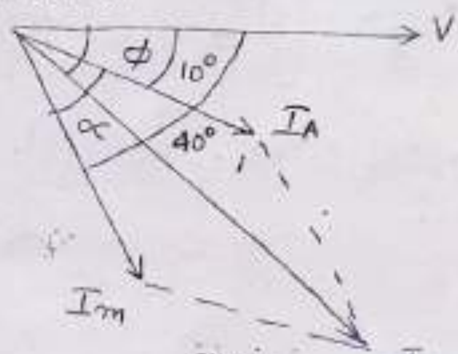


FIG 9

In a split phase Induction Motor, the stator is provided with two parallel windings displaced in space by 90°. Fig.8 shows the windings of the split phase Induction Motor. The starting winding or Auxiliary winding has less turns of smaller diameter to make the winding more resistive. ($R\uparrow = \frac{\rho l}{A\downarrow}$). The running or main winding has thicker turns and a large number of turns to make the winding more inductive ($L\uparrow = \frac{N^2\uparrow}{S}$)

The vector diagram shows the phase relations of starting winding current I_A & current through main winding I_m. The resistance of the starting winding is increased by connecting a high resistance R in series with it. Hence the current I_A lags behind V by angle of 10°. The current I_m lags behind the voltage V by a large angle (40°). The two currents I_A and I_m displaced by an angle 30° produce a Rotating Magnetic Field (RMF) in the stator. This RMF cuts the rotor conductors. A voltage is induced in the rotor winding. This voltage circulate a current in the rotor conductors. The current carrying rotor conductors experience a force and rotate in the direction of RMF.

After the motor reaches 75% of the rated speed, the switch connected in series with the starting winding is disconnected. Thus the starting winding is connected only at the time of starting. The torque developed $\propto \sin\alpha$. Since α is around 30°, the starting torque is less.

Disadvantages: (1) Low starting torque (2) Noisy.

Applications : (i) Oil burners, (ii) Machine Tools, (iii) Grinders (iv) Washing Machines, (v) Air blowers.

2. Split Phase Capacitor Start Induction Motor

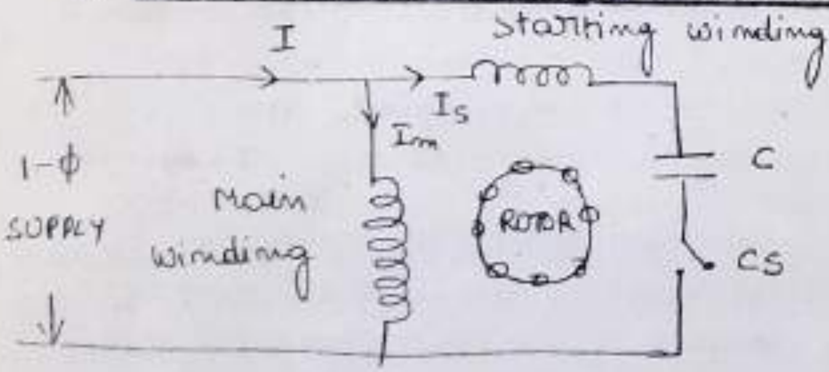


FIG:10

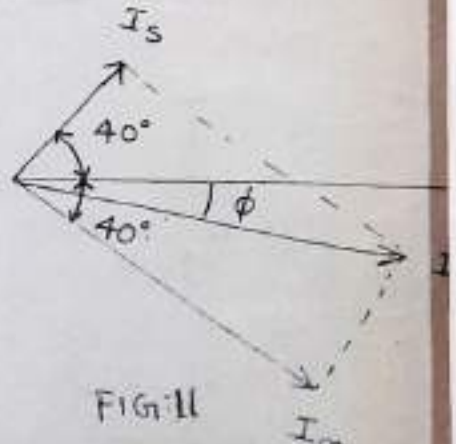


FIG:11

In this motor, a capacitor is connected in series with the starting winding. Therefore the current in the starting winding will lead the applied voltage. The current through the main winding is lagging the voltage by an angle of 40° as shown in Fig.11. The angle (α) between currents I_m and I_s is 80°. The torque is proportional to sin α. Since α is large, starting torque is large for this motor. The power factor angle ϕ is less when compared with resistance split phase motor. The power factor of the capacitor split phase motor is improved. The starting torque of this motor is 3 to 4.5 times the full load torque. Once the motor reaches 75% of rated speed, the centrifugal switch (CS) opens and disconnects the starting winding from the circuit.

Applications: 1) Pumps, (2) Compressors, (3) Refrigerators (4) Air-conditioners (5) Washing Machines.

3. Permanent Split Capacitor Induction Motor

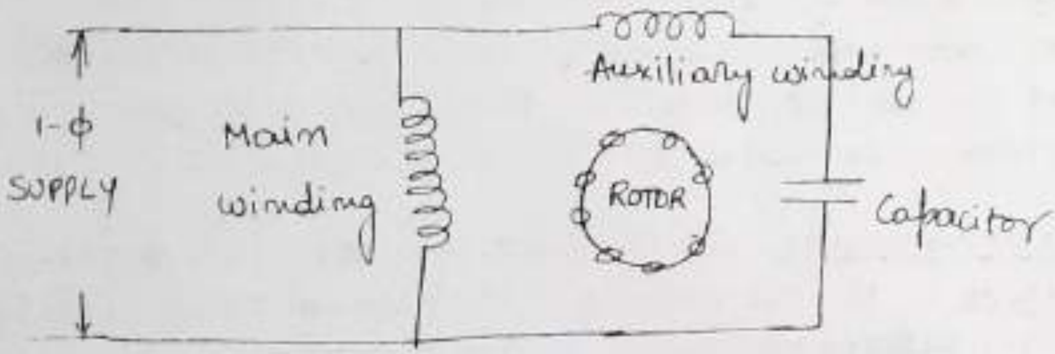


FIG: 12

In this motor, the capacitor connected in series with the auxiliary winding is used ~~in both~~ for starting and running conditions. Since the motor runs continuously with the capacitor, centrifugal switch is not required. The advantages of this motor are (1) increased overload capacity (2) Higher power factor (3) Higher η (4) Reduced noise. The motor behaves like a 2- ϕ Induction Motor. The capacitor used in this motor must be designed for continuous duty. The capacitor used is an oil filled capacitor. The noise is reduced because the motor produces a uniform RMF. This motor is costlier than the split phase capacitor motor as the auxiliary winding has to be designed for continuous duty.

Applications: (1) Exhaust fans, (2) Blowers, (3) Office Machines.

4. Shaded Pole Induction Motor

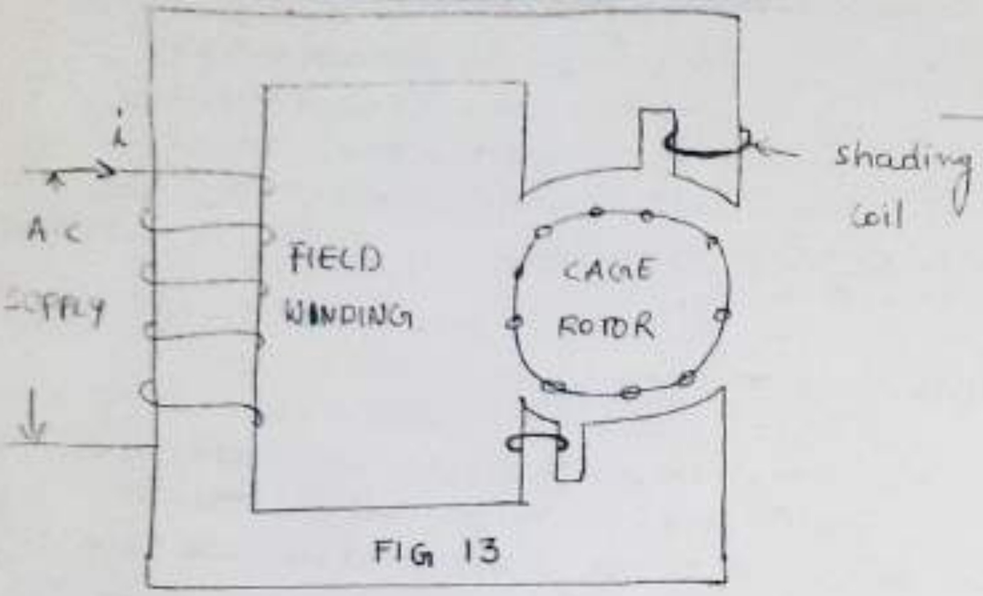


FIG 13

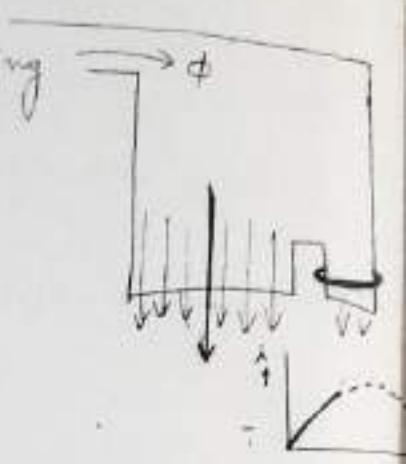


FIG 14a

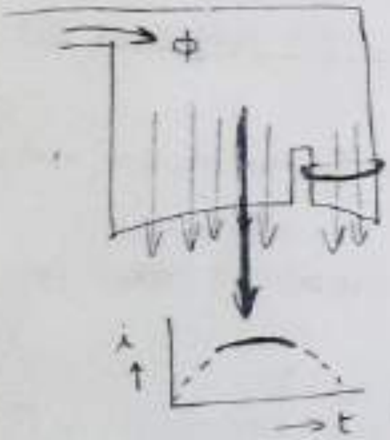


FIG 14b

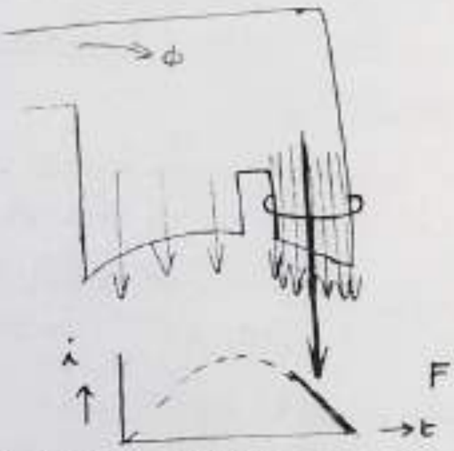


FIG 14c

This motor has salient poles in stator and squirrel cage type rotor. The pole is cut at 1/3rd distance from one edge. A thick short circuited copper coil (or band) is provided on the smaller part of the pole. This part is called shaded part and the coil is called shading coil.

Principle: When an alternating current is passing though the field winding, the axis of the field will be moving from unshaded part to the shaded part.

Consider the first 1/3rd of the positive half cycle shown in Fig.14(a). The alternating current through the coil is increasing. The flux due to this current induce a voltage in the shading coil. A current circulates in shading coil since the coil is short circuited. This produce a flux in a direction opposite to the main flux according to Lenz's law. The flux in the shaded part is decreased. The field axis will be at the centre of the unshaded part.

In Fig.14(b), the line current has reached the max. value. The flux is also maximum. There is no change in flux. There is no current in the shading coil. The flux is uniformly distributed across the entire pole. The field axis is shifted to centre of the pole.

Consider the last 1/3rd of the positive half cycle as shown in Fig.14(c). The line current is decreasing. The induced flux opposes the cause of creation. Main flux is the cause of creation of induced voltage. Since main flux is decreasing, induced flux will be increasing. This induced flux concentrate in the shaded portion. The flux in the shaded portion gets weaker as the line current is decreasing. The field axis is shifted to the centre of the shaded portion.

Thus the pole shading create a RMF in the stator and the rotor rotate in the direction of RMF.

Merits: (1) Rugged construction, (2) Chaper (3) Small in size (4) Less maintenance.

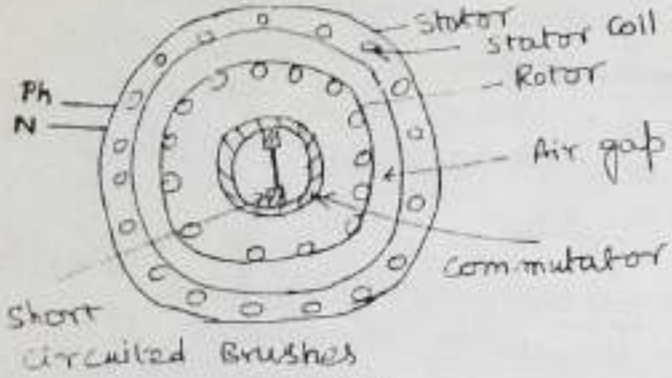
Demerits: (1) Low T_{st} (2) Low η (3) Low Pf

Uses: (1) Motion picture projectors, (2) Small fans (3) blowers, (4) toys, (5) hair dryers, (6) ventilators, (7) Electric clocks.

Repulsion Motor

A repulsion motor is a 1-ϕ motor having a stator winding connected to supply and a rotor winding connected to a commutator. The brushes on the commutator are short circuited as shown in Fig.15.

The stator of a repulsion motor is similar to that of the 1-ϕ Induction Motor. stator winding is distributed in the slots of the stator core. Rotor of repulsion motor is similar to the rotor of the D.C. machine. Rotor winding is provided in the rotor slots and it is connected to the commutator.



FIG(15)

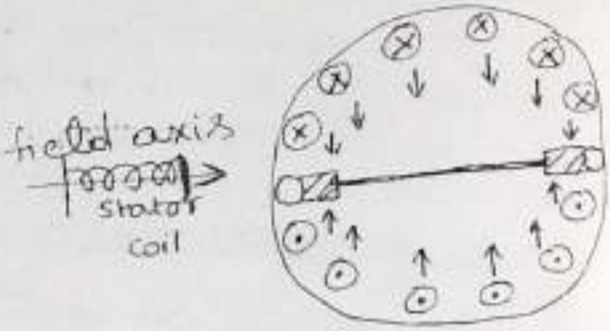
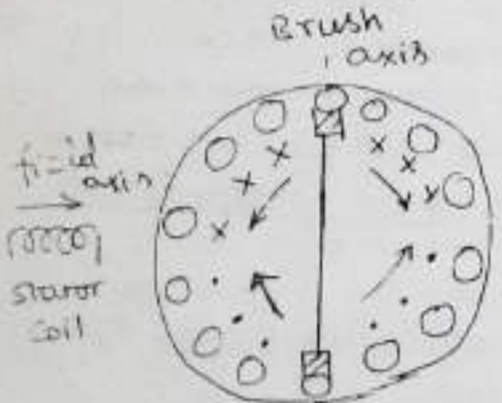
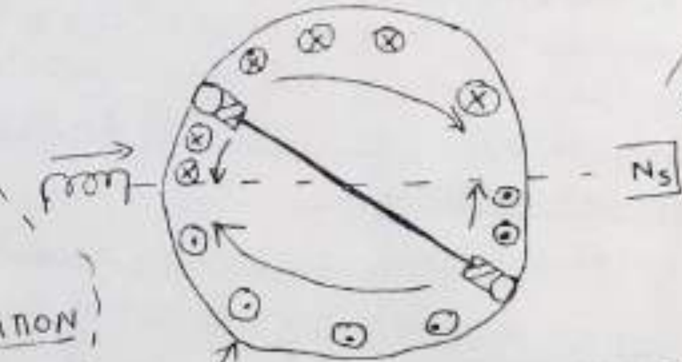


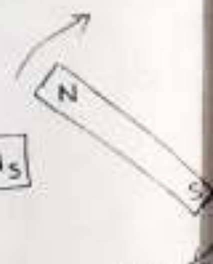
FIG (16): HARD NEUTRAL POS



FIG(17): SOFT NEUTRAL POSITION



FIG(18): BRUSHES MOVED IN CLO WISE DIRECTION



FIG(1

When a-c voltage is applied to the stator winding, alternating flux is produced. This flux induce an emf in the rotor winding according to faraday's law. In Fig.16 brush axis coincides with the main field axis. The direction of the induced currents are shown in Fig.16. Applying flemings left hand rule, the upper half of the conductors experience a force in downward direction. The lower half conductors will experience a force in upward direction. Resulting force is zero and hence the resulting torque is zero.

In Fig.17, the brush axis is perpendicular to the main field axis. i.e. the brushes are shifted by 90°. The direction of the induced voltage in the armature are exactly similar to the directions in Fig.16. The net voltage on the RHS of the brush axis is zero. Similarly the net voltage on LHS of the brush axis is zero. The armature conductors carry no current and hence no torque is developed in this position also.

In Fig.17, the brushes are shifted such that the brush axis is neither in line with main field axis nor perpendicular with the field axis. A net voltage is available between the brushes. This voltage will circulate a current in the armature conductors and a torque is produced.

The armature will act as an electromagnet and develope poles N & S as shown in Fig.18a. The stator poles are shown as N_s and S_s. The rotor north pole is repelled by the stator north pole and rotor south pole is repelled by the stator south pole. The motor rotates in clockwise direction for the brush position shown in Fig.18. Since the forces are repulsive forces, the motor is called as a repulsion motor.

Applications: (1) Machine tools (2) hoists (3) Mixing Machines (4) Centrifugal pumps, (5) fans, (6) Blowers.

A.C. Series Motor

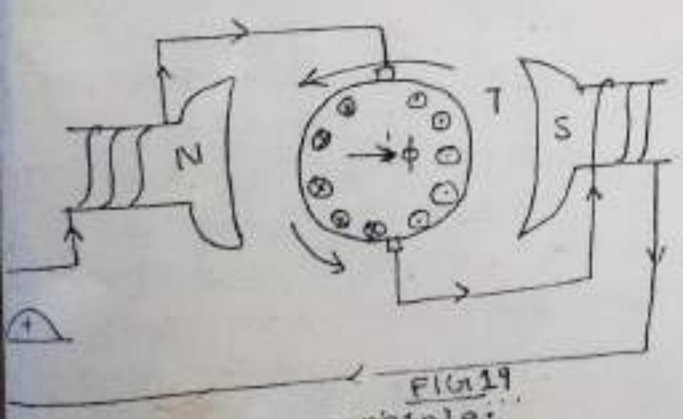


FIG 19

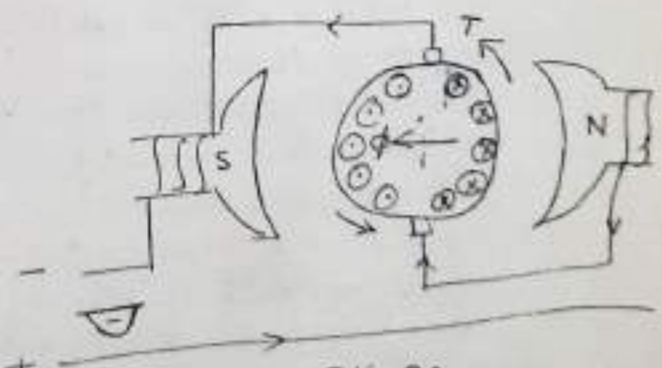


FIG 20

Working Principle:

The working of A.C. series motor is similar to the working of D.C. series motor. In this motor, armature and field are connected in series similar to a D.C. series motor.

During the positive half cycle, the top terminal is positive and bottom terminal is negative. The polarities of poles and induced currents are shown in Fig.19. By applying fleming's left hand rule, we find that a torque is produced in anticlockwise direction.

During the negative half cycle, the top terminal is negative and bottom terminal is positive. The polarities of poles and induced currents are shown in Fig.20. The field and armature windings are connected in series. Hence the direction of field flux ø and armature current reverse simultaneously for every half cycle. Therefore the direction of the torque remains unchanged.

This motor suffers from the following disadvantages:
(1) Low power factor, (2) poor commutation, (3) Excessive Iron loss and heating of machine.

(1) Low power factor:

The cause of low pf is due to the emf induced in the rotor winding due to transformer action of the alternating flux produced by stator winding. This emf can be minimised by providing an extra winding called compensating winding. Two methods of compensations are (1) conductive compensation (2) Inductive compensation.

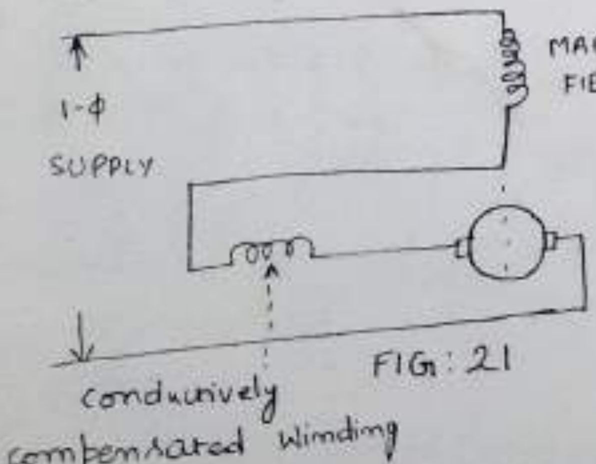


FIG: 21

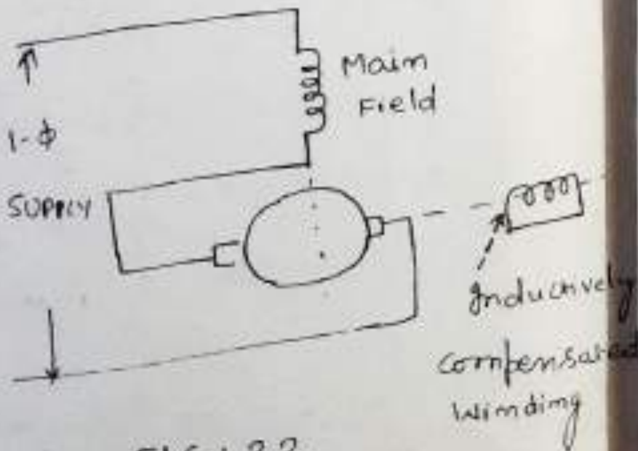


FIG: 22

2. Poor Commutation

This is also due to the voltage induced in the rotor winding during commutation period. This is improved by connecting an additional winding called Interpole winding as shown in the Fig.23.

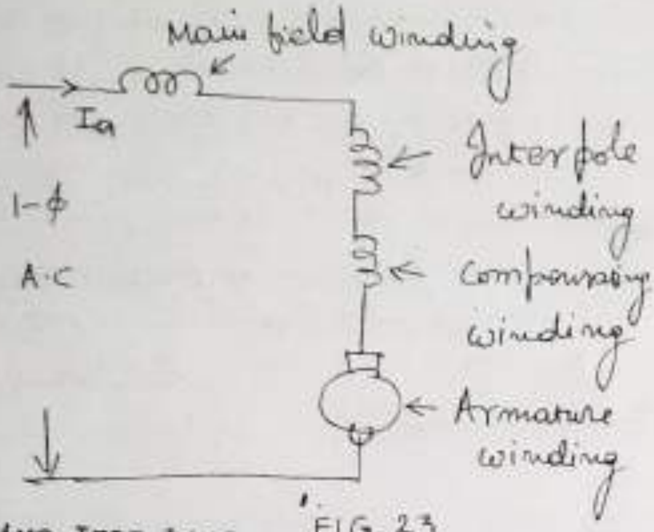


FIG 23

3. Excessive Iron Loss

These are due to the alterations of the flux. To reduce the Iron loss, both stator and rotor cores are laminated. Reduced frequencies like 25 hz, 16 $\frac{2}{3}$ hz are used for reducing the Iron loss.

Let R_a, X_a = Resistance and reactance of armature winding

R_C, X_C - Resistance and reactance of compensating winding

R_I, X_I - Resistance and reactance of Interpole winding

R_m, X_m - Resistance and reactance of Main field winding

E - EMF induced in the armature due to the cutting of flux

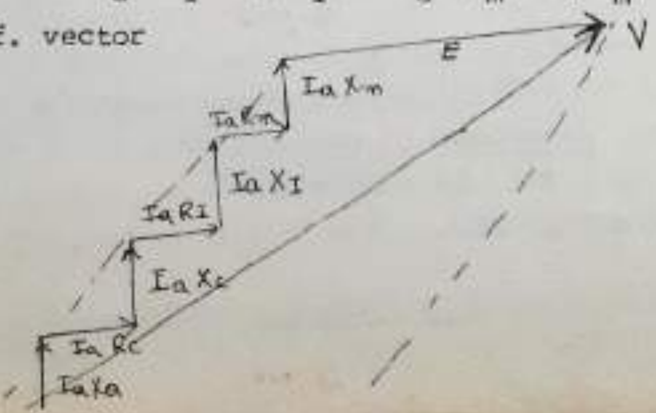
In D/C machine $V = E + I_a R_a$

In A/C machine $V = E + I_a (R_a + j X_a) + I_a(R_c + j X_c)$

$+ I_a (R_I + j X_I) + I_a (R_m + j X_m)$

Take I_a as ref. vector

Vector diagram of A.C. Series Motor



VIT / SRR

Universal Motor

This motor is a fractional H.P. series motor which can operate satisfactorily on A.C. and D.C. The main parts of the universal motor are: (1) Yoke or stator frame (2) stator core (3) stator winding (4) Rotor core (5) Rotor winding (6) Commutator (7) Brushes and (8) shaft.

Principle of Operation

The principle of operation is similar to the principle of operation of A.C. Series motor.

(REPEAT THE PORTION
A.C. SERIES MOTOR NOTES)

The motor works on the same principle of D.C. motor i.e. force between main pole flux and current carrying conductors produce torque. This motor developes indirectional torque whether it operates on A.C. or D.C. supply.

Speed control of universal motor:

The following methods are generally adopted.

1. Resistance Method:

The motor speed is controlled by controlling the resistance in the circuit.

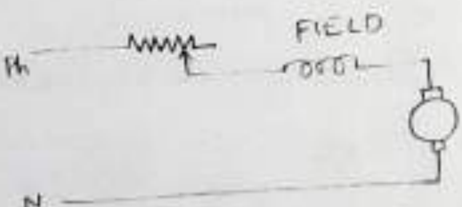


FIG 25

2. Tapped Field Control

The field coil is split into two coils C_1 and C_2. From Coil 1, taps are brought outside. By varying the top position, the field strength can be varied and hence the speed can be varied. The power loss is minimised in this method.

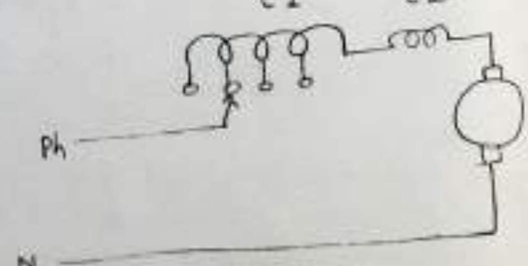


FIG 26

Reversal of Rotation: The direction of rotation can be interchanged by reversing either the current through armature or the current through the field winding.

The torque $T = 0.159 \phi Z I_a P/A$ N-M.

FIG 27

The characteristics of universal motor are similar to those of D.C. series motor.

Performance of Universal Motor with A.C. and D.C.

1. Field Construction :

With D.C., the flux produced by motor winding is constant. Hence there is no loss due to Hysteresis and eddy currents in stator core. The flux produced is pulsating with A.C. The hysteresis and eddy current loss are more with A.C. Hence the stator core of universal motor has to be laminated to reduce iron loss.

2. Speed:

The inductive reactance with A.C. supply is more. X_L with D.C. is zero. Hence the voltage drop with A.C. is more. Voltage applied to the armature with A.C. is less. Hence the speed of universal motor is less with A.C. supply.

3. Commutation:

The emf induced in the short circuited coil during commutation period will be more on A.C. than on D.C. supply. This emf is due to the alternating flux produced by A.C. Due to the emf, more sparking at the brushes will take place and reduces the life of the brushes on A.C. supply.

Advantages:

1. High speeds from 3000 RPM to 10,000 RPM are possible.
2. High power output is obtained from a small machine.
3. High starting torque.
4. Variable speed operation is easy by controlling the speed.

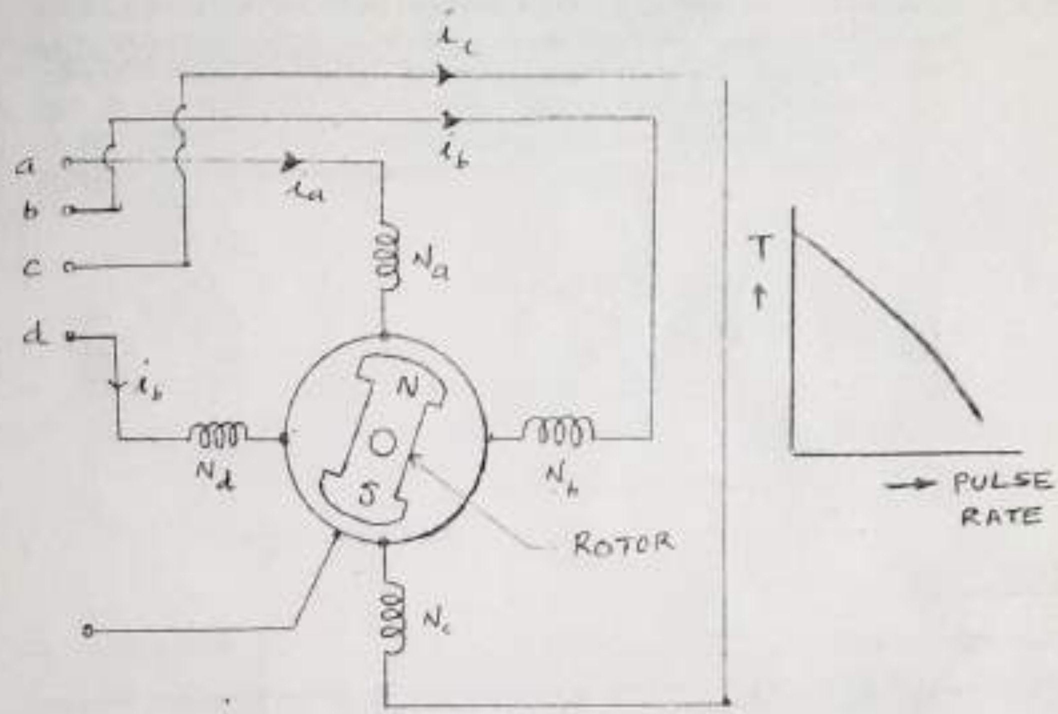
Disadvantages:

1. More maintenance is required due to the brushes.
2. More noise at high speeds.
3. Reduction gears are required for portable tool applications.
4. Life of the brushes is reduced.

Applications:

1. Vaccum cleaner, (2) Seiwing machines, (3) Food Mixers, (4) Electric Showers, (5) Electric Sirens (6) Hair Dryers.

Stepper Motor



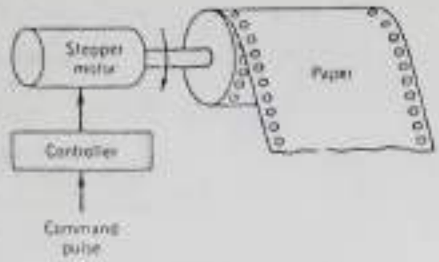
The construction of stepper motor is similar to a synchronous motor. It moves in steps unlike any other motor. The stator contains multiphase winding. The rotor can be either permanent magnet type or variable reluctance type Fig shows a four phase stepper motor with permanent magnet rotor. A stepper motor uses permanent magnet rotor. A stepper motor always operate from a digital circuit which can supply electric pulses. The rotor moves in steps of 90° if the winding are excited in the sequence N_a, N_b, N_c and N_d.

The characteristics of a stepper motor are drawn between steps per second (pulse rate). As the pulse rate is increased the torque is reduced.

A stepper motor has a small size and is a cheap drive unit. Typical applications are: table positioning for machine tools, X-Y plotters, tap drivers, line printers and other computer peripheral devices. It has many other applications in manufacture of packages, food stuffs, commercial and products and production of science fiction movies.

STEPPER MOTORS

A stepper motor rotates by a specific number of degrees in response to an input electrical pulse. Typical step sizes are 2°, 2.5°, 5°, 7.5°, and 15° for each electrical pulse. The stepper motor is an electromagnetic incremental actuator that can convert digital pulse inputs to analog output shaft motion. It is therefore used in digital control systems. A train of pulses is made to turn the shaft of the motor by steps. Neither a position sensor nor a feedback system is normally required for the stepper motors to make the output response follow the input command. Typical applications of stepper motors requiring incremental motion are printers, tape drives, disk drives, machine tools, process control systems, X–Y recorders, and robotics. Figure illustrates a simple application of a stepper motor in



Paper drive using stepper motor.

the paper drive mechanism of a printer. The stepper motor is directly coupled to the platen so that the paper is driven a certain incremental distance whenever the controller receives a digital command pulse.

Typical resolution of commercially available stepper motors ranges from several steps per revolution to as many as 400 steps per revolution and even higher. Stepper motors have been built to follow signals as rapid as 1200 pulses per second with power ratings up to several horsepower.

Two types of stepper motors are widely used: (1) the variable-reluctance type and (2) the permanent magnet type.

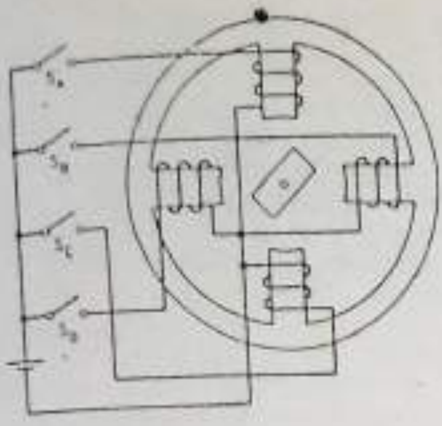
VARIABLE RELUCTANCE STEPPER MOTOR

A variable reluctance stepper motor can be of the single-stack type or the multiple-stack type.

Single-Stack Stepper Motor

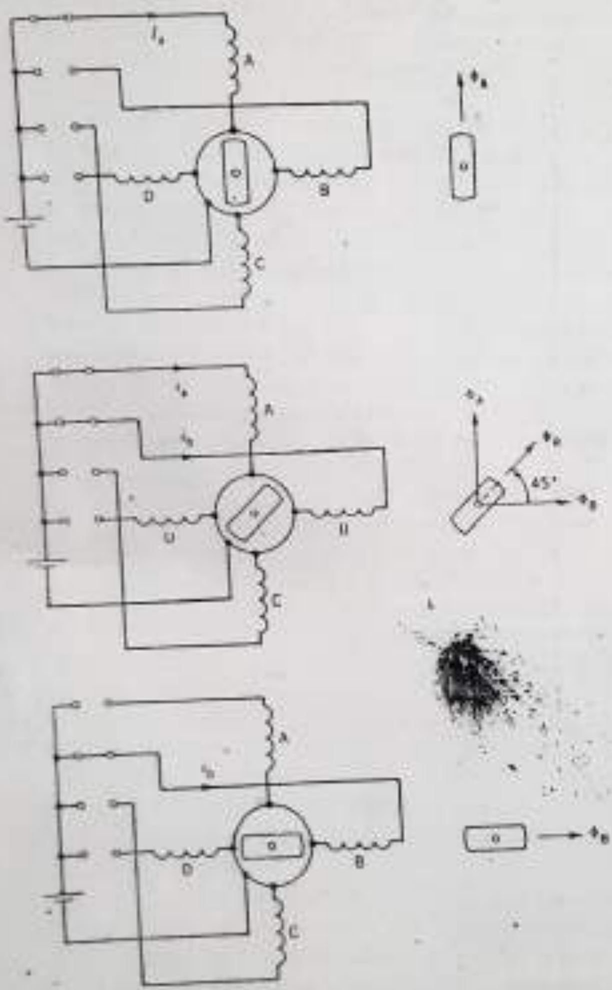
A basic circuit configuration of a four-phase, two-pole, single-stack, variable reluctance stepper motor is shown in Fig. When the stator phases are excited with dc current in proper sequence, the resultant air gap field steps around and the rotor follows the axis of the air gap field by virtue of reluctance torque. This reluctance torque is generated because of the tendency of the ferromagnetic rotor to align itself along the direction of the resultant magnetic field.

Figure shows the mode of operation for a 45° step in the clockwise direction. The windings are energized in the sequence A, A + B, B, B + C, and so forth, and this sequence is repeated. When winding A is excited, the rotor aligns with the axis of phase A. Next, both windings A and B are



FIGURE

Basic circuit for a four-phase, two-pole stepper motor.



FIGURE

Operating modes of stepper motor for 45° step.

excited, which makes the resultant mmf axis move 45° in the clockwise direction. The rotor aligns with this resultant mmf axis. Thus, at each transition the rotor moves through 45° as the resultant field is switched around. The direction of rotation can be reversed by reversing the sequence of switching the windings, that is, A, A + D, D, D + C, etc.

A multipole rotor construction is required in order to obtain smaller step sizes. The construction of a four-phase, six-pole stepper motor is shown in Fig. When phase A winding is excited, pole P_1 is aligned with the axis of phase A as shown in Fig. Next, phase A and phase B windings are excited. The resultant mmf axis moves in the clockwise direction by 45° and pole P_2, nearest to this new resultant field axis, is pulled to align with it. The motor therefore steps in the anticlockwise direction by 15°. Next, phase A winding is de-excited and the excitation of phase B winding pulls pole P3 to align with the axis of phase B. Therefore, if the windings are excited in the sequence A, A + B, B, B + C, C, . . . , the rotor rotates in steps of 15° in the anticlockwise direction.

Multistack Stepper Motor

Multistack variable reluctance-type stepper motors are widely used to give smaller step sizes. The motor is divided along its axial length into magnetically isolated sections ("stacks") and each of these sections can be excited by a separate winding ("phase"). Three-phase arrangements are most common, but motors with up to seven stacks and phases are available.

Figure shows the longitudinal cross section (i.e., parallel to the shaft) of a three-stack variable reluctance stepper motor. The stator of each stack has a number of poles. Figure) shows an example with four poles. Adjacent poles are wound in the opposite sense, and this produces four main flux paths as shown in Fig. Both stator and rotor have the same number of teeth (12 in Fig. Therefore, when a particular phase is excited, the position of the rotor relative to the stator in that stack is accurately defined, as shown in Fig. The rotor teeth in each stack are aligned, whereas the stator teeth have a different orientation between stacks as shown in the developed diagram of rotor and stator teeth in Fig. Therefore, when stack A is energized, the rotor and stator teeth in stack A are aligned but those in stacks B and C are not aligned. ~~as shown in~~

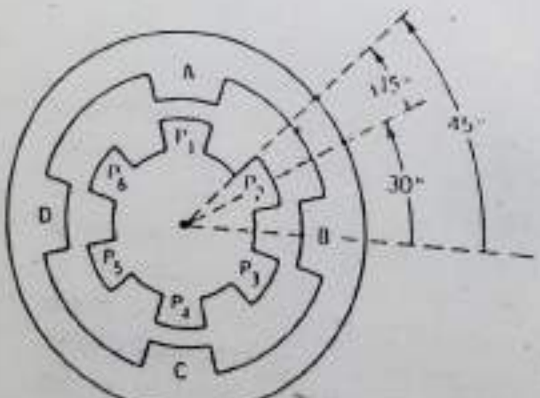


FIGURE
Multiple stepper motor for 15° step

PERMANENT MAGNET STEPPER MOTOR

The permanent magnet stepper motor has a stator construction similar to that of the single-stack variable reluctance type, but the rotor is made of a permanent magnet material. Figure shows a two-pole, permanent magnet stepper motor. The rotor poles align with two stator teeth (or poles) according to the winding excitation. Figure shows the alignment if phase A winding is excited. If the excitation is switched to phase B,

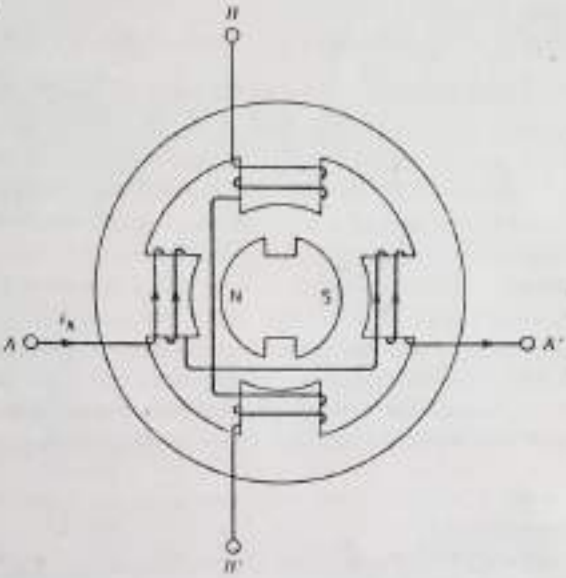


FIGURE
Permanent magnet stepper motor.

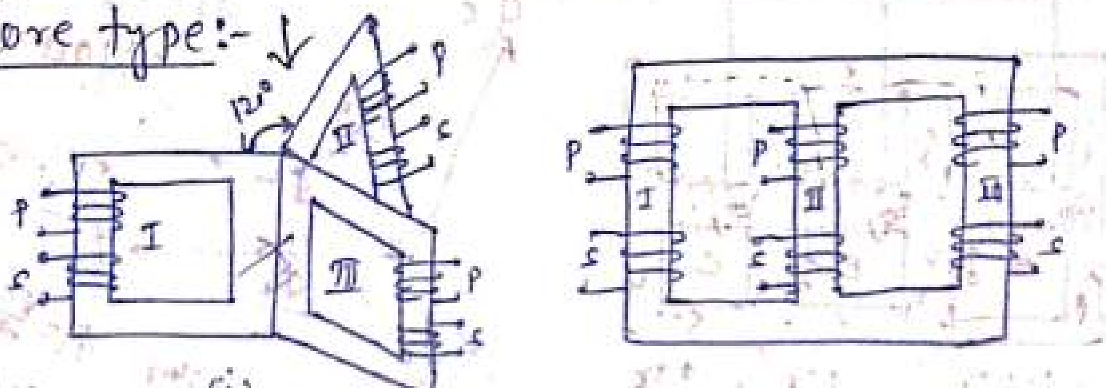
the rotor moves by a step of 90°. Note that current polarity is important in the permanent magnet stepper motor, because it decides the direction in which the motor will move. Figure illustrates the rotor position for positive current in phase A. A switch over to positive current in phase B winding will produce a clockwise step, whereas a negative current in phase B winding will produce an anticlockwise step. It is difficult to make a small permanent magnet rotor with a large number of poles, and therefore stepper motors of this type are restricted to larger step sizes in the range 30 to 90 degrees.

Permanent magnet stepper motors have higher inertia and therefore slower acceleration than variable reluctance stepper motors. The maximum step rate for permanent magnet stepper motors is 300 pulses per second, whereas it can be as high as 1200 pulses per second for variable reluctance stepper motors. The permanent magnet stepper motor produces more torque per ampere stator current than the variable reluctance stepper motor.

Hybrid stepper motors are also commercially available in which the rotor has an axial permanent magnet at the middle and ferromagnetic teeth at the outer sections as shown in Fig. Smaller step sizes can be obtained from these motors, but they are more expensive than the variable reluctance-type stepper motors.

3 Phase transformer

Core type:-



(i)

when three identical units of 1-ϕ T/F's are used the arrangement is commonly called a bank of 3 T/F or a 3-ϕ T/F bank.

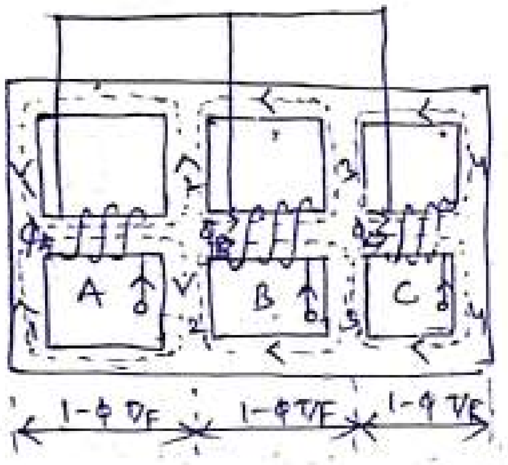
A 3-ϕ T/F may be of core type or shell type as in 1-ϕ T/F.

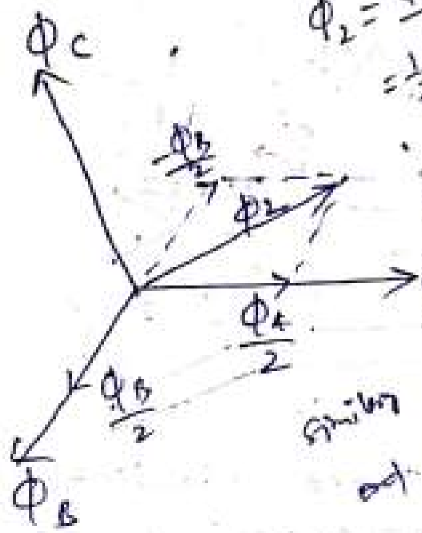
In the above fig.(i) 3 single phase T/F's with their yokes placed 120° appart. The py & sy windings are wound over the limbs I, II, III and the 3 unwound limbs (or legs) are brought in close contact. 3-ϕ current in 3 py's produce 3-phase fluxes displaced by 120°. These fluxes flow through their respective yokes and then through the central limbs placed together. The resultant flux in the 3 central limbs must be zero since the phasor sum of 3 equal fluxes displaced by 120° is zero.

From the top view the 3 yokes appears to be in star and the resultant flux at the star point, made up by the 3 central limbs is zero. Since the central limb carries no flux, it can be eliminated as shown in fig (ii)

The flux produced in any one leg, would return through the other two legs

Shell Type:-





$\phi_2 = \frac{\phi_A}{2} - \frac{\phi_B}{2}$ ②

$= \frac{1}{2}\left[\phi\angle 0 - \phi\angle{-120^\circ}\right]$

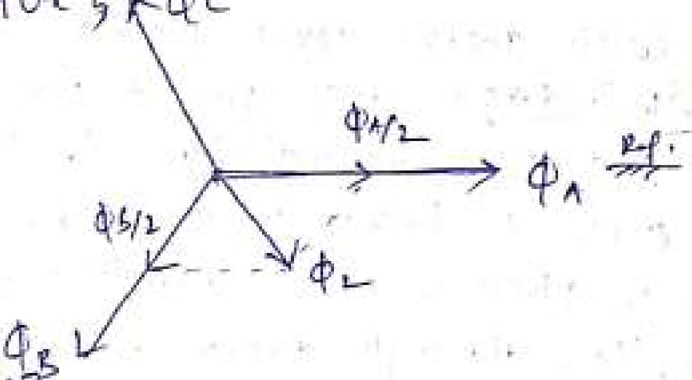
$\boxed{\phi_2 = \frac{\sqrt{3}}{2}\phi}$

$\phi_3 = \frac{\sqrt{3}}{2}\phi$

similarly $\phi_1 = \phi_4 = \frac{\phi}{2}$

A 3-φ shell type T/F is obtained if the 3 single phase shell type cores are placed side by side

Here winding B is wound in reverse direction. The distribution of flux is



$\phi_2 = \frac{\phi_A}{2} + \frac{\phi_B}{2}$

$= \frac{1}{2}\left[\phi\angle 0 + \phi\angle{-120^\circ}\right]$

$= \frac{1}{2}\left[\phi + \phi(\cos 120^\circ - j\sin 120^\circ)\right]$

$= \frac{\phi}{2}\left[1 - \frac{1}{2} - j\frac{\sqrt{3}}{2}\right] = \frac{\phi}{2}\left[\frac{1}{2} - j\frac{\sqrt{3}}{2}\right]$

$|\phi_2| = \frac{\phi}{2}\sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{\sqrt{3}}{2}\right)^2} = \frac{\phi}{2}$

It is very economic since the cross-sectional part of all area remains same.

3-φ T/F Connections and phasor Groups:- ③

In representing a T/F

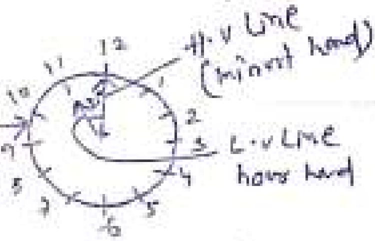
→ The H.V winding is indicated by a capital letter i.e. Y and D.

→ The L.V winding is indicated by a small letter i.e. y and d.

→ The time phase displacement between the HV line emf and LV line emf is expressed in degree or by clock method.

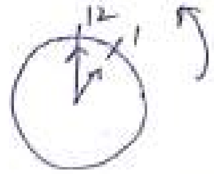
According to clock method the HV line phasor is represented by minute hand which is always set at 12 o'clock. LV line phasor is represented by hour hand.

Yd0 ⟶ 

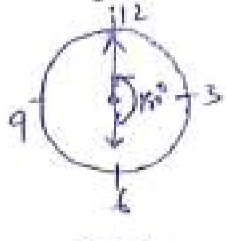
Yd11 ⟶ 

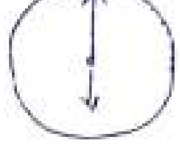
30° Leading

11 Leads 12 by 30°

Yd1 ⟶ 

30° Lag. 1 o'clock lags 12 by 30° { ∵ $\frac{360}{12} = 30°$, 1 hr ⇒ 30° }

Yd6 ⟶ 

Dy6 ⟶ 

Yy0 ⟶ phase shift is zero
12 o'clock.

6 stands for 180° shift i.e. 6×30 = 180°

Yy11 ⟶ phase shift of 180° (6 o'clock in circuit are displaced by 180°)

Phasor Group:-

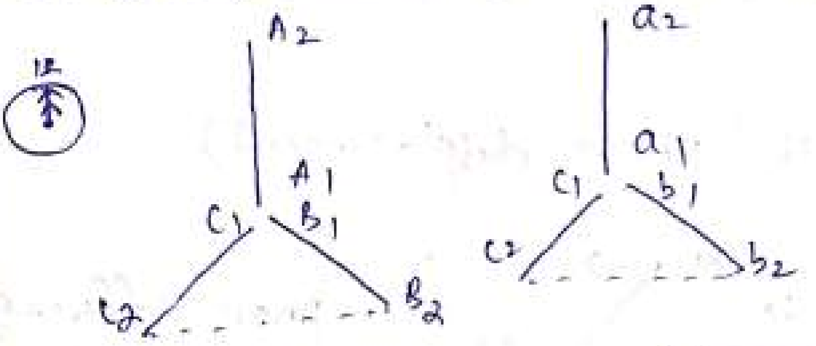
Depending on type of connections and phase displacements between the H.V and L.V line emfs there are 4 phasor groups.

Some points to be noted –

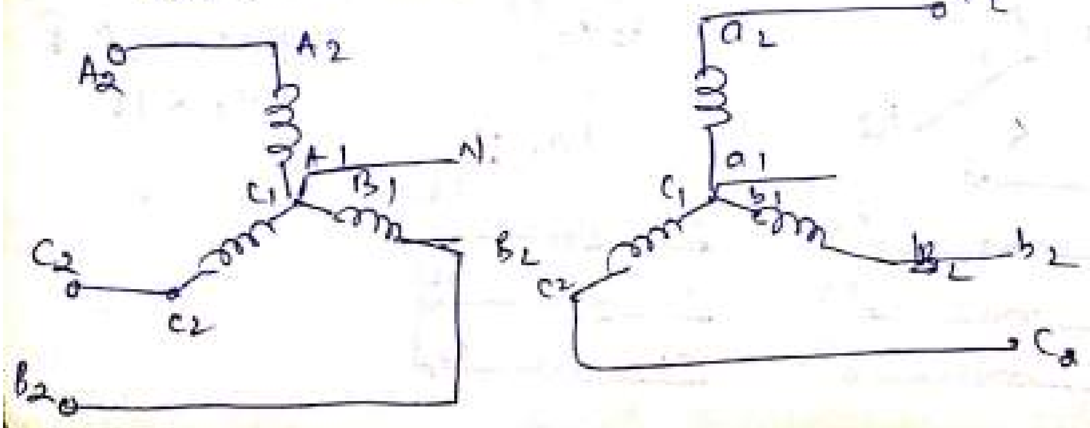
1. The phasor rotate in counter clockwise direction.
2. The phasor representing the induced emf in H.V & L.V windings for a particular phase, are drawn parallel to each other.

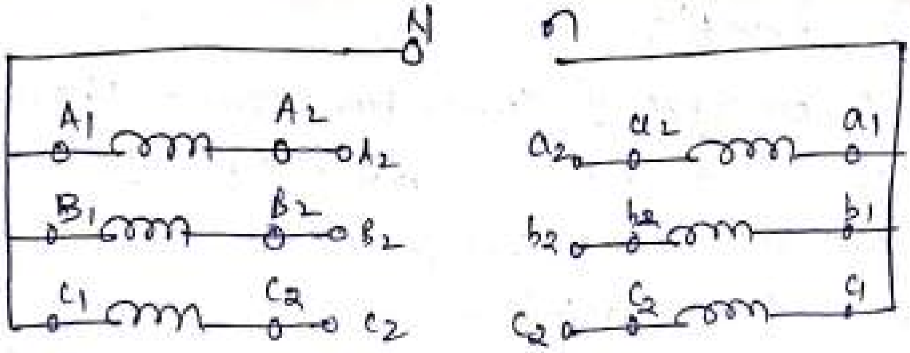
   Fr example ⇒ For phase A, the L.V line phasor a_1a_2 must be drawn parallel to H.V line phasor A_1A_2.
3. The H.V. winding is assumed to be the primary and L.V winding the secondary.
4. The position of H.V terminals A_2, B_2, C_2 is assumed fixed, for convenience in the top, bottom right and bottom left corners respectively of a equilateral triangle.

ⓐ Group No - 1 (Zero degree phase displacement)



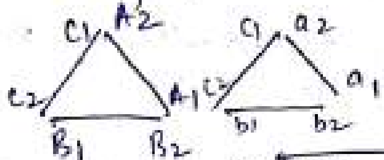
phase displacement between B_2C_2 & b_2c_2 is zero.

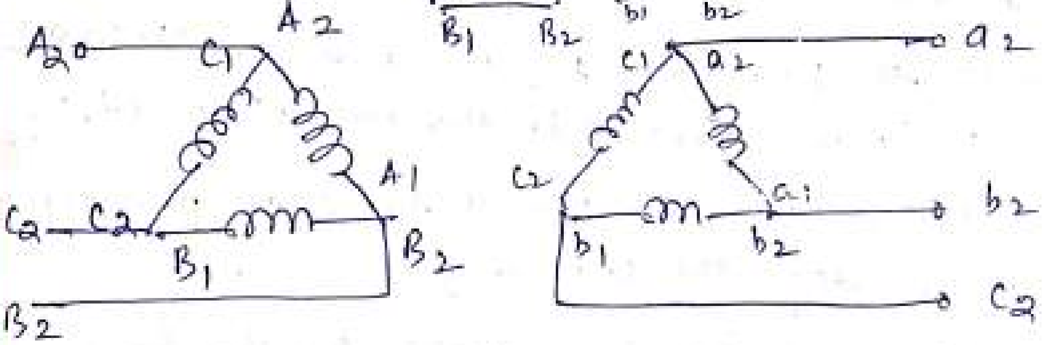


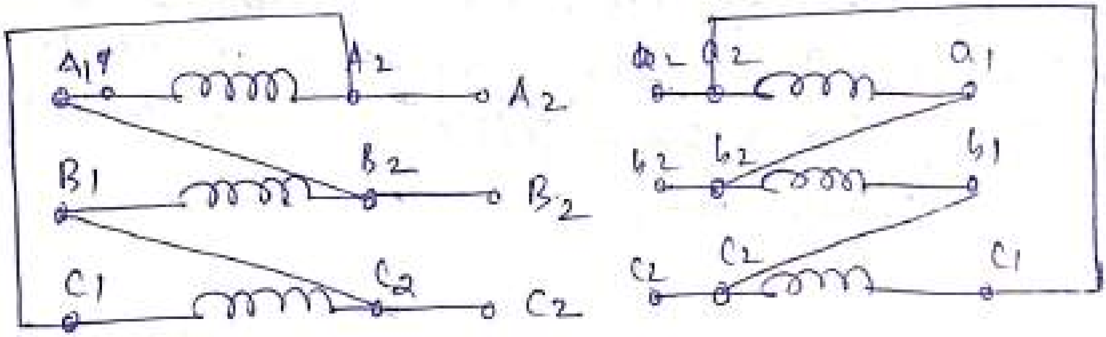


It can be represented as Yy0

for Dd0

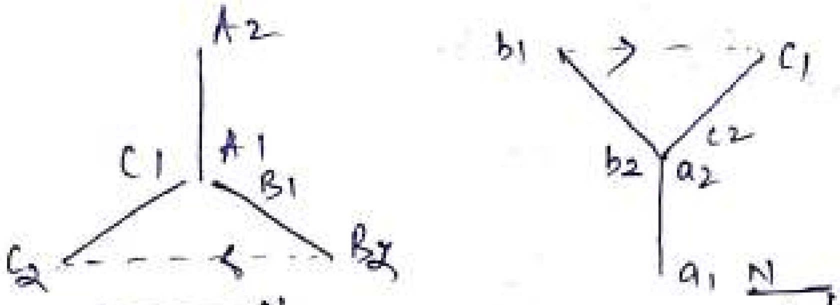




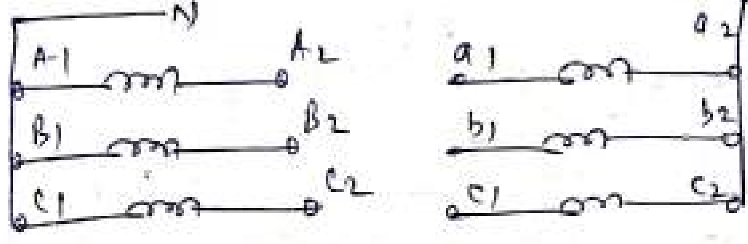


The L.V Line emf a_2b_2 in phase with H.V Line emf A_2B_2.

(b) Group 2 (180° phase displacement)



phase difference between B_2C_2 & b_1C_1 is 180°



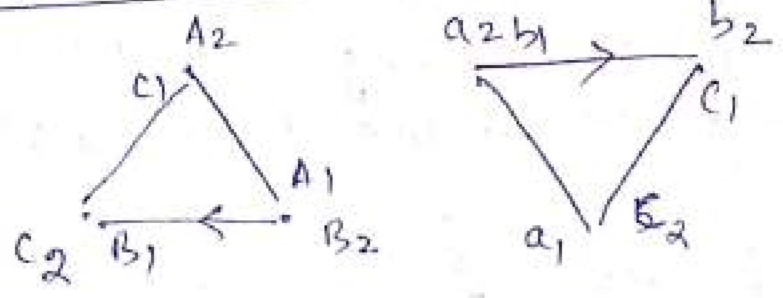
The phase displacement betn H.V & L.V line emf for 'group 2' is 180°. ⑥

For this group the connection of all the secondary terminal are reversed w.r.t PY connections.

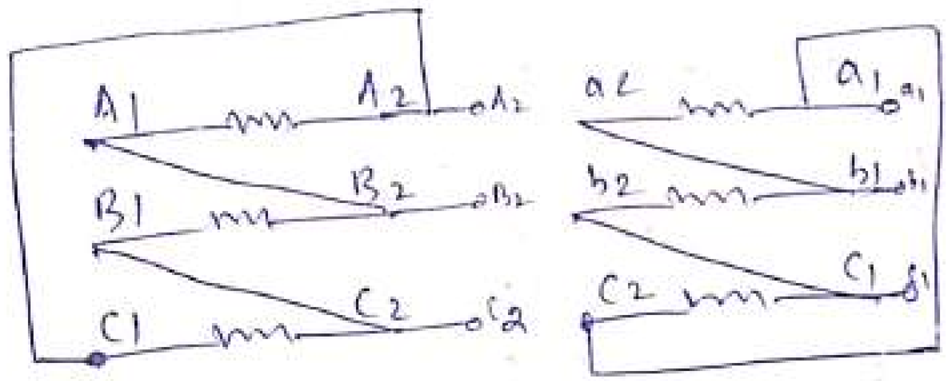
If b_1 is made to coincide B_2, then the phase angle between H.V line phasor B_2C_2 and L.V line phasor b_1c_1 is 180°

So it can be represented as <u>Yy6</u>.

<u>Dd6 connections:-</u>



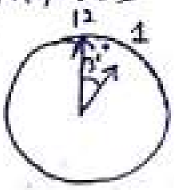
$a_2 \to$ bottom left
$b_2 \to$ bottom right
$A_1A_2 \parallel a_1a_2$
$B_1B_2 \parallel b_1b_2$
$C_1C_2 \parallel c_1c_2$



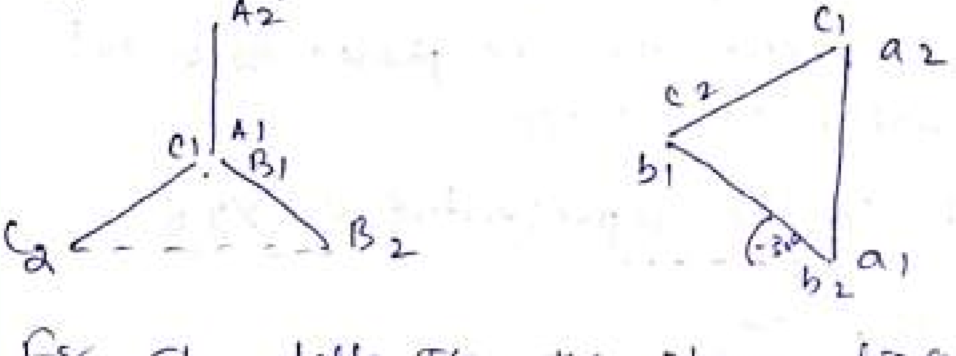
The H.V terminals A_1 & B_2 are joined together as before. For reversing the secondary connections a_2 & b_1 should be joined together. The i/p terminals on H.V. side are A_2, B_2, C_2 and the L.V o/p terminals are a_1, b_1, c_1. The phase angle betn B_2C_2 and b_1c_1 is 180°.

(c) Group 3 (minus 30° phase displacement) (7)

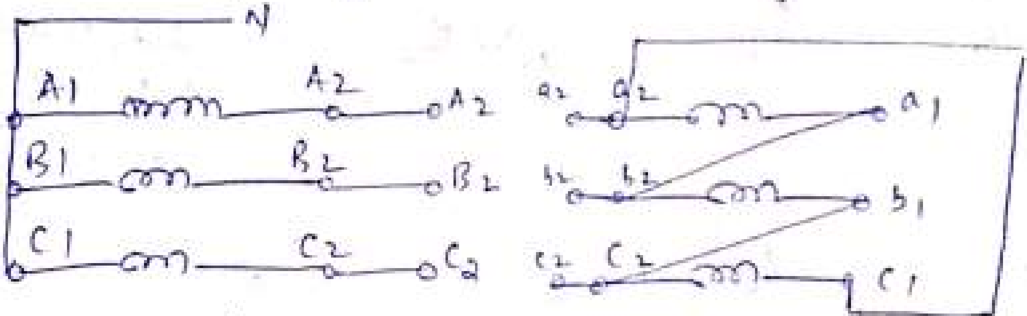
Yd1



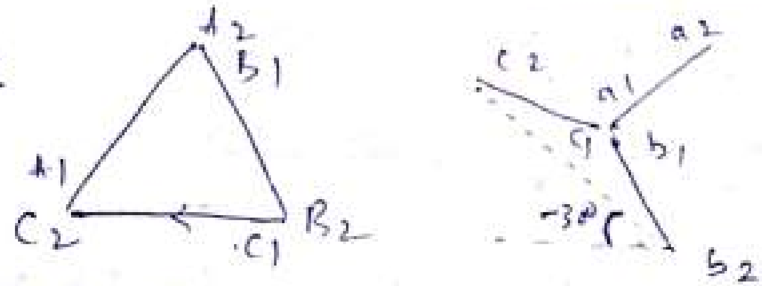
A phase displacement of −30° means that the L.V line phasor lags the corresponding H.V line phasor by 30°.



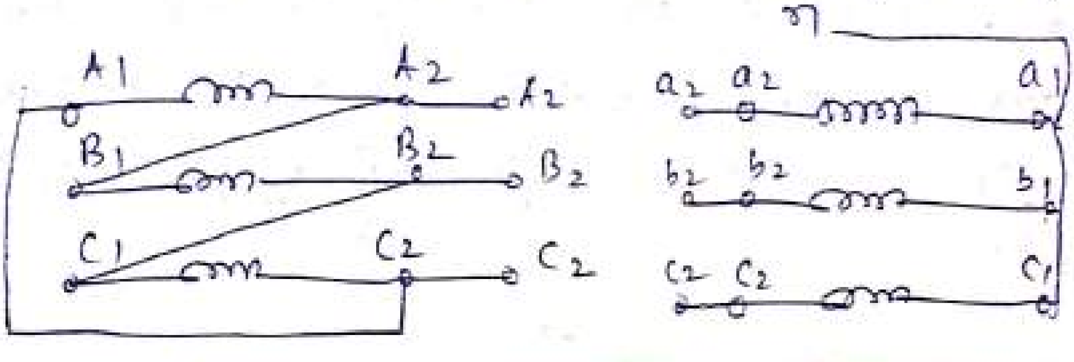
For star-delta T/F, the phasor diagram is shown above. When B_2 is coinciding b_2, the L.V line phasor b_2c_2 lags the H.V line phasor B_2C_2 by 30°.



DY1



For delta-star, the phasor orientation of H.V line voltages A_1A_2, B_1B_2 and C_1C_2 have been changed to get Dy1.

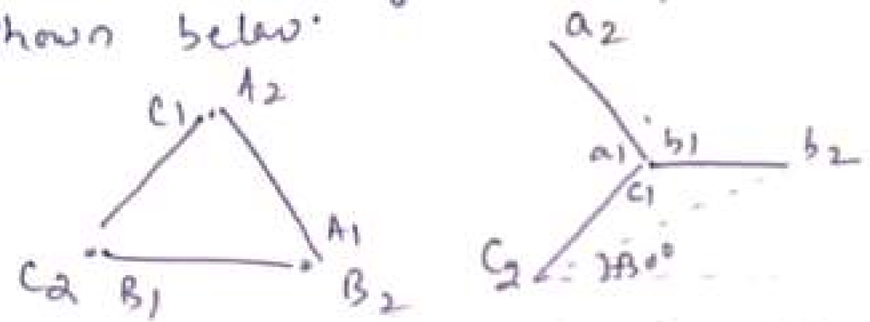


(4) <u>Group 4</u> (plus 30° phase displacement) (8)

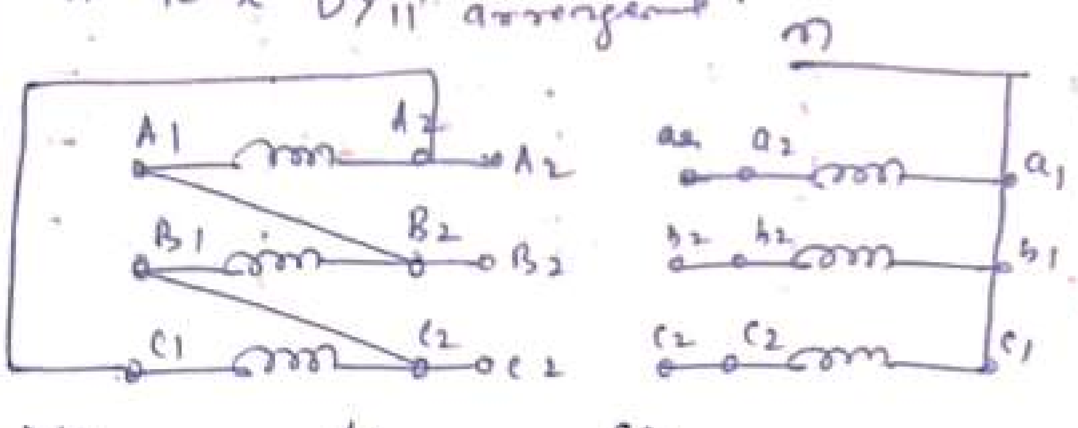
For group no 3 and 4, H.V & L.V windings must be connected differently to get a suitable phase displacement.

+30° phase displacement means that the L.V line phasor leads the corresponding H.V line phasor by 30°. ~~(Dy11)~~

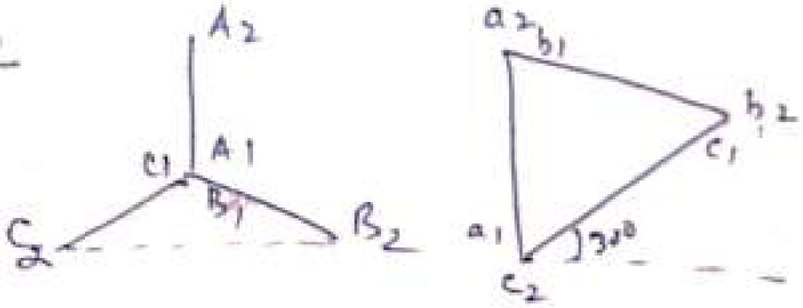
for Dy11 arrangement the phasor diagram is shown below.



when C2 coincides C2, L.V phasor C2b2 is seen to be lead H.V phasor C2B2 by 30° and this proves it to be DY11 arrangement.

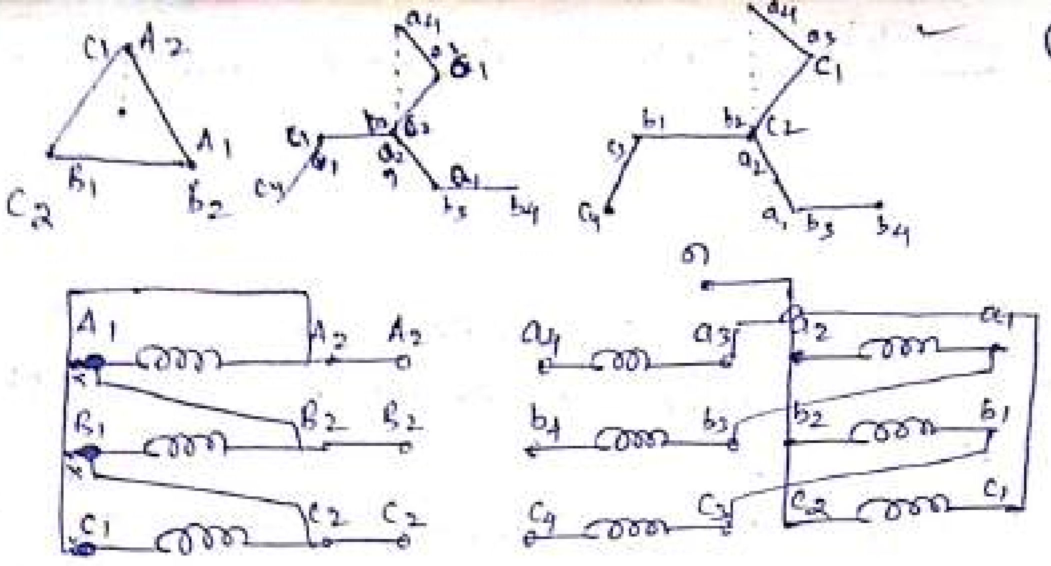


<u>Yd11</u>

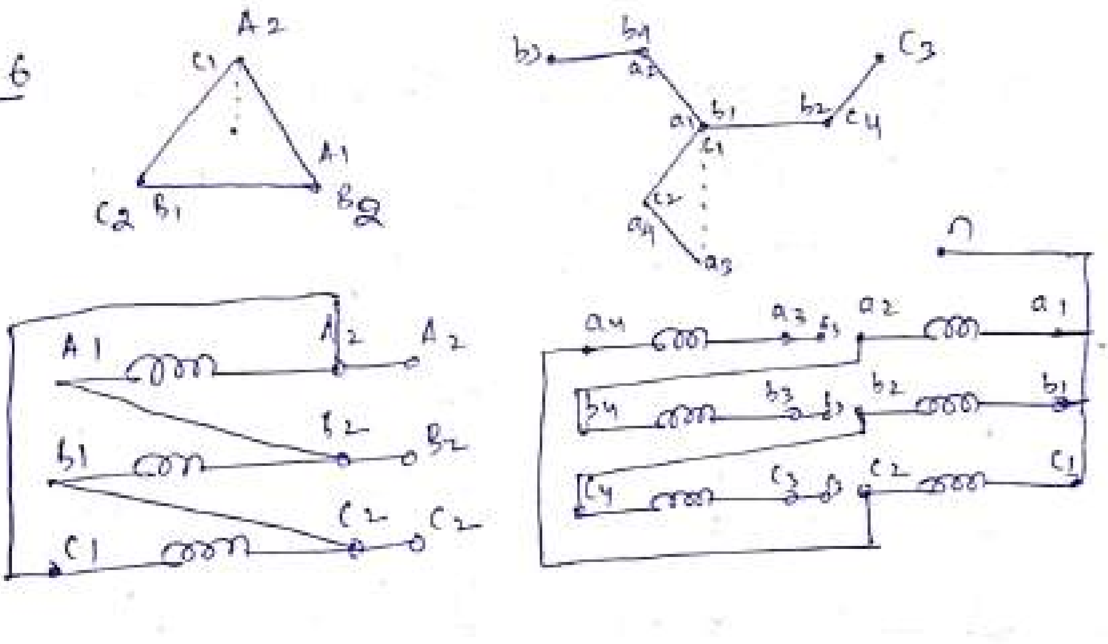


DZ0

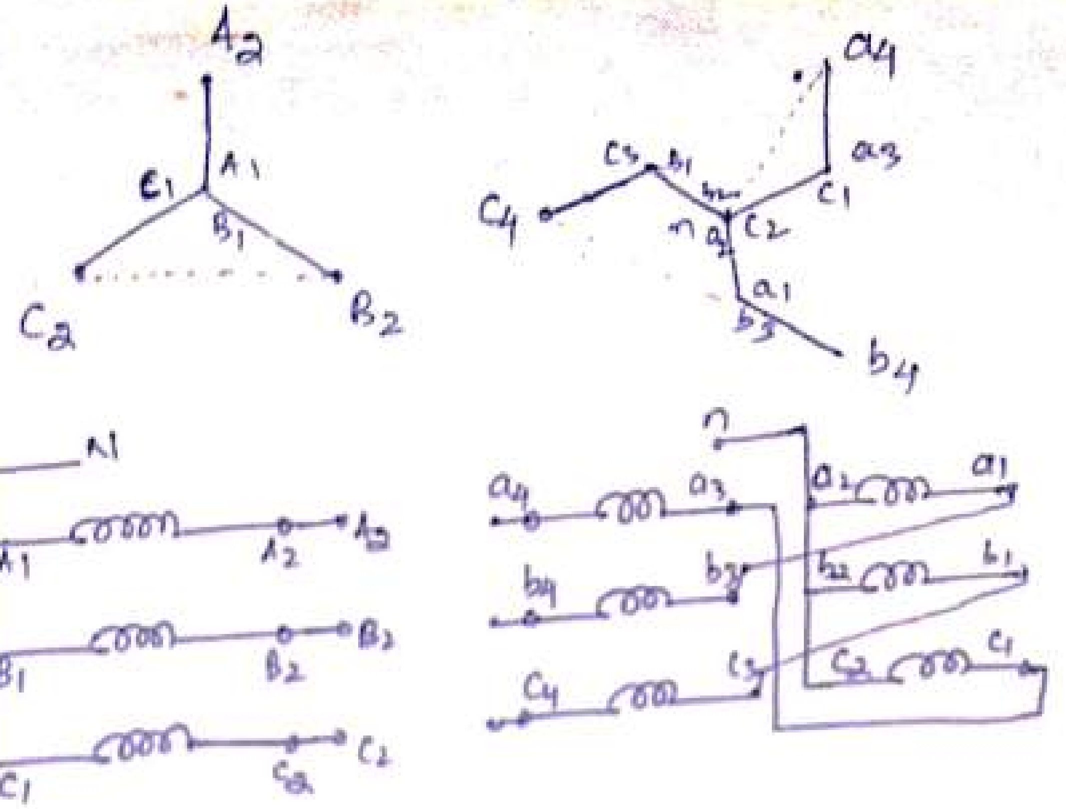
(Zig Zag = interconnected Star) 0°



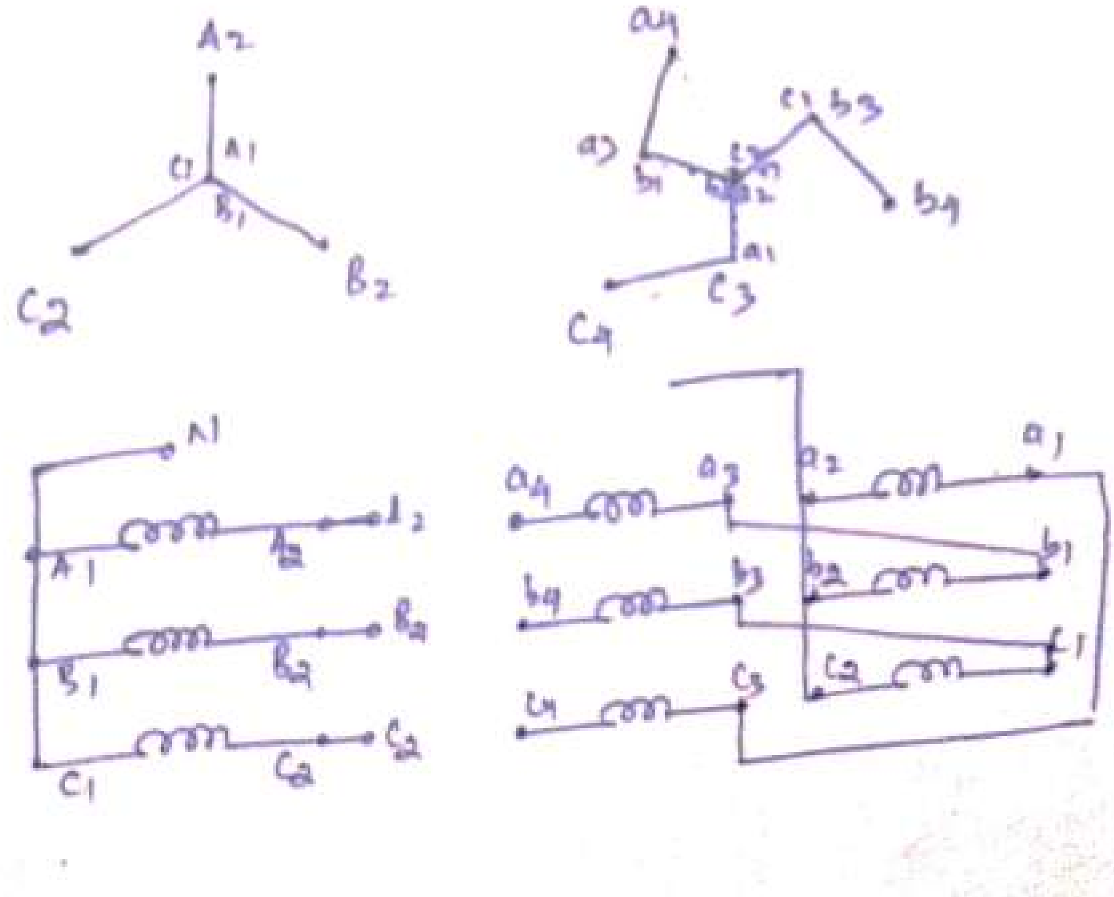
DZ6



YZ1

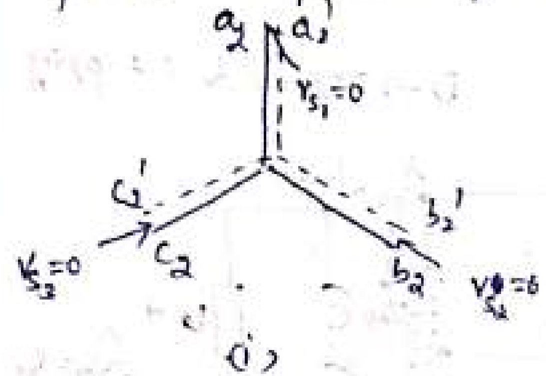

A2
A1
B1
C1
C2
B2
a4
a3
a1
b4
C4
A2
B2
C2
C1
a4
a3
a2
a1
b4
b1
C4

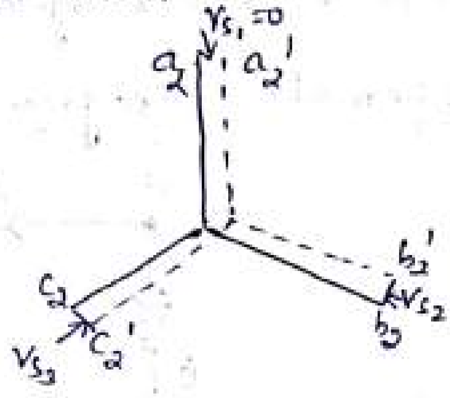
YZ11


A2
A1
B1
C2
B2
a4
a3
a1
b4
C4
C3
A1
B1
C1
a4
a3
a2
a1
b4
b3
b2
b1
C4
C3

phase sequence :-

phase sequence of 2 T/F's must be same.





$V_{s_2} = V_{s_3} = V_{b_2 b_2'} = V_{c_2 c_2'} = V_L$

(Different phase sequence)

If the sy line voltages are of the same phase sequence as shown in (i) then the voltage across switches S_1, S_2 & S_3 would be zero and the parallel operation is possible.

Different phase sequence would give zero voltage across S_1 and line voltages across S_2 and S_3 for which parallel operation is not possible.

Conversion from 3-ϕ to 2-ϕ (Scott Connection or T-Connection)

At present 3-ϕ power energy system are most common, but for certain specialized applications 2-ϕ supplies are essential.

Application of 2-ϕ supply

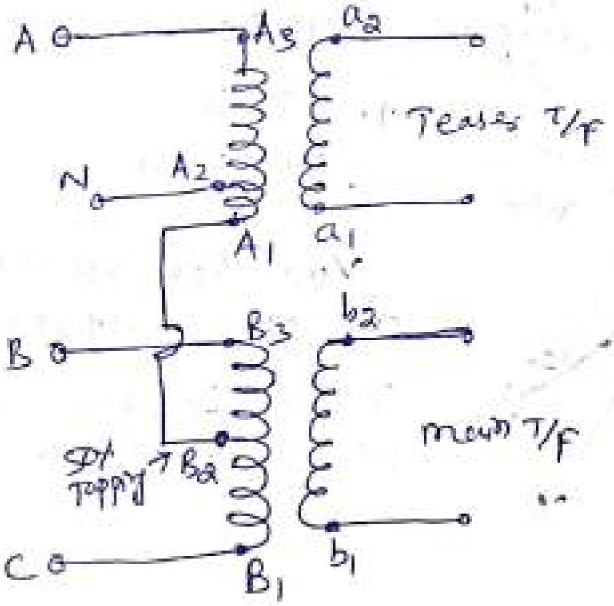
(i) Arc furnaces (60V, 10,000A) (ii) Low voltage rural area

(iii) Electrified tracks in electric traction

(iv) 2-ϕ control motors.

$3\overset{\downarrow}{P_1} = 2\overset{\uparrow}{P_2}$ ($P_2 > P_1$)

* 2-ϕ power is low voltage & high current requires 2 step down T/F



parallel operation of 3-ϕ T/F

Conditions for successful operation →

(i) The V_L (line voltage) ratio of T/F must be same.

(ii) The T/F should have equal per unit leakage impedance.

(iii) The ratio of equivalent leakage reactance (X_L) to equivalent resistance (R) should be same for all T/F's.

(iv) The T/Fs should have same polarity.

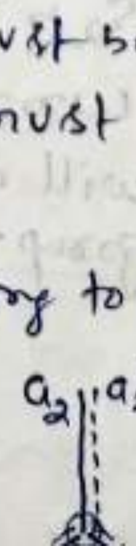
(v) Relative phase displacement

(vi) phase sequence.

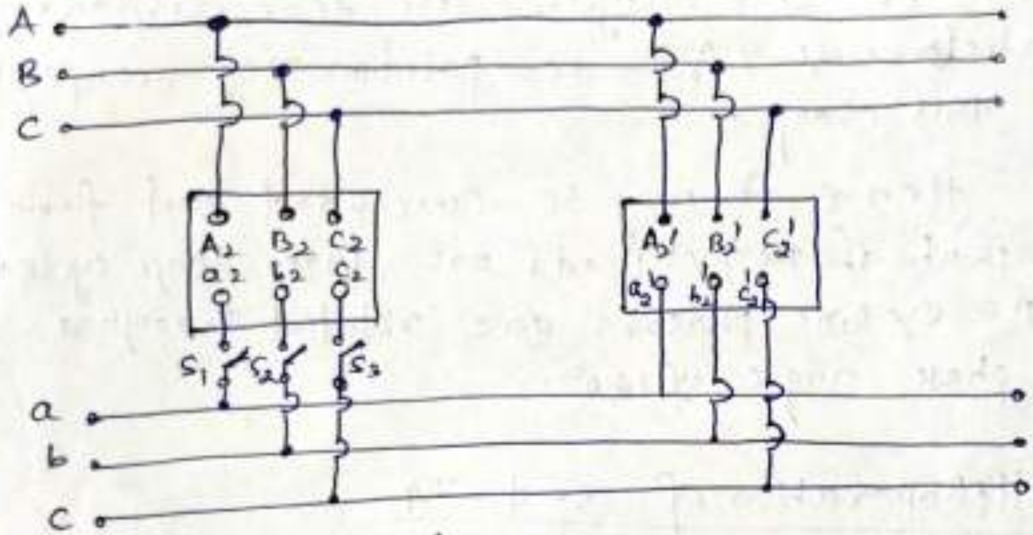
Relative phase displacement:-

The relative phase displacement between the sy - line voltage of all the T/Fs must be zero. i.e. the T/Fs to be connected in parallel must belong to the same group numbers.

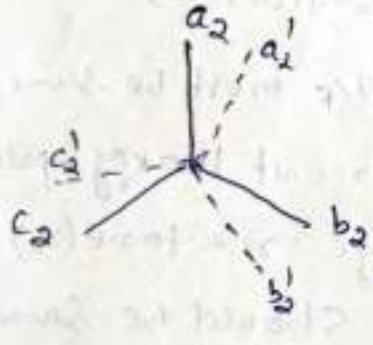
For eg: YY0 & Dd0 belonging to group no -1



⇐ For proper connection

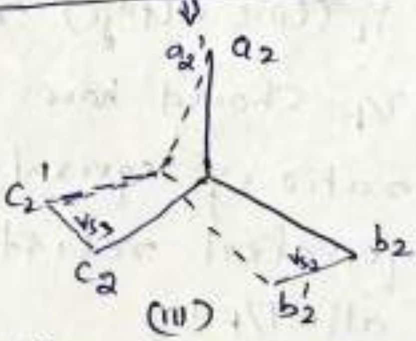


(fig-1)



(ii)

If switch S_1 is closed



(iii)

For Ex. Two T/F's having different phasor group are connected and phasor diagram for secondary line voltage are given in fig(-ii) are not in phase. In this figure The phasors joining a_2a_2', b_2b_2', c_2c_2' represents the voltage acrosses switches S_1, S_2 & S_3.

If switch S_1 is closed → There will be no circulating current "2" because the sy ckt is not closed. After closing S_1,-

- suppose S_2 is closed. $V_{b_2b_2'}$ will send a large circulating current in the phase A & B, This large current will damage the T/F. So T/F's should be of same group.