EE8401	ELECTRICAL MACHINES – II	L	T	P	C
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OBJECTIVES:
To impart knowledge on the following Topics

- Construction and performance of salient and non – salient type synchronous generators.
- Principle of operation and performance of synchronous motor.
- Construction, principle of operation and performance of induction machines.
- Starting and speed control of three-phase induction motors.
- Construction, principle of operation and performance of single phase induction motors and special machines.

UNIT I SYNCHRONOUS GENERATOR 6+6
Constructional details – Types of rotors –winding factors- emf equation – Synchronous reactance – Armature reaction – Phasor diagrams of non salient pole synchronous generator connected to infinite bus--Synchronizing and parallel operation – Synchronizing torque -Change of excitation and mechanical input- Voltage regulation – EMF, MMF, ZPF and A.S.A methods – steady state power- angle characteristics– Two reaction theory –slip test -short circuit transients - Capability Curves

UNIT II SYNCHRONOUS MOTOR 6+6
Principle of operation – Torque equation – Operation on infinite bus bars - V and Inverted V curves – Power input and power developed equations – Starting methods – Current loci for constant power input, constant excitation and constant power developed-Hunting – natural frequency of oscillations – damper windings- synchronous condenser.

UNIT III THREE PHASE INDUCTION MOTOR 6+6
Constructional details – Types of rotors –- Principle of operation – Slip –cogging and crawling- Equivalent circuit – Torque-Slip characteristics - Condition for maximum torque – Losses and efficiency – Load test - No load and blocked rotor tests - Circle diagram – Separation of losses – Double cage induction motors –Induction generators – Synchronous induction motor.

UNIT IV STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR 6+6
Need for starting – Types of starters – DOL, Rotor resistance, Autotransformer and Star-delta starters – Speed control – Voltage control, Frequency control and pole changing – Cascaded connection-V/f control – Slip power recovery scheme-Braking of three phase induction motor: Plugging, dynamic braking and regenerative braking.

UNIT V SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES 6+6
Constructional details of single phase induction motor – Double field revolving theory and operation – Equivalent circuit – No load and blocked rotor test – Performance analysis – Starting methods of single-phase induction motors – Capacitor-start capacitor run Induction motor- Shaded pole induction motor - Linear induction motor – Repulsion motor - Hysteresis motor - AC series motor- Servo motors- Stepper motors - introduction to magnetic levitation systems.

TOTAL : 60 PERIODS

OUTCOMES:

- Ability to understand the construction and working principle of Synchronous Generator
- Ability to understand MMF curves and armature windings.
- Ability to acquire knowledge on Synchronous motor.
- Ability to understand the construction and working principle of Three phase Induction Motor
- Ability to understand the construction and working principle of Special Machines
- Ability to predetermine the performance characteristics of Synchronous Machines.

TEXT BOOKS:

1. A.E. Fitzgerald, Charles Kingsley, Stephen. D. Umans, 'Electric Machinery', Mc Graw Hill publishing Company Ltd, 2003.
2. Vincent Del Toro, 'Basic Electric Machines' Pearson India Education, 2016.
3. Stephen J. Chapman, 'Electric Machinery Fundamentals'4th edition, McGraw Hill Education Pvt. Ltd, 2010.

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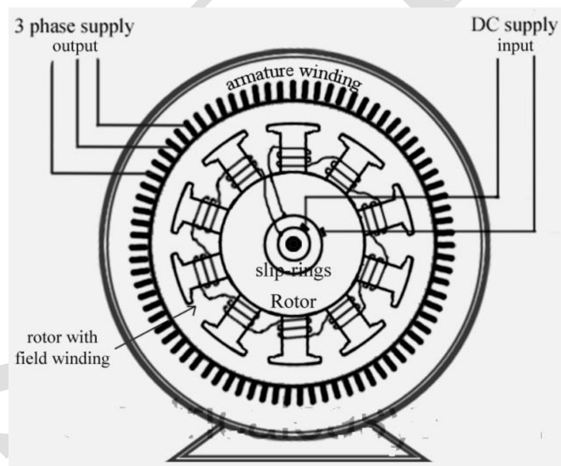
1. D.P. Kothari and I.J. Nagrath, 'Electric Machines', McGraw Hill Publishing Company Ltd, 2002.
2. P.S. Bhimbhra, 'Electrical Machinery', Khanna Publishers, 2003.
3. M.N. Bandyopadhyay, Electrical Machines Theory and Practice, PHI Learning PVT LTD., New Delhi, 2009.
4. B.R.Gupta, 'Fundamental of Electric Machines' New age International Publishers,3rd Edition ,Reprint 2015.
5. Murugesh Kumar, 'Electric Machines', Vikas Publishing House Pvt. Ltd, 2002.
6. Alexander S. Langsdorf, 'Theory of Alternating-Current Machinery', McGraw Hill Publications, 2001.

UNIT I SYNCHRONOUS GENERATOR

Constructional details – Types of rotors –winding factors- emf equation – Synchronous reactance – Armature reaction – Phasor diagrams of non salient pole synchronous generator connected to infinite bus--Synchronizing and parallel operation – Synchronizing torque -Change of excitation and mechanical input- Voltage regulation – EMF, MMF, ZPF and A.S.A methods – steady state power- angle characteristics– Two reaction theory –slip test - short circuit transients - Capability Curves

Constructional Details

AC generators or alternators operate on the principle of electromagnetic induction.
The construction consists of armature winding mounted on a stationary element called **stator** and field windings on a rotating element called rotor.



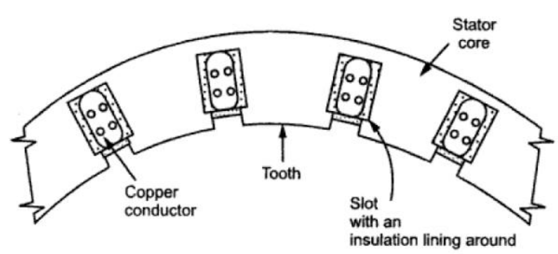
- The stator consists of a cast-iron frame, which supports the armature core, having slots on its inner periphery for housing the armature conductors.
- The rotor is like a flywheel having alternate *N* and *S* poles fixed to its outer rim.
- The magnetic poles are excited (or magnetized) from direct current supplied by a d.c. source at 125 to 600 volts.
- Because the field magnets are rotating, this current is supplied through two slip rings.
- As the exciting voltage is relatively small, the slip-rings and brush gear are of light construction.
- When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them.
- Because the magnetic poles are alternately *N* and *S*, they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other.
- Hence, an alternating e.m.f. is produced in the stator conductors **(*i*)** whose frequency depends on the number of *N* and *S* poles moving past a conductor in one second and **(*ii*)** whose direction is given by Fleming's Right-hand rule.

Advantages of having stationary armature (and a rotating field system) are:

1. The output current can be led directly from fixed terminals on the stator (or armature windings) to the load circuit, without having to pass it through brush-contacts.
2. It is easier to insulate stationary armature winding for high a.c. voltages, which may have as high a value as 30 kV or more.
3. The sliding contacts *i.e.* slip-rings are transferred to the low-voltage, low-power d.c. field circuit which can, therefore, be easily insulated.
4. The armature windings can be more easily braced to prevent any deformation, which could be produced by the mechanical stresses set up as a result of short-circuit current and the high centrifugal forces brought into play.

Stator

(i) Stator Frame

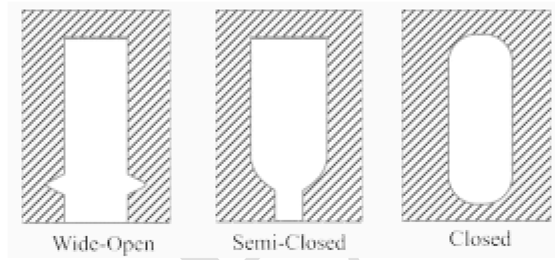


- It is used for holding the armature stampings and windings in position.
- Ventilation is maintained with the help of holes cast in the frame itself.
- The provision of radial ventilating spaces in the stampings assists in cooling the machine.

(ii) Stator core

- The armature core is supported by stator frame and is made up of laminations of special magnetic iron or steel alloy.

- The core is laminated to minimize loss due to eddy currents.
- The laminations are stamped out in complete rings (for smaller machine) or in segments (for larger machines).
- The laminations are insulated from each other and have spaces between them for allowing the cooling air to pass through.
- The slots for housing the armature conductors lie along the inner periphery of the core and are stamped out at the same time when laminations are formed.
- Different shapes of the armature slots are shown in Fig.



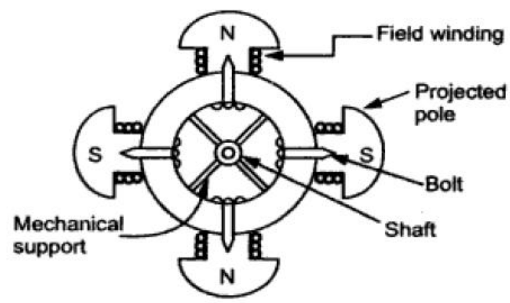
- The wide-open type slot has the advantage of permitting easy installation of form-wound coils and their easy removal incase of repair. But it has the disadvantage of distributing the air-gap flux into bunches or tufts, that produce ripples in the wave of the generated e.m.f.
- The semi-closed type slots are better in this respect, but do not allow the use of form-wound coils.
- The wholly-closed type slots or tunnels do not disturb the air-gap flux but ***(i)*** they tend to increase the inductance of the windings ***(ii)*** the armature conductors have to be threaded through, thereby increasing initial labour and cost of winding and ***(iii)*** they present a complicated problem of end connections. Hence, they are rarely used.

Rotor

Two types of rotors are used in alternators ***(i)*** salient-pole type and ***(ii)*** smooth-cylindrical type.

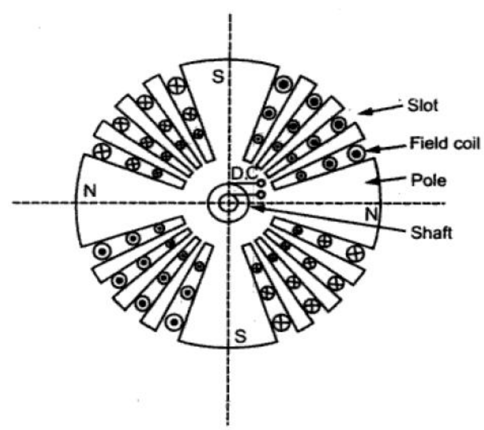
(i) **Salient (or projecting) Pole Type**

- It is used in low-and medium-speed (engine driven) alternators.
- It has a large number of projecting (salient) poles, having their cores bolted or dovetailed onto a heavy magnetic wheel of cast-iron, or steel of good magnetic quality.
- Such generators are characterized by their large diameters and short axial lengths.
- The poles and pole-shoes are laminated to minimize heating due to eddy currents.



(ii) Smooth Cylindrical Type Rotor

- Smooth Cylindrical Type Rotor is also called non-salient type or non-projected pole type or round rotor construction.
- The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coil.
- The slots are covered at the top with the help of steel or manganese wedges.
- The un-slotted portions of the cylinder itself act as the poles.
- The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor.
- These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits.
- The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging between 1500 to 3000r.p.m.



- Such high speed alternators are called **'turbo-alternators'**.
- The prime movers used to drive such type of rotors are generally steam turbines, electric motors.
- The cylindrical rotor alternators are generally designed for 2-pole type giving very high speed of $N_s = (120 \times f)/P = (120 \times 50) / 2 = 3000$ rpm.

Frequency of Induced E.M.F.

P = Number of poles

N = Speed of the rotor in r.p.m.

and f = Frequency of the induced e.m.f.

One mechanical revolution of rotor = P/2 cycles of e.m.f. electrically

Thus there are P/2 cycles per revolution.

As speed is N r.p.m., in one second, rotor will complete (N/60) revolutions.

But cycles/sec. = Frequency = f

∴ Frequency f = (No. of cycles per revolution) x (No. of revolutions per second)

$f = (P/2) \times (N/60) = (PN/120)$ Hz (cycles per sec).

So there exists a fixed relationship between three quantities, the number of poles P. the speed of the rotor N in r.p.m. and f the frequency of an induced em.f. in Hz (Hertz).

Synchronous Speed $N_s = 120f/P$ rpm

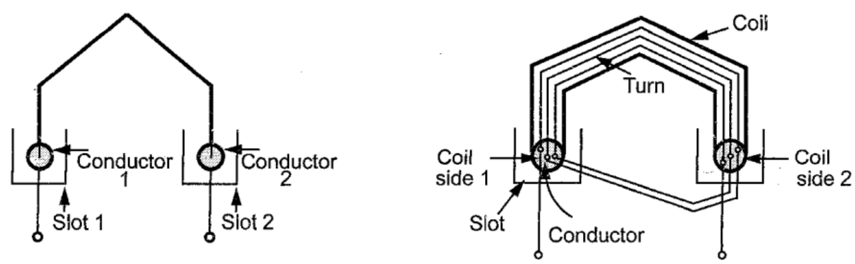
Winding Terminologies

(i) Conductor: The part of the wire, which is under the influence of the magnetic field and responsible for the induced e.m.f. is called active length of the conductor. The conductors are placed in the armature slots.

(ii) Turn: A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.

(iii) Coil: As there are number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called multiturn coil. A coil may consist of single turn called single turn coil.

(iv) Coil Side: Coil consists of many turns. Part of the coil in each slot is called coil side of a coil as shown in the Fig.



(a) Turn (b) Multiturn coil

(v) Pole Pitch (n): It is center to center distance between the two adjacent poles.

Pole pitch = 180° electrical

= slots per pole (number of slots / P) = n

(vi) Slot Angle (β) : The phase difference contributed by one slot in degrees electrical is called slot angle β.

As slots per pole contributes 180° electrical which is denoted as n,

$$1 \text{ slot angle} = \frac{180^0}{n} \text{ or } \beta = \frac{180^0}{n}$$

Types of Armature Windings

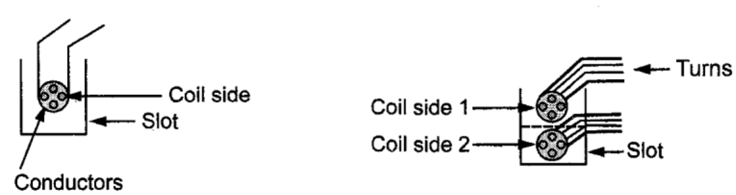
i) Single layer and double layer winding

ii) Full pitch and short pitch winding

iii) Concentrated and distributed winding.

(i) Single Layer and Double Layer Winding

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

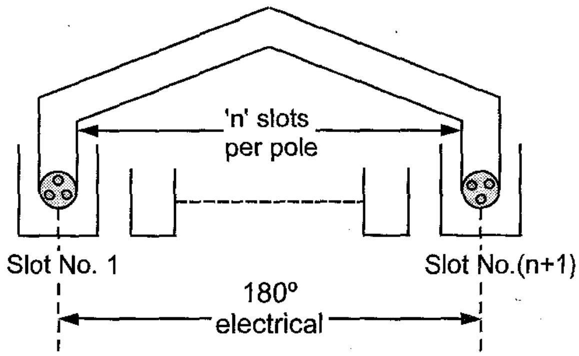


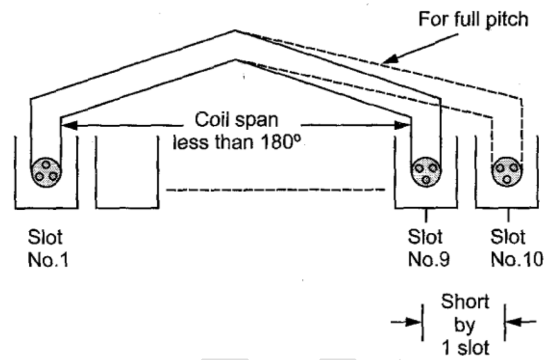
(a) Single layer (b) Double layer

(ii) Full Pitch and Short Pitch Winding

If coil side in one slot is connected to a coil side in another slot which is one pole pitch distance way from first slot, the winding is said to be full pitch winding.

Coil span It is the distance on the periphery of the armature between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is n slots or 180° electrical the coil is called full pitch coil. This is shown in the Fig.





If coil span is slightly less than a pole pitch i.e. less than 180^0 electrical, the coils are called, short pitched coils or fractional pitched coils. Generally coils are shorted by one or two slots.

Advantages of Short Pitch Coils

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

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

c) As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised. This increases the efficiency.

(iii) Concentrated and Distributed Winding

If all conductors or coils belonging to a phase are placed in one slot under every pole, it is concentrated winding.

If 'x' conductors per phase are distributed among the available slots per phase under every pole, the winding is called distributed winding.

Winding Factors

Winding Factor (K_w) is defined as the product of Distribution factor (K_d) and the coil span factor (K_c).

Pitch factor or Chording factor or Coil span factor:

The factor by which, induced emf gets reduced due to short pitching is called pitch factor or coil span factor denoted by K_c.

Pitch factor or coil span factor K_p or K_c is defined as

$$= \frac{\text{vector sum of the induced emfs per coil}}{\text{arithmetic sum of the induced emfs per coil}}$$

$$= \frac{\text{resultant emf when coil is short pitched}}{\text{resultant emf when coil is full pitched}}$$

∴ $K_c = \cos(\alpha/2)$ where α = angle of short pitch (the angle by which coils are short pitched)

$\alpha = 180^0$ – actual coil span of the coils.

Distribution factor or Breadth factor or Winding factor or Spread factor (K_d)

The factor by which there is a reduction in the emf due to distribution of coils is called distribution factor K_d.

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

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

Where m = slots/pole/phase

β = slot angle = $180^0/n$

n = slots/ pole

Equation of Induced E.M.F.

Let Z = No. of conductors or coil sides in series/phase

= 2T — where T is the No. of coils or turns per phase

P = No. of poles

f = frequency of induced e.m.f. in Hz

Φ = flux/pole in webers

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

K_c or K_p = pitch factor or coil span factor = cos (α/2)

K_f = form factor = 1.11

N = rotor rpm

In one revolution of the rotor (i.e. in 60/N second) each stator conductor is cut by a flux of ΦP webers.

∴ $d\Phi = \Phi P$ and $dt = 60/N$

∴ Average emf induced per conductor $= \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$

$f = PN/120$ or $N = 120f/P$

∴ Average emf per conductor $= \frac{\Phi P}{60} \times \frac{120\ f}{P} = 2\ f\ \Phi$ volt

If there are Z conductors in series/phase, then average emf/phase = 2fΦZ volt = 4fΦT volt

RMS value of emf/phase = 1.11 x 4fΦT = 4.44 fΦT

Actual available voltage/phase = 4.44 K_c K_d fΦT volt.

= 4 K_c K_d K_f fΦT volt.

If alternator is star connected, then line voltage is $\sqrt{3}$ times the phase voltage.

Effect of Harmonics on Pitch and Distribution Factors

(a) If the short-pitch angle or chording angle is α degrees (electrical) for the fundamental flux wave, then its values for different harmonics are

pitch-factor, k_c = cos α /2 —for fundamental

= cos 3 α /2 —for 3rd harmonic

= cos 5 α /2 —for 5th harmonic etc.

(b) Similarly, the distribution factor is also different for different harmonics. Its value becomes

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

where n is the order of the harmonic

for fundamental, $n = 1$ $kd1 = \frac{\sin m\beta/2}{m \sin \beta/2}$

for 3rd harmonic, $n = 3$ $kd3 = \frac{\sin 3m\beta/2}{m \sin 3\beta/2}$

for 5th harmonic, $n = 5$ $kd5 = \frac{\sin 5m\beta/2}{m \sin 5\beta/2}$

(c) If fundamental frequency is 50 Hz. Then for 3^{rd} harmonic f_3 = 3 x 50 = 150 Hz, for 5^{th} harmonic, f_5 = 5 x 50 = 250 Hz.etc.

Alternator on Load

As the load on an alternator is varied, its terminal voltage is also found to vary as in d.c. generators.
This variation in terminal voltage V is due to the following reasons:

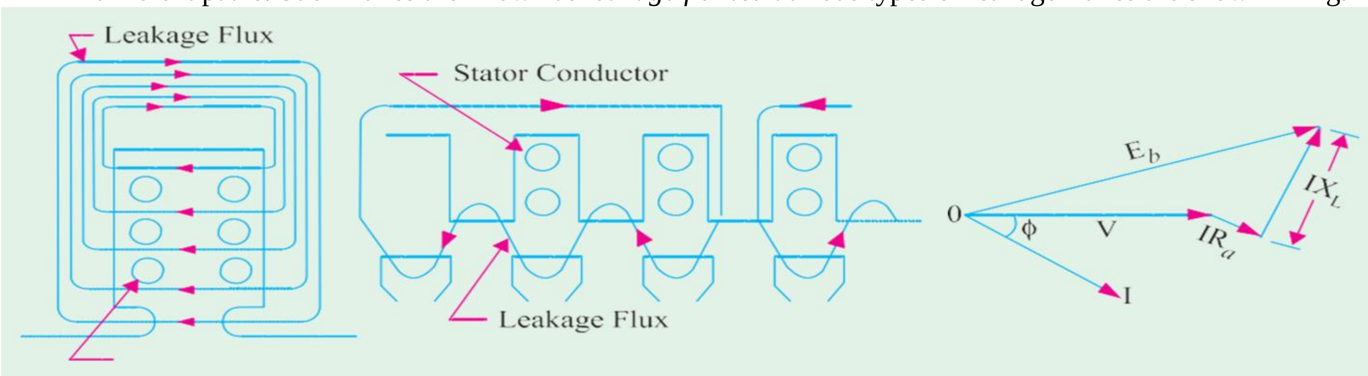
- voltage drop due to armature resistance R_a
- voltage drop due to armature leakage reactance X_L
- voltage drop due to armature reaction

Armature Resistance

The armature resistance/phase R causes a voltage drop/phase of IR_a which is in phase with the armature current I. However, this voltage drop is practically negligible.

Armature Leakage Reactance

- When current flows through the armature conductors, fluxes are set up which do not cross the air-gap, but take different paths. Such fluxes are known as *leakage fluxes*. Various types of leakage fluxes are shown in Fig.



- The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V.
- This leakage flux sets up an e.m.f. of self-inductance which is known as *reactance e.m.f.* and which is ahead of I by 90°.
- Hence, armature winding is assumed to possess leakage reactance X_L (also known as Potier rectance X_P) such that voltage drop due to this equals IX_L.
- A part of the generated e.m.f. is used up in overcoming this reactance e.m.f.

$$E = V + I\,(R + jX_L)$$

Armature Reaction

- There are two fluxes present in the air gap,
    - Due to armature current
    - Due to current in field (main) winding
- Armature reaction is the effect of armature flux on the main field flux.
- The effect of armature flux not only depends on the magnitude of the current flowing through the armature winding but also depends on the nature of the power factor of the load connected to the alternator.

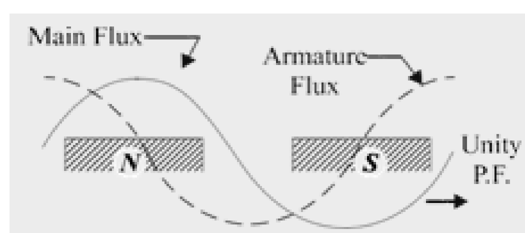
Consider three cases:

(i) When load of p.f. is unity

(ii) when p.f. is zero lagging and

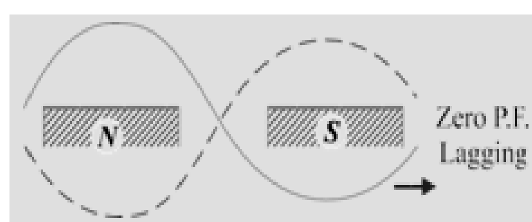
(iii) When p.f. is zero leading.

Unity Power Factor



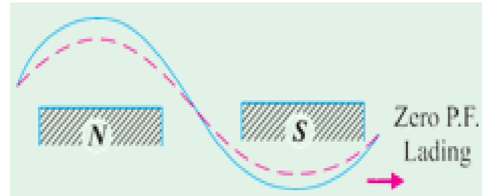
- In this case the armature flux is cross-magnetizing.
- The result is that the flux at the leading tips of the poles is reduced while it is increased at the trailing tips.
- However, these two effects nearly offset each other leaving the average field strength constant.
- Armature reaction for unity p.f. is distortional.

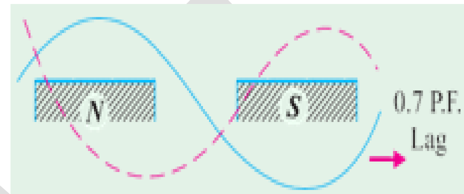
Zero P.F. lagging



- the armature flux (whose wave has moved backward by 90°) is in direct opposition to the main flux.
- Hence, the main flux is decreased. Therefore, it is found that armature reaction, in this case, is wholly ***demagnetizing***, with the result, that due to weakening of the main flux, less e.m.f. is generated.

- To keep the value of generated e.m.f. the same, field excitation will have to be increased to compensate for this weakening.





Zero P.F. leading

- armature flux wave has moved forward by 90° so that it is in phase with the main flux wave. This results in added main flux. Hence, in this case, armature reaction is wholly *magnetising*, which results in greater induced e.m.f.
- To keep the value of generated e.m.f. the same, field excitation will have to be reduced somewhat.

- For intermediate power factor, the effect is partly distortional and partly demagnetising (because p.f. is lagging).

Synchronous Reactance

- For the same field excitation, terminal voltage is decreased from its no-load value E_0 to V (for a lagging power factor). This is because of
  - drop due to armature resistance, IR_a
  - drop due to leakage reactance, IX_L
  - Drop due to armature reaction.
- The drop in voltage due to armature reaction may be accounted for by assuming the presence of a fictitious reactance X_a in the armature winding. The value of X_a is such that IX_a represents the voltage drop due to armature reaction.
- The leakage reactance X_L and the armature reactance X_a may be combined to give synchronous reactance X_S.

  Hence $X_S = X_L + X_a$
- Therefore, total voltage drop in an alternator under load is

  $= IR_a + jIX_S = I(R_a + jX_S) = IZ_S$

  where Z_S is known as synchronous impedance of the armature,
- Hence, the vector difference between no-load voltage E_0 and terminal voltage V is equal to IZ_S.

Voltage Equation of an Alternator

$E_{ph} = V_{ph} + I_aR_a + I_aX_s$

Phasor or Vector Diagram of a Loaded Alternator

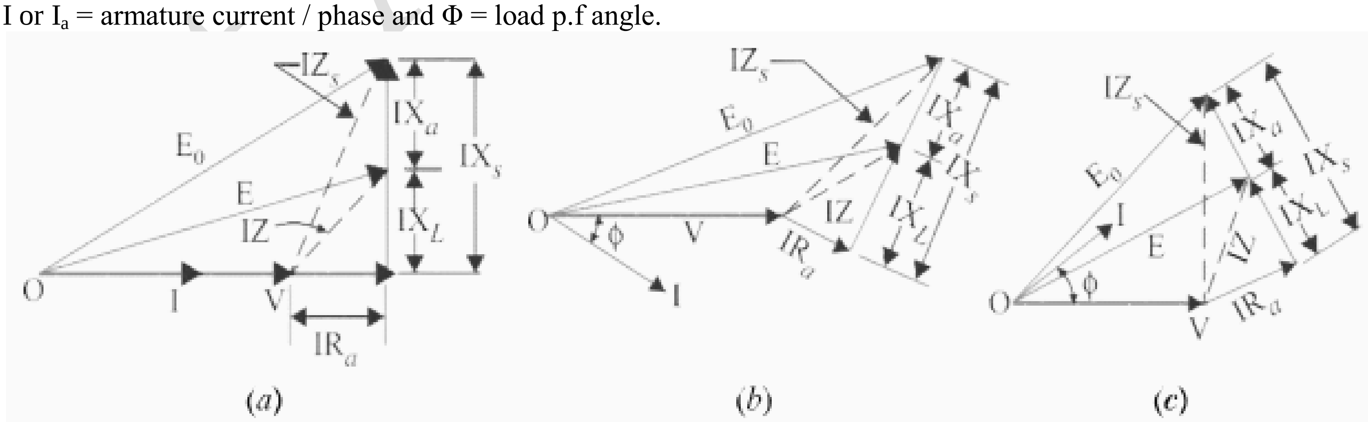
E_0 or Eph = No load emf - Voltage induced in armature in the absence of all voltage drops. Hence it represents the maximum value of the induced emf.

E = load induced emf – it is the induced emf after allowing for armature reaction. E is vectorially less than E_{ph} by I_aX_a.

V_{ph} = terminal voltage – it is vectorially less than E_{ph} by I_aZ_s.

Where $Z_s = \sqrt{R_a^2 - X_s^2}$

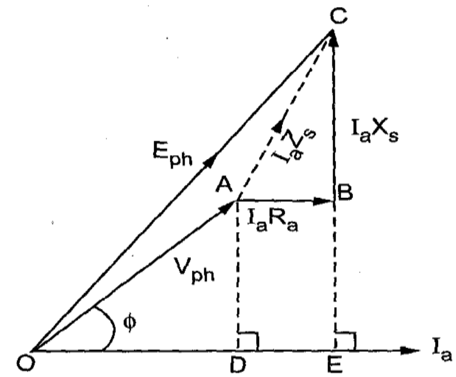
I or I_a = armature current / phase and Φ = load p.f angle.



(a) Unity p.f. (b) Lagging p.f (c) leading p.f.

<u>To find the value of induced emf.</u>

<u>*Lagging power factor load.*</u>



The vector diagram can be redrawn and the value of induced emf can be found.

From vector diagram, $OD = V_{ph}\cos\Phi$

$AD = BE = V_{ph}\sin\Phi$

$DE = I_aR_a$

From Δ OCE, $OC^2 = OE^2 + EC^2$

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

$E_{pf}^2 = (Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi + IaXs)^2$

$E_{ph} = \sqrt{(Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi + IaXs)^2}$

Where,

V_{ph} – phase value of rated voltage

I_a – phase value of current

Cos φ – p.f. of load

Similarly, the equation can be derived for other power factors.

In general,

No load induced e.m.f per phase,

$$E_{ph} = \sqrt{(Vph\cos\varphi + IaRa)^2 + (Vph\sin\varphi \pm IaXs)^2}$$

Where,

V_{ph} – phase value of rated voltage

I_a – phase value of current

Cos φ – p.f. of load

+ ve sign for lagging power factor

-ve sign for leading power factor

Voltage Regulation of an Alternator

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

So if V_{ph} = Rated terminal voltage and E_{ph} = No load induced e.m.f.

then voltage regulation is defined as,

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

Methods of Determining the Regulation

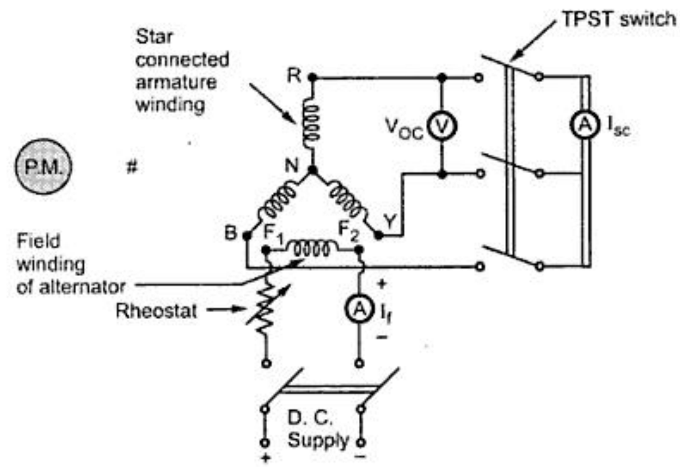
A. **Synchronous Impedance Method or E.M.F. Method**

The method requires following data to calculate the regulation.

1. The armature resistance per phase (R_a).
2. **Open circuit characteristics -** which is the graph of open circuit voltage against the field current. This is possible by conducting open circuit test on the alternator.
3. **Short circuit characteristics -** which is the graph of short circuit current against field current. This is possible by conducting short circuit test on the alternator.

The alternator is coupled to a prime mover capable of driving the alternator at its synchronous speed. The armature is connected to the terminals of a switch. The other terminals of the switch are short circuited through an ammeter. The voltmeter is connected across the lines to measure the open circuit voltage of the alternator.

The field winding is connected to a suitable d.c. supply with rheostat connected in series. The field excitation i.e. field current can be varied with the help of this rheostat. The circuit diagram is shown in the Fig.



O.C. Test:

Procedure:

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

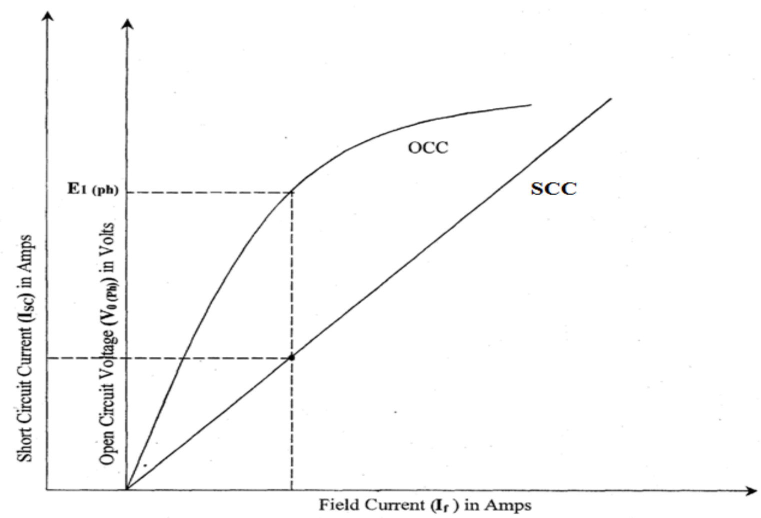
ii) Keeping rheostat in the field circuit maximum, switch on the d.c. supply.

iii) The T.P.S.T switch in the armature circuit is kept open.

iv) With the help of rheostat, field current is varied from its minimum value to the rated value. Due to this, flux increases, increasing the induced e.m.f. Hence voltmeter reading, which is measuring line value of open circuit voltage increases. For various values of field current, voltmeter readings are observed. Graph of $(V_{oc})_{ph}$ against I_f is plotted.

S.C.Test

After completing the open circuit test observation, the field rheostat is brought to maximum position, reducing field current to a minimum value. The T.P.S.T switch is closed. As ammeter has negligible resistance, the armature gets short circuited. Then the field excitation is gradually increased till full load current is obtained through armature winding. This can be observed on the ammeter connected in the armature circuit. The graph of short circuit armature current against field current is plotted from the observation table of short circuit test. This graph is called short circuit characteristics, S.C.C.



- The S.C.C. is a **straight line** graph passing through the origin while O.C.C. resembles B-H curve of a magnetic material.

Determination of Impedance from O.C.C. and S.C.C.

The synchronous impedance of the alternator changes as load condition changes. O.C.C. and S.C.C. can be used to determine Z_s for any load and load p.f. conditions.

$$\text{Synchronous impedance, } Z_s = \frac{\text{open circuit voltage }, E1(ph)}{\text{short circuit current }, Isc} \text{ (from graph)}$$

4. Regulation Calculations:

From O.C.C. and S.C.C., Z_s can be determined for any load condition.

The armature resistance per phase (R_a) can be measured by different methods. One of the method is applying d.c. known voltage across the two terminals and measuring current. So value of R_a per phase is known.

$$\text{Synchronous reactance, } X_s = \sqrt{(Zs^2 - Ra^2)}\ \Omega/ph$$

So synchronous reactance per phase can be determined.

No load induced e.m.f per phase,

$$E_{ph} = \sqrt{(V_{ph}\cos\varphi + I_aR_a)^2 + (V_{ph}\sin\varphi \pm I_aX_s)^2}$$

Where,

V_{ph} – phase value of rated voltage, I_a – phase value of current, Cos φ – p.f. of load
+ ve sign for lagging power factor, -ve sign for leading power factor

$$\% \text{ regulation} = \frac{(E_{ph} - V_{ph})}{V_{ph}} \times 100$$

5.Advantages and Limitations of Synchronous Impedance Method:

Advantage:

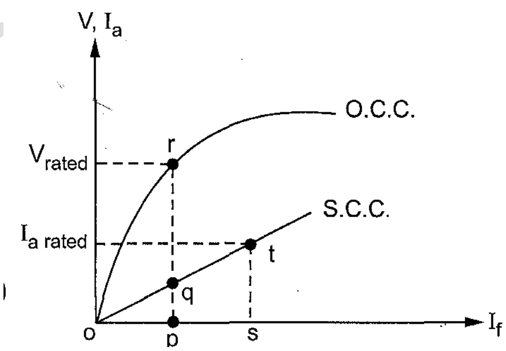
Synchronous impedance Z_s for any load condition can be calculated. Hence regulation of the alternator at any load condition and load power factor can be determined.

Limitation:

The main limitation of this method is that the method gives large values of synchronous reactance. This leads to high values of percentage regulation than the actual results. Hence this method is called **pessimistic method.**

Short Circuit Ratio and Its Significance

The short circuit ratio is the ratio of the excitation required to produce open circuit voltage equal to the rated voltage to the excitation required to produce rated full load current under short circuit.



$$\text{SCR (short circuit ratio)} = \frac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}}$$

From open and short circuit test, $Z_s = \frac{V_{oc\ (ph)}}{I_{asc\ (ph)}}$ for same I_f

$= X_s$ (neglecting R_a)

The per unit value of X_s is, $X_{s\ (pu)} = \frac{X_s}{\text{Base impedance}}$

$$\text{Base impedance} = \frac{\text{rated voltage per phase}}{\text{rated armature current per phase}}$$

From fig. base impedance $= \frac{V_{rated}}{I_{a\ rated}} = \frac{pr}{st}$

But $X_s = \frac{pr}{pq}$ at same I_f = op

$$\therefore X_{s\ (pu)} = \frac{\frac{pr}{pq}}{\frac{pr}{st}} = \frac{st}{pq}$$

$$\text{But SCR} = \frac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}} = \frac{op}{os}$$

Triangle opq and ost are similar, hence $\frac{op}{os} = \frac{pq}{st}$

$$\therefore X_{s\ (pu)} = \frac{1}{\frac{pq}{st}} = \frac{1}{SCR}$$

Significance of SCR

- For low value of.SCR, the value of Xs is more hence the drop IaXs is more. Hence the machine requires large changes in the field current (excitation) for the small changes in the load, to keep terminal voltage constant.
- A low value of SCR indicates smaller air gap and poor regulation due to large IaXs drop.
- The synchronous power is inversely proportional to Xs. This is the power which keeps alternators in synchronism during parallel operation and maintains the stability. Any disturbances from equilibrium conditions are compensated by synchronizing power. For low value of SCR, X is very large and synchronizing power is very low.

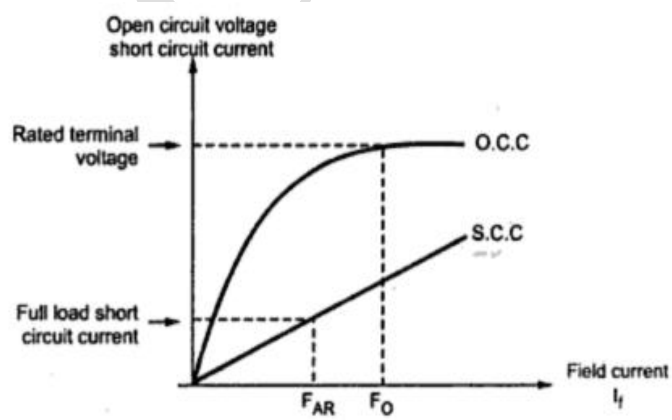
As synchronizing power decreases, tendency of alternators to remain in synchronism decreases. This decreases the stability. Thus low SCR puts the stability limit.

- The SCR can be increased by increasing the air gap but this needs more mmf to obtain same emf . Hence the pole size increases which increases the overall size and cost of the machine.
- Practically the SCR value is selected between 0.5 to 1.2.

B. Rothert's MMF or Ampere turn Method or MMF method

- The method is based on the results of open circuit test and short circuit test on an alternator.
- For any synchronous generator i.e. alternator, it requires m.m.f. which is product of field current and turns of field winding for two separate purposes.

  1. It must have an m.m.f. necessary to induce the rated terminal voltage on open circuit.
  2. It must have an m.m.f. equal and opposite to that of armature reaction m.m.f.
- The field m.m.f. required to induce the rated terminal voltage on open circuit can be obtained from open circuit test results and open circuit characteristics. This is denoted as F_O.
- The synchronous impedance has two components, armature resistance and synchronous reactance.
- Synchronous reactance also has two components, armature leakage reactance and armature reaction reactance.
- In short circuit test, field m.m.f. is necessary to overcome drop across armature resistance and leakage reactance and also to overcome effect of armature reaction.
- But drop across armature resistance and leakage reactance is very small and can be neglected.
- Thus in short circuit test, field m.m.f. circulates the full load current balancing the armature reaction effect.
- The value of ampere-turns required to circulate full load current can be obtained from short circuit characteristics. This is denoted as F_{AR}.
- The armature reaction reactance is dominating and hence the power factor of such purely reactive circuit is zero lagging. Hence F_{AR} gives demagnetizing ampere turns.
- The two components of total field m.m.f. which are F_O and F_{AR} are indicated in O.C.C. (open circuit characteristics) and S.C.C. (short circuit characteristics) as shown in the Fig.



- If the alternator is supplying full load, then total field m.m.f. is the vector sum of its two components F_O and F_{AR}.
- This depends on the power factor of the load which alternator is supplying.
- The resultant field m.m.f. is denoted as F_R.

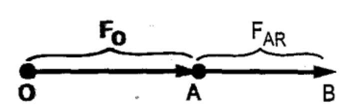
Zero lagging p.f. : As long as power factor is zero lagging, the armature reaction is completely demagnetising. Hence the resultant F_R is the algebraic sum of the two components F_O and F_{AR}. Field m.m.f. is not only required to produce rated terminal voltage but also required to overcome completely demagnetising armature reaction effect.

$OA = F_O$

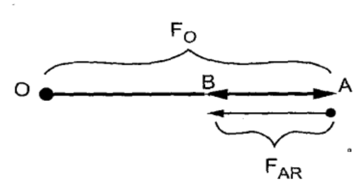
$AB = F_{AR}$ demagnetizing

$OB = F_R = F_O + F_{AR}$

Total field m.m.f. is greater than F_O.



Zero leading p.f.: When the power factor is zero leading then the armature reaction is totally magnetising and helps main flux to induce rated terminal voltage. Hence net field m.m.f. required is less than that required to induce rated voltage normally, as part of its function is done by magnetising armature reaction component. The net field m.m.f. is the algebraic difference between the two components F_O and F_{AR}.



$OA = F_O$

$AB = F_{AR}$ magnetizing

$OB = F_O - F_{AR} = F_R$

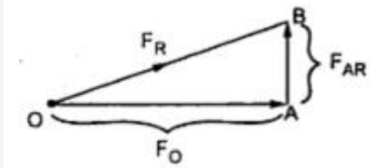
Total m.m.f. is less than F_O

Unity p.f. : Under unity power factor condition, the armature reaction is cross magnetising and its effect is to distort the main flux. Thus and F are at right angles to each other and hence resultant m.m.f. is the vector sum of F_O and F_{AR}.

$OA = F_O$

$AB = F_{AR}$ cross magnetising

$OB = F_R = F_0 + F_{AR}$ (adding vectorially)

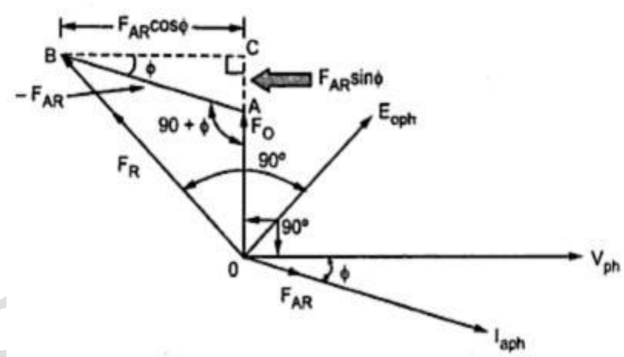


General Case:

The resultant m.m.f. is to be determined by vector addition of F_O and F_{AR}.

cosΦ, lagging p.f. :

- When the load p.f. is cosΦ lagging, the phase current I_{aph} lags V_{ph} by angle Φ.
- The component F_O is at right angles to V_{ph} while F_{AR} is in phase with the current I_{aph}. This is because the armature current I_{aph} decides the armature reaction.
- The armature reaction F_{AR} due to current I_{aph} is to be overcome by field m.m.f.
- Hence while finding resultant field m.m.f., - F_{AR} should be added to vectorially. This is because resultant field m.m.f. tries to counterbalance armature reaction to produce rated terminal voltage. The phasor diagram is shown in the Fig.



From the phasor diagram the various magnitude are,

$OA = F_O$, $AB = F_{AR}$, $OB = F_R$

Consider triangle OCB which is right angle triangle. The F_{AR} is split into two parts as,

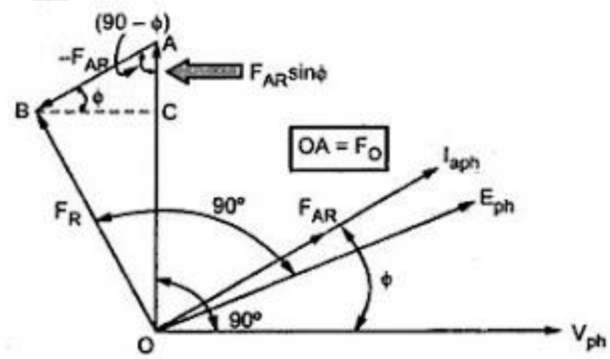
$AC = F_{AR} \sin\Phi$ and $BC = F_{AR} \cos\Phi$

$\therefore \quad (F_R)^2 = (F_O + F_{AR} \sin\Phi)^2 + (F_{AR} \cos\Phi)^2$ .... (1)

From this relation (1), F_R can be determined.

cosΦ, leading p.f. :

- When the load p.f. is cosΦ leading, the phase current I_{aph} leads V_{ph} by Φ.
- The component F_O is at right angles to V_{ph} and F_{AR} is in phase with I_{aph}.
- The resultant F_R can be obtained by adding - F_{AR} to F_O.
- The phasor diagram is shown in the Fig.



From the phasor diagram, various magnitudes are,

$AC = F_{AR} \sin\Phi$ and $BC = F_{AR} \cos\Phi$

$OA = F_O$, $AB = F_{AR}$ and $OB = F_R$

Consider triangle OCB which is right angles triangle.

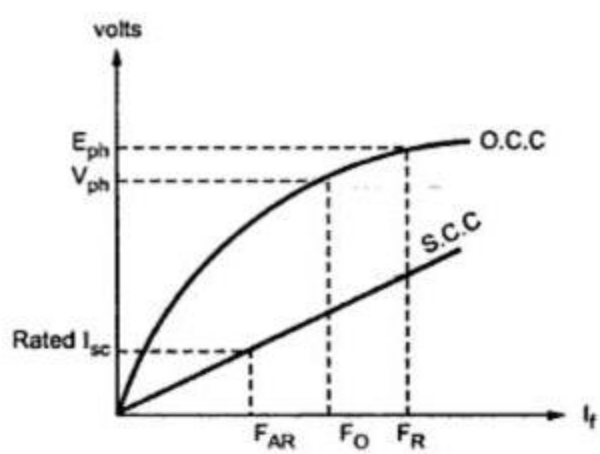
$\therefore \quad (OB)^2 = (OC)^2 + (BC)^2$

$\therefore \quad (F_R)^2 = (F_O - F_{AR} \sin\Phi)^2 + (F_{AR} \cos\Phi)$ .... (2)

From the relation (2), F_R can be obtained.

Using relations (1) and (2), resultant field m.m.f. F_R for any p.f. load condition can be obtained.

Once F_R is known, obtain corresponding voltage which is



induced e.m.f. E_{ph}, required to get rated terminal voltage V_{ph}. This is possible from open circuit characteristics drawn.

Once E_{ph} is known then the regulation can be obtained as,

$$\% \text{ regulation} = \frac{(Eph - Vph)}{Vph} \times 100$$

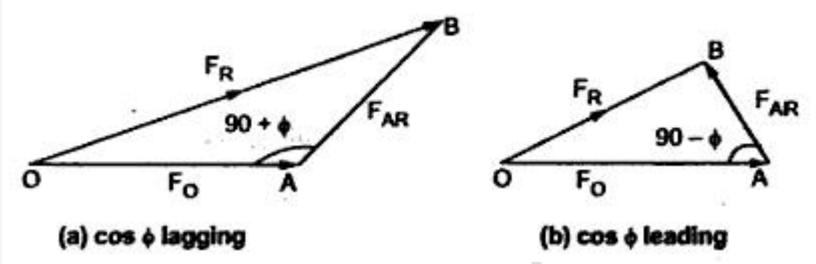
Note: This ampere-turn method gives the regulation of an alternator which is lower than actually observed. Hence the method is called **optimistic method**.

- When the armature resistance is neglected then F_O is field m.m.f. required to produce rated V_{ph} at the output terminals. But if the effective armature resistance is given then F_O is to be calculated from O.C.C. such that F_O represents the excitation (field current) required a voltage of $V_{ph} + I_{aph} R_{aph} \cos\Phi$ where

  V_{ph} = rated voltage per phase, I_{aph} = full load current per phase

  R_a = armature resistance per phase, $\cos\Phi$ = power factor of the load

F_R can be obtained using the cosine rule to the triangle formed by F_O, F_{AR} and F_O as shown in the Fig. 8.



Using cosine rule to triangle OAB,

$$F_R^2 = F_0^2 + F_{AR}^2 - 2 F_0 F_{AR} \cos (F_0 \wedge F_{AR})$$

$$F_0 \wedge F_{AR} = 90 + \Phi \text{ if } \Phi \text{ is lagging}$$

$$= 90 - \Phi \text{ if } \Phi \text{ is leading}$$

The angle between E_o and V_{ph} is denoted as δ and is called power angle. Neglecting R_a, we can write,

$$I_a X_s \cos\Phi = E_o \sin\delta$$

$$P_d = V_{ph} I_a \cos\Phi = \text{internal power of machine}$$

$$P_d = \frac{V_{ph} E_0}{X_s} \sin \delta$$

C. Potier's Triangle Method or Zero Power Factor (ZPF) Method

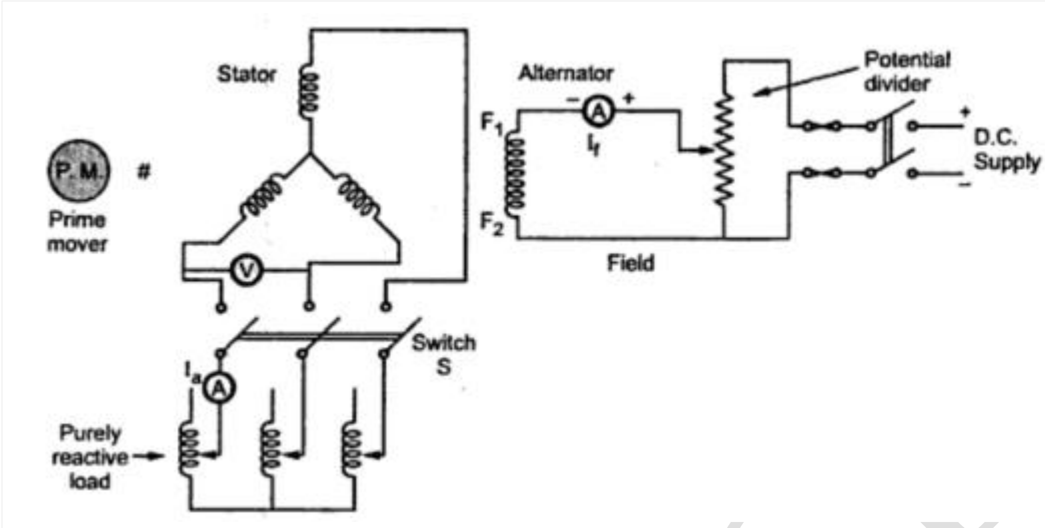
- This method is also called potier method.
- In the operation of any alternator, the armature resistance drop and armature leakage reactance drop IX_L are actually e.m.f. quantities while the armature reaction is basically m.m.f. quantity.
- In the synchronous impedance all the quantities are treated as e.m.f. quantities as against this in M.M.F. method all are treated as m.m.f. quantities. Hence in both the methods, we are away from reality.
- This method is based on the separation of armature leakage reactance and armature reaction effects.
- The armature leakage reactance X_L is called Potier reactance in this method; hence method is also called potier reactance method.

To determine armature leakage reactance and armature reaction m.m.f. separately, two tests are performed on the given alternator. The two tests are,

1. Open circuit test
2. Zero power factor test

1. Open Circuit Test

The experimental setup to perform this test is shown in the Fig.

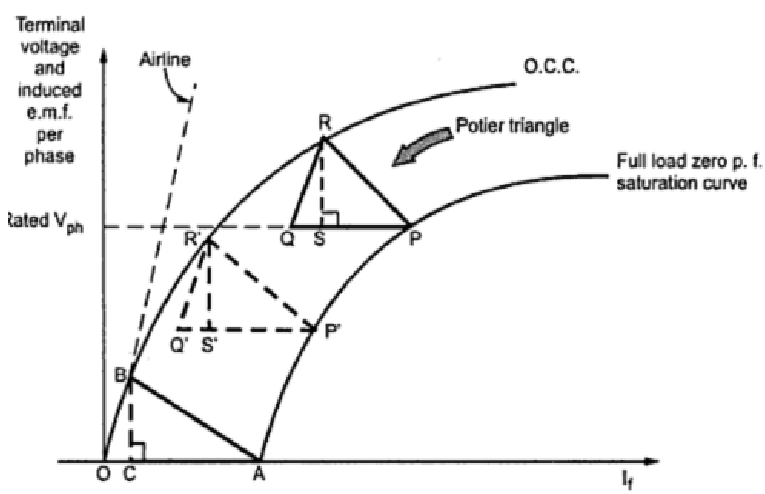


The steps to perform open circuit test are,

- ✓ The switch S is kept open.
- ✓ The alternator is driven by its prime mover at its synchronous speed and same is maintained constant throughout the test.
- ✓ The excitation is varied with the help of potential divider, from zero upto rated value in definite number of steps. The open circuit e.m.f. is measured with the help of voltmeter. The readings are tabulated.
- ✓ A graph of I_f and (V_{oc}) i.e. field current and open circuit voltage per phase is plotted to some scale. This is open circuit characteristics.

2. Zero Power Factor Test

- ✓ To conduct zero power factor test, the switch S is kept closed.
- ✓ Due to this, a purely inductive load gets connected to an alternator through an ammeter. A purely inductive load has power factor of $\cos 90^0$ i.e. zero lagging hence the test is called zero power factor test.
- ✓ The machine speed is maintained constant at its synchronous value.
- ✓ The load current delivered by an alternator to purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive load.
- ✓ In this test, there is no need to obtain number of points to obtain the curve. Only two points are enough to construct a curve called zero power factor saturation curve.
- ✓ This is the graph of terminal voltage against excitation when delivering full load zero power factor current.
- ✓ One point for this curve is zero terminal voltage (short circuit condition) and the field current required to deliver the full load short circuit armature current.
- ✓ While other point is the field current required to obtain rated terminal voltage while delivering rated full load armature current. With the help of these two points the zero p.f. saturation curve can be obtained as,



1. Plot open circuit characteristics on graph as shown in the Fig.

2. Plot the excitation corresponding to zero terminal voltage i.e. short circuit full load zero p.f. armature current. This point is shown as A in the Fig. which is on the x-axis. Another point is the rated voltage when alternator is delivering full load current at zero p.f. lagging. This point is P as shown in the Fig.

3. Draw the tangent to O.C.C. through origin which is line OB as shown dotted in the Fig. This is called air line.
4. Draw the horizontal line PQ parallel and equal to OA.
5. From point Q draw the line parallel to the air line which intersects O.C.C. at point R. Join RQ and join PR. The triangle PQR is called potier triangle.
6. From point R, drop a perpendicular on PQ to meet at point S.
7. The zero p.f. full load saturation curve is now be constructed by moving a triangle PQR so that R remains always on O.C.C. and line PQ always remains horizontal. The doted triangle is shown in the Fig. The potier triangle once obtained is constant for a given armature current and hence can be transferred as it is.
8. Through point A, draw line parallel to PR meeting O.C.C. at point B. From B, draw perpendicular on OA to meet it at point C. Triangles OAB and PQR are similar triangles.
9. The perpendicular RS gives the voltage drop due to the armature leakage reactance i.e. IX_L.
10. The length PS gives field current necessary to overcome demagnetising effect of armature reaction at full load.
11. The length SQ represents field current required to induce an e.m.f. for balancing leakage reactance drop RS.

These values can be obtained from any Potier triangle such as OAB, PQR and so on.

So armature leakage reactance can be obtained as,

$$\boldsymbol{L\,(RS) = l\,(BC) = (I_{a\,ph})_{F.L}\ x\ X_{L\,ph}}$$

$$\therefore \qquad X_{L\,ph} = \frac{l\,(RS)\text{ or }l\,(BC)}{(I_{a\,ph})_{F.L}}\ \Omega$$

This is nothing but the potier reactance.

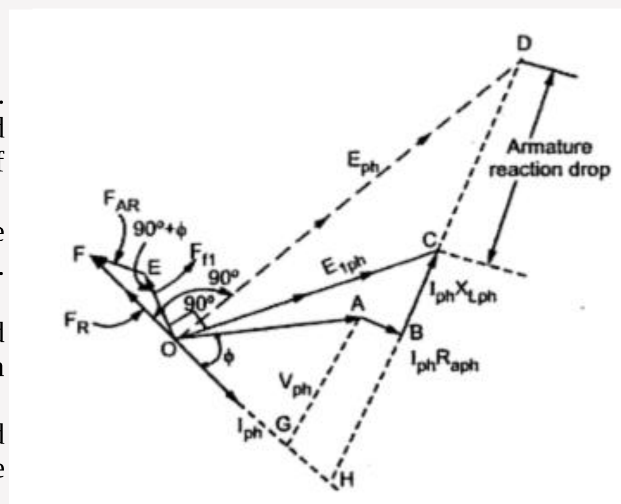
1.3 Use of Potier Reactance to Determine Regulation

To determine regulation using Potier reactance, draw the phasor diagram using following procedure:

- Draw the rated terminal voltage V_{ph} as a reference phasor. Depending upon at which power factor (cosΦ) the regulation is to be predicted, draw the current phasor I_{ph} lagging or leading V_{ph} by angle Φ.
- Draw $I_{ph} R_{aph}$ voltage drop to V_{ph} which is in phase with I_{ph}. While the voltage drop $I_{ph} X_{Lph}$ is to be drawn perpendicular to $I_{ph} R_{aph}$ vector but leading $I_{ph} R_{aph}$ at the extremely of V_{ph}.
- The R_{aph} is to be measured separately by passing a d.c. current and measuring voltage across armature winding. While X_{Lph} is Potier reactance obtained by Potier method.

Phasor sum of V_{ph} rated, $I_{ph} R_{aph}$ and $I_{ph} X_{Lph}$ gives the e.m.f. E_{1ph}.

$$\overline{E_{1\,ph}} = \overline{V_{ph}} + \overline{I_{ph}\ R_{a\,ph}} + \overline{I_{ph}\ X_{L\,ph}}$$



- Obtain the excitation corresponding to $\bar{E}_{1ph}$ from O.C.C. drawn. Let this excitation be $F_{f\,1}$. This is excitation required to induce e.m.f. which does not consider the effect of armature reaction.
- The field current required to balance armature reaction can be obtained from Potier triangle, which is say F_{AR}. ∴ $F_{AR} = l\,(PS) = l\,(AC)$ =.....

The total excitation required is the vector sum of the $F_{f\,1}$ and F_{AR}. This can be obtained exactly similar to the procedure used in M.M.F. method.

Draw vector $F_{f\,1}$ to some scale, leading E_{1ph} by 90^o. Add F_{AR} to F_{f1} by drawing vector F_{AR} in phase opposition to I_{ph}. The total excitation to be supplied by field is given by F_R.

The complete phasor diagram is shown in the Fig.

Once the total excitation is known which is F_R, the corresponding induced e.m.f. E_{ph} can be obtained from O.C.C. This E_{ph} lags F_R by 90^o. The length CD represents voltage drop due to the armature reaction. Drawing perpendicular from A and B on current phasor meeting at points G and H respectively, we get triangle OHC as right angle triangle. Hence E_{1ph} can be determined analytically also.

Once E_{ph} is known, the regulation of an alternator can be predicted as,

$$\%\ \text{regulation} = \frac{(Eph - Vph)}{Vph} \times 100$$

This method takes into consideration the armature resistance and leakage reactance voltage drops as e.m.f. quantities and the effect of armature reaction as m.m.f. quantity. This is reality hence the **results obtained by this method are nearer to the reality** than those obtained by synchronous impedance method and ampere-turns method.

The only **drawback** of this method is that the **separate curve for every load condition is necessary** to plot if potier triangles for various load conditions are required.

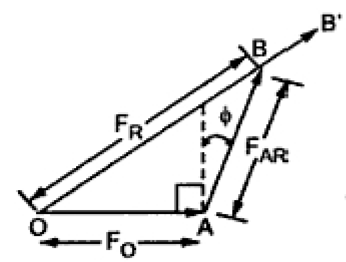
D. ASA Modification of MMF Method

- Neither of the two methods, M.M.F. method and E.M.F. method is capable of giving the reliable values of the voltage regulation.
- The error in the results of these methods is mainly due to the two reasons,

1. In these methods, the magnetic circuit is assumed to be unsaturated. This assumption is unrealistic as in practice. It is not possible to have completely unsaturated magnetic circuit.

2. In salient pole alternators, it is not correct to combine field ampere turns and armature ampere turns.
   - This is because the field winding is always concentrated on a pole core while the armature winding is always distributed.
   - Similarly the field and armature m.m.f.s act on magnetic circuits having different reluctances in case of salient pole machine hence phasor combination of field and armature m.m.f. is not fully justified.

Inspite of these short comings, due to the simplicity of constructions the ASA modified form of M.M.F. method is very commonly used for the calculation of voltage regulation.



- Consider the phasor diagram according to the M.M.F. method as shown in the Fig. for cosΦ lagging p.f. load.
- The F_R is resultant excitation of F_O and F_{AR} where F_O is excitation required to produce rated terminal voltage on open circuit while F_{AR} is m.m.f. required for balancing armature reaction effect.

  Thus OB = F_R = resultant m.m.f.
- The angle between F_{AR} and perpendicular to F_O is Φ, where cosΦ is power factor of the load.

  But OB = F_R = resultant is based on the assumption of unsaturated magnetic circuit which is not true in practice.
- Actually m.m.f. equal to BB' is additionally required to take into account the effect of partially saturated magnetic field. Thus the total excitation required is OB' rather than OB.

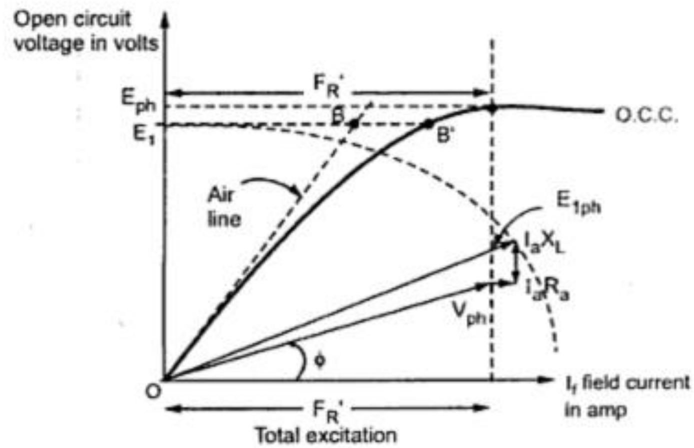
<u>Method of determining the additional excitation needed to take into account effect of partially saturated magnetic circuit.</u>

- Construct the no load saturation characteristics i.e. O.C.C. and zero power factor characteristics.
- Draw the potier triangle and determine the leakage reactance X_L for the alternator.
- The excitation necessary to balance armature reaction can also be obtained from the potier triangle. The armature resistance is known.

$$\overline{E}_{1\,ph} = \overline{V}_{ph} + \overline{I_{ph} R_{a\,ph}} + \overline{I_{ph} X_{L\,ph}}$$

- Construct ASA diagram, and draw phasor diagram related to the above equation.
- The ASA diagram has x-axis as field current and y-axis as the open circuit voltage.
- Draw O.C.C. on the ASA diagram. Then assuming x-axis as current phasor, draw V_{ph} at angle Φ, above the horizontal. The V_{ph} is the rated terminal voltage.
- Add $I_a R_a$ in phase with I_a i.e. horizontal and $I_a X_L$ perpendicular to $I_a R_a$ to V_{ph}. This gives the voltage E_{1ph}.
- With O as a centre and radius E_{1ph} draw an arc which will intersect y-axis at E_1.

- From E_1, draw horizontal line intersecting both air gap line and O.C.C.
- These points of intersection are say B and B'. The distance between the points BB' corresponding to the field current scale gives the additional excitation required to take into account effect of partially saturated field.
- Adding this to F_R we get the total excitation as F_R'.
- From this F_R', the open circuit voltage E_{1ph} can be determined from O.C.C. using which the regulation can be determined. The ASA diagram is shown in the Fig.



The resultant obtained by ASA method is reliable for both salient as well as non salient pole machines.

THEORY OF CYLINDRICAL ROTOR MACHINES

Let us consider the Phasor diagram for alternator for lagging power factor.

Let E = E.M.F induced in each phase

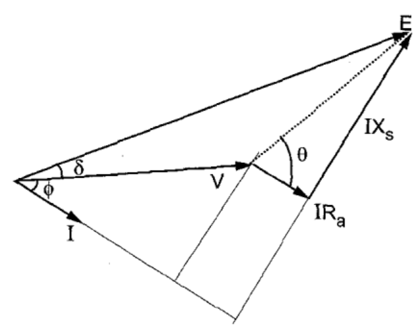
V = Terminal voltage

Φ = Phase angle between voltage and current

δ = Power angle

Ra = Resistance of armature

X_s = Synchronous reactance of alternator



$\text{Tan}\ \theta - \frac{X_s}{R_a}$

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

$\alpha = \Phi + \delta$

The voltage equation of alternator is given by

$E = V + IZ_s$ i.e. $I = \frac{E - V}{Z_s}$

$V = V\angle 0^0$, $E = E\angle\delta$, $Z_s = Z_s\angle\theta$

Therefore $I = \frac{E\angle\delta - V\angle 0^0}{Z_s\angle\theta}$

Electrical power output of alternator

$P = V.I^* = V\angle 0^0 . \frac{E\angle\delta - V\angle 0^0}{Z_s\angle\theta} * = \frac{E.V}{Z_s} \angle(\theta-\delta) - \frac{V^2}{Z_s} \angle\theta$

Therefore, $P = \frac{E.V}{Z_s} [\cos(\theta-\delta) + j \sin(\theta-\delta)] - \frac{V^2}{Z_s} [\cos\theta + j \sin\theta]$

Taking real part from above equation,

$P = \frac{E.V}{Z_s} \cos(\theta-\delta) - \frac{V^2}{Z_s} \cos\theta$

In case of large machines, $X_s >> R_a$, therefore $\theta = \tan^{-1} \frac{X_s}{R_a} = 90^0$ (R_a neglected)

Substituting $\theta = 90^0$, the net electrical power output is given by

$P = \frac{E.V}{X_s} \cos(90-\delta) - \frac{V^2}{X_s} \cos 90$

Therefore, $P = \frac{E.V}{X_s} \sin \delta$

Maximum Power Output

The condition for maximum power output is $\frac{dP}{d\delta} = 0$

Differentiating, we get o + $\frac{E.V}{X_s}$ [-sin(θ-δ)] = 0

sin(θ-δ) = 0 (θ-δ) = 0 i.e. θ = δ

Substituting the condition for maximum output, we get,

$$P_{max} = \frac{E.V}{Z_s}\cos(\theta-\theta) - \frac{V^2}{Z_s}\cos\theta$$

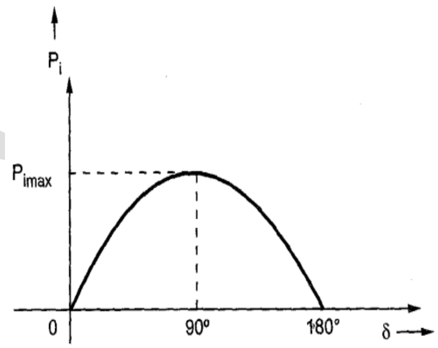
$$P_{max} = \frac{E.V}{Z_s} - \frac{V^2}{Z_s}\cos\theta$$

If R_a is Neglected, $Z_s = X_s$ and $\theta = 90^0$

$$P_{max} = \frac{E.V}{X_s} - \frac{V^2}{X_s}\cos 90^0 = \frac{E.V}{X_s}$$

Power Angle Characteristics

$$P = \frac{E.V}{X_s}\sin\delta$$

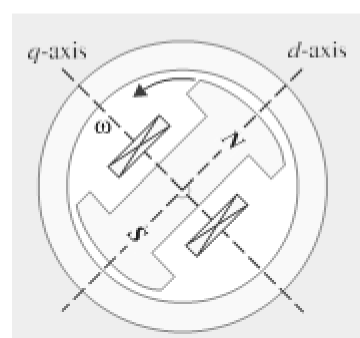


The relationship between P and δ is known as power angle characteristics of the machine.

The maximum power occurs at δ = 90°. Beyond this point the machine falls out of step and loses synchronism. The machine can be taken upto P_{max} only by gradually increasing the load. This is known as the steady state stability limit of the machine. The machine is normally operated at δ much less than 90°.

OPERATION OF A SALIENT POLE SYNCHRONOUS MACHINE

- A multipolar machine with cylindrical rotor has a uniform air-gap, because of which its reactance remains the same, irrespective of the spatial position of the rotor.
- A synchronous machine with salient or projecting poles has non-uniform air-gap due to which its reactance varies with the rotor position.
- Consequently, a cylindrical rotor machine possesses one axis of symmetry (pole axis or direct axis) whereas salient-pole machine possesses two axes of geometric symmetry



(i) field poles axis, called direct axis or *d*-axis and

(ii) axis passing through the centre of the interpolar space, called the quadrature axis or *q*-axis, as shown in Fig.

- two mmfs act on the *d*-axis of a salient-pole synchronous machine *i.e.* field m.m.f. and armature m.m.f. whereas only one m.m.f., *i.e.* armature mmf acts on the *q*-axis, because field mmf has no component in the *q*-axis.
- The magnetic reluctance is low along the poles and high between the poles.
- The above facts form the basis of the two-reaction theory proposed by Blondel.

Two Reaction theory

According to this theory

(i) armature current I_a can be resolved into two components

i.e. I_d perpendicular to E_0 and I_q along E_0.

(ii) armature reactance has two components *i.e.* *q*-axis armature reactance X_{ad} associated with I_d and *d*-axis armature reactance X_{aq} linked with I_q.

If the armature leakage reactance X_l is included which is the same on both axes, we get

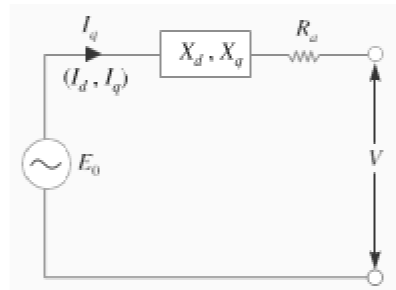
$$X_d = X_{ad} + X_l \text{ and } X_q = X_{aq} + X_l$$

Since reluctance on the q-axis is higher, owing to the larger air-gap, hence,

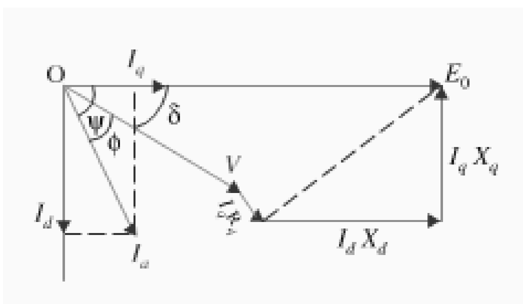
$$X_{aq} < X_{ad} \text{ or } X_q < X_d \text{ or } X_d > X_q$$

Phasor Diagram for a salient pole synchronous machine

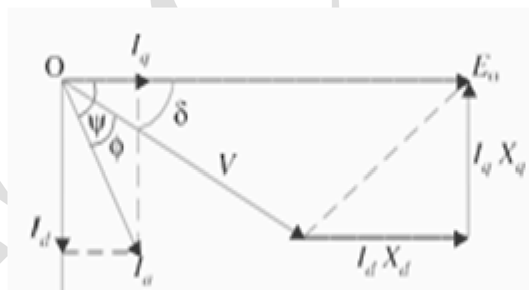
- The equivalent circuit of a salient-pole synchronous generator is shown in Fig. (a).
- The component currents I_d and I_q provide component voltage drops $jI_d X_d$ and $j I_q X_q$ as shown in Fig. (b) for a lagging load power factor.
- The armature current I_a has been resolved into its rectangular components with respect to the axis for excitation voltage E_0.
- The angle ψ between E_0 and I_a is known as the internal power factor angle.
- The vector for the armature resistance drop $I_a R_a$ is drawn parallel to I_a.
- Vector for the drop $I_d X_d$ is drawn perpendicular to I_d whereas that for $I_q X_q$ is drawn perpendicular to I_q.
- The angle δ between E_0 and V is called the power angle.



(a)



(b)



If Ra neglected

- From Phasor diagram,

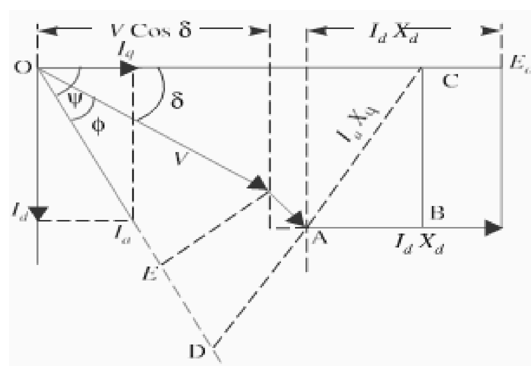
$$E_0 = V + I_a R_a + jI_d X_d + jI_q X_q \text{ and } I_a = I_d + I_q$$

If R_a is neglected the Phasor diagram becomes as shown in Fig. In this case,

$$E_0 = V + jI_d X_d + jI_q X_q$$

Calculations from Phasor Diagram

- In Fig., dotted line AC has been drawn perpendicular to I_a and CB is perpendicular to the phasor for E_0.
- The angle ACB = ψ because angle between two lines is the same as between their perpendiculars.



$I_d = I_a \sin\psi$; $Iq = I_a \cos\psi$;

Hence, $I_a = Iq/\cos\psi$

In □ ABC, $BC/AC = \cos\psi$ or $AC = BC/\cos\psi$

$= I_q X_q / \cos\psi$

$AC = I_a X_q$

From ΔODC, ψ can be found by

$$\tan\psi = \frac{AD + AC}{OE + ED} = \frac{V \sin\Phi + IaXq}{V\cos\Phi + IaRa}$$

Then, $\delta = \psi - \Phi$

From the Phasor diagram, the excitation voltage is given by

$E_0 = V \cos\delta + I_q R_a + I_d X_d$

If we neglect the armature resistance, then δ can be found as below;

$\psi = \Phi + \delta$

$I_d = I_a \sin(\Phi + \delta)$; $I_q = I_a \cos(\Phi + \delta)$

$V\sin\delta = I_q X_q = I_a X_q \cos(\Phi + \delta)$

$= I_a X_q (\cos\Phi \cos\delta - \sin\Phi \sin\delta)$

$V = I_a X_q \cot\delta \cos\Phi - I_a X_q \sin\Phi$

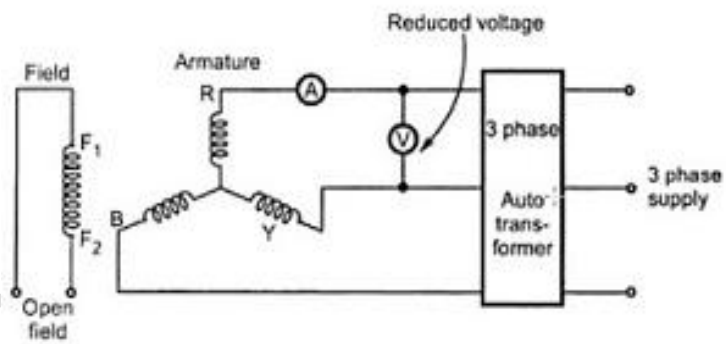
$I_a X_q \cot\delta \cos\Phi = V + I_a X_q \sin\Phi$

$$\cot\delta = \frac{V + I_a X_q \sin\Phi}{I_a X_q \cos\Phi} \quad \text{or} \quad \tan\delta = \frac{I_a X_q \cos\Phi}{V + I_a X_q \sin\Phi}$$

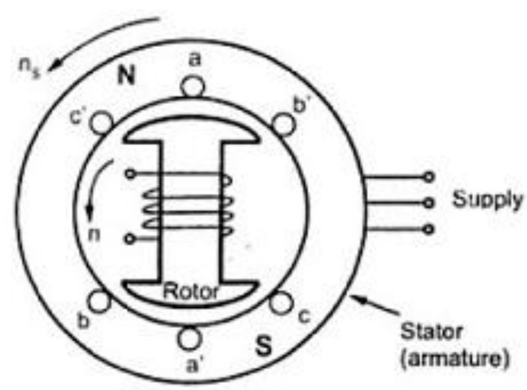
If R_a is neglected, $E_0 = V \cos\delta + I_d X_d$

Determination of X_d and X_q using slip test

- The method used to determine X_q and X_d, the direct and quadrature axis reactance is called slip test.
- In the slip test, a three phase supply is applied to the armature, having voltage must less than the rated voltage while the field winding circuit is kept open. The circuit diagram is shown in the Fig.
- The alternator is run at a speed close to synchronous but little less than synchronous value.
- The three phase currents drawn by the armature from a three phase supply produce a rotating flux.



- Thus the armature m.m.f. wave is rotating at synchronous speed as shown in the Fig.
- The rotor is made to rotate at a speed little less than the synchronous speed.
- Thus armature m.m.f. having synchronous speed, moves slowly past the field poles at a slip speed (n_s -n) where n is actual speed of rotor. This causes an e.m.f. to be induced in the field circuit.
- When the stator m.m.f. is aligned with the d-axis of field poles then flux Φ_d per poles is set up and the effective reactance offered by the alternator is X_d.
- When the stator m.m.f. is aligned with the q-axis of field poles then flux Φ_q per pole is set up and the effective reactance offered by the alternator is X_q.
- As the air gap is non uniform, the reactance offered also varies and hence current drawn the armature also varies cyclically at twice the slip frequency.
- The r.m.s. current is minimum when machine reactance is X_d and it is maximum when machine reactance is X_q.



- As the reactance offered varies due to non uniform air gap, the voltage drops also varies cyclically.
- Hence the impedance of the alternator also varies cyclically. The terminal voltage also varies cyclically.
- The voltage at terminals is maximum when current and various drops are minimum while voltage at terminals is minimum when current and various drops are maximum.
- When rotor field is aligned with the armature m.m.f., its flux linkages are maximum, but the rate of change of flux is zero. Hence voltage induced in field goes through zero at this instant. This is the position where alternator offers reactance X_d.

- While when rate of change of flux associated with rotor is maximum, voltage induced in field goes through its maximum. This is the position where alternator offers reactance X_q.

The reactances can be calculated as

$$X_d = \frac{\text{Maximum voltage}}{\text{Minimum current}} = \frac{(\text{Vt})\text{line (at minimum Ia)}}{\sqrt{3}\,\text{Ia (min)}}$$

$$X_q = \frac{\text{Minimum voltage}}{\text{Maximum current}} = \frac{(\text{Vt})\text{line (at maximum Ia)}}{\sqrt{3}\,\text{Ia (max)}}$$

Power developed by a Salient Pole Alternator (Reluctance Power)

If Ra is neglected, then copper loss is also negligible, then the power developed (P_d) by an alternator is equal to the power output (p_{out}).

Hence per phase power output of an alternator is

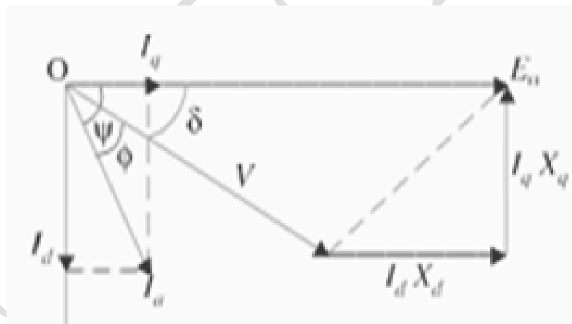
$P_{out} = V\, I_a \cos\Phi$ = power developed (P_d) …..(i)

From fig., $I_q X_q = V \sin\delta$ …..(ii)

$I_d X_d = E_0 - V\cos\delta$ ... (iii)

$I_d = I_a \sin(\Phi + \delta)$ … (iv)

$I_q = I_a \cos(\Phi + \delta)$ … (v)



If Ra neglected

Substituting Eqn. (iv) and (v) in Eqn. (ii) and (iii) and solving for $I_a \cos\Phi$, we get

$$I_a \cos\Phi = \frac{E_0}{X_d}\sin\delta + \frac{V}{2X_q}\sin 2\delta - \frac{V}{2X_d}\sin 2\delta$$

Substituting the above equation in (i), we get

$$P_d = \frac{E_0 V}{X_d}\sin\delta + \frac{1}{2}V^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta = \frac{E_0 V}{X_d}\sin\delta + \frac{V^2 (X_d - X_q)}{2\,X_d X_q}\sin 2\delta$$

The total power developed is three times the above power.

The power developed consists of two components,

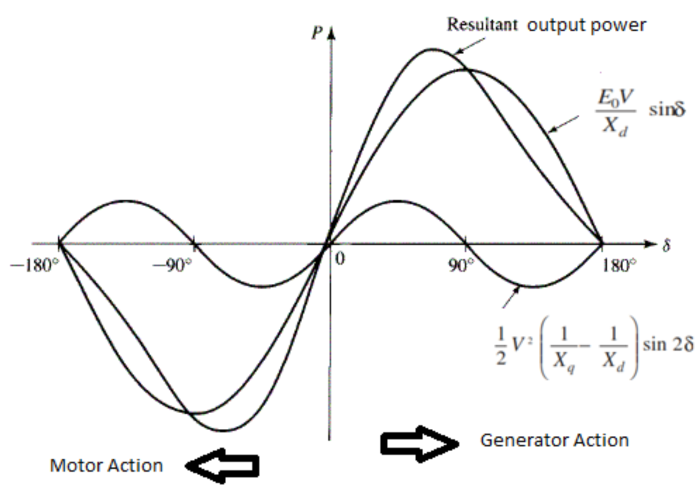
- The first term represents power due to field excitation
- Second term gives the reluctance power i.e. power due to saliency.

If $X_d = X_q$ i.e. the machine has a cylindrical rotor, then the second term is zero and the power is given by the first term only.

Power Angle Characteristics of Salient Pole Alternator

From the output power equation, the power against load angle characteristics can be obtained as shown in the figure.

Condition of δ for maximum power can be obtained by equating $dP/d\delta = 0$ and solving for δ.



Parallel Operation of Alternators

The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as ***synchronizing***.

Synchronization of alternator and methods of synchronization of alternator

What is meant by synchronization of alternator?

Connecting a group of alternators parallel to a bus bar and the alternators should have same voltage and frequency as that of bus-bar. This is called **synchronization of alternator.**

There are some conditions to be satisfied by the alternators which are to be connected in parallel to bus-bar to be in synchronization.

Conditions for synchronization of alternators:

1. The terminal voltage of incoming alternator must be equal to the bus bar voltage.
2. The frequency of voltage generated by incoming alternator must be equal to bus bar frequency.
3. The phase sequence of the three phases of the incoming alternator must be same as phase sequence of bus-bars.
4. The phase angle between the voltage generated by incoming alternator and voltage of bus-bar must be zero.
5. Always connect running alternator to bus-bar. If a stationary alternator is connected to bus-bar it will result in short circuit of stator winding.

The above conditions are to be satisfied by alternators to satisfy synchronization.

Why synchronization of alternators is necessary?

1. An alternator cannot deliver power to electric power system until its voltage, frequency, phase sequence and other parameters matches with the network to which the alternator is connected.
2. The case of synchronization arises because we are connecting many alternators in parallel to supply the demanded load. So we need to match all the parameters of connected alternators with bus-bar to deliver power to load.
3. By synchronization we can match all the parameters of one alternator with the other alternator and also with the bus-bar and deliver the required power to load.
4. **Synchronization of alternator** is also called as **paralleling of alternators.**

Advantages of paralleling of alternators:

Continuity of service:

In case of any damage to one of the alternators it can be removed. Supply to load is not interrupted because other alternators can supply the required load. But if we use a larger single unit even a small damage causes the interruption of supply.

Requirement of load:

As the load demanded is not same all the time, during light load periods we can run two or three alternators in parallel. When the demand is high we can add the required amount of alternators in parallel to meet the load demanded.

Reliability:

Several single units connected in parallel is more reliable than single larger unit because if a single unit gets damaged it can be removed and its work is compensated by other units which are running.

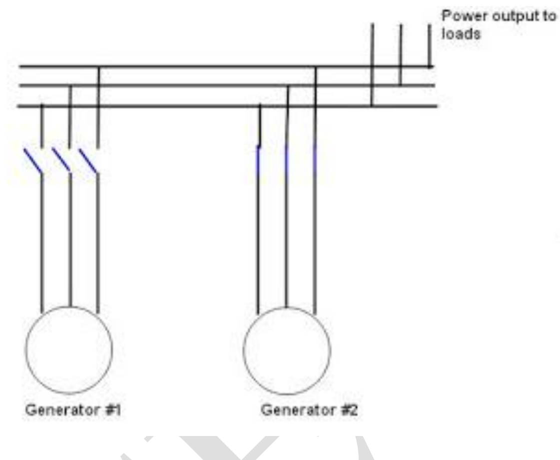
High efficiency:

An alternator runs efficiently when it is loaded at their rated value. By using required number of alternators for required demand i.e, light load or peak load we can load an alternator efficiently.

Steps to connect alternators in parallel or synchronization of alternators:

1. Consider an alternator-1. It is supplying power to bus bar at rated voltage and frequency.
2. Now we need to connect another alternator let it be alternator-2 in parallel with the alternator-1. In order to match the frequency of alternator-2 with the frequency of bus-bar or alternator-1 (since alternator-1 and bus-bar are already in synchronism) we need to adjust the speed of alternator-2. Now the voltage of alternator-2 is to be matched with the voltage of bus-bar or voltage of alternator-1 (since alternator-1 and bus-bar are already in synchronism). For this purpose we need to vary the field rheostat until the voltage matches.

3. The three phase voltages generated by alternator must be same as the three phase voltages of bus-bar or alternator-1(since alternator-1 and bus-bar are already in synchronism).This can be achieved by matching the phase sequence and frequency of alternator-2 with bus bar or alternator-1(since alternator-1 and bus-bar are already in synchronism) phase sequence and frequency.



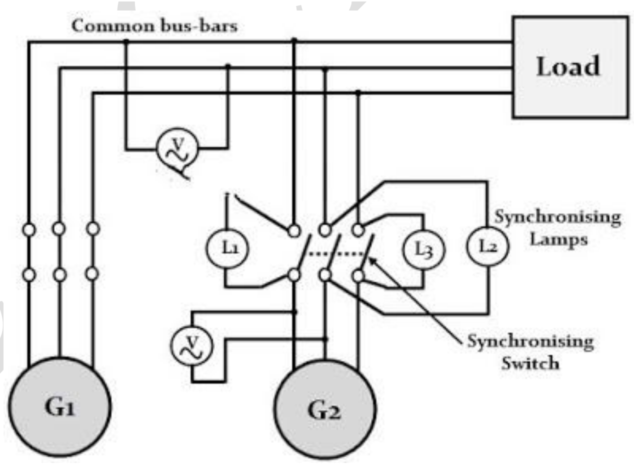
Methods for synchronization of alternators:

There are three methods for synchronization of alternators. These methods check whether the above mentioned conditions for **synchronization of alternators** are satisfied or not. The three methods are.

1. Three dark lamps method.
2. Two bright, one dark method.
3. Synchroscope method.

Three dark lamps method for synchronization of alternators:

Procedure:



1. Consider alternator-1 is supplying power to load at rated voltage and rated frequency which means alternator-1 is already in synchronism with bus-bar.
2. Now we need to connect alternator-2 in parallel with alternator-1.
3. Across the 3 switches of alternator-2 three lamps are connected as shown in the figure.
4. To match the frequency of alternator-2 with the bus-bar frequency we need to run the prime mover of alternator-2 at nearly synchronous speed which is decided by the frequency of bus-bar and number poles present in alternator-2.
5. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
6. To know whether the phase sequence of alternator -2 matches with the bus-bar phase sequence we have a condition. If all the three bulbs ON and OFF concurrently then we say the phase sequence of alternator-2 matches with the phase sequence of bus-bar. If the bulbs ON and OFF one after the other then the phase sequence is mismatching.
7. To change the connections of any two leads during the mismatch of phase sequence first off the alternator and change the connections.
8. ON and OFF rate of bulbs depends upon frequency difference of alternator-2 voltage and bus-bar voltage. Rate of flickering of bulbs is reduced when we match the frequency of alternator-2 with bus-bar voltage by adjusting the speed of prime mover of alternator-2.
9. If all the conditions required for synchronization are satisfied then the lamps will become dark.
10. Now close the switches of alternator -2 to synchronize with alternator-1.
11. Now the alternators are in synchronism.

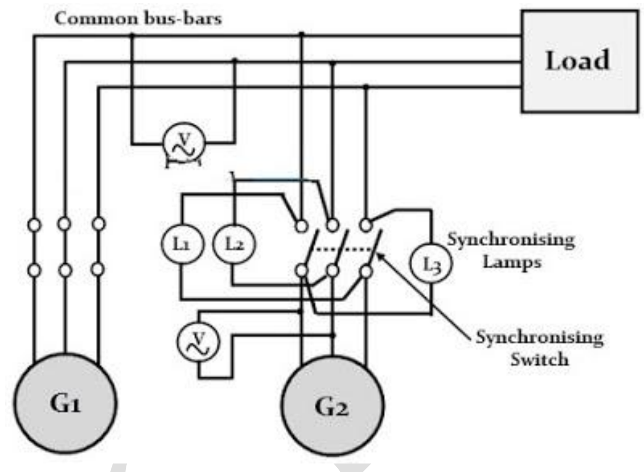
Disadvantage of three dark lamps method for synchronization of alternators:

Flickering only says difference between frequency of voltages of alternator and bus bar but correct value of frequency of voltage of alternator cannot be found.

For example, if the bus bar frequency of voltage is 50 Hz and difference in frequency of voltage of bus-bar and alternator is 1 Hz the alternator frequency of voltage can be either 49 Hz or 51 Hz.

Two bright and one dark lamp method for synchronization of alternators:

Procedure:



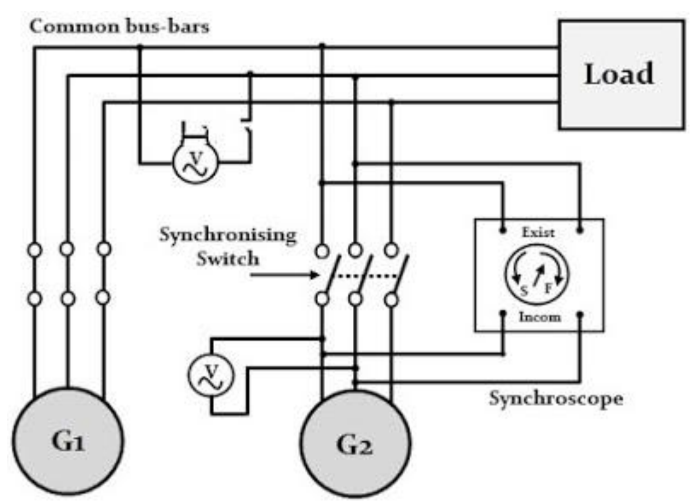
1. Consider alternator-1 is supplying power to load at rated voltage and rated frequency which means alternator-1 is already in synchronism with bus-bar.
2. Now we need to connect alternator-2 in parallel with alternator-1.
3. Here lamp L-2 is connected similar to the **three dark lamp method.**
4. Lamps L-1 and L-3 are connected in different manner. One end of lamp L-1 is connected to one of the phases other that the phase to which lamp L-2 is connected and the other end of lamp L-1 is connected to the phase to which lamp L-3 is connected.
5. Similarly one end of lamp L-3 is connected to a phase other than the phase to which lamp L-2 is connected and other end of lamp L-3 is connected to the phase to which lamp L-1 is connected as shown in the following circuit.
6. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
7. Depending upon the sequence of lamps L1, L2, L3 becoming dark and bright we can decide whether the alternator-2 frequency of voltage is higher or lower than bus-bar frequency.
8. If the sequence of bright and dark of lamps is L1-L2-L3 then the frequency of voltage of alternator-2 is higher than the bus-bar voltage. Now until the flickering reduces to a low value decreases the speed of prime mover of alternator-2.
9. If the sequence of bright and dark of lamps is L1-L3-L2 then the frequency of voltage of alternator-2 is less than the bus-bar voltage. Now until the flickering reduces to a low value increase the speed of prime mover of alternator-2.
10. When the L1 and L3 are equally bright and lamp L2 is dark then close the switches.
11. Now the alternators are in synchronism.

Disadvantage of two bright and one dark lamp method for synchronization of alternators:

Phase sequence of the alternator cannot be checked by this method.

Synchroscope method for synchronization of alternators:

Procedure:

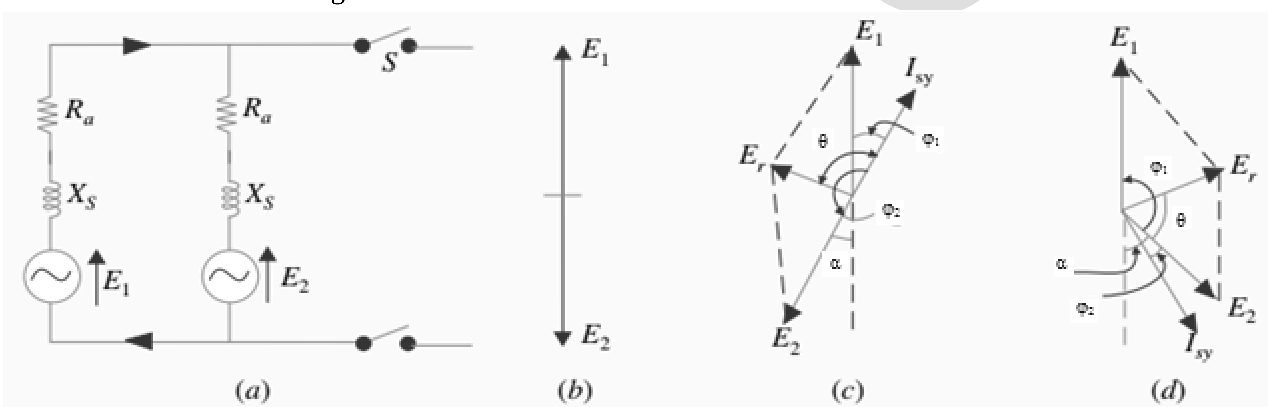


1. A synchroscope is used to achieve synchronization accurately.
2. It is similar to **two bright and one dark lamp method** and tells whether the frequency of incoming alternator is whether higher or lower than bus bar frequency.
3. This contains two terminals they are a) existing terminal b) incoming terminal.
4. Existing terminals are to be connected to bus-bar or existing alternator here in the diagram it is alternator-1 and incoming terminals are connected to incoming alternator which is alternator-2 according to the diagram which we have considered.
5. Synchroscope has a circular dial inside which a pointer is present and it can move both in clockwise and anti clockwise direction.

6. To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2 until terminal voltage of alternator-2 matches with the bus-bar voltage. The required value of voltage can be seen in the voltmeter connected to bus-bar.
7. Depending upon the rate at which the pointer is rotating the difference of frequency of voltage between incoming alternator and bus-bar can be known.
8. And also if the pointer moves anti clockwise then the incoming alternator is running slower and has frequency less than the bus bar or existing alternator frequency and if the pointer moves clock-wise then the incoming alternator is running faster and has frequency greater than bus-bar or existing alternator frequency. So by adjusting the speed of prime mover of incoming alternator we can match the frequency with bus bar or existing alternator frequency. Frequency matches when the pointer is straight up-wards. At this point close the switch.
9. Now both the alternators are in synchronism.
So by these three methods **synchronization of alternators** is checked.

Synchronizing Current and Synchronizing power

- Once synchronized properly, two alternators continue to run in synchronism.
- Any tendency on the part of one to drop out of synchronism is immediately counteracted by the production of a synchronizing torque, which brings it back to synchronism.
- When in exact synchronism, the two alternators have equal terminal p.d.'s and are in exact phase opposition. Hence, there is no current circulating round the local circuit.



- As shown in Fig. (*b*) e.m.f. E_1 of machine No. 1 is in exact phase opposition to the e.m.f. of machine No. 2 *i.e.* E_2. Hence, there is no resultant voltage.
- Suppose due to change in the speed of the governor of second machine, E_2 falls back by a phase angle of α, as shown in Fig. (*c*) ($E_1 = E_2$). They have a resultant voltage E_r, which circulates a current known as synchronizing current.
- The value of this current is given by $I_{SY} = E_r / Z_S$ where Z_S is the synchronous impedance of the phase windings of both the machines (or of one machine only if it is connected to infinite bus- bars).
- The current I_{SY} lags behind E_r by an angle θ given by tan $\theta = X_S / R_a$ where X_S is the combined synchronous reactance of the two machines and R_a their armature resistance.
- Since R_a is negligibly small, θ is almost 90 degrees. So I_{SY} lags E_r by 90° and is almost in phase with E_1.
- I_{SY} is generating current with respect to machine No.1 and motoring current with respect to machine No. 2
- This current I_{SY} sets up a synchronizing torque, which tends to retard the generating machine (*i.e.* No. 1) and accelerate the motoring machine (*i.e*. No. 2).
- Similarly, if E_2 tends to advance in phase [Fig. (*d*)], then I_{SY}, being generating current for machine No. 2, tends to retard it and being motoring current for machine No. 1 tends to accelerate it.

- Hence, any departure from synchronism results in the production of a synchronizing current I_{SY} which sets up synchronizing torque. This re-establishes synchronism between the two machines by retarding the leading machine and by accelerating the lagging one.
- Consider Fig. (*c*) where machine No. 1 is generating and supplying the Synchronizing power,

  $P_{SY} = E_1 I_{SY} \cos \varphi_1$

  $\approx E_1 I_{SY}$ (φ_1 is small).

  Since $\varphi_1 = (90° - \theta)$, synchronizing power $= E_1 I_{SY} \cos \varphi_1 = E_1 I_{SY} \cos (90° - \theta) = E_1 I_{SY} \sin \theta \cong E_1 I_{SY}$ because $\theta \cong 90°$ so that $\sin \theta \cong 1$.
- This power output from machine No. 1 goes to supply

  (*a*) Power input to machine No. 2 (which is motoring) and

  (*b*) The Cu losses in the local armature circuit of the two machines.

Power input to machine No. 2 is $E_2 I_{SY} \cos \varphi_2$ which is approximately equal to $E_2 I_{SY}$.

$\therefore E_1 I_{SY} = E_2 I_{SY}$ + Cu losses

Let $E1 = E2 = E$

Then, $E_r = 2E \cos [(180° - \alpha)/2] = 2E \cos [90° - (\alpha/2)] = 2E \sin \alpha/2 = 2E \times \alpha/2 = \alpha E$ ($\because \alpha$ is small)

Here, the angle α is in electrical radians.

Now, $I_{SY} = \dfrac{E_r}{\text{synchronous impedance}, Z_S} \cong \dfrac{E_r}{2X_S} = \dfrac{\alpha E}{2X_S}$

—if R_a of both machines is negligible

X_S - synchronous reactance of one machine

Synchronizing power (supplied by machine No. 1) is

$P_{SY} = E_1 I_{SY} \cos \varphi_1 = E I_{SY} \cos (90° - \theta) = E I_{SY} \sin \theta \cong E I_{SY}$

Substituting the value of I_{SY} from above,

$P_{SY} = E.\alpha E/2 Z_S = \alpha E^2/2Z_S \cong \alpha E^2/2X_S$ —per phase

(more accurately, $P_{SY} = \alpha E^2 \sin \theta/2X_S$)

Total synchronizing power for three phases

$= 3P_{SY} = 3\alpha E^2/2X_S$ (or $3\alpha E^2 \sin \theta/2X_S$)

This is the value of the synchronizing power when two alternators are connected in parallel and are on no-load.

Alternators Connected to Infinite Bus-bars

Consider the case of an alternator which is connected to infinite bus-bars.

The expression for P_{SY} given above is still applicable but with one important difference *i.e.* impedance (or reactance) of only that one alternator is considered (and not of two as done above).

Hence, expression for synchronizing power becomes

$E_r = \alpha E$

$I_{SY} = E_r/Z_S \cong E_r/X_S = \alpha E/X_S$ —if Ra is negligible

$\therefore$ Synchronizing power $P_{SY} = E I_{SY} = E.\alpha E/Z_S = \alpha E^2/Z_S \cong \alpha E^2/X_S$ — per phase

Now, $E/Z_S \cong E/X_S$ = S.C. current I_{SC}

$\therefore P_{SY} = \alpha E^2/X_S = \alpha E.E/X_S = \alpha E.I_{SC}$ —per phase

(more accurately, $P_{SY} = \alpha E^2 \sin \theta/X_S = \alpha E.I_{SC}.\sin \theta$)

Total synchronizing power for three phases = $3 P_{SY}$

Synchronizing Torque T_{SY}

Let T_{SY} be the synchronizing torque per phase in newton-metre (N-m)

(*a*) When there are two alternators in parallel

$$\therefore \quad T_{SY} \times \frac{2\,\pi\,N_S}{60} = P_{SY} \quad \therefore \quad T_{SY} = \frac{P_{SY}}{2\,\pi\,N_S/60} = \frac{\alpha E^2/2X_S}{2\pi\,N_S/60} \text{ N-m}$$

$$\text{Total torque due to three phases.} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/2X_S}{2\pi N_S/60} \text{ N-m}$$

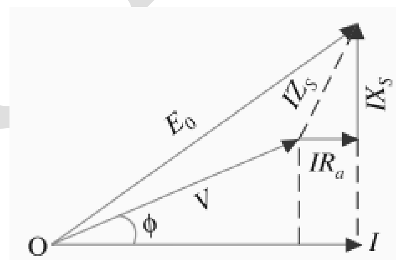
(*b*) Alternator connected to infinite bus-bars

$$T_{SY} \times \frac{2\pi N_S}{60} = P_{SY} \quad \text{or} \quad T_{SY} = \frac{P_{SY}}{2\pi N_S/60} = \frac{\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

$$\text{Again, torque due to 3 phase} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

where N_S = synchronous speed in r.p.m. $= 120\,f/P$

Effect of Load on Synchronizing Power



In this case, instead of $P_{SY} = \alpha\, E^2/X_S$, the approximate value of synchronizing power would be $\cong \alpha EV/X_S$

where V is bus-bar voltage and E is the alternator induced e.m.f. per phase.

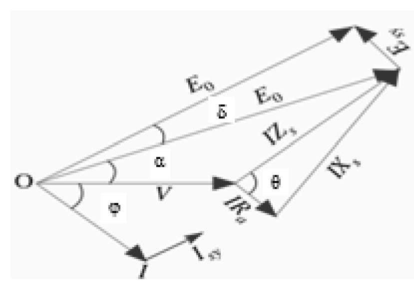
The value of $E = V + IZ_S$

As seen from Fig., for a lagging p.f.,

$$E = (V\cos\varphi + IR_a)^2 + (V\sin\varphi + IX_S)^2]^{1/2}$$

Alternative Expression for Synchronizing Power

As shown in Fig., let V and E (or E_0) be the terminal voltage and induced e.m.f. per phase of the rotor. Then, taking $V = V\angle 0°$, the load current supplied by the alternator is



$$I = \frac{E - V}{Z_S} = \frac{E\angle\alpha - V\angle 0^0}{Z_S\angle\theta}$$

$$= \frac{E}{Z_S}\angle\alpha\text{-}\theta - \frac{V}{Z_S}\angle\text{-}\theta$$

$$= \frac{E}{Z_S}\,[\cos(\theta - \alpha) - j\sin(\theta - \alpha)] - \frac{V}{Z_S}\,[\cos\theta - j\sin\theta]$$

$$= \left[\frac{E}{Z_S}\cos(\theta - \alpha) - \frac{V}{Z_S}\cos\theta\right] - j\left[\frac{E}{Z_S}\sin(\theta - \alpha) - \frac{V}{Z_S}\sin\theta\right]$$

These components represent the $I\cos\varphi$ and $I\sin\varphi$ respectively. The power P converted internally is given be the sum of the product of corresponding components of the current with $E\cos\alpha$ and $E\sin\alpha$.

$$\therefore \quad P = E\cos\alpha\left[\frac{E}{Z_S}\cos(\theta - \alpha) - \frac{V}{Z_S}\cos\theta\right] - E\sin\alpha\left[\frac{E}{Z_S}\sin(\theta - \alpha) - \frac{V}{Z_S}\sin\theta\right]$$

$$= E\left[\frac{E}{Z_S}\cos\theta\right] - E\left[\frac{V}{Z_S}.\cos(\theta + \alpha)\right] = \frac{E}{Z_S}\,[E\cos\theta - V(\cos\theta + \alpha)] \qquad \text{—per phase}$$

If angle α be changed to $(\alpha \pm \delta)$. Since V is held rigidly constant, due to displacement $\pm\,\delta$, an additional e.m.f. of divergence *i.e.* $I_{SY} = 2E$. Sin $\alpha/2$ will be produced, which will set up an additional current I_{SY} given by $I_{SY} = E_{SY}/Z_S$. The internal power will become

$$P' = \frac{E}{Z_s}\,[E\cos\theta - V\cos(\theta + \alpha \pm \delta)]$$

The difference between P' and P gives the synchronizing power.

$$\therefore \quad P_{SY} = P' - P = \frac{EV}{Z_s}\,[\cos(\theta+\alpha) - \cos(\theta + \alpha \pm \delta)]$$

$$= \frac{EV}{Z_s}\,[\sin\delta.\ \text{Sin}(\theta+\alpha) \pm 2\cos(\theta+\alpha)\sin^2\delta/2]$$

If δ is very small, then $\sin^2 \delta/2$ is zero, hence P_{SY} per phase

$$P_{SY} = \frac{EV}{Z_s}\,\text{Sin}(\theta+\alpha)\sin\delta \qquad \text{………. (i)}$$

(i) In large alternators, R_a is negligible, hence $\tan\theta = X_s / R_a = \infty$, so that $\theta = 90^0$.
Therefore, $\sin(\theta + \alpha) = \cos\alpha$

$$\therefore \quad P_{SY} = \frac{EV}{Z_s}\,.\ \text{Cos}\,\alpha\sin\delta \quad \text{------per phase} \qquad \text{………. (ii)}$$

$$= \frac{EV}{X_s}\,.\ \text{Cos}\,\alpha\sin\delta \quad \text{------ per phase} \qquad \text{………. (iii)}$$

(ii) Consider the case of synchronizing an unloaded machine on to a constant voltage bus bars. For proper operation, $\alpha = 0$ so that E coincides with V.

$\therefore \quad \sin(\theta + \alpha) = \sin\theta$

From (i), $P_{SY} = \frac{EV}{Z_s}\sin\theta\sin\delta$

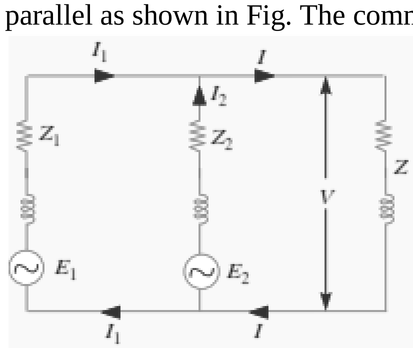
Since δ is very small, $\sin\delta = \delta$

$\therefore \quad P_{SY} = \frac{EV}{Z_s}\,\delta\sin\theta \ = \frac{EV}{X_s}\,\delta\sin\theta$

Usually $\sin\theta = 1$, hence $P_{SY} = \frac{EV}{X_s}\,\delta = V.\frac{E}{X_s}.\delta = V.I_{SC}.\delta$ --------per phase

Parallel Operation of Two Alternators

Consider two alternators with identical speed/load characteristics connected in parallel as shown in Fig. The common terminal voltage **V** is given by



$V = E_1 - I_1Z_1 = \ = E_2 - I_2Z_2$

$\therefore \quad E_1 - E_2 = I_1Z_1 - I_2Z_2$

Also $\quad I = I_1 + I_2$ and $V = IZ$

$\therefore \quad E_1 = I_1Z_1 + IZ = I_1(Z + Z_1) + I_2Z$

$$\mathbf{E_2} = \mathbf{I_2Z_2 + IZ = I_2(Z + Z_2) + I_1Z}$$

$$\therefore \quad \mathbf{I_1} = \frac{\mathbf{(E_1 - E_2)\,Z + E_1Z_2}}{\mathbf{Z\,(Z_1 + Z_2) + Z_1Z_2}}$$

$$\mathbf{I_2} = \frac{\mathbf{(E_2 - E_1)\,Z + E_2Z_1}}{\mathbf{Z\,(Z_1 + Z_2) + Z_1Z_2}};$$

$$\mathbf{I} = \frac{\mathbf{E_1Z_2 + E_2Z_1}}{\mathbf{Z\,(Z_1 + Z_2) + Z_1Z_2}}$$

$$\mathbf{V} = \mathbf{IZ} = \frac{\mathbf{E_1\,Z_2 + E_2Z_1}}{\mathbf{Z_1 + Z_2 + (Z_1Z_2/Z)}};\ \mathbf{I_1} = \frac{\mathbf{E_1 - V}}{\mathbf{Z_1}};\ \mathbf{I_2} = \frac{\mathbf{E_2 - V}}{\mathbf{Z_2}}$$

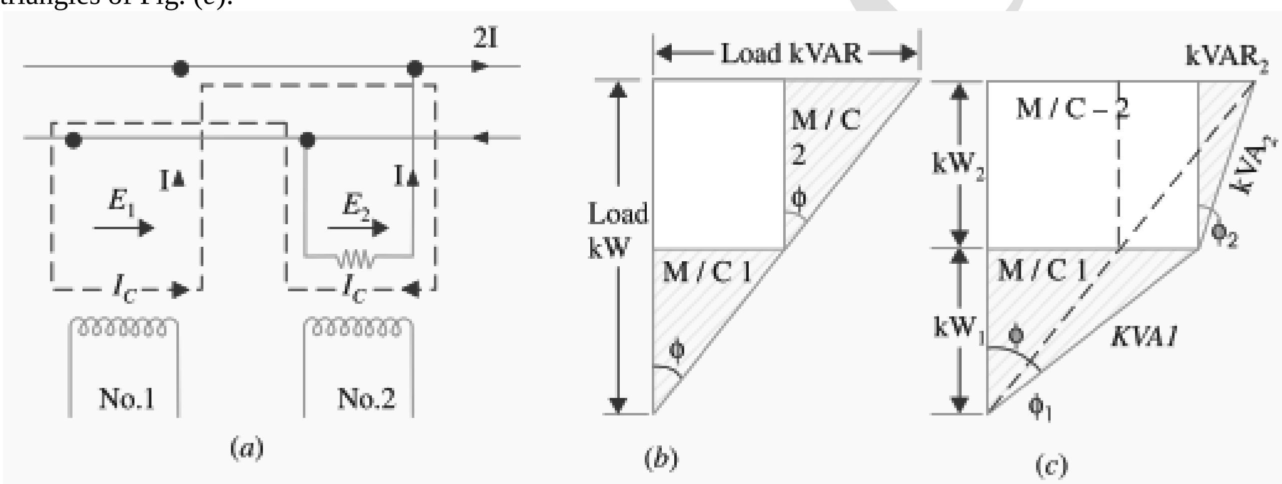
The circulating current under no-load condition is $\mathbf{I_C = (E_1 - E_2)/(Z_1 + Z_2)}$.

Distribution of Load

The amount of load taken up by an alternator running, in parallel with other machines, is solely determined by its driving torque *i.e.* by the power input to its prime mover (by giving it more or less steam, in the case of steam drive). Any alternation in its excitation merely changes its kVA output, but not its kW output. In other words, it merely changes the power factor at which the load is delivered.

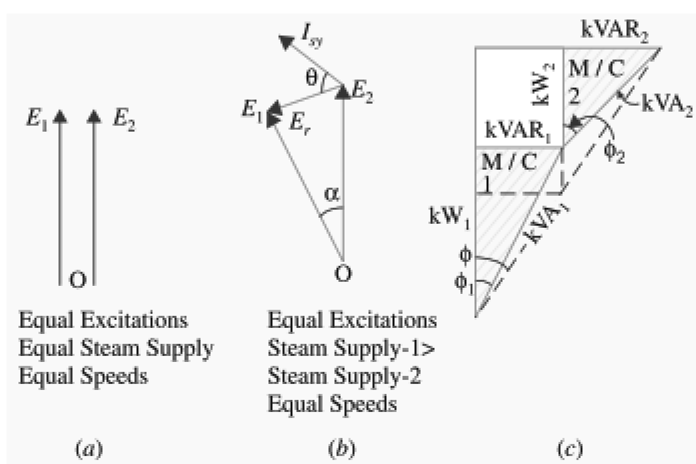
(*a*) Effect of Change in Excitation

- Suppose the initial operating conditions of the two parallel alternators are identical *i.e.* each alternator supplies one half of the active load (kW) and one-half of the reactive load (kVAR), the operating power factors thus being equal to the load p.f.
- In other words, both active and reactive powers are divided equally thereby giving equal apparent power triangles for the two machines as shown in Fig. (*b*).
- As shown in Fig. (*a*), each alternator supplies a load current I so that total output current is $2I$.
- Now, let excitation of alternator No. 1 be increased, so that E_1 becomes greater than E_2.
- The difference between the two e.m.fs. sets up a circulating current $I_C = I_{SY} = (E_1 - E_2)/2Z_S$ which is confined to the local path through the armatures and round the bus-bars.
- This current is superimposed on the original current distribution.
- As seen, I_C is vectorially added to the load current of alternator No. 1and subtracted from that of No. 2.
- The two machines now deliver load currents I_1 and I_2 at respective power factors of cos Φ_1 and cos Φ_2.
- These changes in load currents lead to changes in power factors, such that cos Φ_1 is reduced, whereas cos Φ_2 is increased.
- However, effect on the kW loading of the two alternators is negligible, but $kVAR_1$ supplied by alternator No. 1 is increased, whereas $kVAR_2$ supplied by alternator No. 2 is correspondingly decreased, as shown by the kVA triangles of Fig. (*c*).



(*b*) Effect of Change in Steam Supply

- Suppose that excitations of the two alternators are kept the same but steam supply to alternator No. 1 is increased *i.e.* power input to its prime mover is increased.
- Since the speeds of the two machines are tied together by their synchronous bond, machine No. 1 cannot overrun machine No 2.
- Alternatively, it utilizes its increased power input for carrying more load than No. 2.
- This can be made possible only when rotor No. 1 advances its angular position with respect to No. 2 as shown in Fig. (*b*) where E_1 is shown advanced ahead of E_2 by an angle α.
- Consequently, resultant voltage E_r (or E_{sy}) is produced which, acting on the local circuit, sets up a current I_{sy} which lags by almost 90° behind E_r but is almost in phase with E_1 (so long as angle α is small).



- Hence, power per phase of No. 1 is increased by an amount = $E_1 I_{sy}$ whereas that of No. 2 is decreased by the same amount (assuming total load power demand to remain unchanged).
- Since I_{sy} has no appreciable reactive (or quadrature) component, the increase in steam supply does not disturb the division of reactive powers, but it increases the active power output of alternator No. 1 and decreases that of No. 2. Load division, when steam supply to alternator No. 1 is increased, is shown in Fig. (*c*).

Points to remember:

1. The load taken up by an alternators directly depends upon its driving torque or in other words, upon the angular advance of its rotor.

2. The excitation merely changes the p.f. at which the load is delivered without affecting the load so long as steam supply remains unchanged.

3. If input to the prime mover of an alternator is kept constant, but its excitation is changed, then kVA component of its output is changed, not kW.

SHORT CIRCUIT TRANSIENTS

- The alternator running with full excitation may undergo a sudden short circuit because of the abnormal conditions.
- Due to sudden short circuit of alternator, large mechanical forces are developed which may not be sustained by the alternator.
- These forces are proportional to square of the current value, hence large pressure is built up between adjacent stator conductors.
- The short circuit transients in a synchronous machine is a complicated phenomenon due to number of circuits coupled to each other are involved.
- When a synchronous generator undergoes short circuit, it has a characteristic time varying behaviour.
- During short circuit, flux pet pole dynamically changes. Thus the transients are seen in the field and damper windings.
- The alternator can be represented by an equivalent circuit wherein the reactance is seen to be changed from subtransient reactance to final steady state synchronous reactance.
- After the moment of short circuit, the time period followed by it can be divided into three periods.
- The first one is very short period of one or two cycles the conditions of which are dependent on the flux linkages between stator and rotor during short circuit.
- The second interval is longer one which is nothing but transient decay of short circuit current which is affected by damping and rise of armature reaction.
- The final period is nothing but the steady state short circuit before which the generator is normally open circuited.

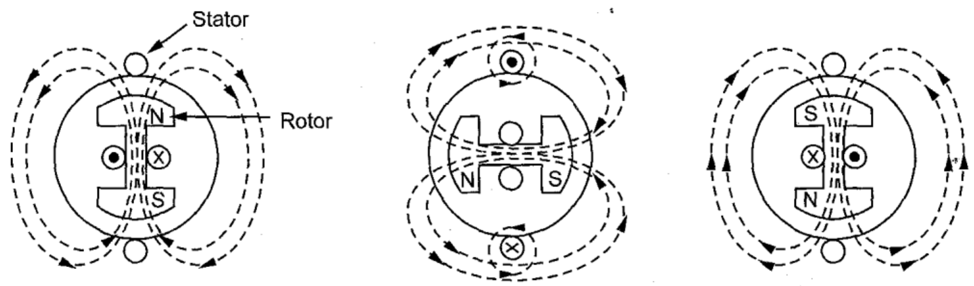
Constant Flux Linkage Theorem

- If a closed circuit with resistance r and inductance L is considered without a source then the equation obtained using KVL will be ri + L = 0.
- If r is very very small then Ldi/dt = 0 or d(Li)/dt = 0.
- This shows that the flux linkages Li remain constant.
- In generator also the effective inductance of stator and rotor windings is large compared to the resistance which can be neglected for first few cycles.
- The rotor circuit is closed through exciter while stator is closed by short circuit. Thus the flux linkage with either winding must remain constant irrespective of the rotation.

Short Circuit Phenomenon

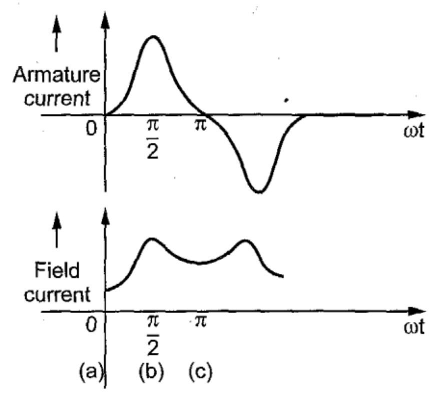
- Consider a two pole elementary single phase alternator with concentrated stator winding as shown in Fig.
- The corresponding waveforms for stator and rotor currents are shown in the Fig.
- Let short circuit occurs at position of rotor shown in Fig. 3.18.3 (a) when there are no stator linkages.
- After ¼ Rev as shown Fig. (b), it tends to establish full normal linkage in stator winding.
- The stator opposes this by a current in the shown direction as to force the flux in the leakage path.
- The rotor current must increase to maintain its flux constant.

- It reduces to normal at position (c) where stator current is again reduces to zero.
- The waveform of stator current and field current shown in the Fig. changes totally if the position of rotor at the instant of short circuit is different.



(a) Short circuit instant (b) ¼ Rev after short circuit (c) ½ Rev after short circuit

- Thus the short circuit current is a function of relative position of stator and rotor.
- After the instant of short circuit the flux linking with the stator will not change.
- A stationary image of main pole flux is produced in the stator. Thus a d.c. component of current is carried by each phase.
- The magnitude of d.c. component of current is different for each phase as the instant on the voltage wave at which short circuit occurs is different for each phase.
- The rotor tries to maintain its own poles. The rotor current is normal each time when rotor poles occupy the position same as that during short circuit and the current in the stator will be zero if the machine is previously unloaded.
- After one half cycle from this position the stator and rotor poles are again coincident but the poles are opposite



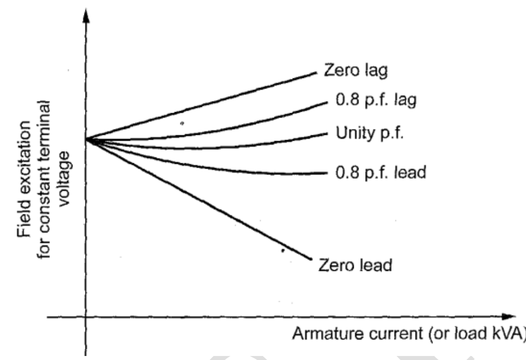
- To maintain the flux linkages constant, the current in rotor reaches to its peak value.
- The stationary field produced by poles on the stator induces a normal frequency emf in the rotor. Thus the rotor current is fluctuating whose resultant a.c. component develops fundamental frequency flux which rotates and again produces in the stator windings double frequency or second harmonic currents.
- Thus the waveform of transient current consists of fundamental, a.c. and second harmonic components of currents.
- Thus whenever short circuit occurs in three phase generator then the stator currents are distorted from pure sine wave and are similar to those obtained when an alternating voltage is suddenly applied to series R-L circuit.

Stator Currents during Short Circuit

- If a generator having negligible resistance, excited and running on no load is suddenly undergoing short circuit at its terminals, then the e.m.f. induced in the stator winding is used to circulate short circuit current through it.
- Initially the reactance to be taken into consideration is not the synchronous reactance but only the leakage reactance of the machine.
- The effect of armature flux (reaction) is to reduce the main field flux.
- But the flux linking with stator and rotor cannot change instantaneously because of the induction associated with the windings.
- Thus at the short circuit instant, the armature reaction is ineffective. It will not reduce the main flux.
- Thus the synchronous reactance will not come into picture at the moment of short circuit.
- The only limiting factor for short circuit current at this instant is the leakage reactance.
- After some time from the instant of short circuit, the armature reaction slowly shows its effect and the alternator then reaches to steady state. Thus the short circuit current reaches to high value for some time and then settles to steady value.

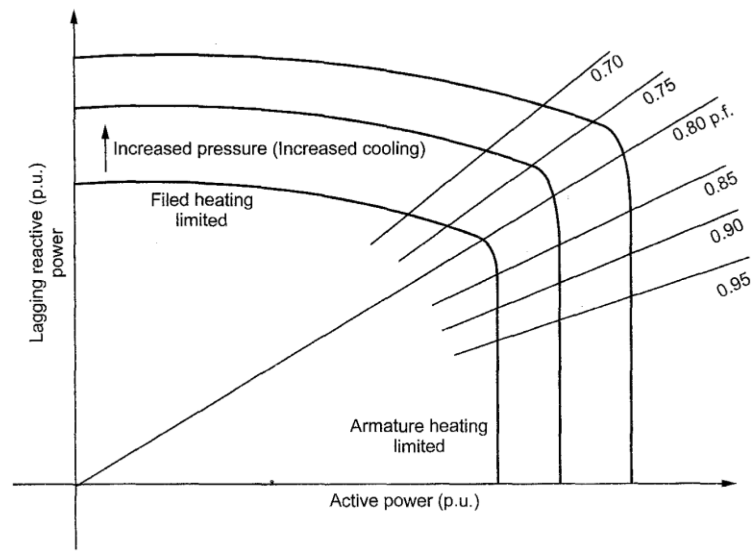
Compounding curve for alternator

If synchronous generator is supplying power at constant frequency to a load whose power factor is constant then curve showing variation of field current versus armature current when constant power factor load is varied is called compounding curve for alternator.



CAPABILITY CURVES

- The ability of prime mover decides the active power output of the alternator which is limited to a value within the apparent power rating.
- The capability curve for synchronous generator specifies the bounds within which it can operate safely.
- The loading on generator should not exceed the generator rating as it may lead to heating of stator.
- The turbine rating is the limiting factor for MW loading.
- The operation of generator should be away from steady state stability limit (δ= 90°).
- The field current should not exceed its limiting value as it may cause rotor heating.
- All these considerations provide performance curves which are important in practical applications.
- A set of capability curves for an alternator is shown in Fig.
- The effect of increased Hydrogen pressure is shown which increases the cooling.
- When the active power and voltage are fixed the allowable reactive power loading is limited by either armature or field winding heating.
- From the capability curve shown in Fig., the maximum reactive power loadings can be obtained for different power loadings with the operation at rated voltage.



- From unity p.f. to rated p.f. (0.8 as shown in Fig.), the limiting factor is armature heating while for lower power factors field heating is limiting factor.

This fact can be derived as follows

- If the alternator is operating at constant terminal voltage and armature current which the limiting value corresponding to heating then the operation of alternator is at constant value of apparent power as the apparent power is product of terminal voltage and current, both of which are constant.
- If P is per unit active power and Q is per unit reactive power then per unit apparent power is given by,

$$\text{Apparent power} = \sqrt{P^2 + Q^2} = V_t \cdot I_a$$

Thus we have,

$$\sqrt{P^2 + Q^2} = V_t \cdot I_a$$

Squaring, $$P^2 + Q^2 = (V_t \cdot I_a)^2$$

The above equation represents a circle with center at origin and radius equal to $V_t\ I_a$.

- Similarly, considering the alternator to be operating at constant terminal voltage and field current (hence E) is limited to a maximum value obtained by heating limits.

Thus induced voltage E is given by,

$$\bar{E} = \bar{V}_t + \bar{I}_a (R_a + jX_s)$$

If R_a is assumed to be zero then

$$\bar{E} = \bar{V}_t + jX_s \bar{I}_a$$

The apparent power can be written as,

$$P - jQ = \bar{V}_t \cdot \bar{I}_a$$

Substituting value of $\bar{I}_a$

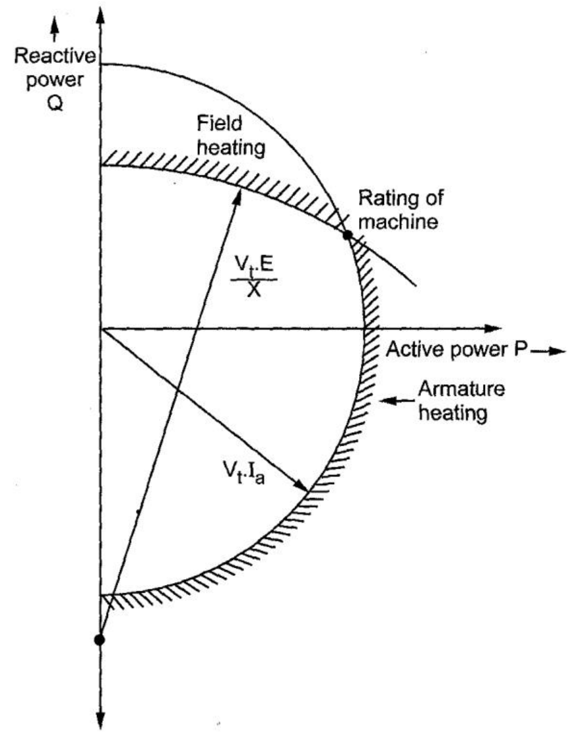
$$P - j\left(Q + \frac{V_t^2}{X_s}\right) = -j\frac{EV_t}{X_s}$$

Taking magnitudes,

$$\sqrt{P^2 + \left(Q + \frac{V_t^2}{X_s}\right)^2} = \frac{EV_t}{X_s}$$

Squaring, $P^2 + \left(Q + \frac{V_t^2}{X_s}\right)^2 = \left(\frac{EV_t}{X_s}\right)^2$

This equation also represents a circle with centre at $\left(0, -\frac{V_t^2}{X_s}\right)$.



These two circles are represented in the Fig. The field heating and armature heating limitations on machine operation can be seen from this Fig. The rating of machine which consists of apparent power and power factor is specified as the point of intersection of these circles as shown in the Fig. So that the machine operates safely.

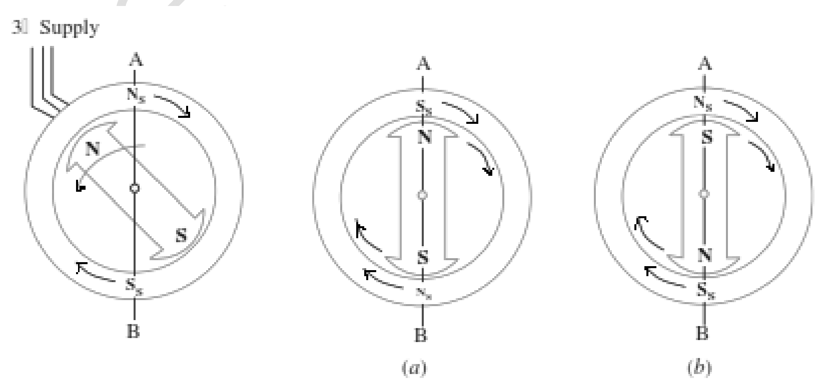
UNIT II SYNCHRONOUS MOTOR

Principle of operation – Torque equation – Operation on infinite bus bars - V and Inverted V curves – Power input and power developed equations – Starting methods – Current loci for constant power input, constant excitation and constant power developed-Hunting – natural frequency of oscillations – damper windings- synchronous condenser.

- If a three phase supply is given to the stator of a three phase alternator, it can work as a motor.
- As it is driven at synchronous speed, it is called synchronous generator.
- So if alternator is run as a motor, it will rotate at a synchronous speed. Such a device which converts an electrical energy into a mechanical energy running at synchronous speed is called synchronous motor.
- Synchronous motor works only at synchronous speed and cannot work at a speed other than the synchronous speed.

PRINCIPLE OF OPERATION (Why Synchronous Motor is not self starting?)

- Synchronous motor works on the principle of the magnetic locking.
- When a 3 phase winding is fed by a 3-phase supply, then a magnetic flux of constant magnitude but ***rotating*** at synchronous speed is produced.
- Consider a two-pole stator of Fig., in which are shown two stator poles (marked N_S and S_S) rotating at synchronous speed, say, in clockwise direction.
- With the rotor position as shown, suppose the stator poles are at that instant situated at points *A* and *B*. The two similar poles, *N* (of rotor) and N_S (of stator) as well as *S* and S_S will repel each other, with the result that the rotor tends to rotate in the anticlockwise direction.
- But half a period later, stator poles, having rotated around, interchange their positions *i.e.* N_S is at point *B* and S_S at point *A*. Under these conditions, N_S attracts *S* and S_S attracts *N*. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction).



- Hence, we find that due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing *i.e.*, in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction.
- Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.
- Now, consider the condition shown in Fig. (*a*). The stator and rotor poles are attracting each other.
- Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig. (*b*).
- Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque *i.e.*, clockwise torque, as shown in Fig.

Procedure to Start a Synchronous Motor

1. Give a three phase a.c. supply to a three phase winding. This will produce rotating magnetic field rotating at synchronous speed N_s r.p.m.
2. Then drive the rotor by some external means like diesel engine in the direction of rotating magnetic field, at a speed very near or equal to synchronous speed.

3. Switch on the d.c. supply given to the rotor which will produce rotor poles. Now there are two fields one is rotating magnetic field produced by stator while the other is produced by rotor which is physically rotated almost at the same speed as that of rotating magnetic field.
4. At a particular instant, both the fields get magnetically locked. The stator field pulls rotor field into synchronism. Then the external device used to rotate rotor can be removed. But rotor will continue to rotate at the same speed as that of rotating magnetic field i.e. N_s due to magnetic locking.

Methods of Starting Synchronous Motor

The various methods to start the synchronous motor are,
1. Using pony motors 2. Using damper winding. 3. as a slip ring induction motor 4. Using small d.c. machine coupled to it.

1. Using Pony Motors

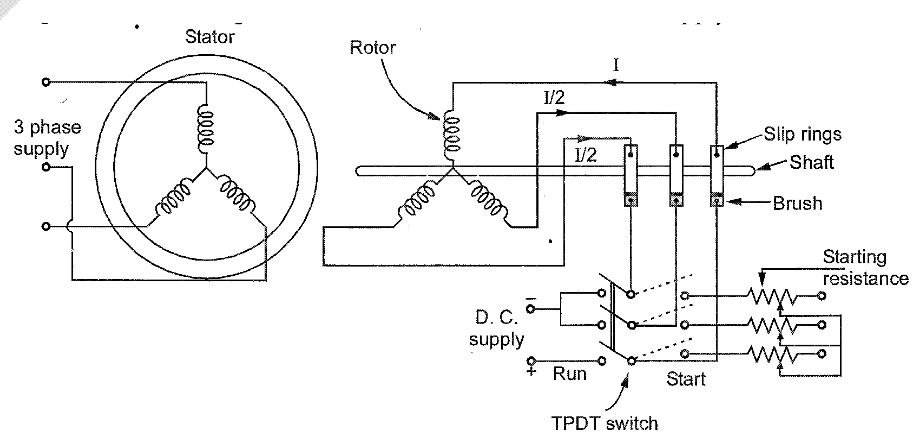
- In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called Pony Motor'.
- Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as a synchronous motor.

2. Using Damper Winding

- In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces.
- The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called damper winding.
- This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor.
- Once the stator is excited by a three phase supply, the motor starts rotating as an induction motor at sub synchronous speed. Then d.c. supply is given to the field winding.
- At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed.
- As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero.
- Hence when motor is running as synchronous motor, there cannot be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit.
- As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

3. As a Slip Ring Induction Motor

- The method of starting synchronous motor as a squirrel cage induction motor does not provide high starting torque.
- So to achieve this, instead of shorting the damper winding, it is designed to form a three phase star or delta connected winding. The three ends of this winding are brought out through slip rings.
- An external rheostat then can be introduced in series with the rotor circuit.
- So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque.



- The resistance is then gradually cut-off, as motor gathers speed.

- When motor attains speed near synchronous, d.c. excitation is provided to the rotor, then motor gets pulled into synchronism and starts rotating at synchronous speed.
- The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a rotor resistance starter.

4. Using Small D.C. Machine

- Large synchronous motors are provided with a coupled d.c. machine.
- This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed.
- Then the excitation to the rotor is provided.
- Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter.
- The field of the synchronous motor is then excited by this exciter itself.

Behaviour of Synchronous Motor on Loading

- When synchronous motor rotates at synchronous speed, the stationary stator (armature) conductors cut the flux produced by rotor.
- Due to this there is an induced e.m.f. in the stator which according to Lenz's law opposes the supply voltage.
- This induced e.m.f. is called back e.m.f. in case of synchronous motor.
- It is denoted as E_{bph} i.e. back e.m.f. per phase.
- This gets generated as the principle of alternator and hence alternating in nature and its magnitude can be calculated by the equation,

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

or $E_{bph}\ \alpha\ \Phi$

- As speed is always synchronous, the frequency is constant and hence magnitude of such back e.m.f. can be controlled by changing the flux (p produced by the rotor.
- Voltage Equation of Synchronous motor is given by

$$V_{ph} = E_{bph} + I_{aph} Z_s$$

Where $Z_s = R_a + j X_s$ Ω/phase

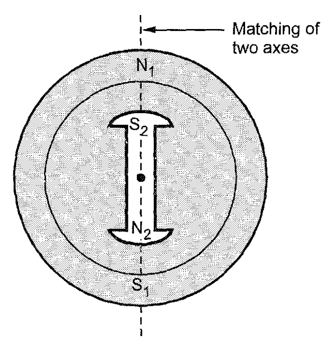
V_{ph} = supply voltage/Phase

Therefore, $I_{aph} = \frac{V_{ph} - E_{bph}}{I_{aph}}$

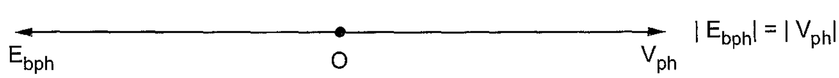
Ideal Condition on No Load

- The ideal condition on no load can be assumed by neglecting various losses in the motor.

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

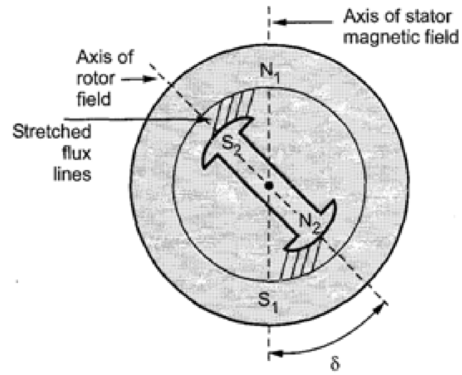


- Under this condition, the magnetic locking between stator and rotor is in such a way that the magnetic axes of both, coincide with each other as shown in the Fig.
- As this is possible only under no losses condition, is said to be ideal in case of synchronous motor.
- As magnitude of E_{bPh} and V_{ph} is same and E_{bph} opposes V_{ph}, the phasor diagram for this condition can be shown as in the Fig.



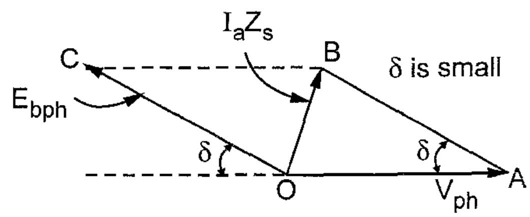
- But, $I_{aph} = \frac{V_{ph} - E_{bph}}{I_{aph}}$
- But the vector difference $V_{ph} — E_{bph} = 0$ as seen from the phasor diagram. Hence $I_a = 0$ under no losses condition.
- In practice this is impossible. Motor has to supply mechanical losses and iron losses along with small copper losses. To produce torque to overcome these losses, motor draws a current from the supply.

Synchronous Motor on No Load (With Losses)



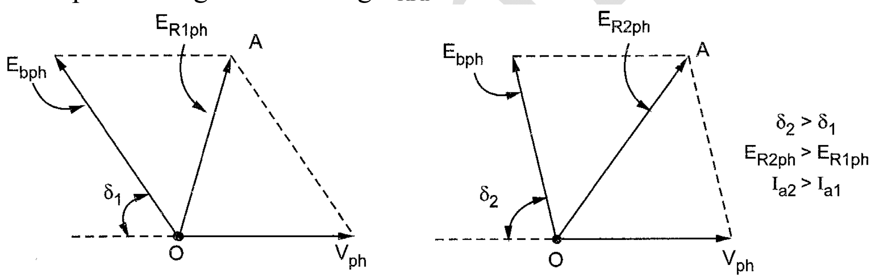
- Due to the various losses practically present on no load, the magnetic locking exists between stator and rotor but in such a way that there exists a small angle difference between the axes of two magnetic fields as shown in the Fig.
- So the rotor axis falls back with respect to stator axis by angle 'δ' as shown in Fig.
- This angle decides the amount of current required to produce the torque to supply various losses.
- Hence this angle is called load angle, power angle, coupling angle, torque angle or angle of retardation and denoted as δ.
- The Phasor diagram for no load condition with losses is shown in fig.
- The resultant phasor is denoted as E_{RPh} which is the product of armature current per phase and armature impedance per phase.

  $E_{Rph} = I_{aph} Z_s$
- This resultant decides the amount of current I_{aph} to be drawn to produce the torque which meets the various losses present in the synchronous motor.
- Under no load condition, δ is very small and hence E_{RPh} is also very small.

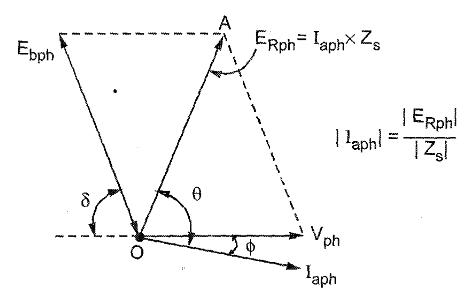


Synchronous Motor on Load

- As the load on the synchronous motor increases, there is no change in its speed. But the load angle δ i.e. the angle by which rotor axis retards with respect to stator axis changes.
- Hence as load increases, δ increases but speed remains synchronous.
- As δ increases, though E_{bph} and V_{ph} magnitudes are same, displacement of E_{bPh} from its ideal position increases. Hence the vector difference V_{ph} — E_{bph} increases.
- As synchronous impedance is constant, the magnitude of I_{aph} drawn by the motor increases as load increases. This current produces the necessary torque which satisfies the increased load demand. The magnetic locking still exists between the rotor and stator.
- The phasor diagrams showing E_{RPh} increases as load increases are shown in Fig. (a) and (b).

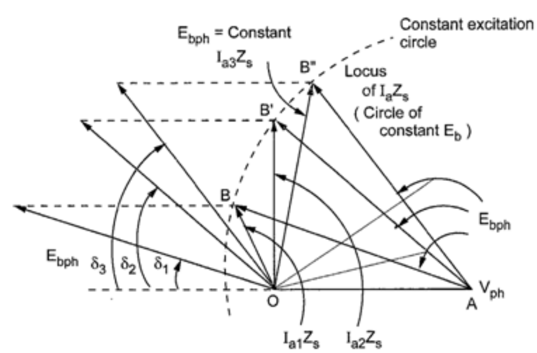


(a) Light load (b) Heavy load



Constant Excitation Circle

- As E_{bph} depends on flux, for constant excitation E_{bph} is constant.
- For constant excitation, if load is varied then δ keeps on changing, due to which V_{ph} - E_{bph} = E_{Rph} = $I_{aph}Z_s$ keeps on changing.
- The locus of extremities of E_{Rph} = $I_{aph}Z_s$ is a circle and as Z_s is constant, represents current locus for the synchronous motor under constant excitation and variable load conditions.
- As δ increases, I_{aph} Z_s increases and motor draws more current.
- As load decreases, δ decreases hence I_{aph} Z_s decreases and motor draws less current. Such a current locus is shown in the Fig.



- The mechanical power developed by the synchronous motor is given by

$$P = \frac{E_b . V_{ph}}{Z_s} \cos(\theta - \delta) - \frac{E_b^2}{Z_s} \cos\theta$$

Where E_b = Induced e.m.f. which is constant for constant excitation

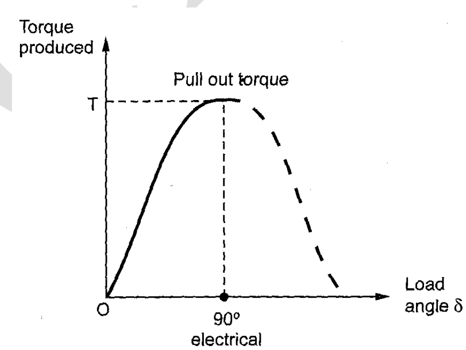
θ = Angle decided by $Z_s = \tan^{-1} \frac{X_a}{R_a}$

Now neglecting R_a, $\theta = 90°$ and using in equation (1),

$$P_m = \frac{E_b V_{ph}}{Z_s} \cos(90-\delta) = \frac{E_b V_{ph}}{X_s} \sin\delta, \quad |Z_s| = |X_s|$$

$$T = \frac{P_m}{\omega_s} = \frac{\left(\frac{E_b V_{ph}}{X_s} \sin\delta\right)}{\left(\frac{2\pi N_s}{60}\right)} \quad \text{i.e.} \quad T \propto \sin\delta$$

- As angle δ increases, the magnetic flux lines producing the force of attraction between the two get more and more stretched. This weakens the force maintaining the magnetic locking, though torque produced by the motor increases.
- As δreaches upto 90^0 electrical i.e. half a pole pitch, the stretched flux lines get broken and hence magnetic locking between the stator and rotor no longer exists. The motor comes out of synchronism.
- So torque produced at δ equal to 90° electrical is the maximum torque, a synchronous motor can produce, maintaining magnetic locking i.e. synchronism. Such a torque is called pull out torque.
- The relationship between torque produced and load angle δ is shown in the Fig.



Synchronous Motor Connected to Infinite Bus Bar

- The synchronous motor connected to an infinite bus bar behaves similarly for the changes in the load at constant excitation.
- As the load increases, the load angle increases, current increases and power factor changes.
- The changes in the power factor depends on the excitation used for synchronous motor i.e. whether it is normally excited ($E_{bph} = V_{ph}$), over excited ($E_{bph} > V_{ph}$) or under excited ($E_{bph} < V_{ph}$).
- Thus effect of change in load on synchronous motor connected to an infinite bus bar can be summarized as,
  1. Irrespective of excitation, as load increases, the load angle δ and armature current I_a increases.
  2. When the motor is normally excited (E_{bph} = Vph), then as load increases, the change in current is more significant than the change in power factor. The power factor tends to become more and more lagging as the load increases.
  3. When the motor is over excited or under excited, the power factor changes are more significant than the changes in the current as load changes.
  4. 4. When the motor is over excited or under excited, the power factor tends to approach to unity as the load increases.

Torques in Synchronous Motor

1) Starting torque: This is the torque developed by the synchronous motor at start when rated voltage is applied to the stator. It is also called breakaway torque. It is necessary to overcome friction and inertia.

2) Running torque: It is the torque developed by the motor under running conditions. It is decided by the output rating of the motor and speed of the driven machine.

3) Pull in torque: Initially synchronous motor is rotated at a speed slightly less than the synchronous speed. When speed is near to synchronous, excitation is switched on and motor gets pulled into synchronism and starts rotating at the synchronous speed. The amount of torque developed by the motor at the time of pulling into synchronism is called pull in torque.

4) Pull out torque: When the synchronous motor is loaded, the rotor falls back with respect to stator by an angle called load angle δ. As δ increases, magnetic locking between stator and rotor decreases. At $\delta = 90^0$, the torque developed is maximum by the motor and magnetic locking is very weak. Any further increase in the load pulls motor out of synchronism and motor stops. Thus the maximum torque developed by the synchronous motor without pulling out of synchronism is called pull out torque.

OPERATION OF SYNCHRONOUS MOTOR AT CONSTANT LOAD VARIABLE EXCITATION

- If excitation i.e. field current is changed keeping load constant, the synchronous motor reacts by changing its power factor of operation.
- Consider a synchronous motor operating at a certain load. The corresponding load angle is δ.

Normal Excitation

- $E_b = V$ i.e. induced e.m.f. is equal to applied voltage.

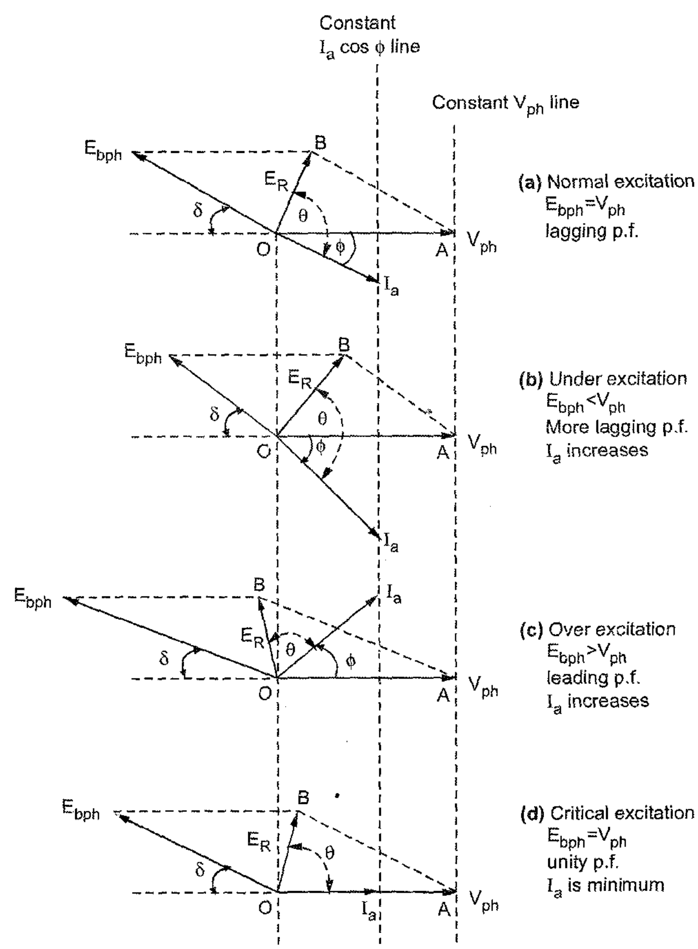
Motor is drawing certain current I_a from the supply and power input to the motor is P_{in}. The power factor of the motor is lagging in nature as shown in the Fig. (a).

Now when excitation is changed, E_b changes but there is hardly any change in the losses of the motor. So the power input also remains same for constant load demanding same power output.

$$P_{in} = \sqrt{3}\ V_L\ I_L \cos \Phi = 3\ V_{ph}\ I_{aph} \cos \Phi$$

Most of the times, the voltage applied to the motor is constant. Hence for constant power input as V_{ph} is constant, $I_{aph} \cos \Phi$ remains constant.

So motor adjusts its $\cos \Phi$ i.e. p.f. nature and value so that $I_a \cos \Phi$ remains constant when excitation of the motor is changed keeping load constant. This is the reason why synchronous motor reacts by changing its power factor to variable excitation conditions.



Under Excitation

- When the excitation is adjusted in such a way that the magnitude of induced e.m.f. is less than the applied voltage ($E_b < V$) the excitation is called Under excitation.
- Due to this, E_R increases in magnitude. This means for constant Z_s, current drawn by the motor increases.
- But E_R phase shifts in such a way that, phasor I_a also shifts (as $E_R \wedge I_a = \theta$) to keep $I_a \cos \Phi$ component constant. This is shown in the Fig. (b).
- So in under excited condition, current drawn by the motor increases. The p.f. $\cos \Phi$ decreases and becomes more and more lagging in nature.

Over Excitation

- The excitation to the field winding for which the induced e.m.f. becomes greater than applied voltage ($E_b > V$), is called over excitation.
- Due to increased magnitude of E_b, E_R also increases in magnitude.
- But the phase of E_R also changes. Now $E_R \wedge I_a = \theta$ is constant, hence I_a also changes its phase.
- So Φ changes. The I_a increases to keep $I_a \cos \Phi$ constant as shown in Fig. (c).
- The phase of E_R changes so that I_a becomes leading with respect to V_{ph} in over excited condition.

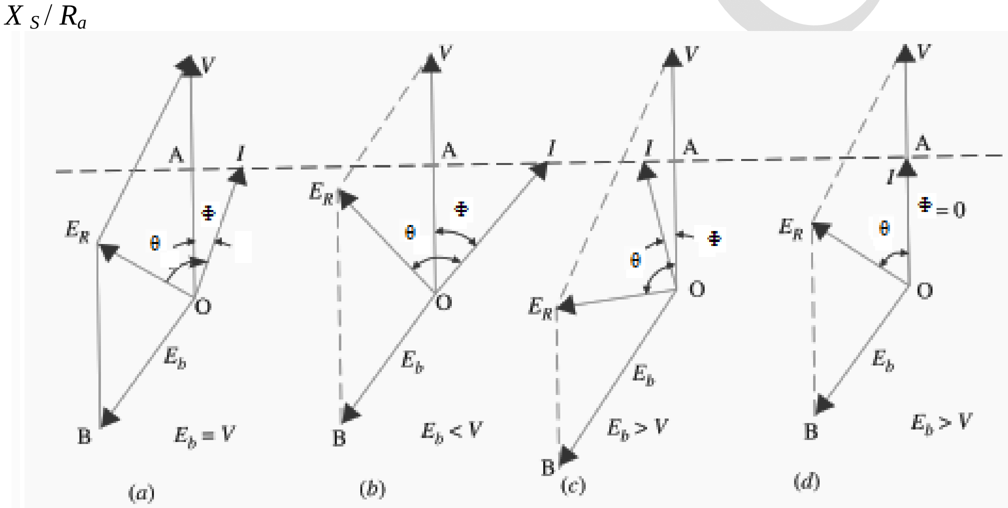
- So power factor of the motor becomes leading in nature.
- So overexcited synchronous motor works on leading power factor. So power factor decreases as over excitation increases but it becomes more and more leading in nature.

Critical Excitation

- When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity (cos $\Phi = 1$) is called critical excitation.
- Then I_{aph} is in phase with V_{ph}.
- Now $I_a \cos \Phi$ must be constant, $\cos \Phi = 1$ is at its maximum hence motor has to draw minimum current from supply for unity power factor condition.
- So for critical excitation, $\cos \Phi = 1$ and current drawn by the motor is minimum compared to current drawn by the motor for various excitation conditions. This is shown in the Fig. (d).

V-Curves and Inverted V-Curves

- The value of excitation for which back e.m.f. E_b is equal (in magnitude) to applied voltage V is known as 100% excitation.
- Consider a synchronous motor in which the mechanical load is constant (and hence output is also constant if losses are neglected). Fig. (*a*) shows the case for 100% excitation *i.e.*, when $E_b = V$.
- The armature current *I* lags behind V by a small angle Φ. Its angle θ with E_R is fixed by stator constants *i.e.*
  $\tan \theta = X_S / R_a$



- In Fig. (*b*) excitation is less than 100% *i.e.*, $E_b < V$. Here, E_R is advanced clockwise and so is armature current (because it lags behind E_R by fixed angle θ).
- The magnitude of *I* is increased but its power factor is decreased (Φ has increased).
- Because input as well as V are constant, hence the power component of *I* *i.e.*, $I \cos \Phi$ remains the same as before, but wattless component $I \sin \Phi$ is increased.
- Hence, as excitation is decreased, *I* will increase but p.f. will decrease so that power component of *I* *i.e.*, $I \cos \Phi = OA$ will remain constant.
- In fact, the locus of the extremity of current vector would be a straight horizontal line as shown.
- Fig. (*c*) represents the condition for overexcited motor *i.e.* when $E_b > V$.
- Here, the resultant voltage vector E_R is pulled anticlockwise and so is *I*.
- It is seen that now motor is drawing a leading current.
- It may also happen for some value of excitation, that *I* may be in phase with V *i.e.*, p.f. is unity [Fig. (*d*)]. At that time, the current drawn by the motor would be ***minimum***.

Two important points stand out clearly from the above discussion:

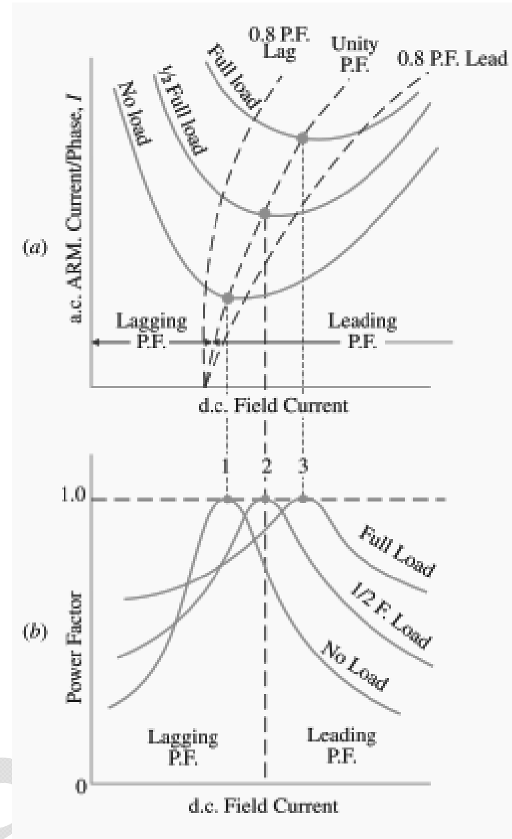
(i) The magnitude of armature current varies with excitation. The current has large value both for low and high values of excitation (though it is lagging for low excitation and leading for higher excitation). In between, it has minimum value corresponding to a certain excitation.

The variations of *I* with excitation are shown in Fig. (*a*) which are known as '*V*' curves because of their shape.

(ii) For the same input, armature current varies over a wide range and so causes the power factor also to vary accordingly.

When over-excited, motor runs with leading p.f. and with lagging p.f. when under-excited. In between, the p.f. is unity.

The variations of *p.f.* with excitation are shown in Fig. (*b*). The curve for p.f. looks like inverted '*V*' curve. It would be noted that ***minimum armature current corresponds to unity power factor***.



EXPRESSION FOR BACK E.M.F. OR INDUCED E.M.F. PER PHASE IN SYNCHRONOUS MOTOR (E_{bph})

Case i] Under excitation, $E_{bph} < V_{ph}$.

$$Z_s = R_a + j X_s = | Z_s | \angle \theta \ \Omega$$

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$

$$E_{Rph} \wedge I_{aph} = \theta, \ I_a \text{ lags } E_R \text{ always by angle } \theta.$$

$$V_{ph} = \text{Phase voltage applied}$$

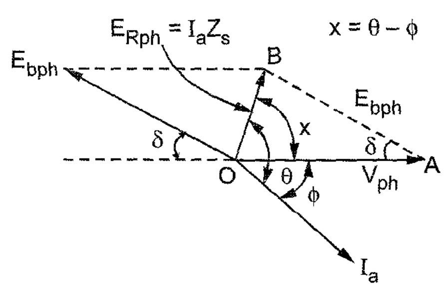
$$E_{bph} = \text{Back e.m.f. induced per phase}$$

$$E_{Rph} = I_a \times Z_s \ V \quad \text{... Per phase}$$

Let p.f. be cos ϕ, lagging as under excited,

$$V_{ph} \wedge I_{aph} = \phi$$

Phasor diagram is shown in the Fig.



Applying cosine rule to Δ OAB,

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} \ E_{Rph} \times \cos(V_{ph} \wedge E_{Rph})$$

but $V_{ph} \wedge E_{Rph} = x = \theta - \phi$

$$\therefore \quad (E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \times \cos(\theta - \phi) \qquad \text{— 1}$$

where $E_{Rph} = I_{aph} \times Z_s$

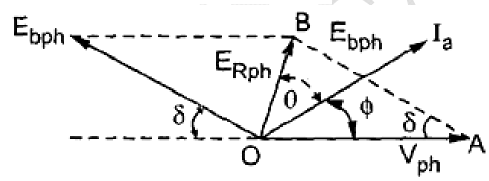
Applying sine rule to Δ OAB,

$$\frac{E_{bph}}{\sin x} = \frac{E_{Rph}}{\sin\delta} \quad \text{i.e.} \quad \sin\delta = \frac{E_{Rph}\sin(\theta - \phi)}{E_{bph}} \qquad \text{— 2}$$

So once E_{bph} is calculated, load angle δ can be determined by using sine rule.

Case ii] Over excitation, $E_{bph} > V_{ph}$

p.f. is leading in nature.



$$E_{Rph} \hat{} I_{aph} = \theta$$

$$V_{ph} \hat{} I_{aph} = \phi$$

The phasor diagram is shown in the Fig.

Applying cosine rule to Δ OAB,

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \times \cos(V_{ph} \wedge E_{Rph})$$

$$V_{ph} \wedge E_{Rph} = \theta + \phi$$

$$\therefore \quad (E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos(\theta + \phi) \qquad \text{— 3}$$

But θ + φ is generally greater than 90°

∴ cos (θ + φ) becomes negative, hence for leading p.f., $E_{bph} > V_{ph}$.

Applying sine rule to Δ OAB,

$$\frac{E_{bph}}{\sin(E_{Rph} \wedge V_{ph})} = \frac{E_{Rph}}{\sin\delta}$$

$$\therefore \quad \sin\delta = \frac{E_{Rph}\sin(\theta + \phi)}{E_{bph}} \qquad \text{— 4}$$

Hence load angle δ, can be calculated once E_{bph} is known.

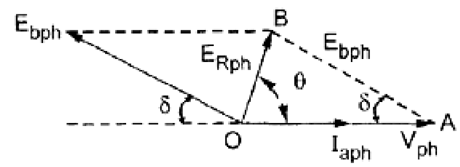
Case iii] Critical excitation

In this case $E_{bph} \cong V_{ph}$, but p.f. of synchronous motor is unity.

$\therefore \quad \cos\phi = 1 \quad \therefore \quad \phi = 0°$

i.e. V_{ph} and I_{aph} are in phase.

and $E_{Rph} \wedge I_{aph} = \theta$



Phasor diagram is shown in the Fig.

Applying cosine rule to Δ OAB,

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2\,V_{ph}\,E_{Rph}\cos\theta \quad \text{———} \quad 5$$

Applying sine rule to Δ OAB,

$$\frac{E_{bph}}{\sin\theta} = \frac{E_{Rph}}{\sin\delta}$$

$$\therefore \quad \boxed{\sin\delta = \frac{E_{Rph}\sin\theta}{E_{bph}}} \quad \text{———} \quad 6$$

Thus in general the induced e.m.f. can be obtained by,

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2\,V_{ph}\,E_{Rph}\cos(\theta \pm \phi)$$

+ sign for leading p.f. while – sign for lagging p.f.

POWER FLOW IN SYNCHRONOUS MOTOR

Net input to the synchronous motor is the three phase input to the stator.

Therefore, $P_{in} = \sqrt{3}\,V_L I_L \cos\Phi$ W

where V_L = Applied line voltage

I_L = Line current drawn by the motor

Cos Φ = Operating p.f. of synchronous motor

$P_{in} = 3\,V_{ph} I_{ph} \cos\Phi$ W

Now in stator, due to its resistance Ra per phase there are stator copper losses.

Total stator copper losses = $3 \times (I_{aph})^2 \times R_a$ W

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

$$\therefore \quad \boxed{P_m = P_{in} - \text{Stator copper losses}}$$

Now $\quad P = T \times \omega$

$$\therefore \quad P_m = T_g \times \frac{2\pi N_s}{60} \quad \text{as speed is always } N_s$$

$$\therefore \quad \boxed{T_g = \frac{P_m \times 60}{2\pi N_s}\ \text{Nm}}$$

This is the **gross mechanical torque developed.** In d.c. motor, electrical equivalent of gross mechanical power developed is $E_b \times I_a$, similar in synchronous motor the electrical equivalent of gross mechanical power developed is given by,

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

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

ii) For lagging p.f., $$E_{bph} \wedge I_{aph} = \phi + \delta$$

iii) For unity p.f., $$E_{bph} \wedge I_{aph} = \delta$$

In general,

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

Positive sign for leading p.f. and Negative sign for lagging p.f.

Net output of the motor then can be obtained by subtracting friction and windage i.e. mechanical losses from gross mechanical power developed.

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

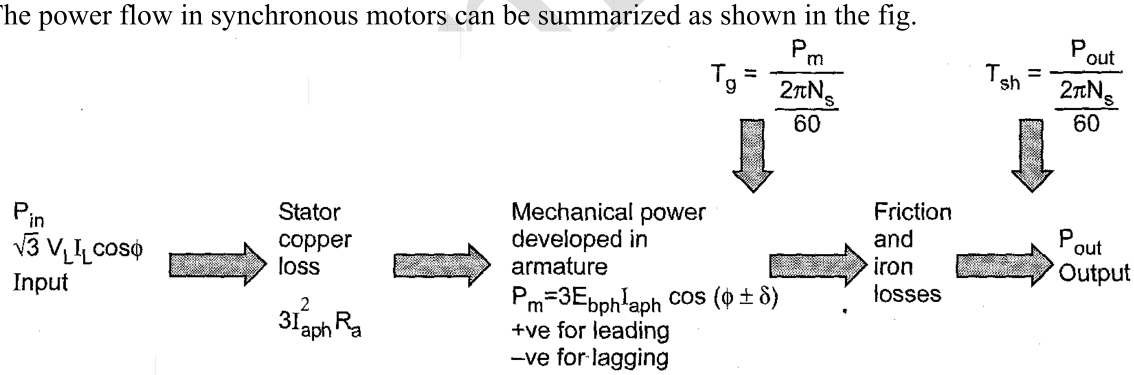
$$\therefore \quad T_{shaft} = \frac{P_{out} \times 60}{2\pi N_s} \text{ Nm}$$

where T_{shaft} = Shaft torque available to load

P_{out} = Power available to load

$$\therefore \quad \%\,\eta = \frac{P_{out}}{P_{in}} \times 100 \qquad \text{... Overall efficiency}$$

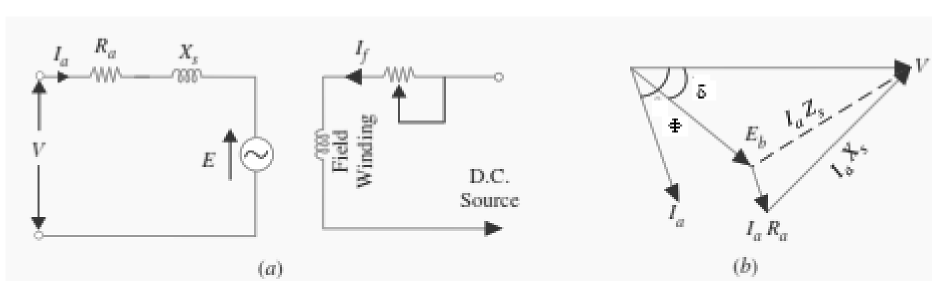
The power flow in synchronous motors can be summarized as shown in the fig.



Equivalent Circuit of a Synchronous Motor

Fig. (*a*) Shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. (*b*) that the phase applied voltage *V* is the vector sum of reversed back e.m.f. *i.e.*, $-E_b$ and the impedance drop $I_a Z_S$.

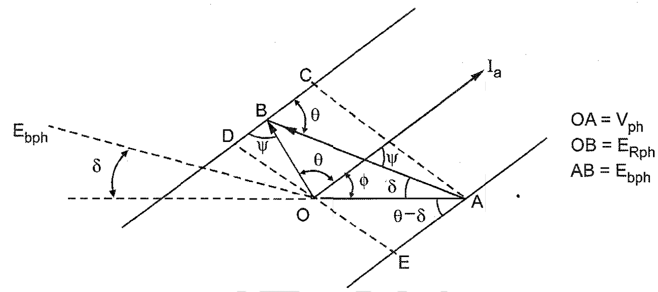


In other words, $V = (-E_b + I_a Z_S)$.
The angle δ between the phasor for V and E_b is called the load angle or power angle of the synchronous motor.

Expression for Power Developed by a Synchronous Motor

Consider the phasor diagram of a synchronous motor running on leading power factor cos Φ as shown in the Fig.

The line CD is drawn at an angle θ to AB.
The lines AC and DE are perpendicular to CD and AE.



$OB = E_{Rph} = I_a Z_s$ and $\angle OBD = \psi$

and angle between $AB = E_{bph}$ and I_{aph} is also ψ.

The mechanical per phase power developed is given by,

$$P_m = E_{bph} I_{aph} \cos (E_{bph} \wedge I_{aph}) \quad \text{------------- (1)}$$

$$= E_{bph} I_{aph} \cos (\psi)$$

In triangle OBD,

$$BD = OB \cos \psi = I_a Z_s \cos \psi$$

$$OD = OB \sin \psi = I_a Z_s \sin \psi$$

Now $BD = CD - BC = AE - BC$

$$AE = OA \cos (\theta - \delta) = V_{ph} \cos (\theta - \delta) \quad \text{--------------- (2)}$$

Substituting in equation **2**

$$\therefore \quad I_a Z_s \cos \psi = V_{ph} \cos (\theta - \delta) - E_b \cos \theta$$

$$\therefore \quad I_a \cos \psi = \frac{V_{ph}}{Z_s} \cos (\theta - \delta) - \frac{E_b}{Z_s} \cos \theta \quad \text{------------- (3)}$$

All values are per phase values

Substituting equation (3) in equation (1),

$$\therefore \quad P_m = E_b \left[\frac{V_{ph}}{Z_s} \cos (\theta - \delta) - \frac{E_b}{Z_s} \cos \theta \right]$$

$$\therefore \quad P_m = \frac{E_b V_{ph}}{Z_s} \cos (\theta - \delta) - \frac{E_b^2}{Z_s} \cos \theta \quad \text{--------------- (4)}$$

This is the expression for the mechanical power developed interms of the load angle δ and the internal machine angle Φ, for constant voltage V_{ph} and constant E_b i.e. excitation.

$$\text{Gross torque } T_g = \frac{P_m}{\omega} = \frac{P_m}{\left(\frac{2\pi N_s}{60}\right)}$$

where N_s = Synchronous speed in r.p.m

$$T_g = \frac{60}{2\pi}\frac{P_m}{N_s} = \frac{9.55\,P_m}{N_s} \qquad \text{-------------- (5)}$$

Condition for Maximum Power Developed

The value of δ for which the mechanical power developed is maximum can be obtained as,

$$\frac{d\,P_m}{d\,\delta} = 0$$

$$\therefore \quad \frac{d}{d\delta}\left[\frac{E_b V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b^2}{Z_s}\cos\theta\right] = 0$$

$$\therefore \quad \frac{E_b V_{ph}}{Z_s}\,.\,\sin(\theta-\delta)\,(-1) = 0 \quad \text{i.e.} \quad \sin(\theta-\delta) = 0$$

$$\therefore \quad \boxed{\theta = \delta} \qquad \text{----------- (6)}$$

The Value of Maximum Power Developed

The value of maximum power developed can be obtained by substituting θ = δ in the equation of P_m.

$$(P_m)_{max} = \frac{E_b V_{ph}}{Z_s}\cos(0) - \frac{E_b^2}{Z_s}\cos(\delta)$$

$$\therefore \quad (P_m)_{max} = \frac{E_b V_{ph}}{Z_s} - \frac{E_b^2}{Z_s}\cos\delta \qquad \text{------------ (7)}$$

$$\therefore \quad (P_m)_{max} = \frac{E_b V_{ph}}{Z_s} - \frac{E_b^2}{Z_s}\cos\theta \qquad \text{------------- (8)}$$

When R_a is negligible, $\theta = 90°$ and $\cos(\theta) = 0$ hence,

$$\therefore \quad \boxed{(P_m)_{max} = \frac{E_b V_{ph}}{Z_s}} \qquad \text{... when } R_a \text{ is negligible}$$

We know that

$$Z_s = R_a + j\,X_s = |Z_s| \angle \theta$$

$$\therefore \quad R_a = Z_s\cos\theta \text{ and } X_s = Z_s\sin\theta$$

Substituting $\cos\theta = R_a/Z_s$ in equation (8) we get,

$$\therefore \quad \boxed{(P_m)_{max} = \frac{E_b V_{ph}}{Z_s} - \frac{E_b^2 R_a}{Z_s^2}} \qquad \text{----------- (9)}$$

The torque is given by P/ω hence the maximum torque developed by a synchronous motor is,

$$T_{max} = \frac{(P_m)_{max}}{\omega_s} = \frac{(P_m)_{max}}{\left(\frac{2\pi N_s}{60}\right)} \quad \text{Nm}$$

$$\therefore \quad T_{max} = \frac{\left[\frac{E_b V_{ph}}{Z_s} - \frac{E_b^2 R_a}{Z_s^2}\right]}{\left(\frac{2\pi N_s}{60}\right)}$$

Condition for Excitation When Motor Develops $(P_m)_{max}$

The excitation controls E_b. Hence the condition of excitation can be obtained as,

$$\frac{dP_m}{dE_b} = 0$$

$$\therefore \quad \frac{d}{dE_b}\left[\frac{E_b V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{E_b^2}{Z_s}\cos\theta\right] = 0$$

Assume load constant hence δ constant.

$$\therefore \quad \frac{V_{ph}}{Z_s}\cos(\theta-\delta) - \frac{2E_b}{Z_s}\cos\theta = 0$$

but $\theta = \delta$ for $P_m = (P_m)_{max}$

$$\therefore \quad \frac{V_{ph}}{Z_s} - \frac{2E_b}{Z_s}\cos\theta = 0$$

Substitute $\cos\theta = \frac{R_a}{Z_s}$

$$\therefore \quad \frac{V_{ph}}{Z_s} - \frac{2E_b}{Z_s}\cdot\frac{R_a}{Z_s} = 0$$

$$\therefore \quad E_b = \frac{V_{ph} Z_s}{2R_a}$$

This is the required condition of excitation.

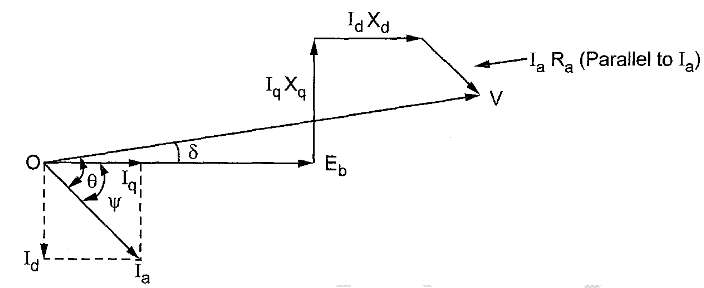
The corresponding value of maximum power is,

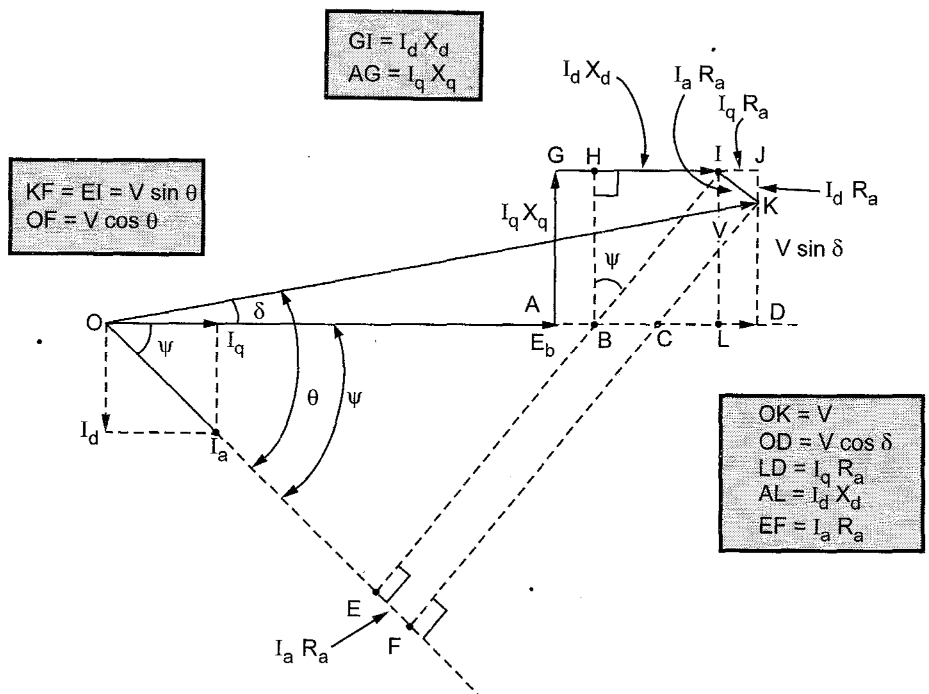
$$\therefore \quad (P_m)_{max} = \frac{V_{ph}^2}{2R_a} - \frac{V_{ph}^2}{4R_a}$$

SALIENT POLE SYNCHRONOUS MOTOR (Two Reaction Theory for Synchronous Motor)

The two reactances according to this theory are direct axis reactance X_d and quadrature axis reactance X_q. The motor armature current has two components I_d and Iq. The phasor diagram for the synchronous motor with a lagging power factor is shown in figure.

The phasor I_qX_q is such that I_q lags I_qX_q by 90^0 while the phasor I_dX_d is such that I_d lags I_dX_d by 90°. The angle between V and E_b is δ, V and I_a is θ and Eb and I_a is ψ. The phasor diagram can be further modified as shown in the Fig.





From the phasor diagram,

$$E_b = OD - DL - AL = V\cos\delta - I_qR_a - I_dX_d$$

$$AG = I_qX_q = DK + KJ = V\sin\delta + I_dR_a$$

In Δ BHI, ∠ HBI = ψ

$$\therefore \quad \cos\psi = \frac{BH}{BI} = \frac{AG}{BI} = \frac{I_qX_q}{BI}$$

From the triangle of I_a, I_d and I_q,

$$\therefore \quad \cos\psi = \frac{I_q}{I_a}$$

$$\therefore \quad \frac{I_q}{I_a} = \frac{I_qX_q}{BI} \quad \text{i.e.} \quad BI = I_aX_q$$

In Δ OBE,

$$\tan\psi = \frac{BE}{OE} = \frac{EI - BI}{OF - EF} = \frac{V\sin\theta - I_a X_q}{V\cos\theta - I_a R_a}$$

$$\therefore \quad \tan\psi = \frac{V\sin\theta - I_a X_q}{V\cos\theta - I_a R_a} \quad \text{(Lagging p.f.)}$$

$$\therefore \quad \begin{aligned} \delta &= \theta - \psi \quad \text{for lagging p.f.} \\ \delta &= \psi - \theta \quad \text{for leading p.f.} \end{aligned}$$

For the leading power factor,

$$\therefore \quad \begin{aligned} E_b &= V\cos\delta + I_q R_a - I_d X_d \\ \tan\psi &= \frac{V\sin\theta - I_a X_q}{V\cos\theta + I_a R_a} \end{aligned}$$

The expression for the total power developed by a salient pole synchronous motor is given by,

$$\therefore \quad P_m = 3\times\left\{\frac{E_b V}{X_d}\sin\delta + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta\right\} \text{ W}$$

For **maximum power** developed, load angle δ can be obtained as ,

$$\frac{dP_m}{d\delta} = 0 \quad \text{i.e.} \quad \frac{d}{d\delta}\left[\frac{E_b V}{X_d}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta\right] = 0$$

$$\therefore \quad \frac{E_b V}{X_d}\cos\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)2\cos 2\delta = 0$$

$$\therefore \quad \frac{E_b V}{X_d}\cos\delta + V^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\cos 2\delta = 0$$

The expression of dPm / dδ gives the rate of change of power with respect to load angle δ and is called stability factor, rigidity factor or the stiffness of coupling.

Blondel Diagram [Constant Power Circle]

For a synchronous motor, the power input to the motor per phase is given by,

$$P_{in} = V_{ph} I_{aph} \cos\phi \qquad \text{... Per phase}$$

The gross mechanical power developed per phase will be equal to the difference between P_{in} per phase and the per phase copper losses of the winding.

$$\text{Copper loss per phase} = (I_{aph})^2 R_a$$

$$\therefore \quad P_m = V_{ph} I_{aph} \cos\phi - (I_{aph})^2 R_a \qquad \text{... Per phase}$$

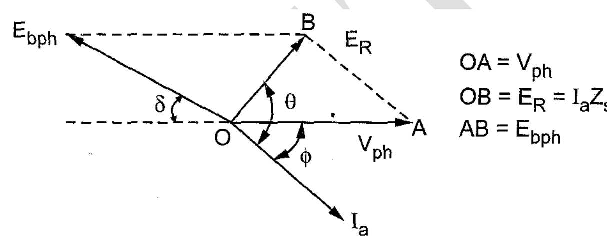
For mathematical convenience let $V_{ph} = V$ and $I_{aph} = I$,

$$\therefore \quad P_m = VI\cos\phi - I^2 R_a$$

$$\therefore \quad I^2 R_a - V I \cos\phi + P_m = 0$$

$$\therefore \quad I^2 - \frac{V I \cos\phi}{R_a} + \frac{P_m}{R_a} = 0$$

---------- (1)

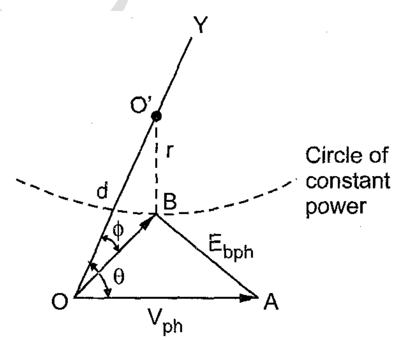


The equation (1) represents polar equation to a circle. To obtain this circle in a phasor diagram, draw a line OY at an angle θ with respect to OA.

∟YOA = θ

∟YOB = Φ

The circle represented by equation (1) has a centre at some point 0' on the line OY. The circle drawn with centre as 0' and radius as O'B represents circle of constant power. This is called Blondel diagram, shown in the Fig.



Thus if excitation is varied while the power is kept constant, then working point B will move along the circle of constant power.

Let O'B = Radius of circle = r

OO' = Distant d

Applying cosine rule to triangle OBO',

$r^2 = (OB)^2 + (OO')^2 - 2\,(OB)\,(OO')\cos(OB \wedge OO')$ ----- (2)

Now OB represents resultant E_R which is I_aZ_s. Thus OB is proportional to current and when referred to OY represents the current in both magnitude and phase.

$OB = I_a = I$ say

Substituting various values in equation (2) we get,

$$r^2 = I^2 + d^2 - 2dI\cos\phi$$

$$\therefore \quad I^2 - 2d\,I\cos\phi + (d^2 - r^2) = 0$$

------- (3)

Comparing equations (1) and (3) we get,

$OO' = d = V/2R_a$ ------ (4)

Thus the point O' is independent of power P_m and is a constant for a given motor operating at a fixed applied voltage V. Comparing last term of equations (1) and (3),

$$d^2 - r^2 = \frac{P_m}{R_a}$$

$$\therefore \quad r^2 = \left(d^2 - \frac{P_m}{R_a}\right)$$

$$\therefore \quad r = \sqrt{d^2 - \frac{P_m}{R_a}} = \sqrt{\left(\frac{V}{2R_a}\right)^2 - \frac{P_m}{R_a}}$$

$$\therefore \quad r = \frac{1}{2R_a}\sqrt{V^2 - 4P_mR_a}$$

--------- (5)

The equation shows that as power P_m must be real, then $4\,P_mR_a \geq V^2$. The maximum possible power per phase is,

$$4\,(P_m)_{max}\,R_a = V^2$$

$$\therefore \quad (P_m)_{max} = \frac{V^2}{4\,R_a} \qquad \text{------------ (6)}$$

And the radius of the circle for maximum power is zero. Thus at the time of maximum power, the circle becomes a point O'.

While when the power $P_m = 0$, then

$r = V / (2\,R_a)$

This shows that the circle of zero power passes through the points O and A.

The radius for any power P_m is given by,

$$r = \frac{V}{2\,R_a}\sqrt{1-\frac{4\,P_mR_a}{V^2}}$$

But $(P_m)_{max} = \dfrac{V^2}{4\,R_a}$, substituting above

$$r = \frac{V}{2\,R_a}\sqrt{1-\frac{P_m}{(P_m)_{max}}}$$

$$\therefore \quad r = \frac{V}{2\,R_a}\sqrt{1-m} \qquad \text{where} \quad m = \frac{P_m}{(P_m)_{max}}$$

We know, $OO' = d = \dfrac{V}{2\,R_a}$

$$\therefore \quad r = d\sqrt{1-m}$$

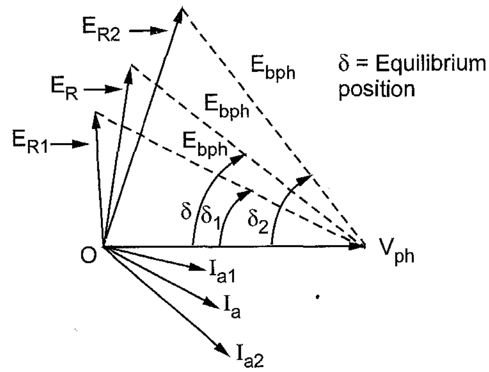
This is generalized expression for the radius for any power P_m.

HUNTING IN SYNCHRONOUS MOTOR

- When synchronous motor is on no load, the stator and rotor pole axes almost coincide with each other.
- When motor is loaded, the rotor pole axis falls back with respect to stator. The angle by which rotor retards is called load angle or angle of retardation δ.
- If the load connected to the motor is suddenly changed by a large amount, then rotor tries to retard to take its new equilibrium position.
- But due to inertia of the rotor, it cannot achieve its final position instantaneously.
- While achieving its new position due to inertia it passes beyond its final position corresponding to new load. This will produce more torque than what is demanded. This will try to reduce the load angle and rotor swings in other direction. So there is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load.
- Such oscillations of the rotor about its new equilibrium position, due to sudden application or removal of load is called swinging or hunting in synchronous motor.
- The main causes of hunting are,

1. Sudden change in the load.
2. Fault in the supply system.
3. Sudden change in the field current.
4. A load containing harmonic torque.

- Due to such hunting, the load angle δ changes its value about its final value.
- As δchanges, for same excitation i.e. E_{bph} the current drawn by the motor also changes.
- Hence during hunting there are changes in the current drawn by the motor which may cause problem to the other appliances connected to the same line.
- The change in armature current due to hunting is shown in the Fig.
- If such oscillations continue for longer period, there are large fluctuations in the current.
- If such variations synchronise with the natural period of oscillation of the rotor, the amplitude of the swing may become so great that motor may come out of synchronism.

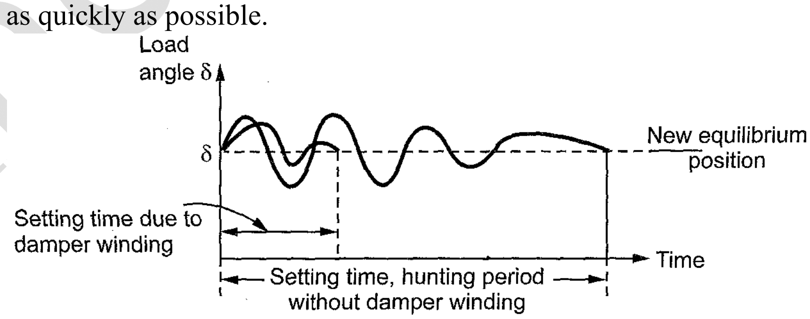


- At this instant mechanical stresses on the rotor are severe and current drawn by the motor is also very large. So motor gets subjected to large mechanical and electrical stresses.
- The various undesirable effects of hunting are,

1. It may lead to loss of synchronism.
2. It produces large mechanical stress.
3. It causes increase in losses and increases temperature rise.
4. It causes large changes in current and power flow.

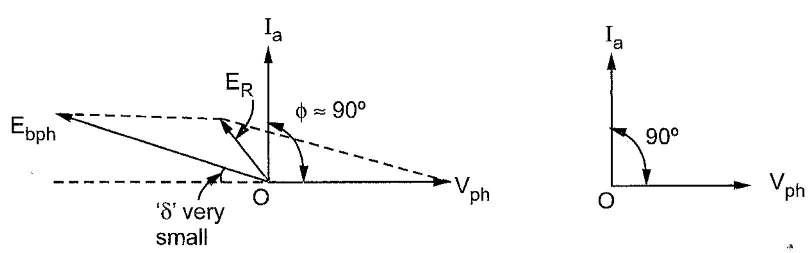
Use of Damper Winding to Prevent Hunting

- When rotor starts oscillating i.e. when hunting starts a relative motion between damper winding and the rotating magnetic field is created.
- Due to this relative motion, e.m.f. gets induced in the damper winding.
- According to Lenz's law, the direction of induced e.m.f. is always so as to oppose the cause producing it.
- The cause is the hunting. So such induced e.m.f. oppose the hunting.
- The induced e.m.f. tries to damp the oscillations as quickly as possible.
- Thus hunting is minimised due to damper winding.
- The time required by the rotor to take its final equilibrium position after hunting is called as setting time of the rotor. If the load angle δ is plotted against time, the schematic representation of hunting can be obtained as shown in the Fig.
- It is shown in the diagram that due to damper winding the setting time of the rotor reduces considerably.



SYNCHRONOUS CONDENSERS

- When synchronous motor is over excited it takes leading p.f. current. If synchronous motor is on no load, where load angle is very small and it is over excited ($E_b > V$) then power factor angle increases almost upto 90°. And motor runs with almost zero leading power factor condition, This is shown in the phasor diagram Fig.
- This characteristics is similar to a normal capacitor which always takes leading power factor current.



- Hence over excited synchronous motor operating on no load condition is called as synchronous condenser or synchronous capacitor.
- This is the property due to which synchronous motor is used as a phase advancer or as power improvement device.

Disadvantages of Low Power Factor

The power is given by,

$$P = V I \cos\phi \quad \text{i.e.} \quad I = \frac{P}{V\cos\phi}$$

The high current due to low p.f. has following disadvantages

1. For higher current, conductor size required is more which increases the cost.
2. The p.f. is given by

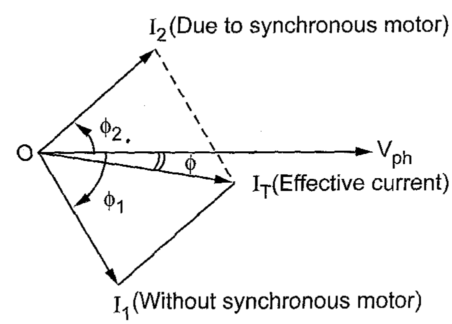
$$\cos\phi = \frac{\text{Active power}}{\text{Apparent power}} = \frac{\text{P in kW}}{\text{S i.e. kVA rating}}$$

Thus for fixed active power F, low p.f. demands large kVA rating alternators and transformers. This increases the cost.

3. Large current means more copper losses and poor efficiency.
4. Large current causes large voltage drops in transmission lines, alternators and other equipments. This results into poor regulation. To compensate such drop extra equipment is necessary which further increases the cost.

Use of Synchronous Condenser in Power Factor Improvement

- The low power factor increases the cost of generation, distribution and transmission of the electrical energy. Hence such low power factor needs to be corrected. Such power factor correction is possible by connecting synchronous motor across the supply and operating it on no load with over excitation.
- Now let V_{ph} is the voltage applied and I_{1ph} is the current lagging V_{ph} by angle Φ_1. This power factor Φ_1 is very low, lagging.
- The synchronous motor acting as a synchronous condenser is now connected across the same supply. This draws a leading current of $I_{2ph.}$
- The total current drawn from the supply is now phasor of I_{1ph} and I_{2ph}.
- This total current I_T now lags V_{ph} by smaller angle Φ due to which effective power factor gets improved. This is shown in the Fig.
- This is how the synchronous motor as a synchronous condenser is used to improve power factor of the combined load.



Features of Synchronous Motor

1. The synchronous motors run only at synchronous seed.
2. By varying its excitation, its power factor can be varied.
3. As it can be operated at leading power factor, it is used as a power factor correction device.
4. They are not self starting and requires an additional facility to make it self starting.
5. Under no load and over excited condition it can be used as a synchronous condenser.

Comparison Between Synchronous and Induction Motors

1. For a given frequency, the synchronous motor runs at a constant average speed whatever the load, while the speed of an induction motor falls somewhat with increase in load.
2. The synchronous motor can be operated over a wide range of power factors, both lagging and leading, but induction motor always runs with a lagging p.f. which may become very low at light loads.
3. A synchronous motor is inherently not self-starting.

4. The changes in applied voltage do not affect synchronous motor torque as much as they affect the induction motor torque. The breakdown torque of a synchronous motor varies approximately as the first power of applied voltage whereas that of an induction motor depends on the square of this voltage.
5. A d.c. excitation is required by synchronous motor but not by induction motor.
6. Synchronous motors are usually more costly and complicated than induction motors, but they are particularly attractive for low-speed drives (below 300 r.p.m.) because their power factor can always be adjusted to 1.0 and their efficiency is high. However, induction motors are excellent for speeds above 600 r.p.m.
7. Synchronous motors can be run at ultra-low speeds by using high power electronic converters which generate very low frequencies. Such motors of 10 MW range are used for driving crushers, rotary kilns and variable-speed ball mills etc.

Synchronous Motor Applications

Synchronous motors find extensive application for the following classes of service:
1. Power factor correction
2. Constant-speed, constant-load drives
3. Voltage regulation

(*a*) Power factor correction

Overexcited synchronous motors having leading power factor are widely used for improving power factor of those power systems which employ a large number of induction motors and other devices having lagging p.f. such as welders and flourescent lights etc.

(*b*) Constant-speed applications

Because of their high efficiency and high-speed, synchronous motors (above 600 r.p.m.) are well-suited for loads where constant speed is required such as centrifugal pumps, belt-driven reciprocating compressors, blowers, line shafts, rubber and paper mills etc. Low-speed synchronous motors (below 600 r.p.m.) are used for drives such as centrifugal and screw-type pumps, ball and tube mills, vacuum pumps, chippers and metal rolling mills etc.

(*c*) Voltage regulation

The voltage at the end of a long transmission line varies greatly especially when large inductive loads are present. When an inductive load is disconnected suddenly, voltage tends to rise considerably above its normal value because of the line capacitance. By installing a synchronous motor with a field regulator (for varying its excitation), this voltage rise can be controlled. When line voltage decreases due to inductive load, motor excitation is increased, thereby raising its p.f. which compensates for the line drop. If, on the other hand, line voltage rises due to line capacitive effect, motor excitation is decreased, thereby making its p.f. lagging which helps to maintain the line voltage at its normal value.

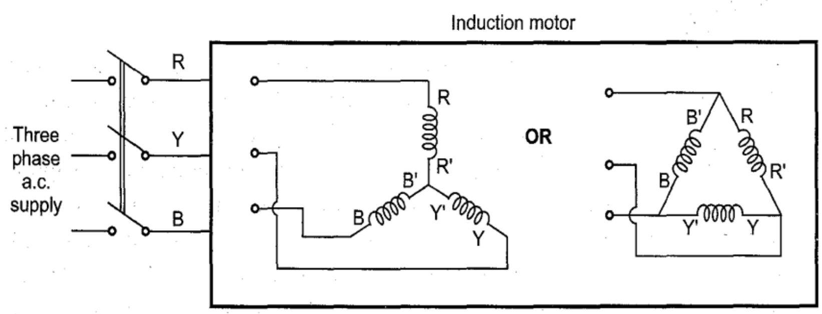
UNIT III THREE PHASE INDUCTION MOTOR

Constructional details – Types of rotors –- Principle of operation – Slip –cogging and crawling- Equivalent circuit – Torque-Slip characteristics - Condition for maximum torque – Losses and efficiency – Load test - No load and blocked rotor tests - Circle diagram – Separation of losses – Double cage induction motors – Induction generators – Synchronous induction motor.

1. Explain how a three phase supply produces a rotating magnetic field of constant value at constant speed with vector diagrams.

The working principle of three phase induction motors is based on the production of rotating magnetic field. The rotating magnetic field can be defined as the field or flux having constant amplitude but whose axis is continuously rotating in a plane with a certain speed.

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



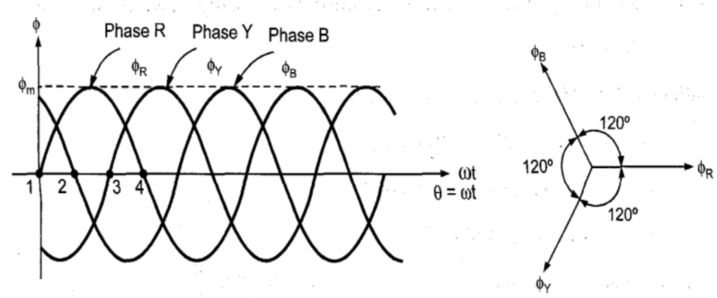
Star or delta connected 3 phase winding

The three phase currents flow simultaneously through the windings and are displaced from each other by 120^0 electrical. Each alternating phase current produces its own flux which is sinusoidal. So all three fluxes are sinusoidal and are separated from each other by 120°. If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes Φ_R, Φ_Y and Φ_B can be written as,

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

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

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



(a) Waveforms of three fluxes (b) Assumed positive directions

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

Case 1: $\theta = 0^0$

Substituting in equation (i), (ii) and (iii),

$\Phi_R = \Phi_m \sin\theta$

$\Phi_Y = \Phi_m \sin(-120^0) = -0.866 \quad \Phi_m$

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

BD is drawn perpendicular from B on Φ_T. It bisects Φ_T .

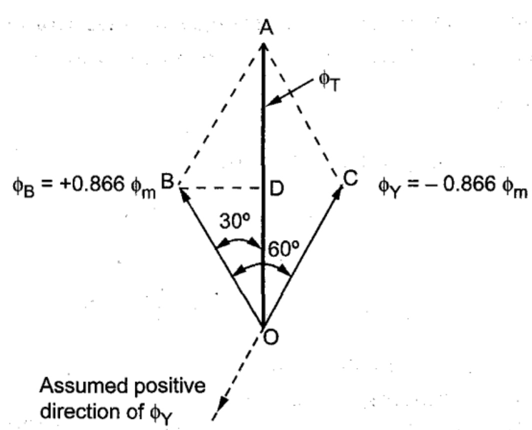
$OD = DA = \Phi_T / 2$

In triangle OBD, ∟BOD = 30°

$\cos 30° = \frac{OD}{OB} = \frac{\Phi T/2}{0.866\ \Phi m}$

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

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



(a) Vector diagram for θ = 0°

Case 2: = θ = 60^0

$\Phi_R = \Phi_m \sin 60^0 = 0.866\ \Phi_m$

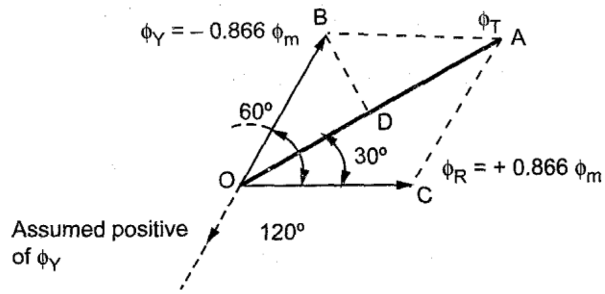
$\Phi_Y = \Phi_m \sin(-60^0) = -0.866\ \Phi_m$

$\Phi_B = \Phi_m \sin(-180^0) = 0$

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

$\Phi_T = 1.5\ \Phi_m$

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



(b) Vector diagram for θ = 60°

Case 3: = $\theta = 120^0$

$\Phi_R = \Phi_m \sin 120^0 = 0.866\ \Phi_m$

$\Phi_Y = \Phi_m \sin 0 = 0$

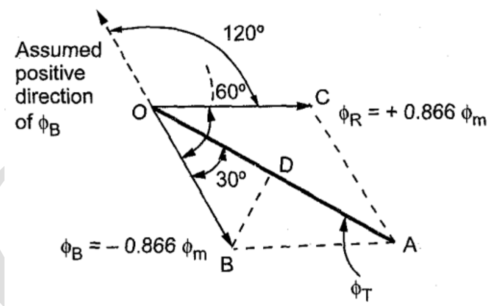
$\Phi_B = \Phi_m \sin(-120^0) = -0.866\ \Phi_m$

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

$\Phi_T = 1.5\ \Phi_m$

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

And from its position at $\theta = 0^0$, it has rotated through 120^0 in space, in clockwise direction.



(c) Vector diagram for θ = 120°

Case 3: = $\theta = 180^0$

$\Phi_R = \Phi_m \sin 180^0 = 0$

$\Phi_Y = \Phi_m \sin(60^0) = 0.866\ \Phi_m$

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

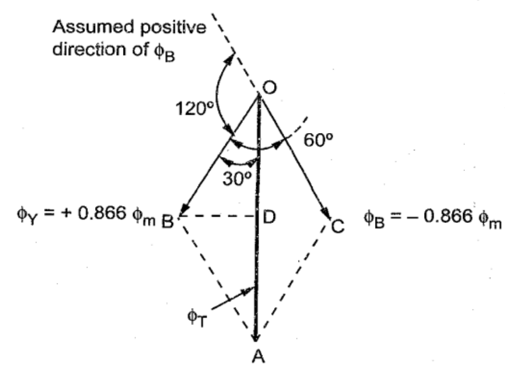
Doing the same construction, drawing perpendicular from B on Φ_T at D we get the same result as,

$\Phi_T = 1.5\ \Phi_m$

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

And from its position at $\theta = 0^0$, it has rotated through 180^0 in space, in clockwise direction.

So for an electrical half cycle of 180^0, the resultant Φ_T has also rotated through 180^0.



(d) Vector diagram for θ = 180°

2. **Describe the constructional features of squirrel cage and slip ring induction motors. Discuss the merits of one over other.**

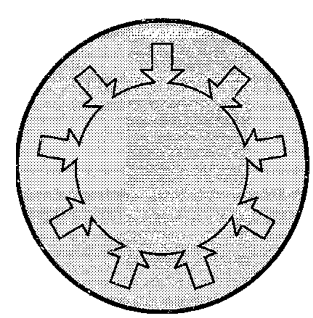
The induction motor consists of two main parts,

1. The part i.e. three phase windings, which is stationary called stator.
2. The part which rotates and is connected to the mechanical load through shaft called rotor.

The conversion of electrical power to mechanical power takes place in a rotor. Hence rotor develops a driving torque and rotates.

Stator

- The stator has a laminated type of construction made up of stampings which are 0.4 to 0.5 mm thick.
- The stampings are slotted on its periphery to carry the stator winding.
- The stampings are insulated from each other to keep the iron losses to a minimum value.
- The number of stampings are stamped together to build the stator core.



Stator Lamination

- The built up core is then fitted in a casted or fabricated steel frame.
- The choice of material for the stampings is generally silicon steel, which minimizes the hysteresis loss.
- The slots on the periphery of the stator core carries a three phase winding, connected either in star or delta.
- This three phase winding is called stator winding. It is wound for definite number of poles.
- This winding when excited by a three phase supply produces a rotating magnetic field.
- The choice of number of poles depends on the speed of the rotating magnetic field required.
- The radial ducts are provided for the cooling purpose.

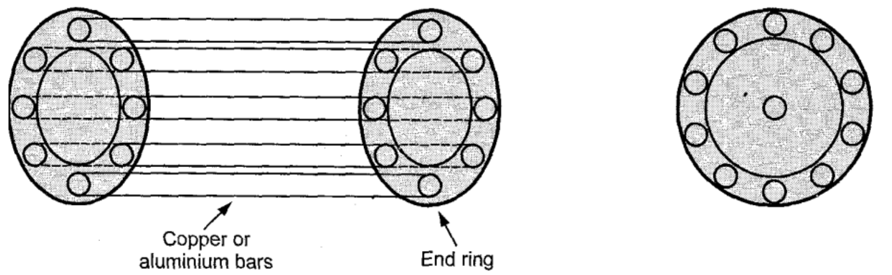
Rotor

The two types of rotor constructions used for induction motors are,

1. Squirrel cage rotor and 2. Slip ring or wound rotor

Squirrel Cage Rotor

- The rotor core is cylindrical and slotted on its periphery.
- The rotor consists of uninsulated copper or aluminium bars called rotor conductors.
- The bars are placed in the slots. These bars are permanently shorted at each end with the help of conducting copper ring called end ring.
- The bars are usually brazed to the end rings to provide good mechanical strength.
- The entire structure looks like a cage, forming a closed electrical circuit. So the rotor is called squirrel cage rotor.
- As the bars are permanently shorted to each other through end ring, the entire rotor resistance is very very small. Hence this rotor also called short circuited rotor.



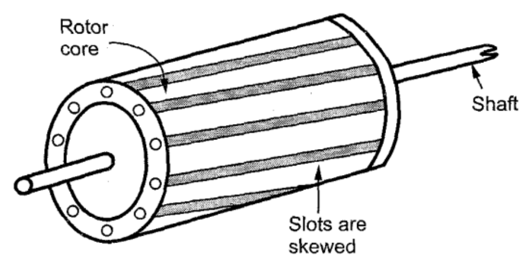
(a) Cage type structure of rotor **(b) Symbolic representation**

- As rotor itself is short circuited, no external resistance can have any effect on the rotor resistance. Hence no external resistance can be introduced in the rotor circuit. So slip ring and brush assembly is not required for this rotor. Hence the construction of this rotor is very simple.

In this type of rotor, the slots are not arranged parallel to the shaft axis but are skewed as shown in the Fig..

The advantages of skewing are,

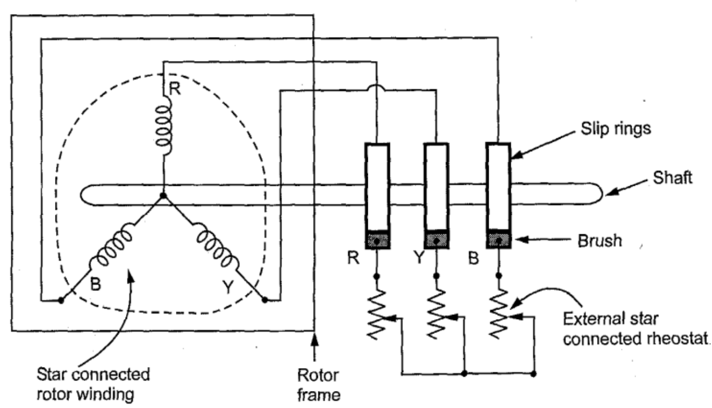
1. A magnetic hum i.e. noise gets reduced due to skewing hence skewing makes the motor operation quieter.
2. It makes the motor operation smooth.
3. The stator and rotor teeth may get magnetically locked. Such a tendency of magnetic locking gets reduced due to skewing.
4. It increases the effective transformation ratio between stator and rotor.



Skewing in rotor construction

Slip Ring Rotor or Wound Rotor

- In this type of construction, rotor winding is exactly similar to the stator.
- The rotor carries a three phase star or delta connected, distributed winding, wound for same number of poles as that of stator.
- The rotor construction is laminated and slotted.
- The slots contain the rotor winding. The three ends of three phase winding, available after connecting the winding in star or delta, are permanently connected to the slip rings.
- The slip rings are mounted on the same shaft.



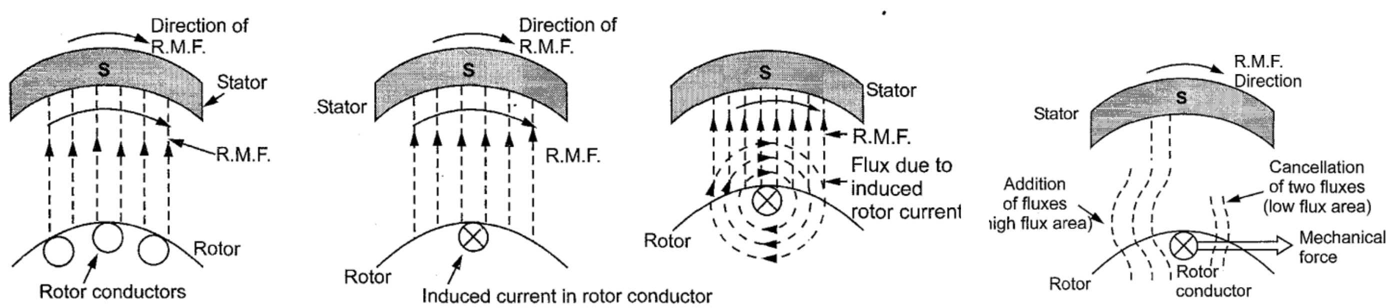
- In this type of rotor, the external resistances can be added with the help of brushes and slip ring arrangement, in series with each phase of the rotor winding.

3. Compare squirrel cage and wound rotor constructions of induction motor.

S.No	Wound or Slip ring rotor	Squirrel cage rotor
1.	Rotor consists of a three phase winding similar to the stator winding.	Rotor consists of bars, which are shorted at the ends with the help of end rings.
2.	Construction is complicated.	Construction is simple
3.	Resistance can be added externally:	As permanently shorted, external resistance cannot be added
4.	Slip rings and brushes are present to add external resistance.	Slip rings and brushes are absent
5.	Frequent maintenance is necessary	Maintenance free
6.	Rotors are costly	Rotors are cheap
7.	High starting torque can be obtained	Moderate starting torque
8.	Rotor must be wound for same number of poles	The rotor automatically adjusts itself for the same number of poles as that of stator
9.	Rotor resistance starter can be used	Rotor resistance starter cannot be used
10.	Rotor copper losses are high hence efficiency is less	Rotor copper losses are less hence efficiency is high
11.	Speed control by rotor resistance is possible	Speed control by rotor resistance is not possible
12.	Used for lifts, hoists, cranes, elevators, compressors etc.	Used for lathes, drilling machines, fans, blowers, waterpumps, grinders, printing machines etc.

4. Describe the principle of operation of a 3 phase induction motor with a neat sketch. Explain why a rotor is forced to rotate in the direction of rotating magnetic field.

When a three phase supply is given to the three phase stator winding, a rotating magnetic field of constant magnitude is produced. The speed of this rotating magnetic field is synchronous speed, N_s r.p.m. The R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever conductor cuts the flux, e.m.f. gets induced in it according to Faraday's Law of electro-magnetic induction. As rotor forms closed circuit, induced e.m.f. circulates current through rotor called rotor current whose direction is given by Lenz's law. According to Lenz's law the direction of induced current in the rotor is so as oppose the cause producing it. The cause of rotor current is the induced e.m.f. which is induced because of relative motion present between the rotating magnetic field and the rotor conductors. Hence to oppose the relative motion i.e. to reduce the relative speed, the rotor experiences a torque in the same direction as that of R.M.F. and tries to catch up the speed of rotating magnetic field.



So,

N_s = Speed of rotating magnetic field in r.p.m.

N = Speed of rotor i.e. motor in r.p.m.

N_s - N = Relative speed between the two, rotating magnetic field and the rotor conductors.

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

5. Define the term slip of an induction motor. Explain its significance.

Slip of the induction motor is defined as the difference between the synchronous speed (N_s) and actual speed of rotor i.e. motor (N) expressed as a fraction of the synchronous speed (N_s). This is also called absolute slip or fractional slip and is denoted as s.

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

The percentage slip is expressed as,

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

In terms of slip, the actual speed of motor (N) can be expressed as,

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

At start, motor is at rest and hence its speed N is zero.

$$s = 1 \text{ at start}$$

This is maximum value of slip s possible for induction motor which occurs at start. While s = 0 gives us N = N_s which is not possible for an induction motor. So slip of induction motor cannot be zero under any circumstances.

Practically motor operates in the slip range of 0.01 to 0.05 i.e. 1 % to 5 %. The slip corresponding to full load speed of the motor is called full load slip.

6. Explain the effect of slip on the rotor parameters

(a) Effect on Rotor Frequency

The speed of rotating magnetic field is,

$$N_s = 120f/P \qquad \text{(i)}$$

where f = frequency of supply in Hz.

At start when N = 0, s = 1 and stationary rotor has maximum relative motion with respect to R.M.F. Hence maximum e,m.f. gets induced in the rotor at start. The frequency of this induced e.m.f. at start is same as that of supply frequency.

In running condition the magnitude of the induced emf decreases as its frequency.

$$(N_s - N) = 120 f_r / P \qquad \text{(ii)}$$

Where, f_r = frequency of rotor induced emf in running condition at slip speed (N_s – N)

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

$$\frac{Ns - N}{Ns} = \frac{120 \ fr \ / \ P}{120 \ f \ / \ P}$$

Therefore $s = f_r / f$ or $f_r = sf$

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

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

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

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

E_{2r} = Rotor induced e.m.f. per phase in running condition

$E_2 \ \alpha \ N_s$ and $E_{2r} \ \alpha \ (N_s - N)$

$$\frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s} \qquad \text{but } \frac{N_s - N}{N_s} = \text{slip } s$$

$$\therefore \qquad \frac{E_{2r}}{E_2} = s \qquad\qquad E_{2r} = sE_2$$

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

(c) Effect on Rotor Resistance and Reactance

R_2 = Rotor resistance per phase on standstill

X_2 = Rotor reactance per phase on standstill

Now at standstill, $f_r = f$ hence if L2 is the inductance of rotor per phase,

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

While R_2 = Rotor resistance in Ω /ph

Now in running condition, $f_r = sf$ hence

$X_{2r} = 2\pi f_r L_2 = 2\pi sf L_2 = s.\ 2\pi f L_2$

$X_{2r} = s X_2$

Where X_{2r} = Rotor reactance in running condition

If Z_2 = Rotor impedance on standstill condition

$= R_2 + j X_2$ Ω / ph

$Z_2 = \sqrt{R2^2 + X2^2}$ Ω / ph

While Z_{2r} = rotor impedance in running condition

$= \sqrt{R2^2 + (sX2)^2}$ Ω / ph

(d) Effect on Rotor Power Factor

Cos φ_2 = rotor power factor on standstill

$$= \frac{R2}{Z2} = \frac{R2}{\sqrt{R2^2+X2^2}}$$

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

$$= \frac{R2}{Z2r} = \frac{R2}{\sqrt{R2^2+(sX2)^2}}$$

(e) Effect on Rotor Current

I_2 = Rotor current per phase on standstill condition

$$= \frac{E2 \text{ per phase}}{Z2 \text{ per phase}} = \frac{E2}{\sqrt{R2^2+X2^2}} \text{ A}$$

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

$$= \frac{E2r}{Z2r} = \frac{sE2}{\sqrt{R2^2+(sX2)^2}} \text{ A}$$

7. Derive the torque equation for a three phase induction motor.

The torque produced in the induction motor depends on the following factors.

1. The part of rotating magnetic field which reacts with rotor and is responsible to produce induced e.m.f. in rotor.
2. The magnitude of rotor current in running condition.
3. The power factor of the rotor circuit in running condition.

$$T \ \alpha \ \Phi \ I_{2r} \cos \Phi_{2r} \qquad (1)$$

Where Φ = Flux responsible to produce induced e.m.f.

I_{2r} = Rotor running current

Cos Φ_{2r} = Running p.f. of rotor

The flux Φ produced by stator is proportional to E_1 i.e. stator voltage.

$$\Phi \ \alpha \ E_1 \qquad (2)$$

While E_1 and E_2 are related to each other through ratio of stator turns to rotor turns i.e. K.

$$\frac{E1}{E2} = K \qquad (3)$$

Using equation (3) in (2),

$$E_2 \ \alpha \ \Phi \qquad (4)$$

Thus in equation (1), Φ can be replaced by E_2

While $I_{2r} = \frac{E2r}{Z2r} = \frac{sE2}{\sqrt{R2^2+(sX2)^2}}$ A

And Cos $\varphi_{2r} = \frac{R2}{Z2r} = \frac{R2}{\sqrt{R2^2+(sX2)^2}}$

Therefore, $T \;\alpha\; E_2 . \dfrac{sE2}{\sqrt{R2^2+(sX2)^2}} \cdot \dfrac{R2}{\sqrt{R2^2+(sX2)^2}}$

$$T \;\alpha\; \frac{sE2^2R2}{R2^2+(sX2)^2} \text{ N-m}$$

$$T = \frac{ksE2^2R2}{R2^2+(sX2)^2} \text{ N-m}$$

where k = constant of proportionality

$= \dfrac{3}{2\pi\, ns}$ [n_s = synchronous speed in r.p.s = N/60]

$$T = \frac{3}{2\pi\, ns} \cdot \frac{sE2^2R2}{R2^2+(sX2)^2} \text{ N-m}$$

Starting torque

Starting torque is nothing but the torque produced by an induction motor at start. At start, N = 0 and slip s = 1. So putting s = 1 in the torque equation, the starting torque,

$$T_{st} = \frac{3}{2\pi\, ns} \cdot \frac{E2^2R2}{(R2^2+X2^2)} \text{ N-m}$$

8. **Derive the condition for the maximum torque in a three phase induction motors. Also obtain the expression for the maximum torque.**

For maximum torque,

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

$$\text{Where } T = \frac{ksE2^2R2}{R2^2+(sX2)^2}$$

As load on motor changes, its speed changes and hence slip changes. This slip decides the torque produced corresponding to the load demand.

$$\frac{dT}{ds} = \frac{d}{ds}\left(\frac{ksE2^2R2}{R2^2+(sX2)^2}\right)$$

$$\therefore \quad \frac{dT}{ds} = \frac{(k\,s\,E_2^2\,R_2)\,\frac{d}{ds}\,(R_2^2+s^2\,X_2^2)-(R_2^2+s^2\,X_2^2)\,\frac{d}{ds}\,(k\,s\,E_2^2\,R_2)}{(R_2^2+s^2\,X_2^2)^2} = 0$$

$$\therefore \quad k\,s\,E_2^2\,R_2\,[2s\,X_2^2] - (R_2^2+s^2\,X_2^2)\,(k\,E_2^2\,R_2) = 0$$

$$\therefore \quad 2\,s^2\,k\,X_2^2\,E_2^2\,R_2 - R_2^2\,k\,E_2^2\,R_2 - k\,s^2\,X_2^2\,E_2^2\,R_2 = 0$$

$$\therefore \quad k\,s^2\,X_2^2\,E_2^2\,R_2 - R_2^2\,k\,E_2^2\,R_2 = 0$$

$$\therefore \quad s^2X_2^2 - R_2^2 = 0 \qquad \text{Taking } k\,E_2^2\,R_2 \text{ common.}$$

$$s^2 = \frac{R2^2}{X2^2} \text{ or } s = \frac{R2}{X2}$$

This is the slip at which the torque is maximum and is denoted by s_m.

$$s_m = \frac{R2}{X2}$$

By substituting $s_m = \dfrac{R2}{X2}$ in the torque equation, maximum torque T_m is

$$T_m = \frac{ks_m E2^2R2}{R2^2+(s_m X2)^2} = \frac{kE2^2}{2X_2} \text{ N-m}$$

From the expression of Tm, it can be observed that

1. It is inversely proportional to the rotor reactance.
2. It is directly proportional to the square of the rotor induced e.m.f. at standstill.
3. The maximum torque is not dependent on the rotor resistance R_2. But the slip at which it occurs i.e. speed at which it occurs depends on the value of rotor resistance R_2.

9. **Draw and explain a typical torque-speed characteristic for a 3 phase induction motor. Explain the relation between torque and slip before and after the maximum torque. Show the stable region in the graph.**

The curve obtained by plotting torque against slip from s = 1 (at start) to s =0 (at synchronous speed) is called torque-slip characteristics of the induction motor.

$$T \ \alpha \ \frac{sE2^2R2}{R2^2 + (sX2)^2} \text{ N-m}$$

E_2 is also constant. Therefore,

$$T \ \alpha \ \frac{sR2}{R2^2 + (sX2)^2} \text{ N-m}$$

i) Low slip region

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

Therefore $T = \frac{sR_2{}^2}{R_2{}^2} \ \alpha \ s$ as R_2 is constant.

Hence in low slip region torque is directly proportional to slip. So as load increases, speed decreases, increasing the slip. This increases the torque which satisfies the load demand.

Hence the graph is straight line in nature.

At $N = N_s$, s = 0 hence T = 0. As no torque is generated at $N = N_s$, motor stops if it tries to achieve the synchronous speed. Torque increases linearly in this region, of low slip values.

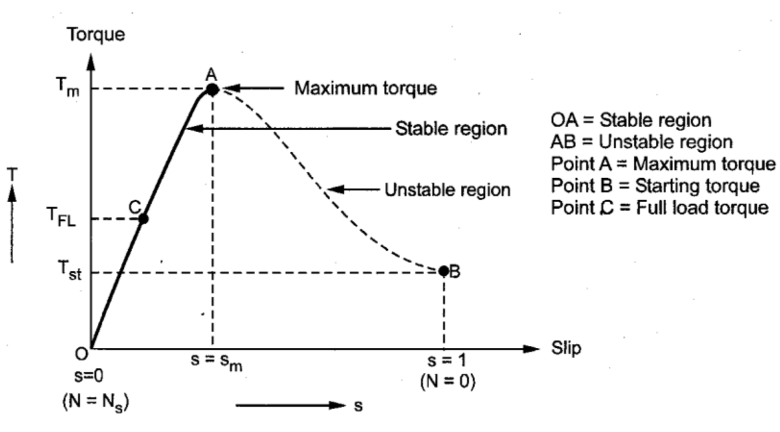
ii) High slip region

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

$$T \ \alpha \ \frac{sR2}{(sX2)^2} \ \alpha \ \frac{1}{s}$$

So in high slip region torque is inversely proportional to the slip. Hence its nature is like rectangular hyperbola.

Now when load increases, load demand increases but speed decreases. As speed decreases, slip increases. In high slip region as T α 1/s. torque decreases as slip increases. But torque must increase to satisfy the load demand. As torque decreases, due to extra loading effect, speed further decreases and slip further increases. Hence speed further drops. Eventually motor comes to standstill condition. The motor cannot continue to rotate at any point in this high slip region. Hence this region is called unstable region of operation.



So torque - slip characteristics has two parts,

1. Straight line called stable region of operation.

2. Rectangular hyperbola called unstable region of operation.

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

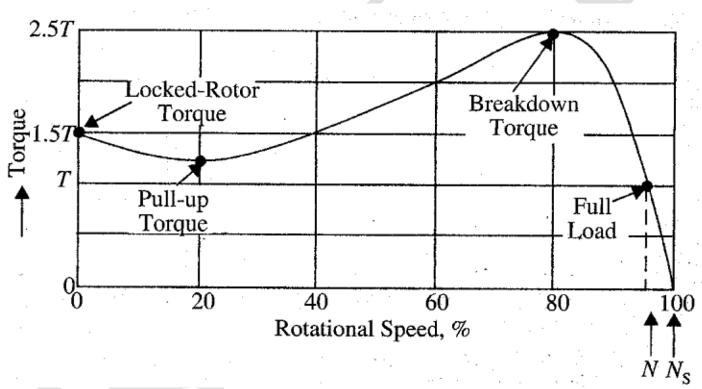
If load is increased beyond this limit, motor slip acts dominantly pushing motor into high slip region. Due to unstable conditions, motor comes to standstill condition at such a load. Hence T_m i.e. maximum torque which motor can produce is also called **breakdown torque or pull out torque**. So range s = 0 to $s = s_m$ is called low slip region, known as stable region of operation. Motor always operates at a point in this region. And range $s = s_m$ to s = 1 is called high slip region which is rectangular hyperbola, called unstable region of operation. Motor cannot continue to rotate at any point in this region.

At s = 1, N = 0 i.e. at start, motor produces a torque called starting torque denoted as T_{st}.

10. Explain the Torque/speed Curve and discuss briefly the effect on the speed-torque characteristics of an induction motor.

The torque developed by a 3-phase motor depends on its speed but the relation between the two cannot be represented by a simple equation. It is easier to show the reIationship in the form of a curve.

In this diagram, T represents the nominal full load torque of the motor. The starting torque (at N = 0) is 1.5 T and the maximum torque (break down torque) is 2.5T.



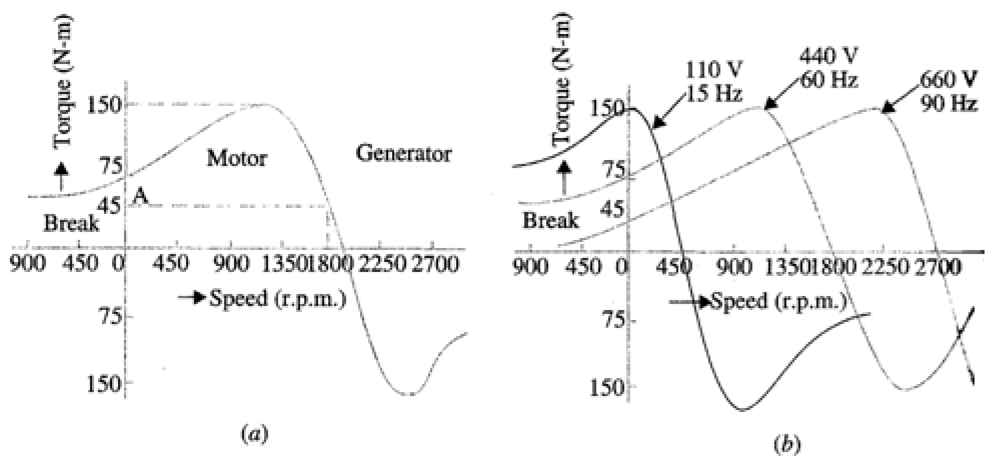
At full-load, the motor runs at a speed of N. When mechanical load increases, the motor speed decreases till the motor torque again becomes equal to the load torque. As long as the two torques are in balance, the motor will run at constant (but lower) speed. However If the load torque exceeds 2.5T, the motor will suddenly stop.

Shape of Torque/speed curve:

For a squirrel-cage induction motor (SCIM) shape of its torque/speed curve depends on the voltage and frequency applied to its stator.

If f is fixed, $T \alpha V^2$.

Also synchronous speed depends on the supply frequency. In practice, supply voltage and frequency are varied in the same proportion in order to maintain a constant flux in the air-gap. For example, if voltage is doubled, then frequency is also doubled. Under these conditions, shape of the torque/speed curve remains the same but its position along the X-axis (speed axis) shifts with frequency. Since the shape of the torque/speed curve remains the same at all frequencies, it follows that torque developed by a SCIM is the same whenever slip speed is the same.



11. Prove that to increase the starting torque an extra resistance must be added in the rotor circuit.

In slip ring induction motor, externally resistance can be added in the rotor.

R_2 = rotor resistance per phase

Torque $T \alpha \frac{sE2^2R2}{R2^2 + (sX2)^2}$

Externally resistance is added in each phase of rotor through slip rings

R_2' = new rotor resistance per phase

Torque T' α $\frac{sE2^2R_2{'}}{R_2{'}^2+(sX2)^2}$

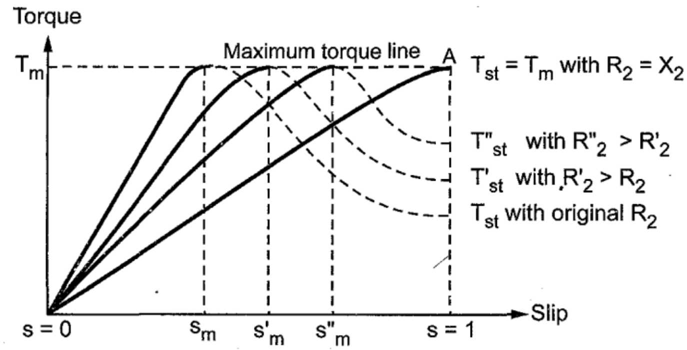
The starting torque at s = 1 R_2 and R_2' are

T_{st} α $\frac{E2^2R_2}{R_2{}^2+X_2{}^2}$ and T_{st}' α $\frac{E2^2R_2{'}}{R_2{'}^2+X_2{}^2}$

Maximum torque T_m α $\frac{E2^2}{2X_2}$

For R_2, $s_m = \frac{R2}{X2}$ where T_m occurs

For R_2', $s_{m'} = \frac{R2'}{X2}$ where same T_m occurs.



As R_2' > R_2, the slip s_m' > s_m. the starting torque T_{st}' for R_2' is more than T_{st} for R_2. Thus by controlling the rotor resistance the starting torque can be controlled. If resistance is further added to rotor, maximum torque is constant but slip at which it occurs increases and so starting torque increases.

12. Discuss the different power stages of a 3 phase induction motor with losses with the help of a power flow diagram.

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

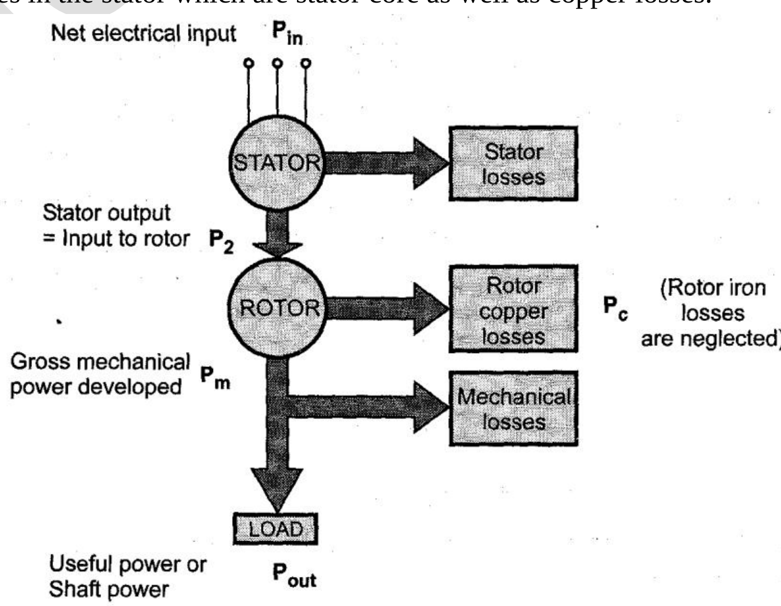
The three phase supply given to the stator is the net electrical input to the motor.

The net input electrical power supplied to the motor is,

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

This is the stator input.

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



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

$P_2 = P_{in}$ – Stator losses (core + copper)

The rotor is not able to convert its entire input to the mechanical as it has to supply rotor losses. The rotor losses are dominantly copper losses as rotor iron losses are very small and hence generally neglected. So rotor losses are rotor copper losses denoted as

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

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

R_2 = Rotor resistance per phase

After supplying these losses, the remaining part of P_2 is converted into mechanical which is called gross mechanica1 power developed by the motor denoted as P_m.

$P_m = P_2 - P_c$

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

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

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

13. Derive the relation between input, rotor copper losses and mechanical power developed in terms of a slip of a three phase induction motor.

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

Power P = T x ω

Where ω = angular speed = $\frac{2\pi N}{60}$, N = speed in r.p.m

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

$P_2 = T \times \omega_s$, where $\omega_s = \frac{2\pi Ns}{60}$ rad /sec (1)

$P_2 = T \times \frac{2\pi Ns}{60}$ where N_s is in r.p.m

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

$P_m = T \times \omega$ where $\omega = \frac{2\pi N}{60}$

$P_m = T \times \frac{2\pi N}{60}$ (2)

Rotor copper loss $P_c = P_2 - P_m = T \times \frac{2\pi Ns}{60} - T \times \frac{2\pi N}{60} = T \times \frac{2\pi}{60}(N_s - N)$ (3)

Dividing equation (3) by (1),

$$\frac{P_c}{P_2} = \frac{T \times \frac{2\pi}{60}(Ns - N)}{T \times \frac{2\pi Ns}{60}} = \frac{Ns - N}{Ns} = s$$

Rotor copper loss P_c = s x rotor input P_{in}

Thus total rotor copper loss is slip times the rotor input.

$P_2 - P_c = P_m$

$P_2 - sP_2 = P_m$

$(1-s) P_2 = P_m$

Thus gross mechanical power developed is (1 — s) times the rotor input.

The relationship can be expressed in the ratio form as,

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

14. Develop an equivalent circuit of a 3 phase induction motor. What do the various parameters represent? Represent the approximate equivalent circuit and state its significance.

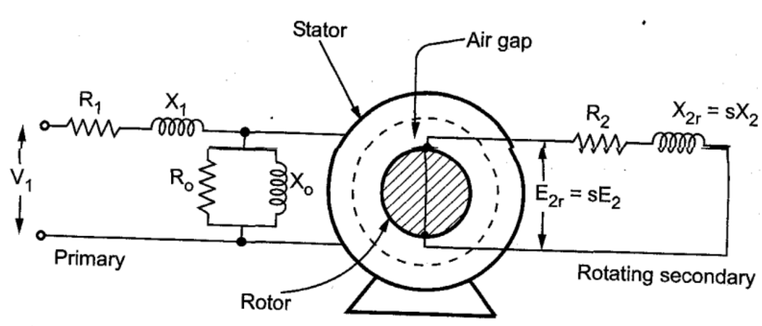
The energy transfer from stator to rotor of the induction motor takes place entirely with the help of a flux mutually linking the two. Thus stator acts as a primary while the rotor acts as a rotating secondary when induction motor is treated as transformer.

If

E_1 = Induced voltage in stator per phase

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

K = $\frac{\text{rotor turns}}{\text{stator turns}} = \frac{E_2}{E_1}$



E_{2r} = Rotor induced e.m.f. in running condition per phase

R_2 = Rotor resistance per phase

X_{2r} = Rotor reactance per phase in running condition
R_1 = Stator resistance per phase
X_1 = Stator reactance per phase
When induction motor is on no load, it draws a current from the supply to produce the flux in air gap and to supply iron losses.
This current I_0 has two components.

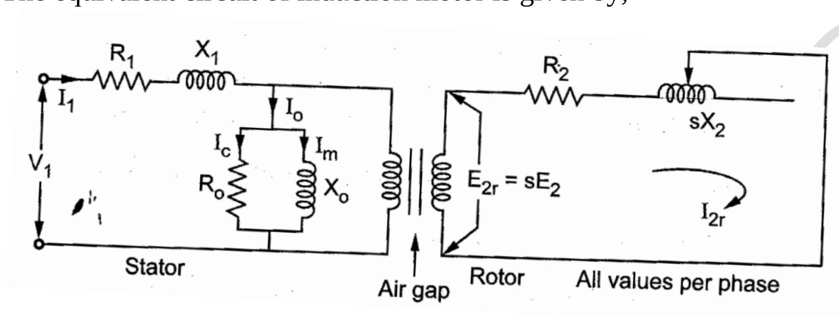
1. I_c = Active component which supplies no load losses
2. I_m = Magnetising component which sets up flux in core and air gap

These two currents give us the elements of an exciting branch as,

R_0 = Representing no load losses = $\frac{V_1}{I_c}$

X_0 = representing flux set up = $\frac{V_1}{I_m}$

The equivalent circuit of induction motor is given by,



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

$$= \frac{E2r}{Z2r} = \frac{sE2}{\sqrt{R2^2+(sX2)^2}} \text{ A}$$

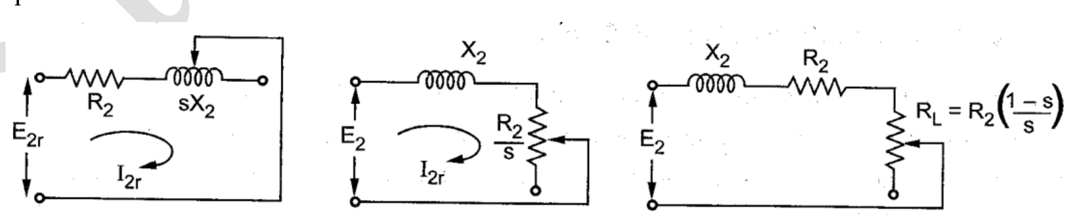
$$= \frac{E2}{\sqrt{(\frac{R2}{s})^2+(X2)^2}}$$

So it can be assumed that equivalent rotor circuit in the running condition has fixed reactance X_2, fixed voltage E_2 but a variable resistance R_2/s.

$$\frac{R_2}{s} = R_2 + \frac{R_2}{s} + R_2$$

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

So the variable rotor resistance R_2/s has two parts,
1. Rotor resistance R_2 itself which represents copper loss.
2. R_2 (1 — s)/s which represents load resistance R_L. So it is electrical equivalent of mechanical load on the motor.
The rotor equivalent circuit is



(a) (b) (c)

Equivalent circuit referred to stator:

$K = \frac{E_2}{E_1}$ = transformation ratio

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

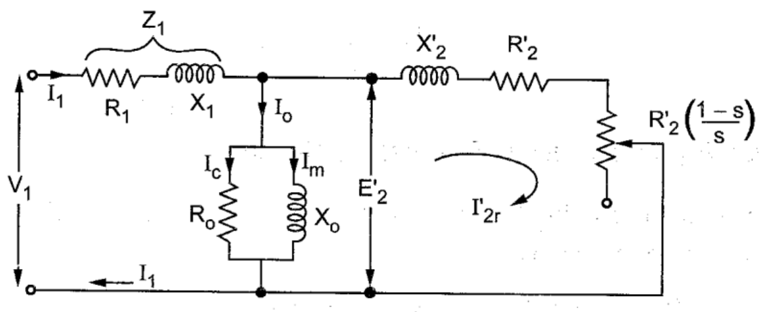
Rotor current referred to stator $I_{2r}' = K\, I_{2r} = \frac{KsE\,2}{\sqrt{R2^2+(sX2)^2}}$

Rotor reactance referred to stator $X_2' = \frac{X_2}{K^2}$

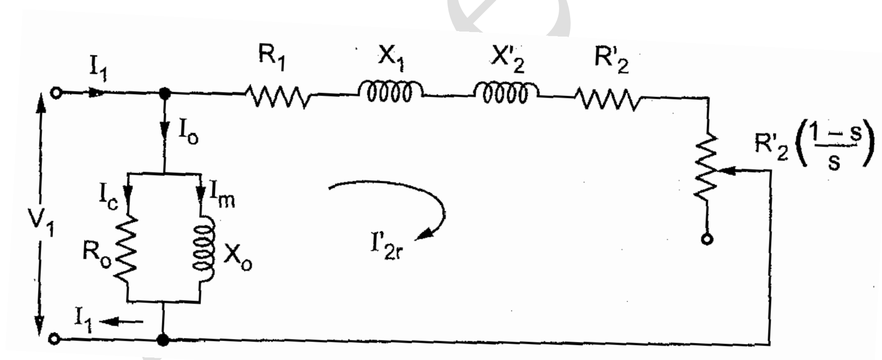
Rotor resistance referred to stator $R_2' = \frac{R_2}{K^2}$

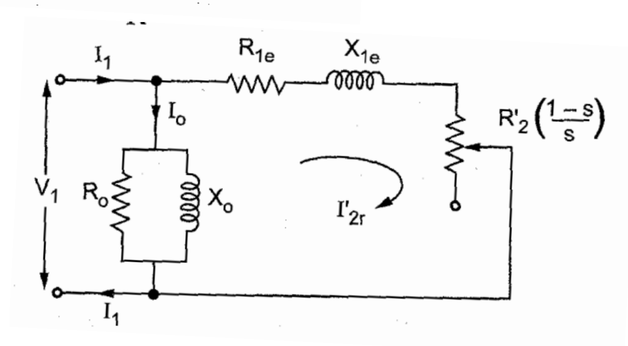
Mechanical load referred to stator $R_L' = \frac{R_L}{K^2} = \frac{R_2}{K^2}\frac{1-s}{s} = R_2'\frac{1-s}{s}$

Equivalent circuit referred to stator is



Approximate Equivalent circuit



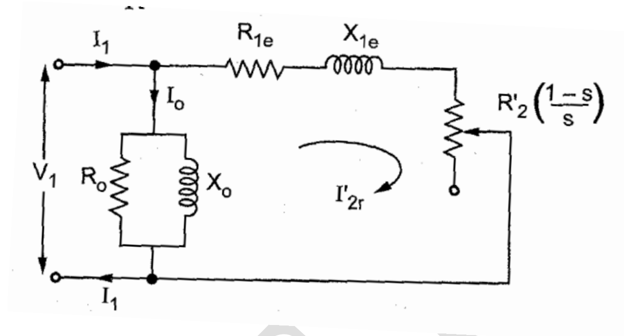


R_{1e} = equivalent resistance referred to stator = $R_1 + R_2'$

X_{1e} = Equivalent reactance referred to stator = $X_1 + X_2'$

$R_{1e} = R_1 + \frac{R_2}{K^2}$ and $X_{1e} = X_1 + \frac{X_2}{K^2}$

15. Derive the power equations from the equivalent circuit.



P_{in} = input power = 3 V_1 I_1 cos φ

Where V_1 = stator voltage per phase

I_1 = current drawn by stator per phase

cos φ = power factor of stator

stator core loss = $I_m^2 R_0$

stator copper loss = 3 $I_1^2 R_1$

where R_1 = stator resistance per phase

P_2 = rotor input = $\frac{3\, I'^{2}_{2r} R'_2}{s}$

P_c = rotor copper loss = $3\, I'^{2}_{2r}\, R'_2$

Thus P_c = s P_2

Gross mechanical power developed $P_m = P_2 - P_c = \frac{3\, I'^{2}_{2r} R'_2}{s} - 3\, I'^{2}_{2r}\, R'_2 = 3\, I'^{2}_{2r}\, R'_2$ (1-s) /s

Torque developed $T = \frac{P_m}{\omega} = \frac{3\, I'^{2}_{2r}\, R'_2\,(1-s)/s}{\frac{2\pi N}{60}}$

Where N = speed of motor

N = N_s (1-s)

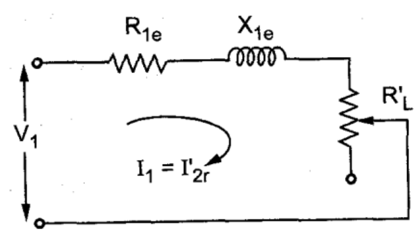
Therefore $T = \frac{3\, I'^{2}_{2r}\, R'_2\ /s}{\frac{2\pi Ns}{60}} = 9.55 \times \frac{3\, I'^{2}_{2r}\, R'_2\ /s}{Ns}$ N-m

$I'_{2r} = \frac{V_1}{(R_{1e} + R'_L) + j\, X_{1e}}$ where $R_L' = R_2' \frac{1-s}{s}$

$I'_{2r} = \frac{V_1}{\sqrt{(R_{1e} + R'_L)^2 + (X_{1e})^2}}$

Maximum Power Output

In this circuit, the exciting current I_0 is neglected. Therefore



$I_1 = I'_{2r}$

Therefore $I_1 = \frac{V_1}{\sqrt{(R_{1e} + R'_L)^2 + (X_{1e})^2}}$

Power supplied to the load

P_{out} = $3\, I_1^2\, R_L'$

$= 3 \frac{V_1^{2}}{(R_{1e} + R'_L)^2 + (X_{1e})^2} R_L'$

To obtain maximum output power, $\frac{d\,P_{out}}{dR'_L} = 0$

∴ $$\frac{d}{dR'_L}\left[\frac{3\,V_1^2 (R'_L)}{[(R_{1e} + R'_L)^2 + (X_{1e})^2]}\right] = 0$$

∴ $[(R_{1e} + R'_L)^2 + (X_{1e})^2]\,[3\,V_1^2] - 3\,V_1^2 (R'_L)\,[2\,(R_{1e} + R'_L)] = 0$

∴ $(R_{1e} + R'_L)^2 + (X_{1e})^2 - 2\,(R'_L)\,(R_{1e} + R'_L) = 0$ … *Taking 3 V_1^2 common*

∴ $R_{1e}^2 + (R'_L)^2 + 2\,R_{1e}\,R'_L + X_{1e}^2 - 2\,R_{1e}\,R'_L - 2(R'_L)^2 = 0$

$$\therefore \quad R_{1e}^2 + X_{1e}^2 = (R_L')^2$$

But $\quad Z_{1e} = \sqrt{R_{1e}^2 + X_{1e}^2}$ = *leakage impedance referred to stator*

$$\therefore \quad Z_{1e}^2 = (R_L')^2$$

Therefore $\quad R_L' = Z_{1e}$

Hence the power output is maximum when the equivalent load resistance is equal to the standstill leakage impedance of the motor.

Corresponding Slip

$$R_L' = Z_{1e} = R_2' \frac{1-s}{s}$$

By solving we get

Slip at maximum output, $s = \frac{R'_2}{R'_2 + Z_{1e}}$

Corresponding maximum gross power output $(P_{out})_{max} = 3 \frac{V_1^2}{(R_{1e} + Z_{1e})^2 + (X_{1e})^2} Z_{1e}$

By solving

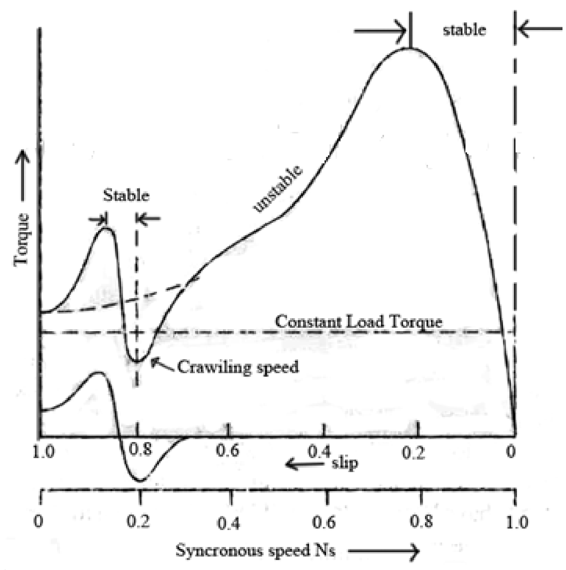
$$(P_{out})_{max} = \frac{3V_1^2}{2(R_{1e} + Z_{1e})} \text{ watts}$$

16. **Explain briefly about crawling and cogging.**

CRAWLING

Squirrel cage induction motors exhibit a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as **crawling of an induction motor**.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed N_s whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at $N_s/3$, $N_s/5$, $N_s/7$ speeds respectively.



Hence, harmonic torques are also developed in addition with fundamental torque. 3rd harmonics are absent in a balanced 3-phase system. Hence 3rd harmonics do not produce rotating field and torque.

The total motor torque now consist three components as:

(i) the fundamental torque with synchronous speed Ns,

(ii) 5th harmonic torque with synchronous speed Ns/5,

(iii) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Now, 5th harmonic currents will have phase difference of 5 x 120 = 600° =2 x 360 - 120 = -120°. Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces braking action and can be neglected.

The 7th harmonic currents will have phase difference of 7 x 120 = 840° = 2 x 360 +120 = + 120°. Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7 th of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate upto its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed. This phenomenon is called as **crawling in induction motors.**

COGGING

This characteristic of induction motor comes into picture when motor refuses to start at all. Sometimes it happens because of low supply voltage. But the main reason for starting problem in the motor is because of cogging in which the slots of the stator get locked up with the rotor slots.

When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this stage the reluctance of the magnetic path is minimum and motor refuse to start. This **characteristic of the induction motor** is called cogging.

Apart from this, there is one more reason for cogging. If the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage then it causes torque modulation. As a result, of it cogging occurs. This characteristic is also known as magnetic teeth locking of the induction motor.

Methods to overcome cogging

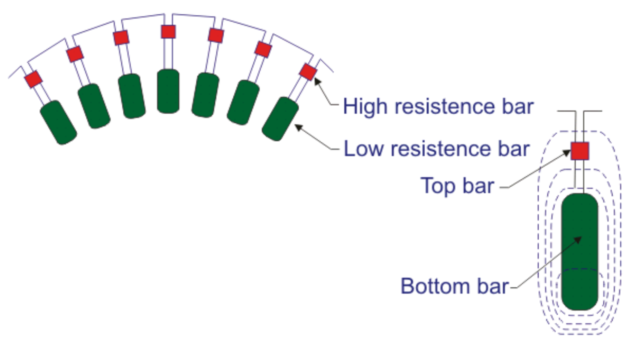
- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

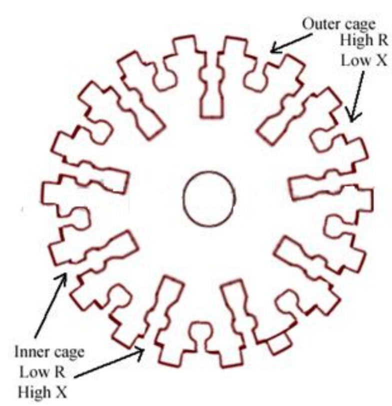
17. Explain with necessary diagrams the principle of operation and characteristics of the double cage induction motor.

Squirrel cage motors are the most commonly used induction motors, but the main drawback in them is their poor starting torque due to low rotor resistance. (Starting torque is directly proportional to the rotor resistance). But increasing the rotor resistance for improving starting torque is not advisory as it will reduce the efficiency of the motor (due to more copper loss). External resistance for starting of purposes cannot be added; as the rotor bars are permanently short circuited. These drawbacks are removed by a **double squirrel cage motor**, which has high starting torque without sacrificing efficiency.

Construction Of Double Squirrel Cage Rotor

Rotor of a **double squirrel cage motor** has two independent cages on the same rotor. Bars of high resistance and low reactance are placed in the outer cage, and bars of low resistance and high reactance are placed in the inner cage. The outer cage has high 'reactance to resistance ratio' whereas, the inner cage has low 'reactance to resistance ratio.



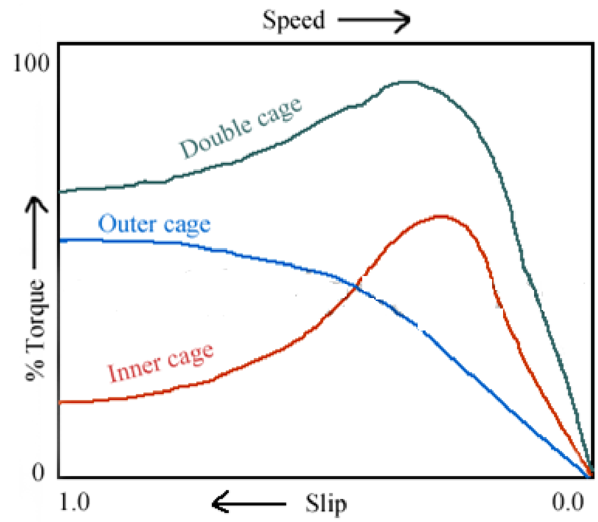


Working Of Double Squirrel Cage Motor

At starting of the motor, frequency of induced emf is high because of large slip (slip = frequency of rotor emf / supply frequency). Hence the reactance of inner cage ($2\pi fL$ where, f = frequency of rotor emf) will be very high, increasing its total impedance. Hence at starting most of the current flows through outer cage despite its large resistance (as total impedance is lower than the inner cage). This will not affect the outer cage because of its low reactance. And because of the large resistance of outer cage starting torque will be large.

As speed of the motor increases, slip decreases, and hence the rotor frequency decreases. In this case, the reactance of inner cage will be low, and most of the current will flow through the inner cage which is having low resistance. Hence giving a good efficiency.

When the double cage motor is running at normal speed, frequency of the rotor emf is so low that the reactance of both cages is negligible. The two cages being connected in parallel, the combined resistance is lower.



The **torque speed characteristics of double squirrel cage motor** for both the cages are shown in the figure.

Comparison between single cage and double cage motors:

1. A double cage rotor has low starting current and high starting torque. Therefore, it is more suitable for direct on line starting.
2. Since effective rotor resistance of double cage motor is higher, there is larger rotor heating at the time of starting as compared to that of single cage rotor.
3. The high resistance of the outer cage increases the resistance of double cage motor. So full load copper losses are increased & efficiency is decreased.
4. The pull out torque of double cage motor is smaller than single cage motor.
5. The cost of double cage motor is about 20-30 % more than that of single cage motor of same rating.

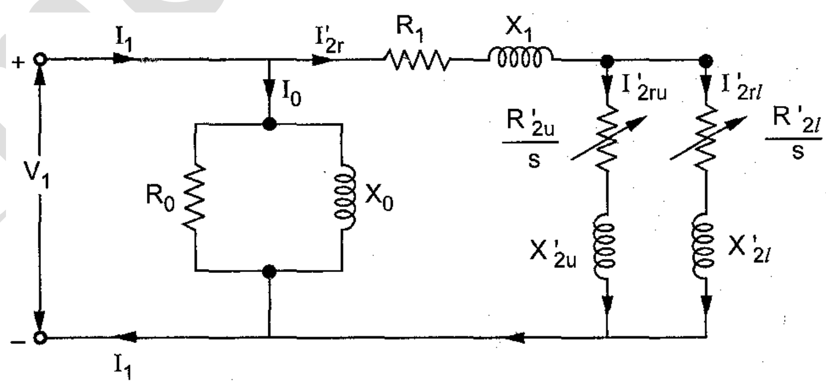
Equivalent Circuit

The two cages are assumed to be parallel.

I'_{2ru} and I'_{2rl} are the currents in the upper and lower cages respectively referred to the stator.

R'_{2u} and R'_{2l} are the resistances of upper and lower cages respectively referred to the stator.

X'_{2u} and X'_{2l} are the leakage reactances of upper and lower cages respectively referred to the stator.

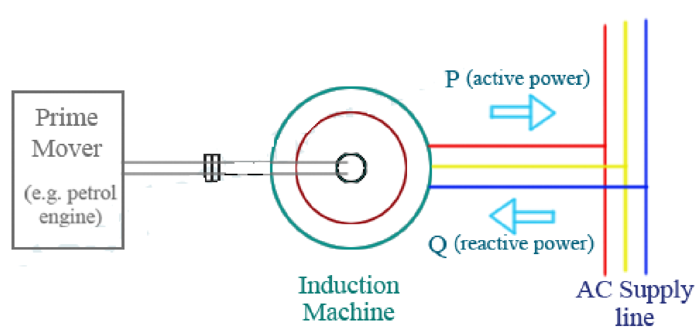


18. Write a brief note on induction generator.

If an AC supply is connected to the stator terminals of an induction machine a rotating magnetic field produced in the stator which pulls the rotor to run behind it (the machine is acting as a motor).

If the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.

If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field.



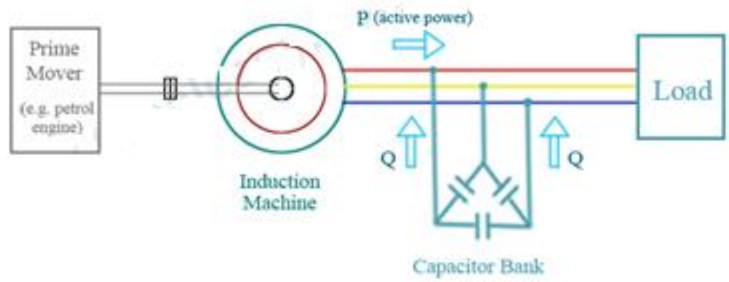
This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now **working as an induction generator (asynchronous generator)**.

Induction generator is not a self-excited machine. Therefore, when running as a generator, the machine takes reactive power from the AC power line and supplies active power back into the line. Reactive power is needed for producing rotating magnetic field. The active power supplied back in the line is proportional to slip above the synchronous speed.

Self-Excited Induction Generator

An induction machine needs reactive power for excitation, regardless whether it is operating as a generator or a motor. When an induction generator is connected to a grid, it takes reactive power from the grid.

A capacitor bank can be connected across the stator terminals to supply reactive power to the machine as well as to the load. When the rotor is rotated at an enough speed, a small voltage is generated across the stator terminals due to residual magnetism. Due to this small generated voltage, capacitor current is produced which provides further reactive power for magnetization.

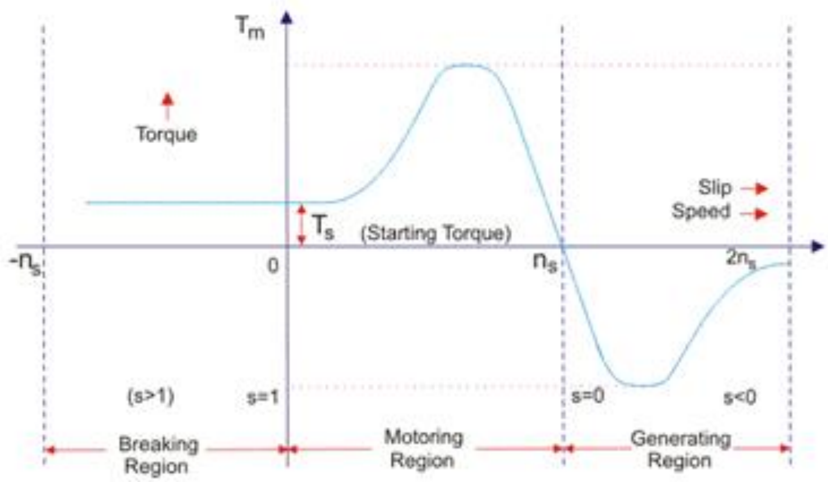


Applications of induction generators: Induction generators produce useful power even at varying rotor speeds. Hence, they are suitable in wind turbines.

Advantages: Induction or **asynchronous generators** are more rugged and require no commutator and brush arrangement (as it is needed in case of synchronous generators).

Disadvantage of induction generators is that they take quite large amount of reactive power.

The torque slip characteristic for motoring and generating action is shown in figure.



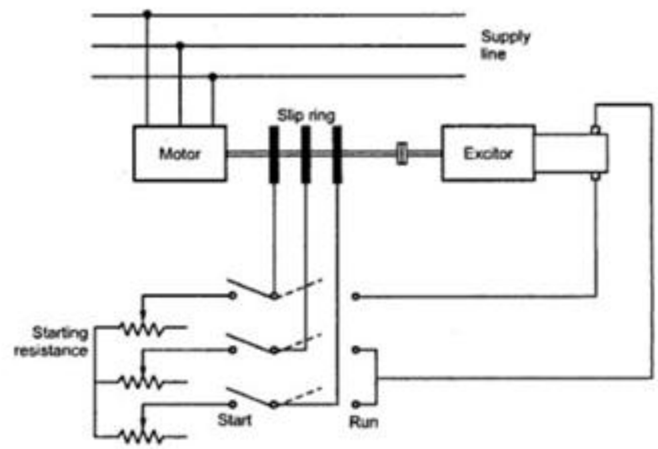
19. Write a brief note on synchronous induction motor.

In the applications where high starting torque and constant speed are desired then synchronous induction motors can be used. It has the advantages of both synchronous and induction motors. The synchronous motor gives constant speed whereas induction motors can be started against full load torque.

Consider a normal slip ring induction motor having 3 phase winding on the rotor as shown in fig. The motor is connected to the exciter which gives d.c. supply to the motor through slip rings. One phase carries full d.c. current while the other two carries half of the full d.c. current as they are in parallel. Due to this d.c. excitation, permanent poles (N and S) are formed on the rotor.

Initially it is run as a slip ring induction motor with the help of starting resistances. When the resistance is cut out the motor runs with a slip. Now the connections are changed and the exciter is connected in series with the rotor windings which will remain in the circuit permanently.

As the motor is running as induction motor initially high starting torque (upto twice full load value) can be developed. When d.c. excitation is provided it is pulled into synchronism and starts running at constant speed. The synchronous induction motor provides constant speed, large starting torque, low starting current and power factor correction.

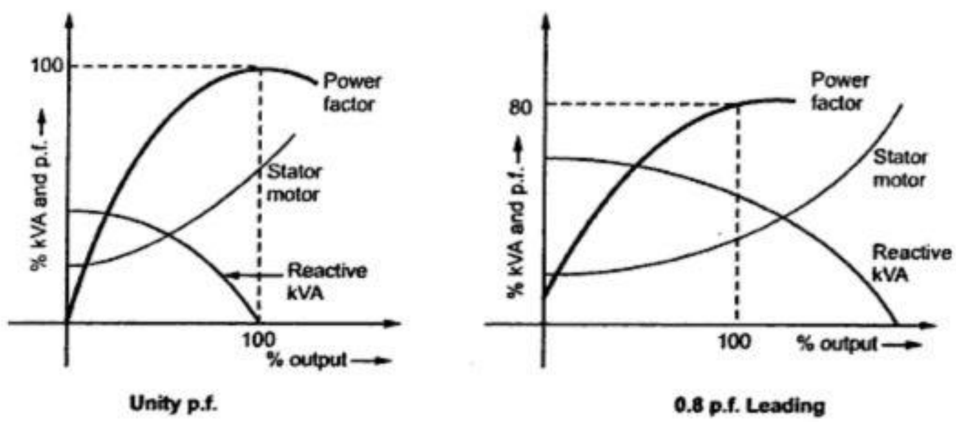


Performance Characteristics of Synchronous Induction Motors

In the performance characteristics of synchronous induction motor, three different types of torques are to be considered. These are

- the starting torque which indicates capacity of motor to start against load,
- pull in torque which indicates the ability of the motor to maintain operation during change over from induction motor to synchronous motor,
- pull out torque which represents the running of motor synchronously at peak load.

The first two torques are closely related with each other and are the characteristics of the machine running as induction motor. The pull out torque is characteristics when it is running synchronously. The characteristics curves for synchronous induction motor operating at full load unity p.f. and at 0.8 p.f. leading is shown in the Fig.



When the load exceeds the synchronous pull out torque, the machine looses synchronism and runs as an induction motor with fluctuation in torque and slip due to d.c. excitation. With reduction in load torque the motor is automatically resynchronized.

Advantages of Synchronism Induction Motor

i) The synchronous induction motor can start and synchronize against more than full load torque which is not possible with salient pole synchronous motor which must be started against light load.

ii) The exciter required for synchronous induction motor is of smaller capacity as the gap is not long as compared to normal salient pole motor.

iii) The rotor winding in synchronous induction motor can function as providing excitation and required damping. So no separate damper winding is required.

iv) No separate starting and control equipments are required.

Disadvantages of Synchronous Induction Motor

i) As the gap is small as compared to normal salient pole synchronous motor it will not give large overload capacity.

ii) The variation of power factor is large as compared to normal synchronous motor.

iii) The speed variation is not possible for synchronous induction motor as it runs at constant motor.

Applications of Synchronous Induction Motor

- The applications where mechanical load is to be driven along with phase advancing properties of synchronous motors are to be used then use of synchronous induction motor is better option.
- applications where in load torque is remaining nearly constant, this motor can be used

20. Which tests are required to be performed to obtain the data for the circle diagram? How these tests are performed?

The data required to draw the circle diagram is obtained by conducting (i) no load or open circuit test and (ii) blocked rotor test or short circuit test.

No Load Test

In this test, the motor is made to run without any load i.e. no load condition. The speed of the motor is very close to the synchronous speed but less than the synchronous speed. The rated voltage is applied to the stator. The input line current and total in put power is measured. The two wattmeter method is used to measure the total input power. The circuit diagram for the test is shown in the Fig. 1.

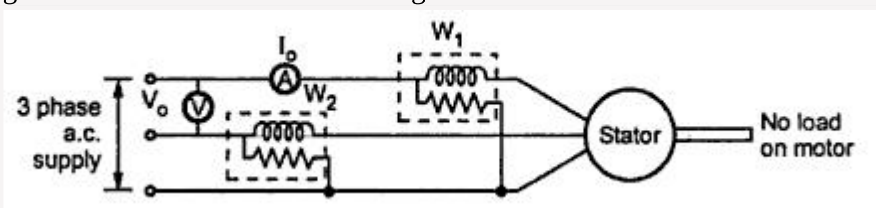


Fig. 1 No load test

The calculations are,

$W_o = \sqrt{3} V_o I_o \cos\Phi_o$

No load power factor, $\cos \Phi_o = \frac{Wo}{\sqrt{3}Vo\ Io}$

The parameters of the equivalent circuit can be obtained as,

$I_c = I_o \cos\Phi_o$ = Active component of no load current

$I_m = I_o \sin\Phi_o$ = Magnetising component of no load current

$R_o = V_o$ (per phase) / I_c (per phase) = No load branch resistance

$X_o = V_o$ (per phase)/ I_m (per phase) = No load branch resistance

The power input W_o consists of following losses,

1. Stator copper loss i.e. $3 I_o^2 R_1^2$ where I_o is no load per phase current and R_1 is stator resistance per phase.
2. Stator core loss i.e. iron loss.
3. Friction and windage loss.

Under no load condition, I_o is also very small and in many practical cases it is also neglected. Thus W_o consists of stator iron loss and friction and windage loss which are consists for all load conditions. Hence W_o is said to give fixed losses of the motor.

$\therefore$ W_o = No load power input = Fixed loss

Blocked Rotor Test

In this test, the rotor is locked and it is not allowed to rotate. Thus the slip s = 1 and $R_L' = R_2' (1-s)/s$ is zero. If the motor is slip ring induction motor then the windings are short circuited at the slip rings.

A reduced voltage (about 10 to 15 % of rated voltage) is applied such that stator carries rated current. Now the applied voltage V_{sc}, the input power W_{sc} and a short circuit current I_{sc} are measured.

As $R_L' = 0$, the equivalent circuit is exactly similar to that of a transformer and hence the calculations are similar to that of short circuit test on a transformer.

V_{sc} = Short circuit reduced voltage (line value)

I_{sc} = Short circuit current (line value)

W_{sc} = Short circuit input power

Now $W_{sc} = \sqrt{3} V_{sc} I_{sc} \cos\Phi_{sc}$ ....Line values

Short circuit power factor of a motor $\cos \Phi_{sc} = \frac{Wsc}{\sqrt{3}Vsc\ Isc}$

$W_{sc} = 3 (I_{sc})^2 R_{1e}$

where I_{sc} = Per phase value

Equivalent resistance referred to stator $R_{1e} = \frac{Wsc}{3(I_{sc})^2}$

Equivalent impedance referred to stator, $Z_{1e} = V_{sc}$ (per phase)/ I_{sc} (per phase)

Equivalent reactance referred to stator, $X_{1e} = \sqrt{{Z_{1e}}^2 - {R_{1e}}^2}$

During this test, the stator carries rated current hence the stator copper loss is also dominant. Similarly the rotor also carries short circuit current to produce dominant rotor copper loss. As the voltage is reduced, the iron loss which is proportional to voltage is negligibly small. The motor is at standstill hence mechanical loss i.e. friction and windage loss is absent. Hence we can write,

W_{sc} = Stator copper loss + Rotor copper loss

But it is necessary to obtain short circuit current when normal voltage is applied to the motor. This is practically not possible. But the reduced voltage test results can be used to find current I_{SN} which is short circuit current if normal voltage is applied.

If V_L = Normal rated voltage (line value)

V_{sc} = Reduced short circuit voltage (line voltage)

Then $I_{Sn} = (V_L / V_{sc}) \times I_{sc}$

where I_{sc} = Short circuit current at reduced voltage

Thus, I_{SN} = Short circuit current at normal voltage

Now power input is proportional to square of the current.

So W_{SN} = Short circuit input power at normal voltage

This can be obtained as,

$W_{SN} = (I_{SN} / I_{sc})^2 \times W_{sc}$

But at normal voltage core loss can not be negligible hence,

W_{SN} = Core loss + Stator and rotor copper loss

21. Explain the procedure of drawing circle diagram of an induction motor. What information can be drawn from the circle diagram and how?

By using the data obtained from the no load test and the blocked rotor test, the circle diagram can be drawn using the following steps:

Step 1: Take reference phasor V as vertical (Y-axis).

Step 2: Select suitable current scale such that diameter of circle is about 20 to 30 cm.

Step3: From no load test, I_o and Φ_o are obtained. Draw vector I_o, lagging V by angle Φ_o. This is the line OO' as shown in the Fig.

Step 4: Draw horizontal line through extremity of I_o i.e. O', parallel to horizontal axis.

Step 5: Draw the current I_{SN} calculated from I_{sc} with the same scale, lagging V by angle Φ_{sc}, from the origin O. This is phasor OA as shown in the Fig.

Step 6: Join O'A. the line O’A is called output line.

Step 7: Draw a perpendicular bisector of O'A. Extend it to meet line O'B at point C. This is the centre of the circle.
Step 8: Draw the circle, with C as a center and radius equal to O'C. This meets the horizontal line drawn from O' at B as shown in the Fig.
Step 9: Draw the perpendicular from point A on the horizontal axis, to meet O'B line at F and meet horizontal axis at D.
Step 10: Torque line.

The torque line separates stator and rotor copper losses.

Thus the vertical distance AD represents power input at short circuit i.e. W_{SN}, which consists of core loss and stator, rotor copper losses.

Now FD = O'G = Fixed loss

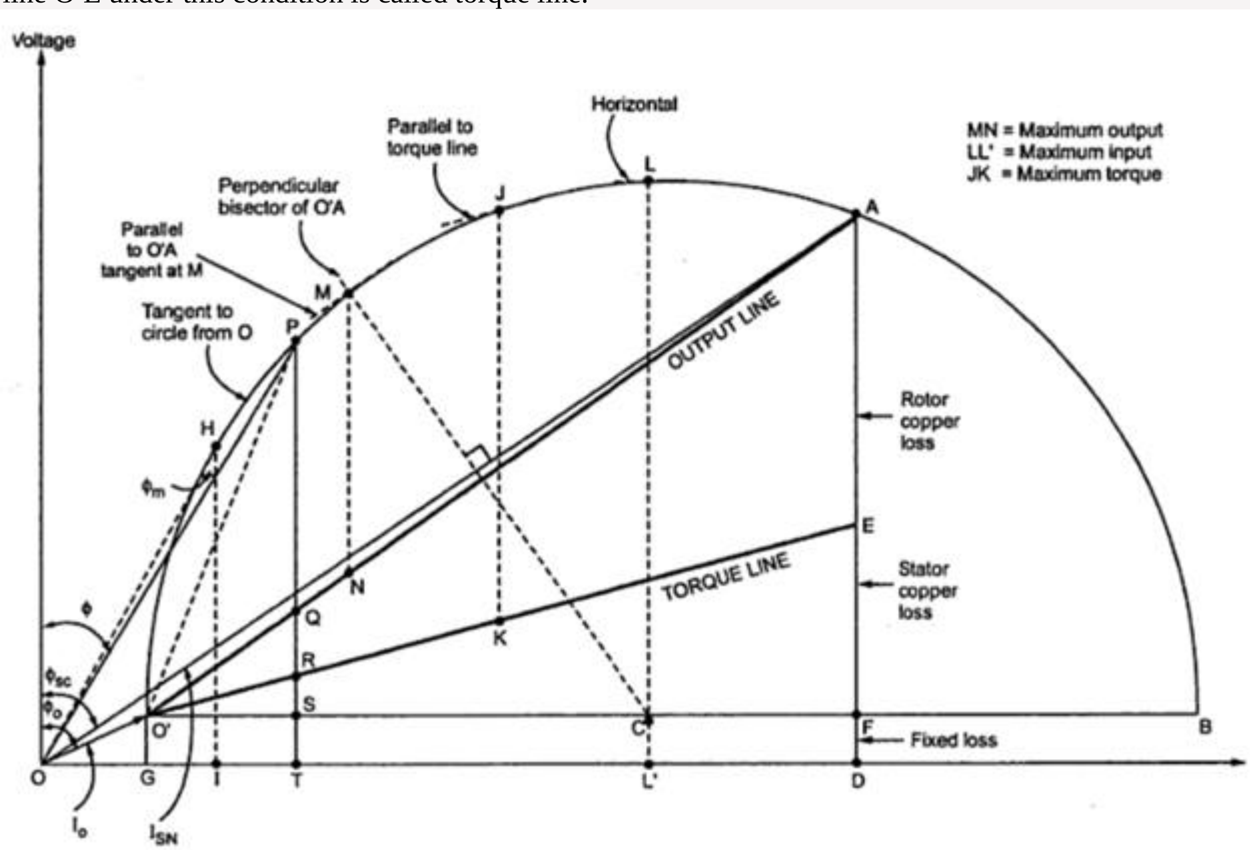
Where O'G is drawn perpendicular from O' on horizontal axis. This represents power input on no load i.e. fixed loss.

Hence AF α Sum of stator and rotor copper losses

Then point E can be located as,

$$\frac{AE}{EF} = \frac{\text{Rotor copper loss}}{\text{Stator copper loss}}$$

The line O'E under this condition is called torque line.



Power scale: As AD represents W_{SN} i.e. power input on short circuit at normal voltage, the power scale can be obtained as,

$$\text{Power scale} = \frac{W_{SN}}{l(AD)} \text{ W/cm}$$

where l(AD) = Distance AD in cm

Location of Point E: In a slip ring induction motor, the stator resistance per phase R_1 and rotor resistance per phase R_2 can be easily measured. Similarly by introducing ammeters in stator and rotor circuit, the currents I_1 and I_2 also can be measured.

∴ $K = I_1/I_2$ = Transformation ratio

Now $\frac{AE}{EF} = \frac{\text{Rotor copper loss}}{\text{Stator copper loss}} = \frac{I_2{}^2 R_2}{I_1{}^2 R_1} = \frac{R_2}{R_1}\left[\frac{I_2}{I_1}\right]^2 = \frac{R_2}{R_1} \cdot \frac{1}{K^2}$

But $R_2' = R_2/K^2$ = Rotor resistance referred to stator

∴ $AE/EF = R_2'/R_1$

Thus point E can be obtained by dividing line AF in the ratio R_2' to R_1.

In **a squirrel cage motor**, the stator resistance can be measured by conducting resistance test.

∴ Stator copper loss = $3I_{SN}{}^2 R_1$ where I_{SN} is phase value.

Neglecting core loss, W_{SN} = Stator Cu loss + Rotor Cu loss

∴ Rotor copper loss = $W_{SN} - 3I_{SN}{}^2 R_1$

∴ $AE/EF = (W_{SN} - 3I_{SN}{}^2 R_1) / (3I_{SN}{}^2 R_1)$

Dividing line AF in this ratio, the point E can be obtained and hence O'E represents torque line.

Predicting Performance Form Circle Diagram

Let motor is running by taking a current OP as shown in the Fig. The various performance parameters can be obtained from the circle diagram at that load condition.

Draw perpendicular from point P to meet output line at Q, torque line at R, the base line at S and horizontal axis at T.

Using the power scale and various distances, the values of the performance parameters can be obtained as,

Total motor input = PT x Power scale
Fixed loss = ST x power scale
Stator copper loss = SR x power scale
Rotor copper loss = QR x power scale
Total loss = QT x power scale
Rotor output = PQ x power scale
Rotor input = PQ + QR = PR x power scale
Slip s = Rotor Cu loss = QR/PR
Power factor cos = PT/OP
Motor efficiency = Output / Input = PQ/PT
Rotor efficiency = Rotor output / Rotor input = PQ/PR
Rotor output / Rotor input = 1 - s = N/N_s = PQ/PR
The torque is the rotor input in synchronous watts.

Maximum Quantities

The maximum values of various parameters can also be obtained by using circle diagram.

1. Maximum Output: Draw a line parallel to O'A and is also tangent to the circle at point M. The point M can also be obtained by extending the perpendicular drawn from C on O'A to meet the circle at M. Then the maximum output is given by l(MN) at the power scale. This is shown in the Fig.

2. Maximum Input: It occurs at the highest point on the circle i.e. at point L. At this point, tangent to the circle is horizontal. The maximum input given l(LL') at the power scale.

3. Maximum Torque: Draw a line parallel to the torque line and is also tangent to the circle at point J. The point J can also be obtained by drawing perpendicular from C on torque line and extending it to meet circle at point J. The l(JK) represents maximum torque in synchronous watts at the power scale. This torque is also called stalling torque or pull out torque.

4. Maximum Power Factor: Draw a line tangent to the circle from the origin O, meeting circle at point H. Draw a perpendicular from H on horizontal axis till it meets it at point I. Then angle OHI gives angle corresponding to maximum power factor angle.

∴ Maximum p.f. = cos {∟{OHI} = HI/OH

5. Starting Torque: The torque is proportional to the rotor input. At s = 1, rotor input is equal to rotor copper loss i.e. *l* (AE).

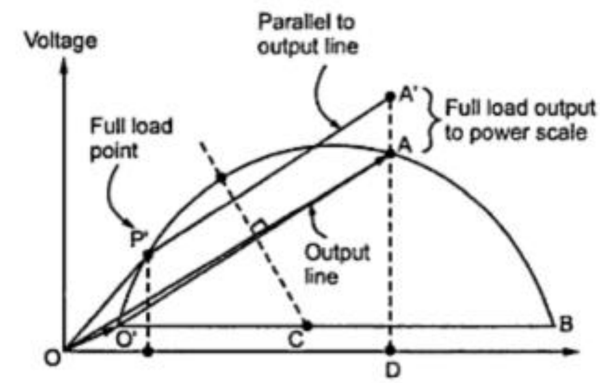
∴ T_{start} = *l*(AE) x Power scale ....in synchronous watts

Full load Condition

The full load motor output is given on the name plates in watts or h.p. Calculate the distance corresponding to the full load output using the power scale.

Then extend AD upwards from A onwards, equal to the distance corresponding to full load output, say A'. Draw parallel to the output line O'A from A' to meet the circle at point P'. This is the point corresponding to the full load condition, as shown in the Fig.

Once point P' is known, the other performance parameters can be obtained easily as discussed above.



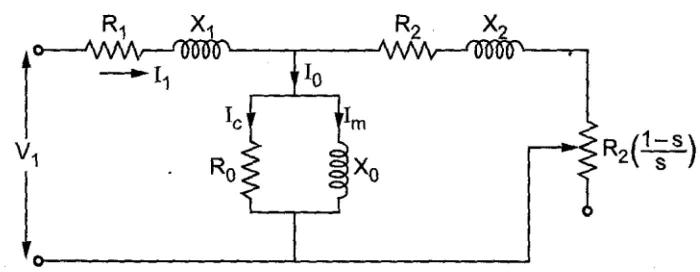
22. Obtain equivalent circuit parameters from the no load and blocked rotor test on induction motor.

NO LOAD TEST

1. No load power factor, $\cos \varphi_0 = W_0 / V_0 I_0$

V_0 – No load voltage per phase in volts
I_0 – No load current per phase in amps
W_0 – No load power per phase in watts

2. Active Component, $I_c = I_{0(ph)} \cos \varphi_0$
3. Magnetising Component, $I_m = I_{0(ph)} \sin \varphi_0$
4. No load resistance $(R_0) = V_0 / I_c$ Ω
5. No load reactance $(X_0) = V_0 / I_m$ Ω



BLOCKED ROTOR TEST

1. Equivalent impedance referred to stator, $Z_{1e\,(ph)} = V_{SC\,(ph)} / I_{SC(ph)}$ Ω
2. Equivalent resistance referred to stator, $R_{1e\,(ph)} = W_{SC\,(ph)} / [3\, I^2_{SC(ph)}]$ Ω
3. Equivalent reactance referred to stator, $X_{1e(ph)} = \sqrt{[(Z_{1e\,(ph)})^2 - (R_{1e\,(ph)})^2]}$ Ω
4. Rotor resistance referred to stator $(R'_{2\,(ph)}) = R_{1e\,(ph)} - R_1$ Ω
5. Rotor reactance referred to stator $(X'_{2\,(ph)}) = X_{1e(ph)} / 2 = X_1$ Ω

Where R_1 - stator resistance per phase
X_1 – stator reactance per phase
$R_1 = R_{(ac)} = 1.6\, R_{(dc)}$

6. Equivalent load resistance, $R'_L = R'_2 (1/s - 1)$ Ω

Where slip, $s = (N_s - N) / N_s$
N_s – Synchronous speed in rpm
N – Speed of motor in rpm

UNIT IV STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

Need for starting – Types of starters – DOL, Rotor resistance, Autotransformer and Star-delta starters – Speed control – Voltage control, Frequency control and pole changing – Cascaded connection-V/f control – Slip power recovery scheme-Braking of three phase induction motor: Plugging, dynamic braking and regenerative braking.

NECESSITY OF A STARTER IN A THREE PHASE INDUCTION MOTOR.

The three phase induction motors are self starting due to rotating magnetic field. But the motors have a tendency to draw very high current at the time of starting. Such a current can be five to eight times the rated current and can damage the motor winding. Hence a starter is used which can limit such high starting current.

In a three phase induction motor, the magnitude of an induced e.m.f. in the rotor circuit depends on the slip of the induction motor. This induced e.m.f. effectively decides the magnitude of the rotor current. The rotor current in the running condition is given by,

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

At start, the speed of the motor is zero and slip is at its maximum i.e. unity. So magnitude of rotor induced e.m.f. is very large at start. As rotor conductors are short circuited, the large induced e.m.f. circulates very high current through rotor at start.

In a three phase induction motor, when rotor current is high, the stator draws a very high current from the supply. This current can be of the order of 5 to 8 times the full load current, at start.

Due to such heavy inrush of current at start

- There is possibility of damage of the motor winding.
- Causes large line voltage drop.
- Other appliances connected to the same line may be subjected to voltage spikes which may affect their working.

To avoid such effects, it is necessary to limit the current drawn by the motor at start. The starter is a device which is basically used to limit high starting current by supplying reduced voltage to the motor at the time of starting. Such a reduced voltage is applied only for short period and once rotor gets accelerated, full normal rated voltage is applied.

Functions of a Starter:

- limits the starting current
- provides the protection against overloading
- Provides the protection against low voltage situations.
- provides protection against single phasing

.

WORKING OF DIRECT ON LINE STARTER

If large rating induction motors are connected directly to the supply, a heavy starting current can damage the motor and also cause disturbance of voltage, i.e., voltage dip on mains supply. This can lead malfunctioning of other equipments connected to the same supply.

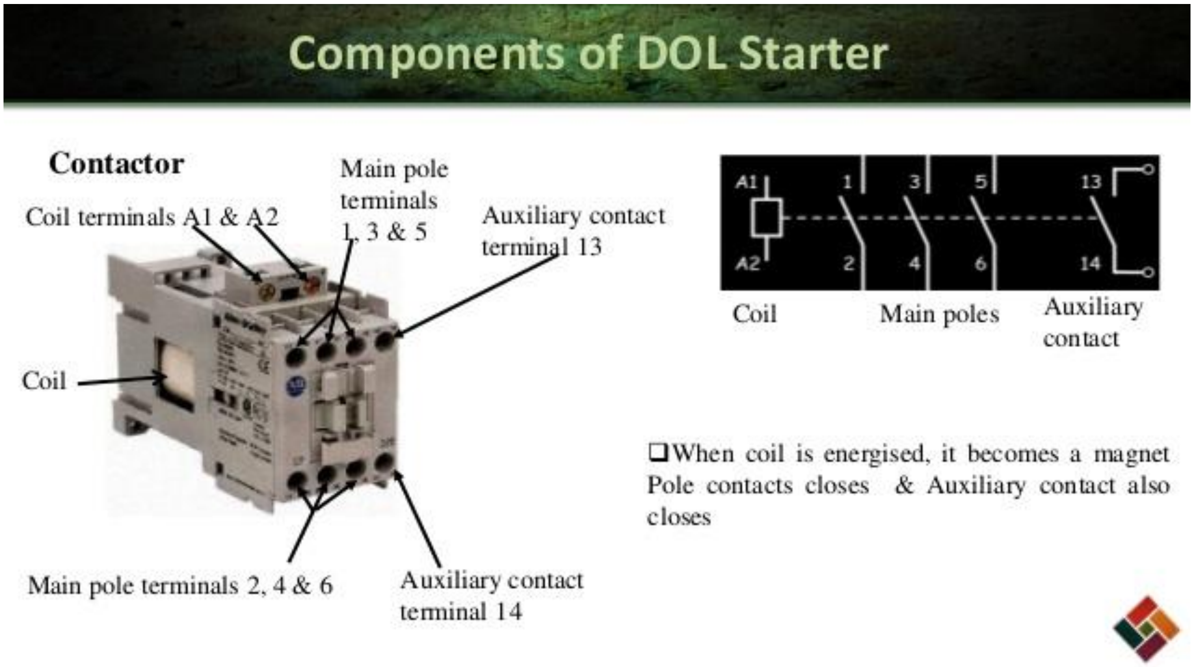
Thus DOL starters are limited to small rating motors where distribution system (mains supply) can withstand high starting currents without excessive voltage dips.

DOL starter consists of MCCB, contactor, and overload relay. It acts as a switch under normal working condition by providing the means to switch ON and switch OFF the motor.

Construction or Parts of DOL Starter

It consists of two push buttons, one is a green button for starting the motor and the other is red for stopping the motor. The switching of power supply is carried through an electromagnetic contactor which can be 3 or 4 pole contactor. This electromagnetic contactor has three NO contacts that connect the motor to the supply line while fourth contact (also called as an auxiliary contact) works as hold-on contact when the start button is released in order to energize the contactor coil.

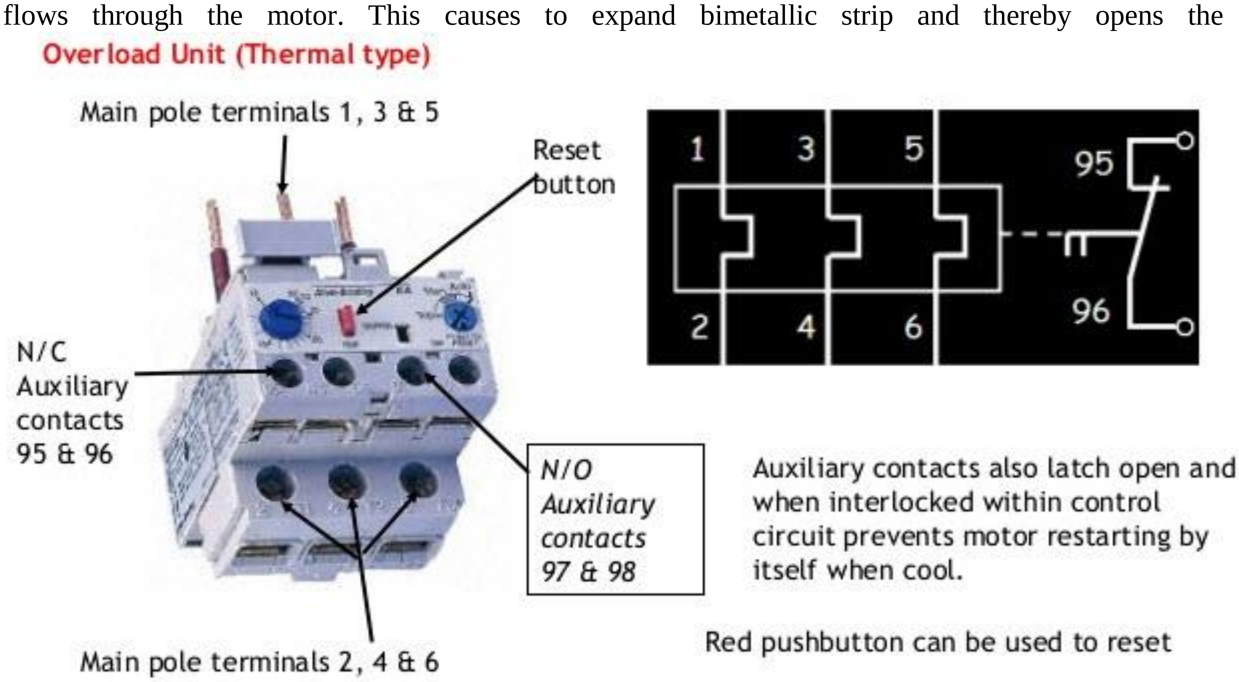
This auxiliary contact (NO or NC) makes the contactor to be electrically latched while motor is operating and these contacts are less power rated than three main NO contacts. If any reason, power supply fails or voltage drops excessively, it releases the latch by de-energizing the coil and thus motor disconnected from the supply.



The contactor coil is connected in series with a start button, stop button and overload trip mechanism. This connection is called control circuit which is generally energized from two lines of three phase supply via a step down transformer.

Overload Protection

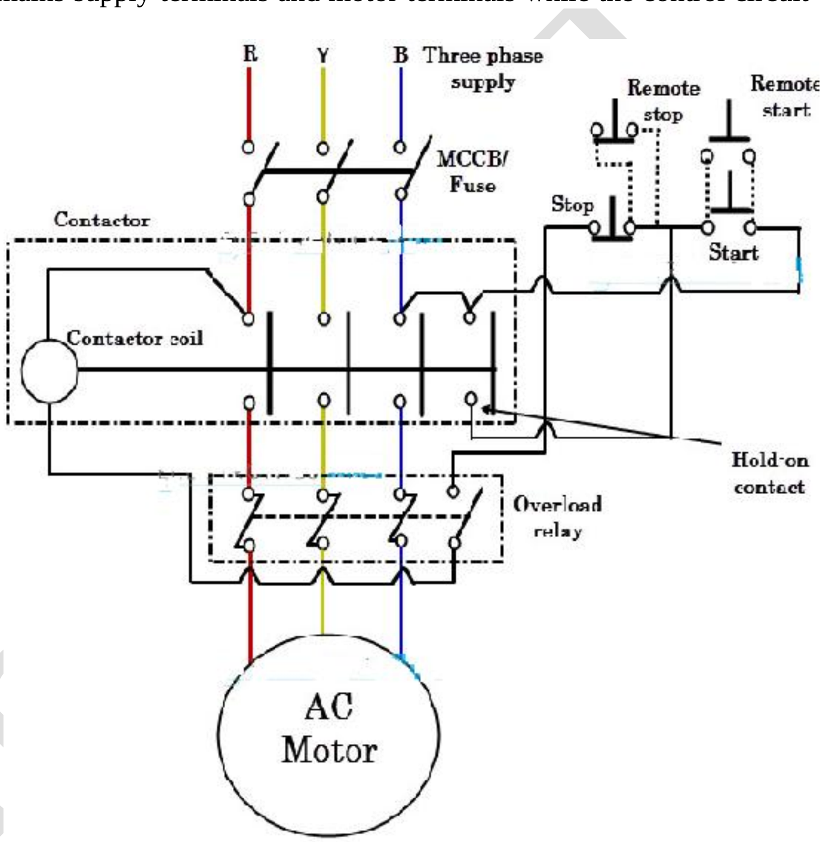
DOL starter is also provided with overload relay to protect the motor from overloads. The overload relays are provided with heating elements inside of which bimetallic strips are arranged. When excessive current flows through the motor, overheating causes to damage the motor winding. The overload coil becomes hot when the over current flows through the motor. This causes to expand bimetallic strip and thereby opens the trip contact.



This overload mechanism should operate at 20 to 30% overload. When the overload coils trips, the current through the contactor coil stops flowing and hence the contactor contacts come to the OFF position.Overload relays are provided with current adjuster such that tripping coil current can be adjusted depending on the load protection requirement.

Working of DOL Starter

- The wiring connection of DOL starter with start and stop buttons is shown in figure below. The DOL starter main terminals are connected between the mains supply terminals and motor terminals while the control circuit is energized with two terminals of three phase supply as illustrated in figure.



- When the start button is pressed, current will flow through one phase to the control circuit and the contactor coil to the other phase. This current energizes the contactor coil which makes to close the contacts thereby three phase supply is connected to the motor. Since the start button is of pushbutton, when it is released the control circuit still maintains the supply through hold-on contact.
- If the stop button is pressed or overload relay coil operate, the current path through contactor coil will break and hence the contactor contacts drops out, thus breaking the supply to the motor. Once the power supply is interrupted, again the supply to the motor is established by pressing the start button.
- The thermal overload protection relay operates depending on the heating effect of the load current. When the load current heats the thermal coils, bimetallic strip inside of it expands such that it trips out the spring-loaded contact in the control circuit. The speed at which relay operates decided by the current adjustment. Typically it will be four to five times the rated motor current.
- DOL starter can be operated remotely for remote control switching of motor from any number of desired places. For remote control switching one should remember that, all the remote ON push buttons must be connected in parallel to ON pushbutton of the starter whereas all remote OFF push buttons must be connected in series with OFF pushbutton of the starter. Connect the remote ON and OFF switches as shown in dotted line in the figure for remote control operation.

Advantages of DOL Starter

- It provides high starting torque.
- Simple to use and most economical.
- Control circuitry is simple to establish and troubleshoot.
- Easy to find fault and make necessary connections.
- More compact in size and thus occupies less space.

Disadvantages of DOL Starter

- High starting current, typically in the range of 6 to 8 times the full load current

- The inrush current of large motor may cause a big voltage dip or drop in electrical supply system which will affect other electrical appliances connected to it.
- The unnecessary high starting torque required by the load may cause increasing mechanical stresses on motor mechanical parts as well as the loads.
- It is not feasible for high rating motors, typically above 10 KW

STARTING METHODS USED FOR THREE PHASE INDUCTION MOTOR

Methods for starting induction motors are:

Squirrel Cage Motor

a. Primary resistors (or reactors or rheostats) or stator resistance starter.
b. Autotransformer (or auto starter)
c. Star-delta starters

Slip ring Motors

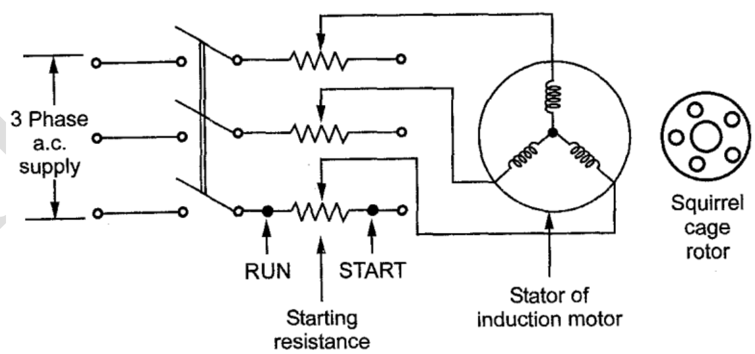
a. Rotor rheostat or rotor resistance starter

Squirrel Cage Motor

a. Primary resistors

In order to apply the reduced voltage to the stator of the induction motor, three resistances are added in series with each phase of the stator winding. Initially the resistances are kept maximum in the circuit. Due to this, large voltage gets dropped across the resistances. Hence a reduced voltage gets applied to the stator which reduces the high starting current. The schematic diagram showing stator resistances is shown in the Fig.

When the motor starts running, the resistances are gradually cut-off from the stator circuit. When the resistances are entirely removed from the stator circuit i.e. rheostats in RUN position then rated voltage gets applied to the stator. Motor runs with normal speed.



- The starter is simple in construction and cheap.
- It can be used for both star and delta connected stator.
- Large power losses due to resistances.
- The starting torque of the motor reduces due to reduced voltage applied to the stator.

$P_2 = T \times \omega$

Where T = torque produced

P_2 = rotor input at N_s

∴ $T \alpha P_2$

But $P_2 = \frac{P_c}{s}$ where P_c = total copper loss

$= \frac{3\, I_{2r}{}^2 R_2}{s}$

Therefore $T \alpha \frac{I_{2r}{}^2}{s}$

But rotor current I_{2r} and stator current are related to each other through transformer action.

∴ $T \alpha \frac{I_1{}^2}{s}$ where I_1 = stator current

At start, s = 1, $T = T_{st}$ and $I_1 = I_{st}$

∴ $T_{st} \alpha I_{st}{}^2$ (1)

When stator resistance starter is used, the factor by which stator voltage reduces is say x< 1. The starting current is proportional to this factor x. So if is the normal current drawn under full rated voltage condition at start then,

$I_{st} = x\, I_{sc}$ (2)

∴ $T_{st} = (x\, I_{sc})^2$ (3)

But $T_{F.L} \propto \frac{I_{FL}^{\ 2}}{s_f}$ where s_f = full load slip (4)

Taking ratio of (3) and (4),

$$\frac{T_{st}}{T_{FL}} = x^2 \left[\frac{I_{sc}}{I_{FL}} \right]^2 s_f$$

This method is useful for the smooth starting of small machines only.

b. Autotransformer (or auto starter) or compensators

. A three phase star connected autotransformer can be used to reduce the voltage applied to the stator. Such a starter is called an autotransformer starter. The schematic diagram of autotransformer starter is shown in the Fig.

It consists of a suitable change over switch.

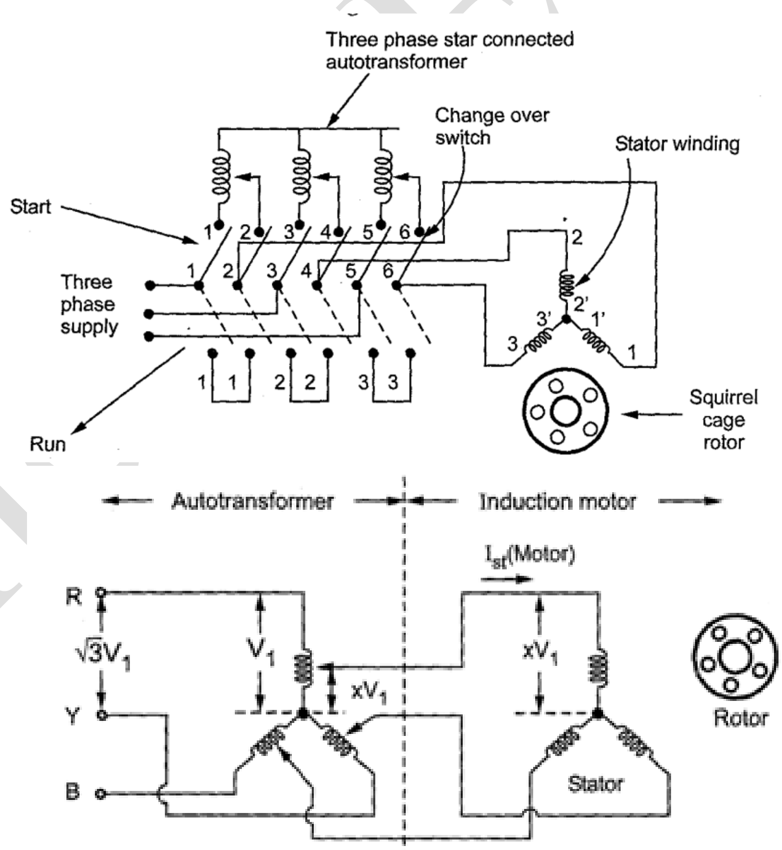
When the switch is in the start position, the stator winding is supplied with reduced voltage. This can be controlled by tappings provided with autotransformer.

The reduction in applied voltage by the fractional percentage tappings x, used for an autotransformer is shown in fig.

When motor gathers 80 % of the normal speed, the change over switch is thrown into run position.

Due to this, rated voltage gets applied to stator winding. The motor starts rotating with normal speed. Changing of switch is done automatically by using relays.

- The power loss is much less in this type of starting.
- It can be used for both star and delta connected motors.
- But it is expensive than stator resistance starter.



Voltage across motor phase on direct switching is V/√3 and starting current is

$I_{st} = I_{sc}$

With auto starter, voltage across motor phase is KV/√3 and $I_{st} = K\, I_{sc}$

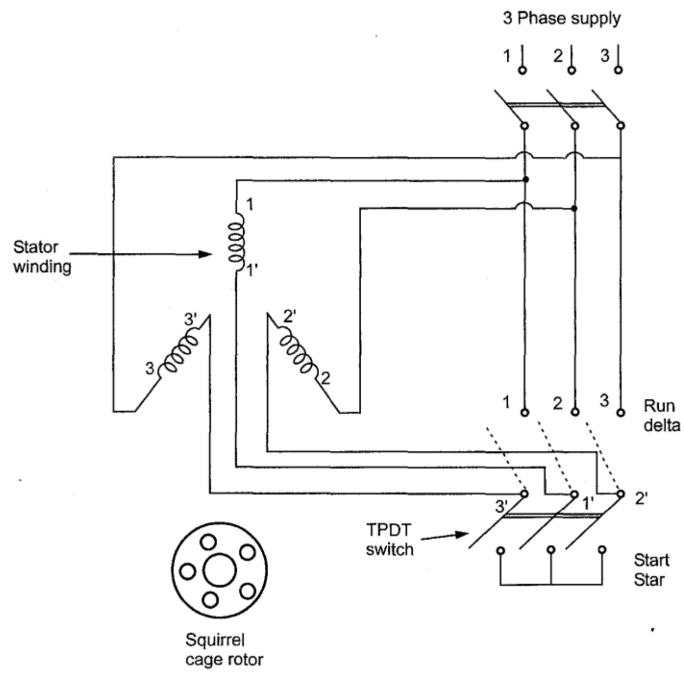
Now, $T_{st} \propto I_{st}^2$ (s = 1) and $T_{FL} \propto \frac{I_{FL}^{\ 2}}{s_f}$

∴ $\frac{T_{st}}{T_{FL}} = \left[\frac{I_{st}}{I_{FL}} \right]^2 s_f$ or $\frac{T_{st}}{T_{FL}} = K^2 \left[\frac{I_{sc}}{I_{FL}} \right]^2 s_f$

c. Star-delta starters

This is the cheapest starter of all and hence used very commonly for the induction motors. It uses Triple Pole Double Throw (TPDT) switch. The switch connects the stator winding in star at start. Hence per phase voltage gets reduced by the factor $1/\sqrt{3}$. Due to this reduced voltage, the starting current is limited.

When the switch is thrown on other side, the winding gets connected in delta, across the supply. So it gets normal rated voltage. The windings are connected in delta when motor gathers sufficient speed. The arrangement of star-delta starter is shown in the Fig.



The operation of the switch can be automatic by using relays which ensures that motor will not start with the switch in Run position.

Advantages

- The cheapest of all and maintenance free operation.

Limitations

- It is suitable for normal delta connected motors and the factor by which voltage changes is $1 / \sqrt{3}$ which cannot be changed.

It is used for machine tools, pumps and motor generators etc.

$$I_{st} \text{ per phase} = \frac{1}{\sqrt{3}} \; I_{sc} \text{ per phase}$$

$$T_{st} \; \alpha \; I_{st}^2 \quad (s = 1)$$

and $$T_{FL} \; \alpha \; \frac{I_{FL}^{\;2}}{s_f}$$

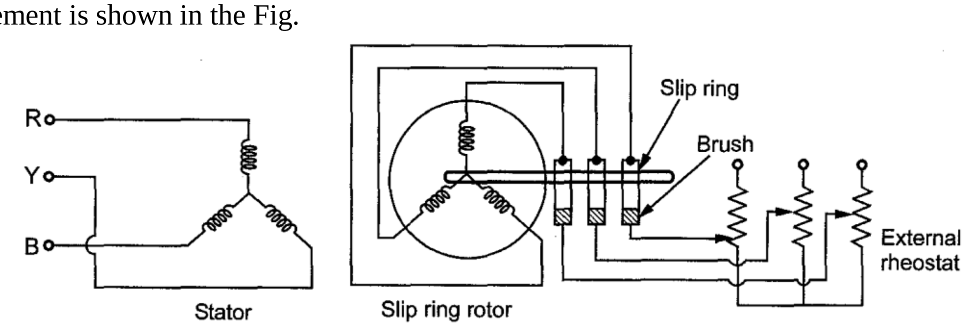
$$\therefore \quad \frac{T_{st}}{T_{FL}} = \left[\frac{I_{st}}{I_{FL}}\right]^2 s_f = \left[\frac{I_{sc}}{\sqrt{3}I_{FL}}\right]^2 s_f = \frac{1}{3}\left[\frac{I_{sc}}{I_{FL}}\right]^2 s_f$$

The star-delta switch is equivalent to an autotransformer of ratio $1/\sqrt{3}$ or 58% approximately.

Slip ring Motors

a. Rotor rheostat or rotor resistance starter

To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor circuit at start. This addition of the resistance in rotor is in the form of 3 phase star connected rheostat. The arrangement is shown in the Fig.



The external resistance is inserted in each phase of the rotor winding through slip ring and brush assembly.

Initially maximum resistance is in the circuit. As motor gathers speed, the resistance is gradually cutoff. The operation may be manual or automatic.

The starting torque is proportional to the rotor resistance.

Advantage

- Not only the starting current is limited but starting torque of the motor also gets improved.

Limitation

- It can be used only for slip ring induction motors as in squirrel cage motors; the rotor is permanently short circuited.

SPEED CONTROL OF INDUCTION MOTOR

1. Control from stator side
   a. By changing the applied voltage
   b. By changing the applied frequency
   c. By changing the number of stator poles
2. Control from rotor side
   d. Rotor rheostat control
   e. By operating two motors in concatenation or cascade
   f. By injecting an emf in the rotor circuit.

(a) By changing the applied voltage

$$T \propto \frac{sE2^2R2}{R2^2 + (sX2)^2}$$

Rotor induced emf at standstill, E_2 depends on the supply voltage V

$\therefore \quad E_2 \propto V$

For low slip region, $(sX_2)^2 << R_2$, hence

$$T \propto \frac{sV^2R2}{R2^2} \propto s\,V^2 \text{ for constant } R_2$$

If supply voltage is reduced below rated value, as per above equation, torque produced also decreases. But to supply the same load it is necessary to develop same torque hence value of slip increases so that torque produced remains same.

Slip increases means motor reacts by running at lower speed, to decrease in supply voltage. So motor produces the required load torque at a lower speed.

This method, though the cheapest and the easiest, is rarely used because

(i) A large change in voltage is required for a relatively small change in speed

(ii) Due to reduction in voltage, current drawn by the motor increases. Due to increased current, the motor may get overheated.

(iii) This large change in voltage will result in a large change in the flux density thereby seriously disturbing the magnetic conditions of the motor.

(b) By changing the applied frequency or supply frequency control or V/f control

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by $N_s = \frac{120f}{P}$

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

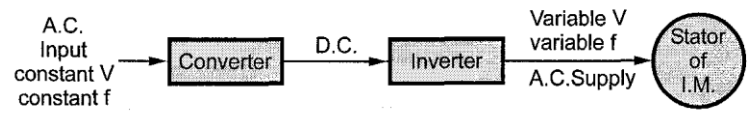
$$E \text{ or } V = 4.44\ \Phi\ K\ T\ f$$

$$\Phi = \frac{V}{4.44\ K\ T\ f}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. If we change frequency, synchronous speed changes. But with decrease in frequency, flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor .

To maintain flux, φ constant, it is only possible if we change voltage. i.e if we decrease frequency, flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

The normal supply available is constant voltage constant frequency a.c. supply. The converter converts this supply into a d.c. supply. This d.c. supply is then given to the inverter. The inverter is a device which converts d.c. supply, to variable voltage variable frequency a.c. supply which is required to keep V/f ratio constant. By selecting the proper frequency and maintaining V/f constant, smooth speed control of the induction motor is possible.



Disadvantages

- Used where the induction motor is the only load on the generators.
- Range over which the motor speed may be varied is limited.
- The supply cannot be used to supply other devices which require constant voltage.

(c) By changing the number of stator poles

The method is called Pole Changing method of controlling the speed. In this method, it is possible to have one, two or four speeds in steps, by changing the number of stator poles. A continuous smooth speed control is not possible by this method.

The stator poles can be changed by following methods

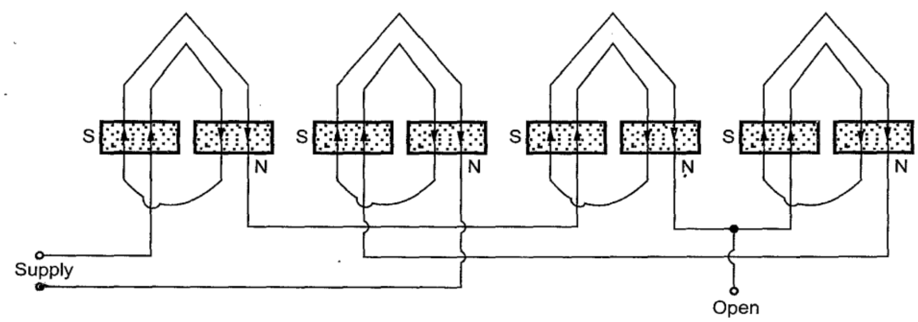
1. Consequent poles method
2. Multiple stator winding method
3. Pole amplitude modulation method.

Consequent Poles Method

In this method, connections of the stator winding are changed with the help of simple switching. Due to this, the number of stator poles get changed in the ratio 2 1. Hence either of the two synchronous speeds can be selected.

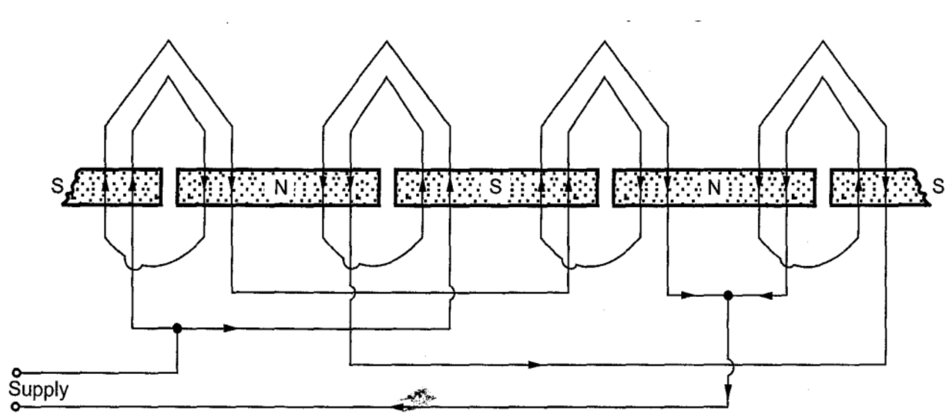
Consider the pole formation due to single phase of a three phase winding, as shown in the Fig. There are three tapping points to the stator winding. The supply is given to two of them and third is kept open.

The current in all the parts of stator coil is flowing in one direction only. Due to this, 8 poles get formed as shown in the Fig. So synchronous speed possible with this arrangement with 50 Hz frequency is N = 750 r.p.m.



If the two terminals to which supply was given earlier are joined together and supply is given between this common point and the open third terminal, the poles are formed as shown in the Fig.

The direction of current through two coils is different than the direction of current through remaining two. Thus upward direction is forming say S pole and downward say N. In this case only 4 poles are formed. So the synchronous speed possible is 1500 r.p.m. for 50 Hz frequency.



Disadvantage

- The speed change is in step and smooth speed control is not possible.

- The method can be used only for the squirrel cage type motors as squirrel cage rotor adjusts itself to same number of poles as stator which is not the case in slip ring induction motor.

Applications

Elevators, traction motors and small motors to drive machine tools.

Multiple stator winding method

In this method instead of one winding, two separate stator windings are placed in the stator core. The windings are placed in the stator slots only but are electrically isolated from each other. Each winding is divided into coils to which, pole changing with consequent poles, facility is provided.

Thus giving supply to one of the two windings and using switching arrangement, two speeds can be achieved. Same is true for other stator winding. So in all four different speeds can be obtained.

Limitations

1. Can be applied to only squirrel cage motor.
2. Smooth speed control is not possible. Only step changes in speed are possible.
3. Two different stator windings are required to be wound which increases the cost of the motor.
4. Complicated from the design point of view.

Pole amplitude modulation method

In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having different number of poles.

Let

$f_1(\theta)$ be the original mmf wave of induction motor whose speed is to be controlled.

$f_2(\theta)$ be the modulation mmf wave.

P_1 be the number of poles of induction motor whose speed is to be controlled.

P_2 be the number of poles of modulation wave.

$$f_1(\theta) = F_1 \sin \frac{P_1\theta}{2}$$

$$f_2(\theta) = F_2 \sin \frac{P_2\theta}{2}$$

After modulation resultant mmf wave

$$F_r(\theta) = F_1 F_2 \sin \frac{P_1\theta}{2} sin \frac{P_2\theta}{2}$$

$$Apply\ formula\ for\ 2\sin A \sin B = \cos \frac{A-B}{2} - \cos \frac{A+B}{2}$$

So we get, resultant mmf wave

$$F_r(\theta) = F_1 F_2 \frac{\cos \frac{(P_1-P_2)\theta}{2} - \cos \frac{(P_1+P_2)\theta}{2}}{2}$$

Therefore the resultant mmf wave will have two different number of poles

$P_{11} = P_1 - P_2$ and $P_{12} = P_1 + P_2$

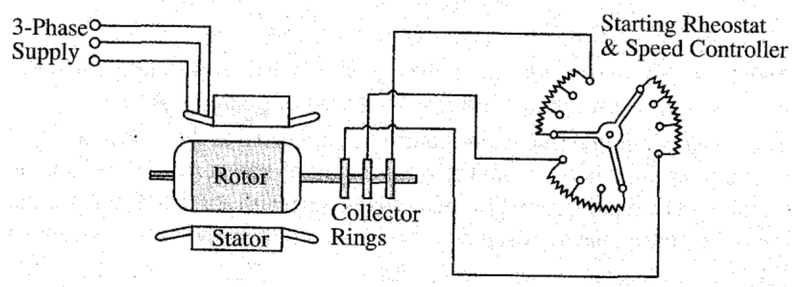
Therefore by changing the number of poles we can easily change the speed of three phase induction motor.

(d) Rotor rheostat control

$$T \ \alpha \frac{sE2^2R2}{R2^2 + (sX2)^2}$$

For low slip region, $(sX_2)^2 << R_2$, and can be neglected and for constant supply voltage E_2 is also constant.

$$\therefore \quad T \propto \frac{sR_2}{R_2^2} \propto \frac{s}{R_2}$$



Thus if the rotor resistance is increased, the torque produced decreases. But when the load on the motor is same, motor has to supply same torque as load demands. So motor reacts by increasing its slip to compensate decrease in T due to R2 and maintains the load torque constant.

So due to additional rotor resistance R_2, motor slip increases i.e. the speed of the motor decreases.

Advantage

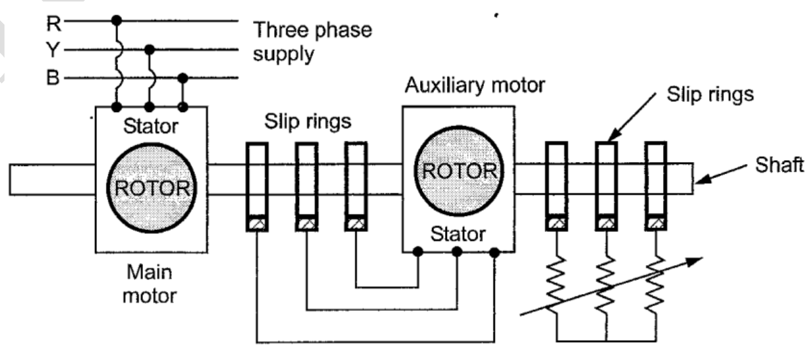
- By increasing the rotor resistance R_2 speeds below normal value can be achieved.
- The starting torque of the motor increases proportional to rotor resistance.

Disadvantage

- The large speed changes are not possible. This is because for large speed change, large resistance is required to be introduced in rotor which causes large rotor copper loss to reduce the efficiency.
- The method cannot be used for the squirrel cage induction motors.
- The speeds above the normal values cannot be obtained.
- Large power losses occur due to large 1^2R loss.
- Sufficient cooling arrangements are required which make the external rheostats bulky and expensive.
- Due to large power losses, efficiency is low.

(e) By operating two motors in concatenation or cascade or Tandem operation

In this method, two induction motors are mounted on the same shaft. One of the two motors must be of slip ring type which is called main motor. The second motor is called auxiliary motor. The arrangement is shown in the Fig.



The auxiliary motor can be slip ring type or squirrel cage type.

The stator of the main motor is connected to the three phase supply while the supply of the auxiliary motor is derived at a slip frequency from the slip rings of the main motor. This is called cascading of the motors.

If the torques produced by both act in the same direction, cascading is called cumulative cascading.

If torques produced are in opposite direction, cascading is called differential cascading.

P_A = Number of poles of main motor

P_B = Number of poles of auxiliary motor

f = Supply frequency

$$N_{SA} = \frac{120\,f}{P}$$

Let N = actual speed of the concatenated set

$$s_A = \frac{N_{SA} - N}{N_{SA}}$$

f_A = frequency of rotor induced emf of motor A

∴ $f_A = s_A f$ as $f_r = sf$

The supply to motor B is at frequency f_A, ie. $f_B = f_A$

∴ $N_{SB} = \frac{120\ f_B}{P_B} = \frac{120\ f_A}{P_B} = \frac{120 s_A\ f}{P_B} = \frac{120(N_{SA} - N)\ f}{P_B \text{ x } N_{SA}}$

On no load, the speed of the rotor B i.e. N is almost equal to its synchronous speed N_{SB}.

∴ $N_{SB} = N$

∴ $N = \frac{120(N_{SA} - N)\ f}{P_B \text{ x } N_{SA}} = \frac{120\ f}{P_B} \text{ x } \left[1 - \frac{N}{N_{SA}}\right] = \frac{120\ f}{P_B} \text{ x } \left[1 - \frac{N}{\frac{120\ f}{P_A}}\right]$

$$N = \frac{120\ f}{P_B} \text{ x } \left[1 - \frac{N P_A}{120 f}\right]$$

$$N \left[1 + \frac{P_A}{P_B}\right] = \frac{120\ f}{P_B}$$

∴ $N = \frac{120\ f}{P_A + P_B}$

If by interchanging any two terminals of motor B, the reversal of direction of rotating magnetic field of B is achieved then the set runs as differentially cascaded set. And in such a case effective number of poles are $P_A - P_B$.

Thus in cascade control, four different speeds are possible as,

a. With respect to synchronous speed of A independently,

$$N_S = \frac{120\ f}{P_A}$$

b. With respect to synchronous speed of B independently with main motor is disconnected and B is directly connected to supply,

$$N_S = \frac{120\ f}{P_B}$$

c. Running set as cumulatively cascaded with,

$$N = \frac{120\ f}{P_A + P_B}$$

d. Running set as differentially cascaded with,

$$N = \frac{120\ f}{P_A - P_B}$$

<u>Disadvantages</u>

1. It requires two motors which makes the set expensive.
2. Smooth speed control is not possible.
3. Operation is complicated.
4. The starting torque is not sufficient to start the set.
5. Set cannot be operated if $P_A = P_B$.

(f) By injecting an emf in the rotor circuit.

In this method, a voltage is injected in the rotor circuit. The frequency of rotor circuit is a slip frequency and hence the voltage to be injected must be at a slip frequency.

The injected voltage may oppose the rotor induced e.m.f. or may assist the rotor induced e.m.f.

- If it is in the phase opposition, effective rotor resistance increases.
- If it is in the phase of rotor induced e.m.f., effective rotor resistance decreases.

Thus by controlling the magnitude of the injected e.m.f., rotor resistance and effectively speed can be controlled.

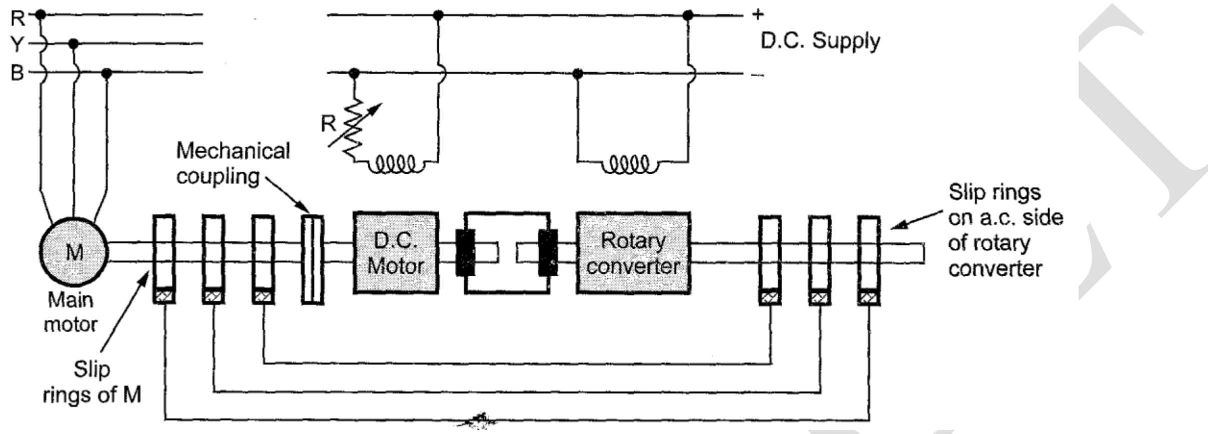
Practically two methods are available which use this principle. These methods are,

1. Kramer system 2. Scherbius system

<u>Kramer system</u>

➢ It consists of main induction motor M, the speed of which is to be controlled. The two additional equipments are, d.c. motor and a rotary converter.

- The slip rings of the main motor are connected to the a.c. side of a rotary converter.
- The d.c. side of rotary converter feeds a d.c. shunt motor commutator, which is directly connected to the shaft of the main motor.
- A separate d.c. supply is required to excite the field winding of d.c. motor and exciting winding of a rotary converter.
- The variable resistance is introduced in the field circuit of a d.c. motor which acts as a field regulator.



- The speed of the set is controlled by varying the field of the d.c. motor with the rheostat R.
- When the field resistance is changed, the back e.m.f. of motor changes. Thus the d.c. voltage at the commutator changes. This changes the d.c. voltage on the d.c. side of a rotary converter.
- Now rotary converter has a fixed ratio between its a.c. side and d.c. side voltages. Thus voltage on its a.c. side also changes.
- This a.c. voltage is given to the slip rings of the main motor.
- So the voltage injected in the rotor of main motor changes which produces the required speed control.

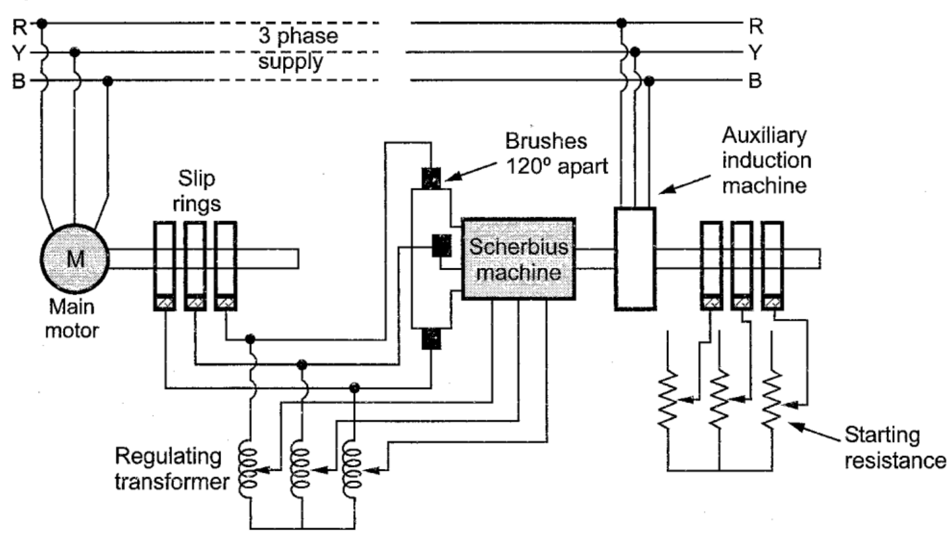
<u>Advantages</u>

- smooth speed control is possible
- wide range of speed control is possible
- the design of a rotary converter is practically independent of the speed control required
- if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control

Very large motors above 4000 kW such as steel rolling mills use such type of speed control.

<u>Scherbius system</u>

- This method requires an auxiliary 3 phase or 6 phase a.c. commutator machine which is called Scherbius machine.
- The difference between Kramer system and this system is that the Scherbius machine is not directly connected to the main motor, whose speed is to be controlled.
- The Scherbius machine is excited at slip frequency from the rotor of a main motor through a regulating transformer.
- The taps on the regulating transformer can be varied, this changes the voltage developed



in the rotor of Scherbius machine, which is injected into the rotor of main motor. This controls the speed of the main motor.

- The Scherbius machine is connected directly to the induction motor supplied from main line so that its speed deviates from a fixed value only to the extent of the slip of the auxiliary induction motor.
- For any given setting of the regulating transformer, the speed of the main motor remains substantially constant irrespective of the load variations.

Similar to the Kramer system, this method is also used to control speed of large induction motors. The only disadvantage is that these methods can be used only for slip ring induction motors.

SLIP POWER RECOVERY SCHEME

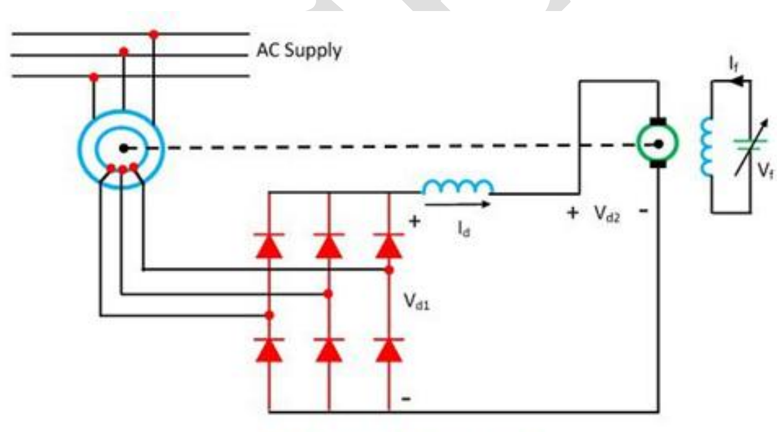
Static Kramer Drive

The static Kramer-drive is the method of controlling the speed of an induction motor by injecting the opposite-phase voltage in the rotor circuit. The injected voltage increases the resistance of the rotor, thus controlled the speed of the motor. By changing the injected voltage, the resistance and speed of an induction motor are controlled.

The static Kramer-drive converts the slip power of an induction motor into AC power and supply back to the line.

The slip power is the air gap power between the stator and the rotor of an induction motor which is not converted into mechanical power.

Thus, the power is getting wasted. The static Kramer drives fed back the wasted power into the main supply. This method is only applicable when the speed of the drive is less than the synchronous speed.



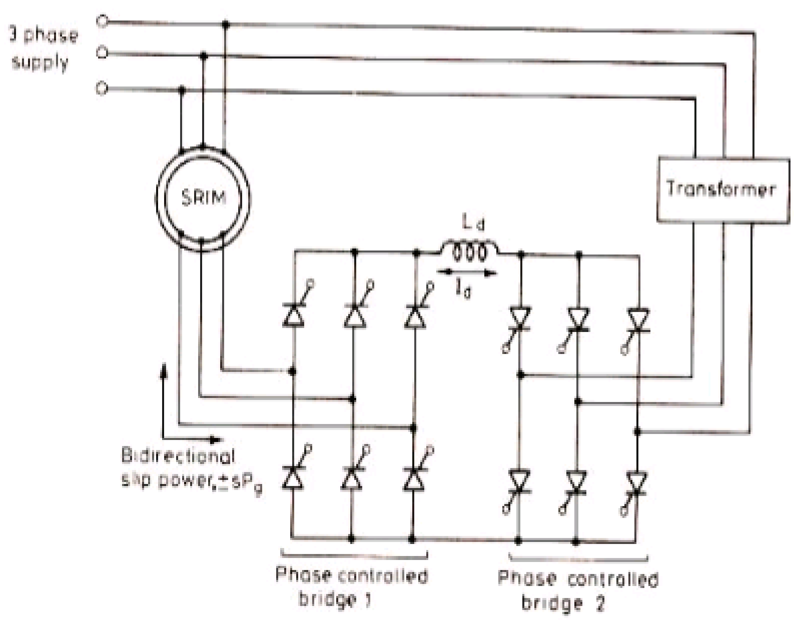
Static Kramer Drive Circuit

Static Scherbius System

- Both the converters are controlled converter. Because of this the power flow in the rotor circuit becomes bidirectional and the induction motor can be operated in sub synchronous as well as super synchronous region of operation.

Sub synchronous mode

- Power must be extracted from the rotor
- Therefore Bridge 1 act as rectifier ($\alpha_1 < 90°$)
- Bridge 2 act as inverter ($\alpha 2 > 90°$) to feed the slip power (extracted from the rotor) back to A.C. supply.
- The slip power flows from the rotor circuit to bridge1, bridge2 and transformer and to the supply.
- At subsynchronous speeds the slip power sP_m is supplied to the rotor by the exciter and so the remaining output power *(1-s) Pm* is supplied to the shaft.



Super- synchronous mode

- Power must be supplied to the rotor

- Bridge ‘1’ act as the inverter ($\alpha_1 > 90°$)
- Bridge ‘2’ operates as the rectifier ($\alpha_2 < 90°$)
- The power flow is now from the supply to transformer, bridge2, bridge1 and to the rotor circuit.
- At supersynchronous speeds, the rotor output power flows in the opposite direction so that the total shaft power increases to (1+s) Pm.

Table shows the summary of operation

Region of operation	Bridge 1	Bridge2	Power flow
Subsynchronous ($\omega < \omega s$)	Rectifier ($\alpha_1 < 90°$)	Inverter ($\alpha_2 > 90°$)	From Rotor to AC supply
Supersynchronous ($\omega > \omega s$)	Inverter ($\alpha_1 > 90°$)	Rectifier($\alpha_2 < 90°$)	From AC supply to rotor

- Rotor voltage and frequency vary linearly with deviation from synchronous speed. For example, if the shaft speed varies in the range of 800-1600 rpm with 1200 rpm as the synchronous speed (s=±0.33) the range of slip frequency will be 0->20Hz for a 60Hz supply frequency.
- Near synchronous speed, slip frequency emf’s are insufficient for natural commutation of thyristors. This difficulty can be overcome by using forced commutation.
- Thus, the provision of both sub synchronous and super synchronous speed operation complicates the static converter system and nullifies the advantages of simplicity and economy which are inherent in a purely sub synchronous drive.
- In addition, static scherbius drive is expensive than static Kramer drive because six diodes are replaced by six thyristors and their controlled circuitry.

Advantages

- The machine can be controlled continuously about 50% above and below the synchronous speed with a converter rating of about 50% of the machine capacity
- The static Scherbius drive overcomes the forward motoring only limitation of the static Kramer drive

BRAKING OF THREE PHASE INDUCTION MOTOR.

The braking is the process of reducing the speed of an induction motor. In braking, the motor works as a generator developing a negative torque which opposes the motion of a motor. The braking of an induction motor is mainly classified into three types. They are

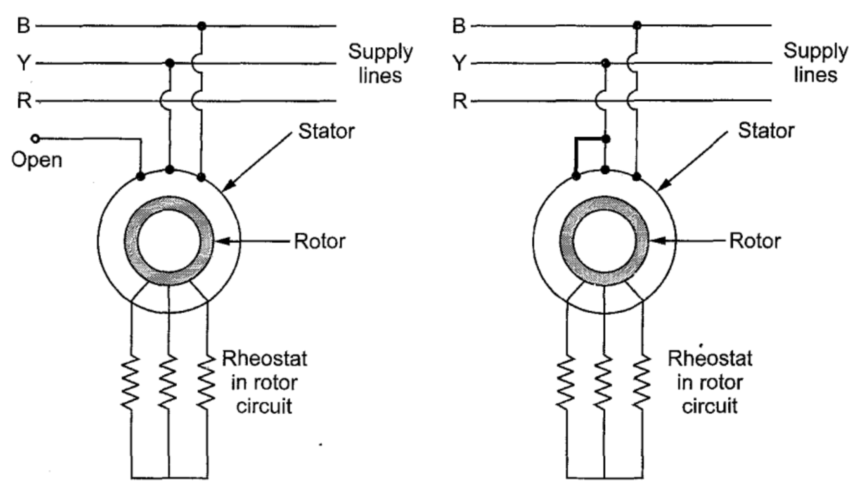
a. Regenerative Braking
b. Plugging or reverse voltage braking
c. Dynamic Braking

Dynamic or Rheostatic Braking

In rheostatic braking, one supply line out of R, Y or B is disconnected from the supply. Depending upon the condition of this disconnected line, two types of rheostatic braking can be achieved.

1. Two lead connections:

In this method, the disconnected line is kept open. This is shown in the Fig. (a) and is called two lead connections.

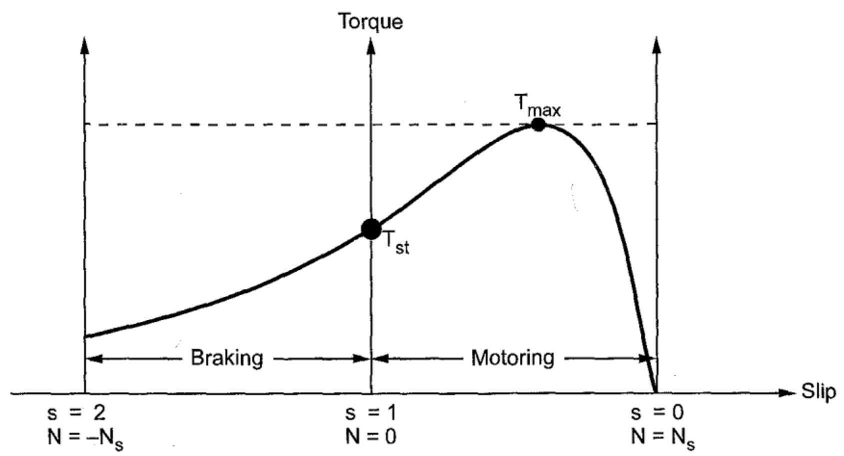


(a) Two lead connections (b) Three lead connections

2. Three lead connections:

In this method, the disconnected line is connected directly to the other line of the machine. This is shown in Fig (b)

- In both cases, a high resistance is inserted in the rotor circuit, with the help of rheostat.
- Thus this method is effective only for slip ring or wound rotor induction motors
- As one of the motor terminal is not connected to the supply, the motor continues to run as a single phase motor. In this case the breakdown torque i.e. maximum torque decreases to 40 % of its original value and motor develops no starting torque at all. And due to high rotor resistance, the net torque produced becomes negative and the braking operation is obtained.

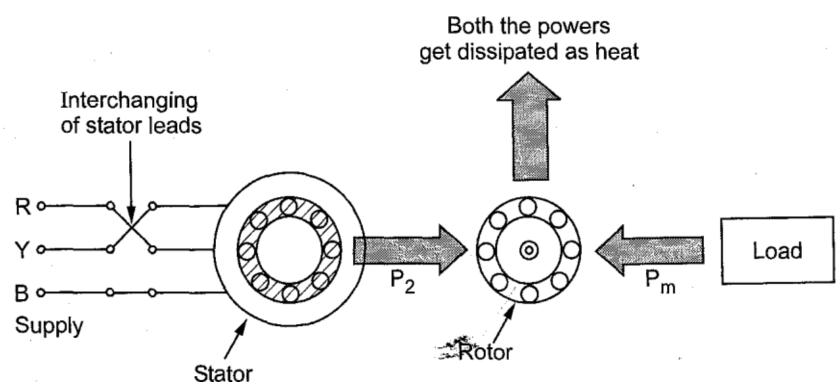


- In two lead connections, the braking torque is small while in three lead connections, the braking torque is high at high speeds.
- But in three lead connections there is possibility of inequality between the contact resistances in connections of two paralleled lines. This might reduce the braking torque and even may produce the motoring torque again.
- Hence inspite of low braking torque, two lead connections is preferred over three lead connections.

The torque-slip characteristic for motoring and braking operation is shown in the Fig.

Plugging or Counter Current Braking

- The reversal of direction of rotation of motor is the main principle in plugging of motor.
- In case of an induction motor, it can be quickly stopped by interchanging any two stator leads.
- Due to this, the direction of rotating magnetic field gets reversed suddenly.
- This produces a torque in the reverse direction and the motor tries to rotate in opposite direction.
- Effectively the brakes are applied to the motor. Thus during the plugging, the motor acts as a brake.
- The method can be applied to both squirrel cage as well as wound rotor induction motors.
- One important aspect about plugging is production of very high heat in the rotor.

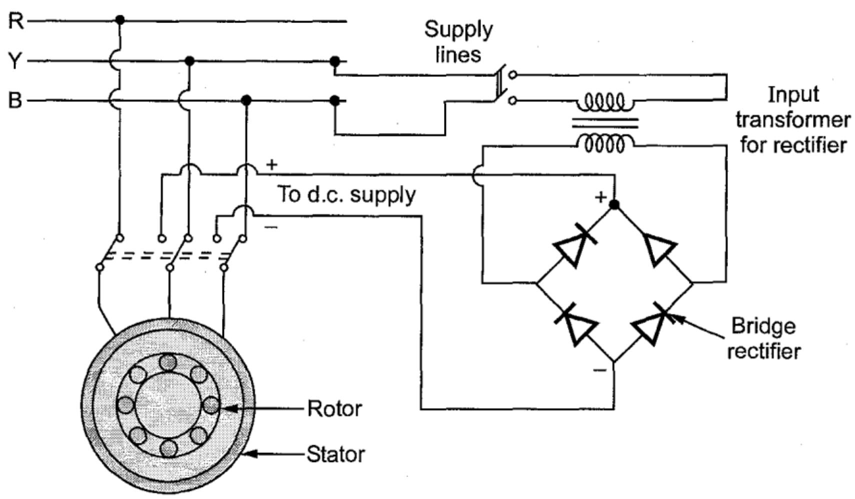


- While plugging, the load keeps on revolving and rotor absorbs kinetic energy from the revolving load, causing speed to reduce.
- The corresponding gross mechanical power P_m is entirely dissipated as heat in the rotor.
- Similarly as stator is connected to supply, rotor continues to receive power P_2 from stator which also gets dissipated as heat in the rotor.

- The plugging should not be done frequently as due to high heat produced rotor may attain high temperature which can melt the rotor bars and even may over heat the stator as well.

D.C. Dynamic Braking

- A quick stopping of an induction motor and its high inertia load can be achieved by connecting stator terminals to a d.c. supply.
- Any two stator terminals can be connected to a d.c. supply and third terminal may be kept open or may be connected directly to other stator terminal. This is called d.c. dynamic braking.
- If third terminal is kept open it is called two lead connections while if it is shorted directly with other stator terminal it is called three lead connections.
- A diode bridge can be used to get d.c. supply.
- The Fig. shows two lead connections with a diode bridge for a d.c. dynamic braking of an induction motor.



- When d.c. is supplied to the stator, stationary poles N, S are produced in stator.
- The number of stationary poles is P for which stator winding is wound.
- As rotor is rotating, rotor cuts the flux produced by the stationary poles. Thus the a.c. voltage gets induced in the rotor.
- This voltage produces an a.c. current in the rotor.
- The motor works as a generator and the $I^2 R$ losses are dissipated at the expenditure of kinetic energy stored in the rotating parts. Thus dynamic braking is achieved.
- When all the kinetic energy gets dissipated as heat in the rotor, the induction motor comes to rest.

ADVANTAGES

1. The heat produced is less compared to the plugging.
2. The energy dissipated in the rotor is not dependent on the magnitude of the d.c. current.
3. The braking torque is proportional to the square of the d.c. current.
4. Quick stopping of the motor is possible.
5. The method can be used for wound rotor or squirrel cage rotor induction motors.

Regenerative Braking

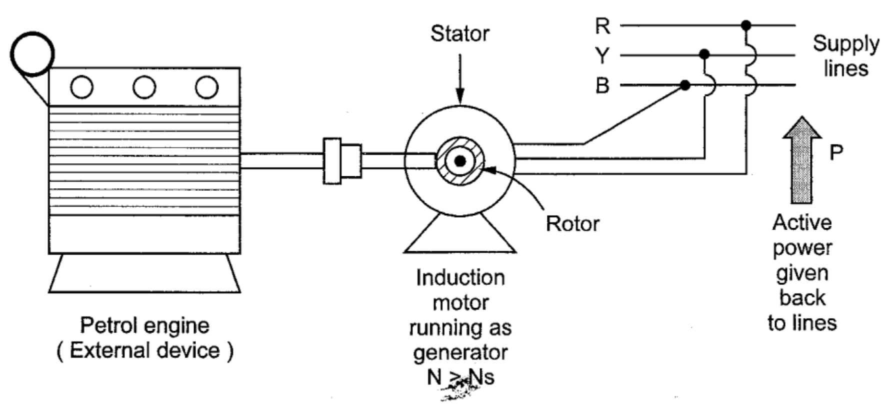
- The input power to a three phase induction motor is given by,

$$P_{in} = 3V_{ph} I_{ph} \cos \Phi$$

where Φ = Angle between stator phase voltage and phase current

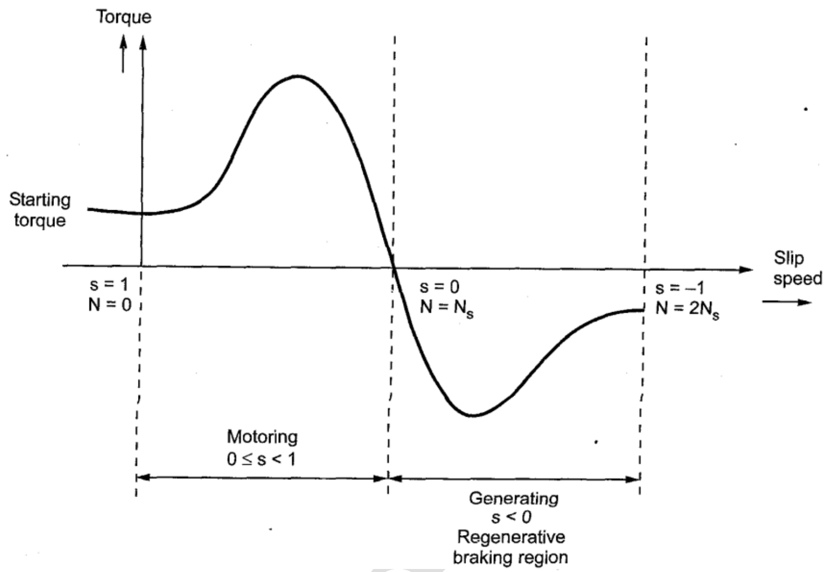
This Φ is less than 90^0 for the motoring action.

- If the rotor speed is increased greater than the synchronous speed with the help of external device, it acts as an induction generator.
- It converts the input mechanical energy to an electrical energy which is given back to supply.



- It delivers active power to the 3 phase line. The Φ becomes greater than 90°.
- The power flow reverses hence rotor induced e.m.f. and rotor current also reverse.
- So rotor produces torque in opposite direction to achieve the braking.
- As the electrical energy is given back to the lines while braking, it is called regenerative braking.
- The arrangement for regenerative braking is shown in the Fig.

The torque-slip characteristic for motoring and generating action is shown in the Fig.



<u>Advantage</u>

- The generated power can be used for useful purposes.

<u>Disadvantage</u>

- For fixed frequency supply it can be used only for speeds above synchronous speed.

<u>QUESTION BANK</u>

PART A

1. What is the effect of change in input voltage on starting torque of induction motor? (April 2017) (April 2016) (Nov 2015)
2. State any two advantages of speed control of induction motor by injecting an emf in the rotor circuit. (April 2017)
3. What is the effect of increasing the rotor resistance on starting current and torque? (Nov 2016)
4. List out the methods of speed control of cage type 3 Φ induction motor. (Nov 2016)
5. What are the different methods of speed control of three phase induction motor? (Nov 2015)
6. Why starter is necessary for the induction motor? (May / June 2012)
7. Mention the various methods of starting of a 3-phase induction motor (May / June 2009)
8. State the effect of rotor resistance on starting torque. (Nov / Dec 2011)
9. State the drawback of star-delta starter. (May / June 2011)
10. What are the advantages of rotor resistance speed control method? (May / June 2011)
11. What are the disadvantages of rotor rheostat speed control method? (may 2010)
12. What is the function of rotary converter? Where it is used?
13. What are the advantages of Kramer system of speed control?
14. Write the expression for concatenated speed of the set.
15. What are the methods of speed control preferred for large motors?

16. How is speed control achieved by changing the number of stator poles?
17. How can varying supply frequency control speed?
18. What is plugging? (May 2014)
19. What is dynamic braking?
20. What is DC dynamic braking?
21. What is regenerative braking?
22. What is slip power recovery scheme? (Dec 2013)
23. Point out the disadvantages of rotor rheostat control to obtain variable speed of induction motor. (Dec-2006)
24. Give the functions performed by induction motor starter. (May 2006)
25. A 3 phase squirrel cage induction motor should not be started directly from the main supply. State reasons. (May 2008)
26. Why is pole changing method of speed control not used with wound rotor motors? (may 2009)
27. Give the advantages of Rotor resistance starter. (Nov 2011)
28. What type of protection is provided in the starter meant for 3 phase induction motors? (Nov 2014)
29. While controlling the speed of an induction motor, how is super synchronous speed achieved? (Nov 2011)
30. Which is the cheapest method of starting a 3 phase induction motor?

PART B

1. Explain the speed control of a 3 phase induction motor with slip power recovery scheme. (16) **(April 2017)**
2. (i) State the different methods of starting of 3 phase induction motor and discuss in detail any two methods. (8)
   (ii) With aid of diagrams explain the principle of the following methods of speed control of a 3 phase induction motor.
   (1) variable Frequency (2) cascade connection (8) (Nov 2016)
3. (i) Describe a starter suitable for a 3 phase slip ring induction motor. (6)
   (ii) Determine approximately the starting torque of an induction, motor in terms of full load torque when. started by
   (1) Star—delta starter and
   (2) Auto—starter with 50% tapping. The short circuit current of the motor at normal voltage is 5 times the full load current and the full load slip is 4%. (10)(Nov 2016)
4. (i) Explain in detail the speed control methods of induction motor. (8)
   (ii) Explain in detail the scherbius system of speed control. (8) (April 2016)
5. (i) Describe a starter available for a 3-phase slip ring induction motor. (8)
   (ii) A small squirrel-cage induction motor has a starting current of six times the full load current and a full-load slip of 0.05. Find in pu of full-load values, the current (line) and starting torque with the following methods of starting ((a) to (d)).
   (a) Direct switching, (b) Stator-resistance starting with motor current limited to 2 p.u, (c) auto-transformer starting with motor current limited to 2 p.u, and (d) Y-delta starting. (e) What auto transformer ratio would give 1 p.u starting torque? (8) (April 2016)
6. Explain the various method of starting of three phase squirrel cage type Induction motor. (16) (Nov 2015)
7. Explain the different methods by which speed control of induction motor is achieved (16) (Nov 2015)
8. Why starters are necessary for starting 3-phase induction motors? What are the various types of starters? Explain any two in detail.
9. Explain the speed control of 3-phase induction motor by slip power recovery scheme with neat sketches.
10. Explain plugging and regenerative braking in 3-phase induction motor.
11. Explain the speed control techniques of induction motor by varying the supply frequency and state the advantages of this method. (May/ June 2011)
12. Explain the various schemes of starting squirrel cage induction motor. (16) (Dec 2006)
13. (i) The rotor of a 4 pole, 50 Hz slip ring induction motor has a resistance of 0.3 Ω per phase and runs at 1440 rpm at full load. Calculate the external resistance per phase which must be added to lower the speed to 1320 rpm, the torque being the same. (6)

(ii) Explain the cascade operation of induction motors to obtain variable speed. (10) (Dec 2006)

14. (i) Is a 3 phase induction motor self starting? How are they started? Discuss the theory of star-delta starter. (8)
    (ii) Explain the speed control of 3 phase squirrel cage induction motor by pole changing. (8) (May 2006)
15. Explain with neat diagram the static Scherbius drive system of slip power recovery scheme. (16) (Dec 2007)
16. (i) With the aid of diagrams, explain the principle of the following methods of speed control of a 3 phase induction motor (a) variable frequency (b) pole changing (10)
    (ii) Describe in detail the different types of electric braking used for 3 phase induction motors. (6) (may 2009)
17. Explain with neat sketches, the working of cascaded connection method and slip power recovery scheme of speed control of induction motor. (16) (May 2009)
18. A 15 HP, three phase, 6 pole, 50 Hz, 400V, delta connected IM runs at 960 rpm on full load. If it takes 86.4 A on direct starting, find the ratio of starting torque to full load torque with a star-delta starter. Full load efficiency and power factor are 88% and 0.85 respectively. (6) (May 2011)
19. A 3 phase 440V distribution circuit is designed to supply not more than 1200 A. Assuming that a 3 phase squirrel cage induction motor has full load efficiency of 0.85 and a full load power factor of 0.8 and that the starting current at rated voltage is 5 times the rated full load current, what is the maximum permissible kW rating of the motor if it is to be started using an auto transformer stepping down the voltage to 80%? (4) (Nov 2014)
20. A 3 phase induction motor takes a starting current which is 5 times full load current at normal voltage. Its full load slip is 4 %. What auto transformer ratio would enable the motor to be started with not more than twice the full load current drawn from the supply? What would be the starting torque under this condition? (8) (May 2014)

UNIT V SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES

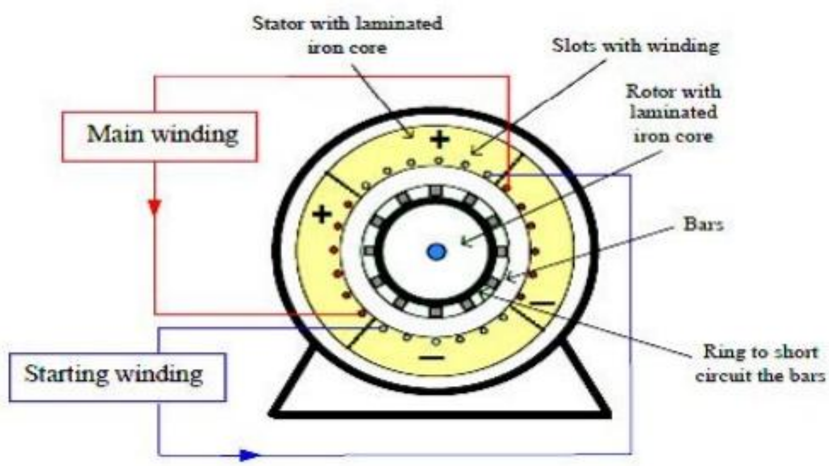
Constructional details of single phase induction motor – Double field revolving theory and operation – Equivalent circuit – No load and blocked rotor test – Performance analysis – Starting methods of single-phase induction motors – Capacitor-start capacitor run Induction motor- Shaded pole induction motor - Linear induction motor – Repulsion motor - Hysteresis motor - AC series motor- Servo motors- Stepper motors - introduction to magnetic levitation systems.

CONSTRUCTIONAL DETAILS OF SINGLE PHASE INDUCTION MOTOR

Constructionally, single phase induction motor is similar to polyphase induction motor except that (i) its stator is provided with a single phase winding and (ii) a centrifugal switch in order to cut out a winding used for starting purposes. It has distributed stator winding and a squirrel cage rotor.

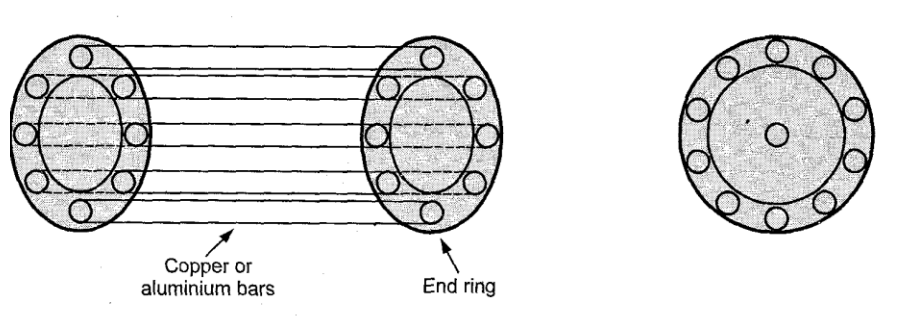
The constructional details of single phase induction motor are shown in figure.

1. Stator of Single Phase Induction Motor



- The single-phase motor stator has a laminated iron core with two windings arranged perpendicularly
- One is the main and other is the auxiliary winding or starting winding.
- The stator has laminated construction, made up of stampings. The stampings are slotted on its periphery to carry the winding called stator winding or main winding.
- This is excited by a single phase a.c. supply. The laminated construction keeps iron losses to minimum, lie stampings are made up of material like silicon steel which minimizes the hysteresis loss.
- The stator winding is wound for certain definite number of poles means when excited by single phase a.c. supply, stator produces the magnetic field which creates the effect of certain definite number of poles.
- The number of poles for which stator winding is wound, decides the synchronous speed of the motor. The synchronous speed is denoted as N_s and it has a fixed relation with supply frequency f and number of poles P. The relation is given by, $N_s = 120f/P$.

2. Rotor of Single Phase Induction Motor

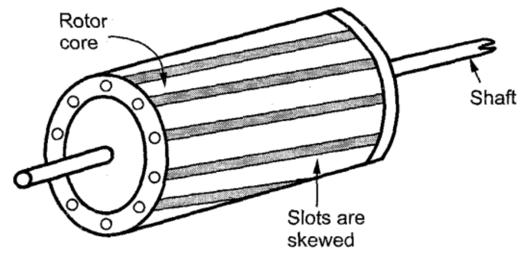


(a) Cage type structure of rotor (b) Symbolic representation

- The rotor of single phase induction motor is shown in figure.
- The construction of the rotor of the single phase induction motor is similar to the squirrel cage three phase inductions motor.
- The rotor is cylindrical in shape and has slots all over its periphery.
- The slots are not made parallel to each other but are bit skewed as the

skewing prevents magnetic locking of stator and rotor teeth and makes the working of induction motor more smooth and quieter.

- The squirrel cage rotor consists of aluminium, brass or copper bars. These aluminium or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor.
- The rotor conductors are permanently shorted by the copper or aluminium rings called the end rings.
- In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor".



Skewing in rotor construction

- As the bars are permanently shorted by end rings, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars are permanently shorted.
- The absence of slip ring and brushes make the construction of single phase induction motor very simple and robust.

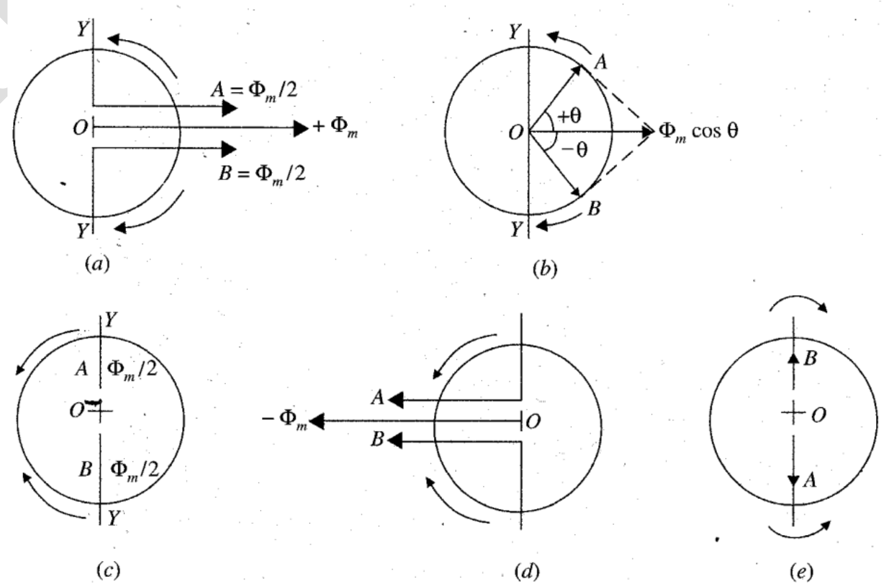
DOUBLE FIELD REVOLVING THEORY

When fed from a single-phase supply, its stator winding produces a flux (or field) which is only alternating i.e. one which alternates along one space axis only. It is a synchronously revolving (or rotating) flux, as in the case of a two- or a three-phase stator winding, fed from a 2-or 3-phase supply. Now, alternating or pulsating flux acting on a stationary squirrel-cage rotor cannot produce rotation (only a revolving flux can). That is why a single-phase motor is not self starting.

However, if the rotor of such a machine is given an initial start by hand (or small motor) or otherwise, in either direction, then immediately a torque arises and the motor accelerates to its final speed (unless the applied torque is too high).

This peculiar behaviour of the motor can be explained in two ways (i) by two -field or double- field revolving theory and (ii) by cross-field theory.

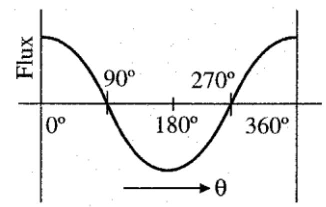
According to double field revolving theory, an alternating uniaxial quantity can be represented by two oppositely rotating vectors of half magnitude. Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously (N_s = 120f/p) in opposite direction.



As shown in fig. (a), let the alternating flux have a maximum value of Φ_m. its component fluxes A and B will each be equal to $\Phi_m/2$ revolving in anticlockwise and clockwise direction respectively.

After some time, when A and B would have rotated through angle +θ and –θ as in fig (b), the resultant flux would be

$= 2 \times \frac{\Phi_m}{2} \cos \frac{2\theta}{2} = \Phi_m \cos \theta$



After a quarter cycle of rotation, fluxes A and B will be oppositely directed as shown in fig (c) so that the resultant flux would be zero.

After half a cycle, fluxes A and B will have a resultant of $-2 \times \frac{\Phi_m}{2} = -\Phi_m$.

After three quarters of a cycle, again the resultant is zero as shown in fig. (e) and so on.

If we plot the resultant flux against θ between $\theta = 0^0$ and 360^0, an alternating flux is obtained. That is why alternating flux is considered to have two fluxes, each half the value and revolving synchronously in opposite directions.

SINGLE PHASE INDUCTION MOTOR IS NOT SELF STARTING

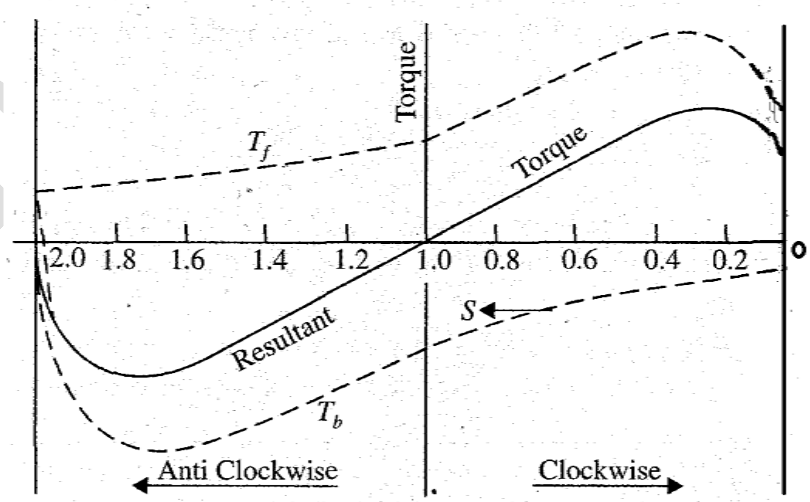
- If the slip of rotor is s with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2-s).
  If N is the r.p.m. of the rotor, then its slip w.r.t forward rotating flux is

  $$s = \frac{Ns - N}{Ns} = 1 - \frac{N}{N_s} \text{ or } \frac{N}{N_s} = 1 - s$$

  Backward rotating flux rotates opposite to the rotor, the rotor slip w.r.t this flux is

  $$s_b = \frac{Ns - (-N)}{Ns} = 1 + \frac{N}{N_s} = 1 + (1 - s) = (2 - s)$$

  Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an emf and this produces its own torque. The two torques, called forward and backward rotating torques are oppositely directed, so that the resultant torque is equal to their difference as shown in figure.



  Power developed by a rotor is $P_g = \frac{1-s}{s} I_2^2 R_2$

  If N is the rotor r.p.s., then torque is given by

  $T_g = \frac{1}{2\pi N} \cdot \frac{1-s}{s} \cdot I_2^2 R_2$

  $N = N_s (1 - s)$

  $T_g = \frac{1}{2\pi N_s} \cdot \frac{I_2^2 R_2}{s} = k. \frac{I_2^2 R_2}{s}$

  Forward torque $T_f = k. \frac{I_2^2 R_2}{s}$

  Backward torque $T_b = - k. \frac{I_2^2 R_2}{(2-s)}$

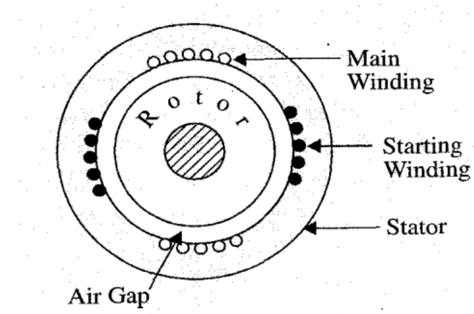
  $T_f = \frac{I_2^2 R_2}{s}$ syn. Watt and $T_b = - \frac{I_2^2 R_2}{(2-s)}$ syn. Watt

  Total torque $T = T_f + T_b$

  The figure shows both the torques and resultant torque for slips between zero and +2.

  At standstill condition, s = 1 and (2-s) = 1.hence T_f and T_b are numerically equal but being oppositely directed, produce no resultant torque. That is why there is no starting torque in a single phase induction motor.

MAKING SINGLE PHASE INDUCTION MOTOR SELF-STARTING



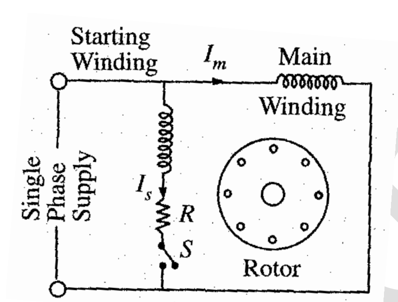
- A single phase induction motor is not self starting. To overcome this drawback and make the motor self starting, it is temporarily converted into a two phase motor during starting period.
- For this purpose, the stator of a single phase motor is provided with an extra winding, known as starting or auxiliary winding, in addition to the main or running winding.
- The two windings are spaced 90^0 electrically apart and are connected in parallel across the single phase supply.
- It is so arranged that the phase difference between the currents in the two stator windings is very large (ideal value is 90^0).
- Hence the motor behaves as a two phase motor. These two currents produce a revolving flux and hence make the motor self starting.

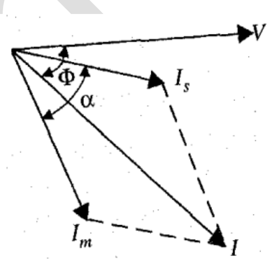
Depending on the methods by which the necessary phase difference between the two currents can be created, the single phase induction motors are classified as,

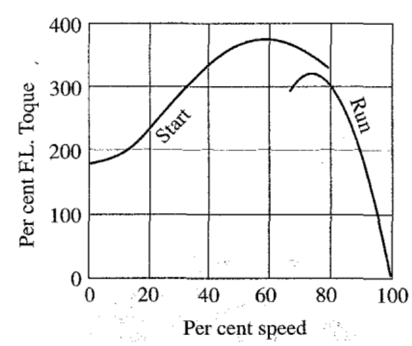
1. Split phase motor
2. Capacitor start induction run motors
3. Capacitor start and run motors
4. Shaded pole single phase motors\

1. Split Phase Motors (Resistance Start split phase induction motors)

- In split phase machine, the main winding has low resistance but high reactance whereas the starting winding has a high resistance but low reactance.
- Hence the current I_s drawn by the starting winding lags behind the applied voltage V by a small angle whereas current I_m drawn by the main winding lags behind V by a very large angle.





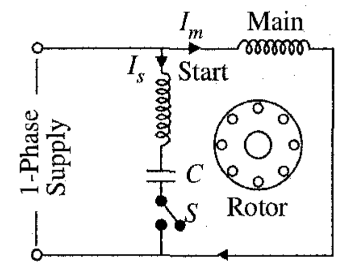


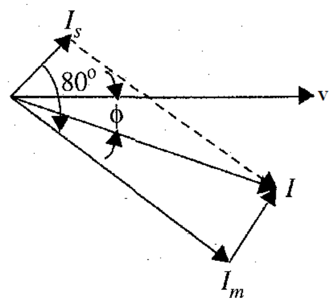
- Phase angle between I_s and I_m is made as large as possible because the starting torque of a split phase motor is proportional to sin α.
- A centrifugal switch S is connected in series with the starting winding and located inside he motor.
- Its function is to automatically disconnect the starting winding from the supply when the motor has reached 70 to 80 percent of its full load speed.
- The starting torque is 150 to 200 percent of the full load torque.
- Starting current is 6 to 8 times the full load current.

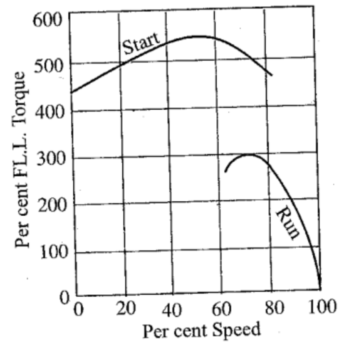
  Applications
- Fans, blowers, centrifugal pumps and separators, washing machines, small machine tools, duplicating machines, domestic refrigerators, and oil burners etc.
- Available sizes range from 1/20 to 1/3 h.p. (40 to 250 W) with speeds ranging from 3450 to 865 rpm.

2. Capacitor Start Induction Run Motors

- In this motor, the phase difference between I_s and I_m is produced by connecting a capacitor in series with the starting winding.
- The capacitor is electrolytic type and is mounted outside the motor as a separate unit.







- When the motor reaches about 75 percent of the full speed, the centrifugal switch S opens and cuts out both the starting winding and capacitor from the supply, thus leaving only the running winding across the lines.
- As shown in figure, current I_m drawn by the main winding lags the supply voltage V by a large angle whereas I_s leads V by a certain angle.
- The two currents are out of phase with each other by about 80^0 as compared to nearly 30^0 for a split phase motor.
- Torque developed is proportional to sin α (angle between I_s and I_m), therefore starting torque is as high as 350 to 450 percent.

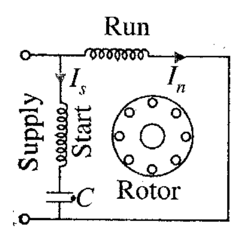
3. Capacitor Start and Run motor

- This motor is similar to the capacitor start motor except that the starting winding and capacitor are connected in the circuit at all times.
- The advantages of leaving the capacitor permanently in the circuit are
  - Improvement of overload capacity of the motor
  - A higher power factor
  - Higher efficiency
  - Quieter running of the motor

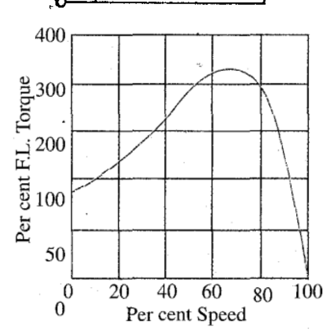
<u>Types</u>

(a) Single value Capacitor Run motor – start and run with one value of capacitance in the circuit
(b) Two Value Capacitor Run motor – start with high value of capacitance but run with low value of capacitance.

(a) <u>Single value Capacitor Run motor</u>



- It has one running winding and one starting winding in series with a capacitor.
- Since capacitor remains in the circuit permanently, this motor is referred to as permanent split capacitor run motor.
- Since the same capacitor is used for starting and running, neither optimum starting not optimum running performance can be obtained.
- Capacitors of 2 to 20 μF are used.
- The low value capacitor result in small starting torque which is about 50 to 100 % of the rated torque.
- This type of motor can be easily reversed by an external switch provided its running and starting windings are identical.

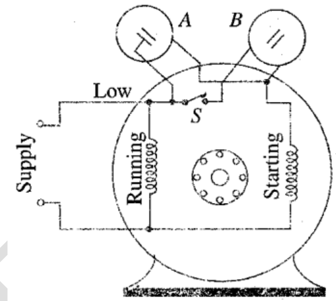


<u>Applications</u>

Fans, blowers, voltage regulators etc.

(b) <u>Two Value Capacitor Run motor</u>

- This motor starts with a high capacitor in series with the starting winding so that the starting torque is high.
- For running, a lower capacitor is substituted by the centrifugal switch.
- Both the running and stating windings remain in the circuit.
- The two values of capacitance can be obtained by using two capacitors in parallel at start and then switching out one for low value run.
- At start, when the centrifugal switch is closed, the two capacitors are put in parallel, so that their combined capacitance is sum of their individual capacitances.
- After the motor has reached 75% of full load speed, the switch opens and only capacitor A remains in the starting winding circuit.
- Thus both optimum starting and running performance is achieved.



<u>Advantages</u>

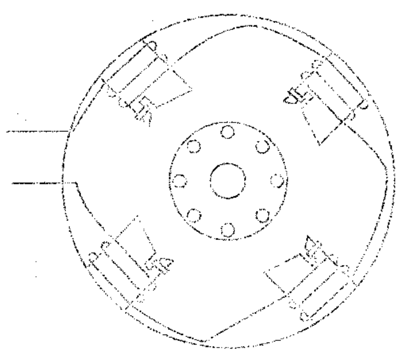
(i) Ability to start heavy loads
(ii) Extremely quiet operation
(iii) Higher efficiency and power factor
(iv) Ability to develop 25 percent overload capacity

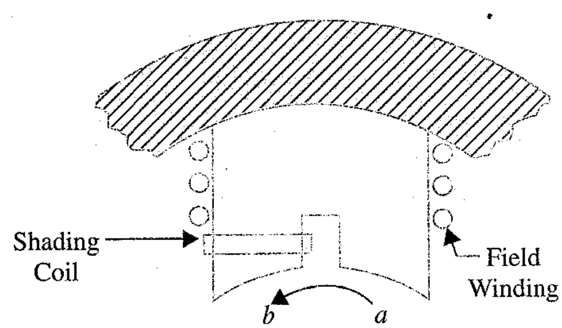
<u>Applications</u>

Compressors, fire strokers etc.

4. Shaded pole Single Phase Motor

- In such motors, the phase splitting is produced by induction.
- These motors have salient poles on the stator and a squirrel cage type rotor.

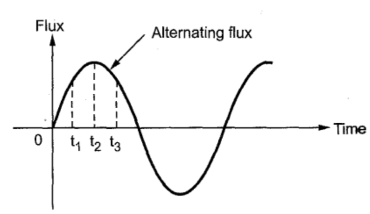




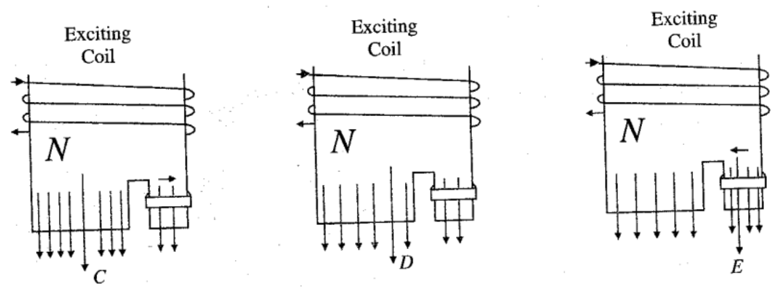
- The figure shows a four pole motor with the field poles connected in series for alternate polarity.
- The laminated pole has a slot cut across the laminations approximately one third distance from one edge.
- Around the small part of the pole is placed a short circuited Cu coil known as shading coil. This part of the pole is known as shaded part and the other as unshaded part.
- When an alternating current is passed through the exciting (or field) winding surrounding the pole, the axis of the pole shifts from the unshaded part a to the shade part b.
- This shifting of magnetic axis is equivalent to the actual physical movement of the pole. Hence the motor starts rotating in the direction of the shift i.e. from unshaded part to the shaded part.

The production of rotating magnetic field is explained as follows:

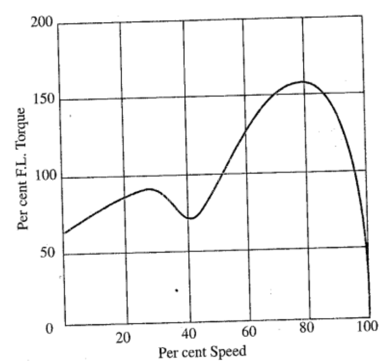
- The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in the Fig.



- Consider the three instants say t1, t2 and t3 during first half cycle of the flux as shown, in the Fig.
- At instant $t = t_1$, rate of rise of current and hence the flux is very high. Due to the transformer action, large e.m.f. gets induced in the copper shading band.
- This circulates current through shading band as it is short circuited, producing its own flux.
- According to Lenz's law, the direction of this current is so as to oppose the cause i.e. rise in current. Hence shading ring flux is opposing to the main flux.
- Hence there is crowding of flux in unshaded part while weakening of flux in shaded part. Overall magnetic axis shifts in unshaded part as shown in the Fig.



- At instant $t = t_2$, rate of rise of current and hence the rate of change of flux is almost zero as flux almost reaches to its maximum value. Hence there is very little induced e.m.f. in the shading ring.
- Hence the shading ring flux is also negligible, hardly affecting the distribution of the main flux. Hence the main flux distribution is uniform and magnetic axis lies at the centre of the pole face as shown in the Fig.
- At instant $t = t_3$, the current and the flux is decreasing. The rate of decrease is high which again induces a very large e.m.f. in the shading ring.
- This circulates current through the ring which produces its own flux. Now direction of the flux produced by the shaded ring current is so as to oppose the cause which is decrease in flux. So it oppose the decrease in flux means its direction is same as that of main flux, strengthening it.
- So there is crowding of flux in the shaded part as compared to unshaded part. Due to this the magnetic axis shifts to the middle of the shaded part of the pole.
- This sequence keeps on repeating for negative half cycle too. Consequently this produces an effect of rotating magnetic field, the direction of which is from unshaded part of the pole to the shaded part of the pole.
- Due to this, motor produces the starting torque and starts rotating. The starting torque is low which is about 40 to 50 % of the full load torque for this type of motor. The torque speed characteristic is shown in the fig.
- Shaded pole motors are built in very small sizes varying from 1/250 h.p. (3W) to 1/6 h.p. (125 W).



  <u>Advantages</u>
  - Simple in construction
  - Extremely rugged
  - Reliable
  - Cheap

  <u>Disadvantages</u>
  - Low starting torque
  - Very little overload capacity
  - Low efficiency
  - Direction of rotation cannot be changed, because it is fixed by the position of copper rings.

  <u>Applications</u>
  - Used for small fans, toys, hair dryers, ventilators, electric clocks etc.

EQUIVALENT CIRCUIT

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

Without Core Loss

Let the stator impedance be Z Ω

$Z = R_1 + jX_1$

Where R_1 = Stator resistance, X_1 = Stator reactance,

X_2 = Rotor reactance referred to stator

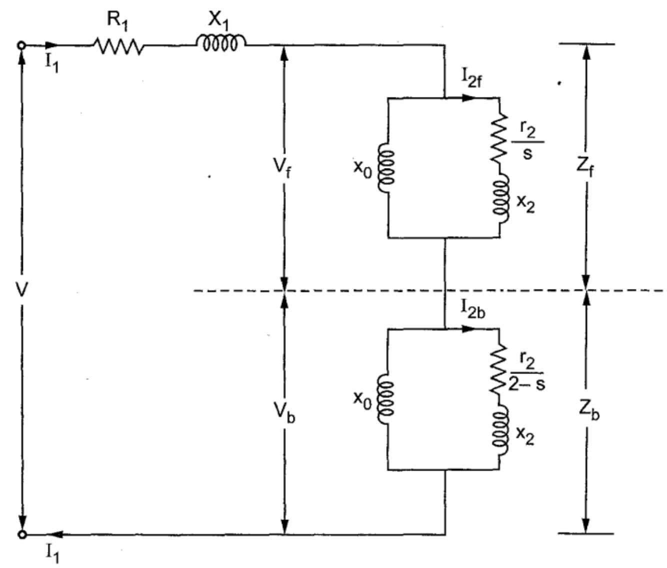
R_2 = Rotor resistance referred to stator

Hence the impedance of each rotor is $r_2 + j\, x_2$

Where $x_2 = \frac{X_2}{2}$; $r_2 = \frac{R_2}{2}$;

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

As the core loss is neglected, R_0 does not exist in the equivalent circuit. The x_0 is half of the actual magnetising reactance of the motor. Therefore, $x_0 = \frac{X_0}{2}$;



So the equivalent circuit referred to stator is shown in the Fig.

The impedance of the forward field rotor is Z_f is parallel combination of ($j\, x_0$) and (r_2/s) + $j\, x_2$.

$$\therefore \qquad Z_f = \frac{j x_0 \left[\left(\frac{r_2}{s} \right) + j\, x_2 \right]}{\frac{r_2}{s} + j\,(x_0 + x_2)}$$

While the impedance of the backward field rotor is Z_b is parallel combination of ($j\, x_0$) and ($r_2/(2-s)$) + $j\, x_2$.

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

Under standstill condition, s = 1 and 2 - s = 1. Hence $Z_f = Z_b$ and $V_f = V_b$. But in the running condition, V_f becomes almost 90 to 95 % of the applied voltage.

Equivalent impedance, $Z_{eq} = Z_1 + Z_f + Z_b$

Let I_{2f} = Current through forward rotor referred to stator

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

$$\therefore \qquad I_{2f} = \frac{V_f}{\left(\frac{r_2}{s} + j\,x_2\right)} \qquad \text{where } V_f = I_1 \times Z_f$$

$$\text{and} \qquad I_{2b} = \frac{V_b}{\left(\frac{r_2}{2-s} + j\,x_2\right)} \qquad \text{where } V_b = I_1 \times Z_b$$

Power input to forward field rotor, $P_f = (I_{2f}^2) . \frac{r_2}{2}$ watts

Power input to backward field rotor, $P_b = (I_{2b}^2) . \frac{r_2}{2-s}$ watts.

Mechanical power developed, Pm = (1 - s) [Net power input] = (1 - s) $(P_f - P_b)$ watts

Output power, $P_{out} = P_m$ - Mechanical loss - Core loss

Forward Torque, $T_f = \frac{P_f}{\frac{2\pi N}{60}}$ N-m

Backward Torque, $T_b = \frac{P_b}{\frac{2\pi N}{60}}$ N-m

Net torque, $T = T_f - T_b$

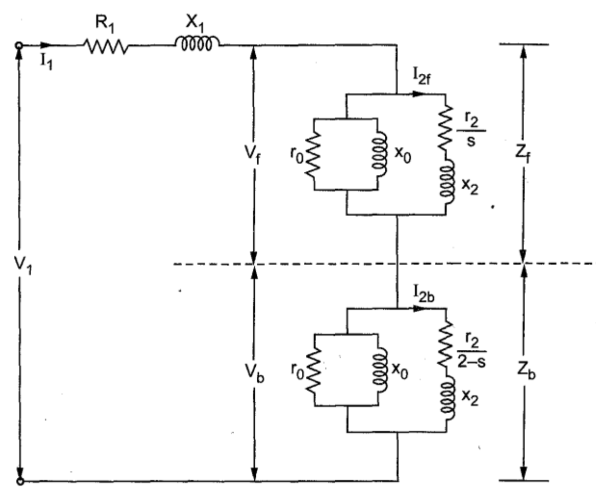
Shaft Torque, $T_{sh} = \frac{P_{out}}{\frac{2\pi N}{60}}$ N-m

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

With Core Loss

If core loss is to be considered then it is necessary to connect a resistance r_0 in parallel with x_0, in an exciting branch of each rotor.

r_0 is half the value of actual core loss resistance. Thus the equivalent circuit with core loss is as shown in the fig.



Let,

Z_{0f} = Equivalent impedance of exciting branch in forward rotor = $r_0 \parallel (jx_0)$

Z_{ob} = Equivalent impedance of exciting branch in backward rotor = $r_0 \parallel (jx_0)$

Therefore, the impedance of the forward field rotor is Z_f is

$$Z_f = Z_{of} \parallel (r_2/s + jx_2)$$

While the impedance of the backward field rotor is Z_b is

$$Z_b = Z_{ob} \parallel (r_2/ (2\text{-}s) + jx_2)$$

All other expressions remain same as in case of equivalent circuit without core loss.

TESTS ON SINGLE PHASE INDUCTION MOTOR

1. No load test or open circuit test

2. Blocked rotor test or short circuit test

No Load Test

The test is conducted by rotating the motor without load. The input current, voltage and power are measured by connecting the ammeter, voltmeter and wattmeter in the circuit. These readings are denoted as V_0, I_0 and W_0.

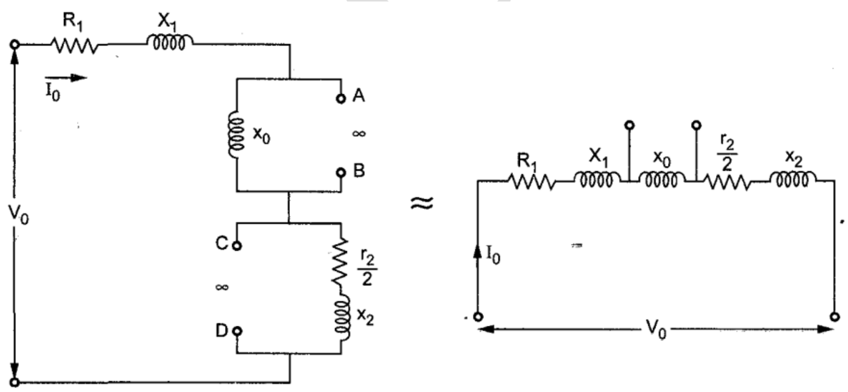
$W_0 = V_0 I_0 \cos\Phi_0$

Therefore, No load power factor, $\cos\Phi_0 = \frac{W_0}{V_0 I_0}$

The motor speed on no load is almost equal to its synchronous speed hence for practical purposes, the slip can be assumed zero. Hence $\frac{r_2}{2}$ becomes ∞ and acts as open circuit in the equivalent circuit. Hence for forward rotor circuit, the branch $r_2/s + j\,x_2$ gets eliminated.

While for a backward rotor circuit, the term $r_2 / (2\text{-}s)$ tends to $r_2/2$. Thus x_0 is much higher than the impedance $\frac{r_2}{2} + j\,x2$. Hence it can be assumed that no current can flow through x_m and that branch can be eliminated.

So circuit reduces to as shown in the Fig.



The voltage across x_0 is V_{AB}

$V_{AB} = V_0 - I_0 [(R_1 + \frac{r_2}{2}) + j(x_1 + x_2)$

Also $V_{AB} = I_0 x_0$

Therefore $x_0 = \frac{V_{AB}}{I_0}$

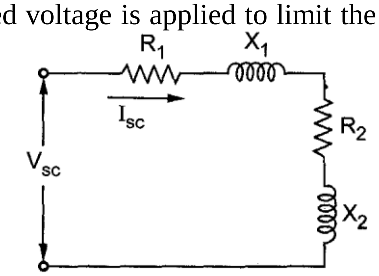
But $x_0 = \frac{X_0}{2}$

Therefore, magnetizing reactance, $X_0 = 2\,x_0 = \frac{2V_{AB}}{I_0}$

No load power W_0 = rotational losses.

Blocked Rotor Test

In blocked rotor test, the rotor is held fixed so that it will not rotate. A reduced voltage is applied to limit the short circuit current. This voltage is adjusted with the help of autotransformer so that the rated current flows through main winding. The input voltage, current and power is measured by connecting voltmeter, ammeter and wattmeter respectively. These readings are denoted as V_{sc}, I_{sc} and W_{sc}.



As rotor is blocked, the slip s = 1. Hence the magnetising reactance x_0 is much higher than the rotor impedance and hence it can be neglected as connected in parallel with the rotor. Thus the equivalent circuit for blocked rotor test is as shown in the Fig.

$W_{sc} = V_{sc} I_{sc} \cos\Phi_{sc}$

Short circuit power factor, $\cos\Phi_{sc} = \frac{W_{sc}}{V_{sc} I_{sc}}$

$Z_{eq} = \frac{V_{sc}}{I_{sc}}$; $R_{eq} = \frac{W_{sc}}{I_{sc}^2}$; but $R_{eq} = R_1 + R_2$; therefore Rotor resistance referred to stator, $R_2 = R_{eq} - R_1$;

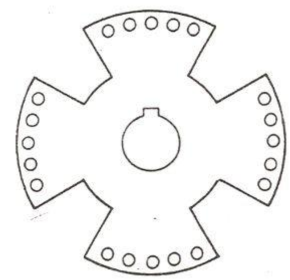
$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$;

Assume, $X_1 = X_2$; therefore rotor reactance referred to stator, $X_2 = \frac{X_{eq}}{2}$

The stator resistance R_1 is measured by voltmeter-ammeter method, by disconnecting the auxiliary winding and capacitors present if any. Due, to skin effect, the a.c. resistance is 1.2 to 1.5 times more than the d.c resistance.

Thus with these two tests, all the parameters of single phase induction motor can be obtained.

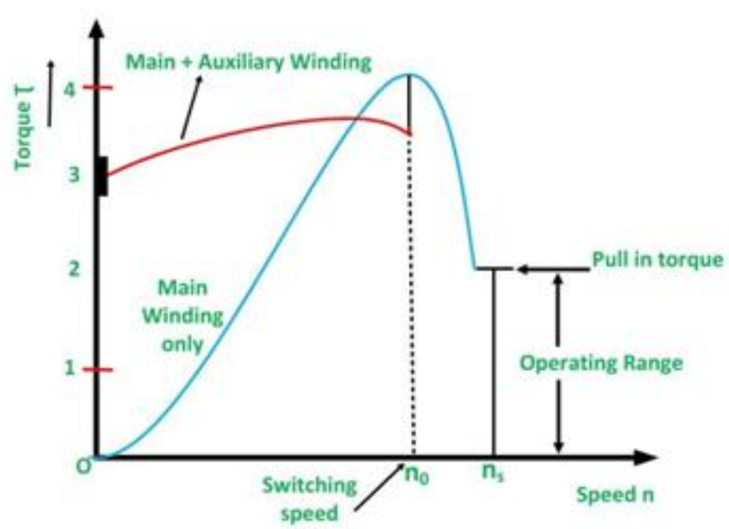
RELUCTANCE MOTOR



- A single phase synchronous **Reluctance Motor** is basically the same as the single cage type induction motor.
- The stator of the motor has the main and auxiliary winding. The stator of the single phase reluctance and induction motor are same.
- The rotor of a reluctance motor is a squirrel cage with some rotor teeth removed in the certain places to provide the desired number of salient rotor poles.

  The figure shows the 4 pole reluctance type synchronous motor.
- In the figure the teeth have been removed in four locations to produce a 4 pole structure. The two end rings are short circuited.
- When the stator is connected to a single phase supply, the motor starts as a single phase induction motor.
- A centrifugal switch disconnects the auxiliary winding as soon as the speed of the motor reaches about 75% of the synchronous speed.
- The motor continues to speed up as a single phase motor with the main winding in operation.
- A reluctance motor torque is produced due to the tendency of the rotor to align itself in the minimum reluctance position, when the speed of the motor is close to the synchronous speed. Thus, the rotor pulls in synchronism.
- The load inertia should be within the limits, for proper effectiveness.
- At synchronism, the induction torque disappears, but the rotor remains in synchronism due to synchronous reluctance torque.

The **Torque Speed Characteristic** of a single phase Reluctance Motor is shown below.



- The starting torque depends upon the rotor position.
- The value of the starting torque varies between 300 to 400 % of its full load torque.
- As motor attains speed nearly of synchronous speed the auxiliary winding is disconnected and the rotor continues to rotate at the synchronous speed.
- The motor operates at a constant speed up to a little over than 200% of its full load torque.
- If the loading of the motor is increased above the value of the pull out torque, the motor loose synchronism but continues to run as a single phase induction motor up to over 500% of its rated torque.
- At the starting the motor is subjected to Cogging. This can be reduced by skewing the rotor bars and by having the rotor slots not exact multiples of the

number of poles.

- The rotor of a Reluctance Motor is unexcited, therefore, the power factor is low as compared to the induction motor.
- As the motor has no DC field excitation so the output of a reluctance motor is reduced.
- Hence, the size of the motor is large as compared to synchronous motor.

Advantages

1) No d.c. supply is necessary for rotor
2) Constant speed characteristics
3) Robust construction
4) Less maintenance.

Limitations

1) Less efficiency
2) Poor power factor
3) Need of very low inertia rotor
4) Less capacity to drive the loads.

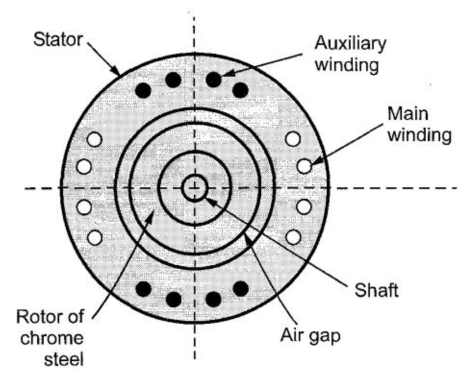
Applications

This motor is used in signalling devices, control apparatus, automatic regulators, recording instruments, clocks and all kinds of timing devices, teleprinters, gramophones etc.

HYSTERESIS MOTOR

- A **Hysteresis Motor** is a synchronous motor with a uniform air gap and without DC excitation. It operates both in single and three phase supply.
- The Torque in a Hysteresis Motor is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.
- The working of the motor depends on the working of the continuously revolving magnetic flux. For the split phase operation, the stator winding of the motor has two single phase supply. This stator winding remains continuously connected to the single phase supply both at the starting as well as the running of the motor.
- The rotor of the motor is made up of smooth chrome steel cylinder and it has no winding. It has high retentivity and because of this, it is very difficult to change the magnetic polarities once they are caused by the revolving flux of the rotor. The rotor of the hysteresis motor moves synchronously because the pole of the motor magnetically locks with the stator which has opposite polarities.

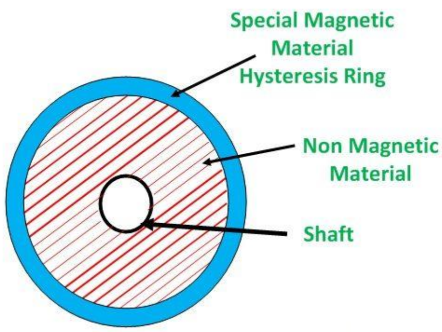
Construction of Stator of Hysteresis Motor

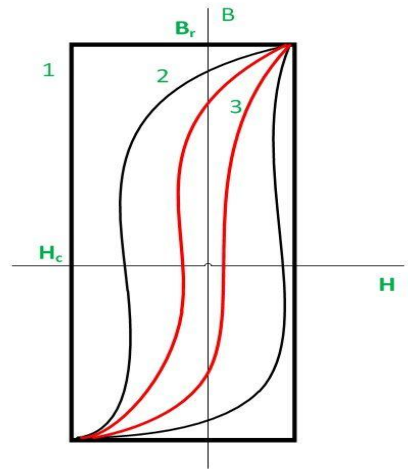


- The stator of the hysteresis motor produces a rotating magnetic field and is almost similar to the stator of the induction motor. Thus, the stator of the motor is connected either to single supply or to the three phase supply.
- The stator winding of the single-phase hysteresis motor is made of permanent split capacitor type or shaded pole type. The capacitor is used with an auxiliary winding in order to produce a uniform field.

Construction of Rotor of Hysteresis Motor

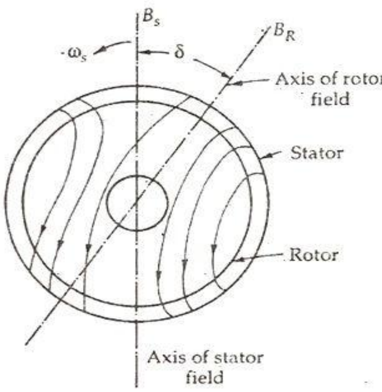
- The rotor of the hysteresis motor consists of the core of aluminium or some other non-magnetic material which carries a layer of special magnetic material. The figure shows the rotor of the hysteresis motor.
- The outer layer has a number of thin rings forming a laminated rotor. The rotor of the motor is a smooth cylinder, and it does not carry any windings. The ring is made of hard chrome or cobalt steel having a large hysteresis loop as shown in the figure below.





Operation of a Hysteresis Motor

- When supply is given applied to the stator, a rotating magnetic field is produced. This magnetic field magnetises the rotor ring and induces pole within it.
- Due to the hysteresis loss in the rotor, the induced rotor flux lags behind the rotating stator flux.
- The angle δ between the stator magnetic field B_S and the rotor magnetic field B_R is responsible for the production of the torque. The angle δ depends on the shape of the hysteresis loop and not on the frequency.
- Thus, the value of Coercive force and residual flux density of the magnetic material should be large.
- The ideal material would have a rectangular hysteresis loop as shown by loop 1 in the hysteresis loop figure. The stator magnetic field produces Eddy currents in the rotor. As a result, they produce their own magnetic field.



The eddy current loss is given by the equation, $P_e = K_e f_2^2 B^2$

Where, k_e is Eddy current constant, f_2 is the eddy current frequency, B is the flux density

The relation between rotor frequency f_2 and supply frequency f_1 is $f_2 = sf_1$
where s is the slip.

Therefore, $P_e = K_e s^2 f_1^2 B^2$

The torque due to eddy current is $T_e = \frac{P_e}{s\omega_s}$ or $T_e = K's$ ………..(1)

Where $K' = \frac{K_e f_1^2 B^2}{\omega_s}$

The hysteresis loss is $P_h = K_h f_2 B^{1.6}$ or $K_h s f_1 B^{1.6}$ ……………..(2)

The Torque due to hysteresis is $T_h = \frac{P_h}{s\omega_s} = k''$ …………….(3)

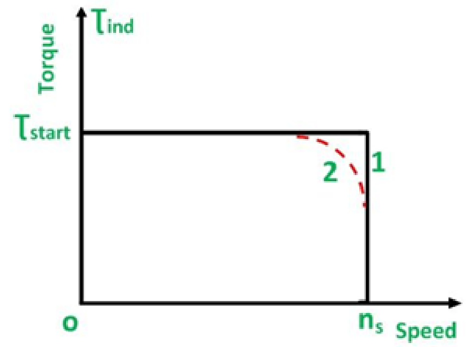
Where $k'' = \frac{K_h\ f_1 B^{1.6}}{\omega_s}$

- From the equation (1) it is clear that the torque is proportional to the slip. Therefore, as the speed of the rotor increases the value of T_e decreases.
- As the speed of the motor reaches synchronous speed, the slip becomes zero and torque also becomes zero.
- As the electromagnet torque is developed by the motor is because of the hysteresis loss and remains constant at all rotor speed until the breakdown torque.

- At the synchronous speed, the eddy current torque is zero and only torque due to hysteresis loss is present.

Torque Speed characteristic of Hysteresis Motor

The speed torque curve of the motor is shown below.



- Curve 1 is the ideal curve, and the curve 2 is the practical hysteresis motor curve.
- The torque-speed characteristic of the hysteresis motor is different from an induction motor.
- Since, at the synchronous speed, the torque developed by an induction motor becomes zero, whereas in the hysteresis motor the torque is constant at all the speed even at the synchronous speed.
- Thus, from the curve, it is seen that the locked rotor, starting and pull out torque is equal.
- The noise level of the hysteresis motor is very low as compared to the induction motor because it operates at a constant speed and its rotor is smooth.
- This type of motor is smoothest running, quietest single phase motor and is used for quality sound reproduction equipment like record players, tape recorders, etc. It is also employed in electric clocks and other timing devices.

Advantages:

The advantages of hysteresis motor are:

1. As rotor has no teeth, no winding, there are no mechanical vibrations.
2. Due to absence of vibrations, the operation is quiet and noiseless.
3. Suitability to accelerate inertia loads.
4. Possibility of multispeed operation by employing gear train.

Disadvantages

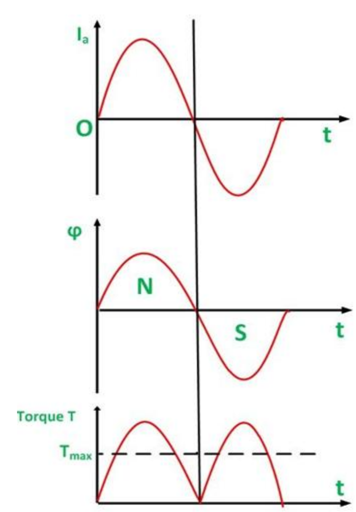
The disadvantages of hysteresis motor are:

1. The output is about one-quarter that of an induction motor of the same dimension.
2. Low efficiency
3. Low power factor
4. Low torque
5. Available in very small sizes

Applications

Due to noiseless operation it is used in sound recording instruments, sound producing equipments, high quality record players, electric clocks, tele printers, timing devices etc.

UNIVERSAL MOTOR



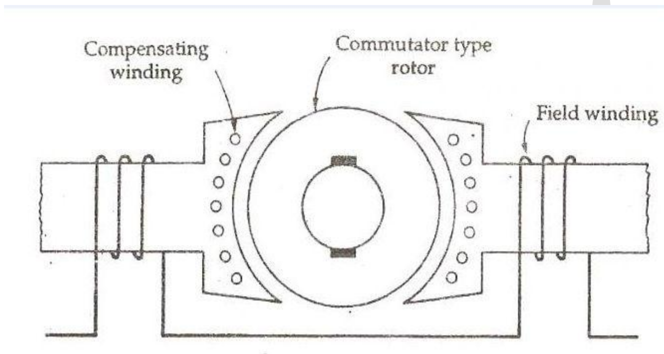
- The motors which can be used with a single phase AC source as well as a DC source of supply and voltages are called as **Universal Motor**. It is also known as **Single Phase Series Motor**.
- A universal motor is a commutation type motor. If the polarity of the line terminals of a DC Series Motor is reversed, the motor will continue to run in the same direction.
- The direction is determined by both field polarity and the direction of current through the armature as torque is proportional to the flux and the armature current.
- Let the DC series motor be connected across a single phase AC supply. Since the same current flows through the field winding and the armature winding, the AC reversal from positive to negative or vice versa will affect the field flux polarity and the current direction through the armature.
- The direction of the developed torque will remain positive, and direction of the rotation will be as it was before.

- The nature of the torque will be pulsating, and the frequency will be twice that of line frequency as shown in the waveform. Thus, a Universal motor can work on both AC and DC.
- However, a series motor which is mainly designed for DC operation if works on single phase AC supply suffers from the following drawbacks.
  - ✓ The efficiency becomes low because of hysteresis and eddy current losses.
  - ✓ The power factor is low due to the large reactance of the field and the armature windings.
  - ✓ The sparking at the brushes is in excess.

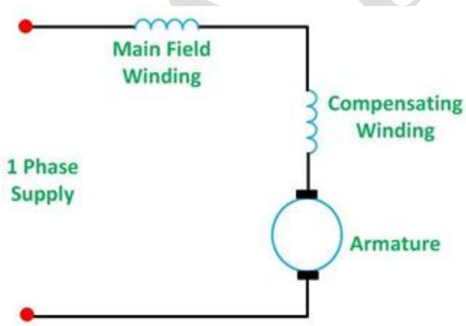
In order to overcome the above following drawbacks, certain modifications are made in a DC series motor so that it can work even on the AC current. They are as follows:-

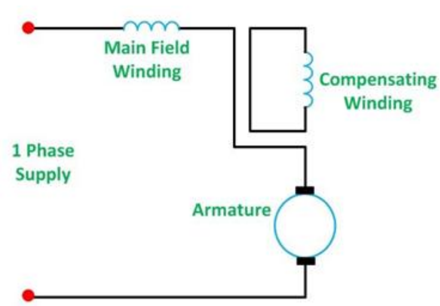
- ✓ The field core is made up of the material having a low hysteresis loss. It is laminated to reduce the eddy current loss.
- ✓ The area of the field poles is increased to reduce the flux density. As a result, the iron loss and the reactive voltage drop are reduced.
- ✓ To get the required torque the number of conductors in the armature is increased.

- A compensating winding is used for reducing the effect of the armature reaction and improving the commutation process. The winding is placed in the stator slots as shown in the figure below.

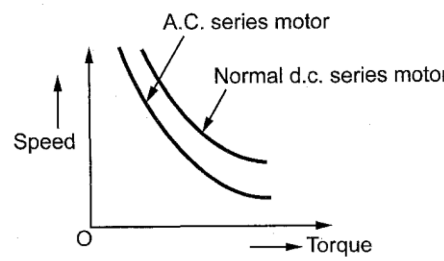


- The winding is put in the stator slot. The axis of compensating winding is 90 degrees with the main field axis. The compensating winding is connected in series with both the armature and the field; hence, it is called conductively compensated.
- If the compensating winding is short circuited, the motor is said to be inductively compensated. The connection diagram is shown below.





- The construction of the universal motor is same as that of the series motor.
- In order to minimize the problem of commutation, high resistance brushes with increased brush area are used.
- To reduce Eddy current losses the stator core and yoke are laminated.
- The Universal motor is simple and less costly. It is used usually for rating not greater than 750 W.



- The characteristic of Universal motor is similar to that of the DC series motor.
- When operating from an AC supply, the series motor develops less torque.
- By interchanging connections of the fields with respect to the armature, the direction of rotation can be altered.
- Speed control of the universal motors is obtained by solid state devices.
- This motor is most suitable for applications requiring high speeds.
- Since the speed of these motors is not limited by the supply frequency and is as high as 20000 rpm.

Applications of Universal Motor

The Universal motor is used for the purposes where speed control and high values of the speed are necessary. The various applications of the Universal Motor are as follows:-

- Pσrtable drill machine.
- Usedin hair dryers, grinders and table fans.
- used in blowers, polishers and kitchen appliances.

REPULSION MOTOR

Repulsion Type Motors

These can be divided into the following four distinct categories:

1. Repulsion Motor. It consists of **(*a*)** one stator winding **(*b*)** one rotor which is wound like a d.c. armature **(*c*)** commutator and **(*d*)** a set of brushes, which are short-circuited and remain in contact with the commutator at all times. It operates continuously on the 'repulsion' principle. No short-circuiting mechanism is required for this type.

2. Compensated Repulsion Motor. It is identical with repulsion motor in all respects, except that
(*a*) It carries an additional stator winding, called compensating winding
(*b*) There is another set of two brushes which are placed midway between the usual short- circuited brush set. The compensating winding and this added set are connected in series.

3. Repulsion-start Induction-run Motor. This motor starts as a repulsion motor, but normally runs as an induction motor, with constant speed characteristics. It consists of **(*a*)** one stator winding **(*b*)** one rotor which is similar to the wire-wound d.c. armature **(*c*)** a commutator and **(*d*)** a centrifugal mechanism which short-circuits the commutator bars all the way round (with the help of a short-circuiting necklace) when the motor has reached nearly 75 per cent of full speed.

4. Repulsion Induction Motor. It works on the combined principle of repulsion and induction. It consists of **(*a*)** stator winding **(*b*)** two rotor windings: one squirrel cage and the other usual d.c. winding connected to the commutator and **(*c*)** a short-circuited set of two brushes.

Repulsion Motor

Constructionally, it consists of the following:

1. Stator winding of the distributed non-salient pole type housed in the slots of a smooth-cored stator (just as in the case of split-phase motors). The stator is generally wound for four, six or eight poles.

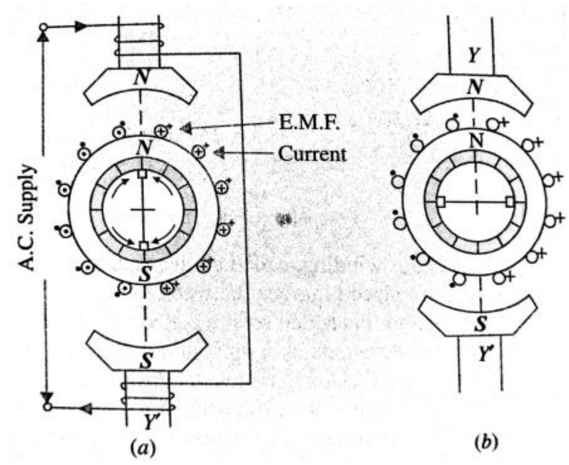
2. A rotor (slotted core type) carrying a distributed winding (either lap or wave) which is connected to the commutator. The rotor is identical in construction to the d.c. armature.

3. A commutator, which may be one of the two types : an axial commutator with bars parallel to the shaft or a radial or vertical commutator having radial bars on which brushes press horizontally.

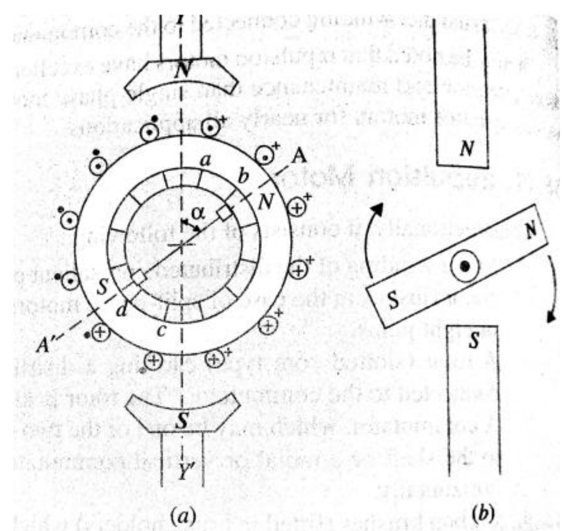
4. Carbon brushes (fitted in brush holders) which ride against the commutator and are used for conducting current through the armature (*i.e*. rotor) winding.

Repulsion Principle

Consider Fig. which shows a 2-pole salient pole motor with the magnetic axis vertical.



- Suppose that the direction of flow of the alternating current in the exciting or field (stator) winding is such that it creates an *N*-pole at the top and an *S*-pole at the bottom.
- The alternating flux produced by the stator winding will induce e.m.f. in the armature conductors by transformer action.
- The direction of the induced e.m.f. can be found by using Lenz's law and is as shown in Fig. (*a*).
- However, the direction of the ***induced*** currents in the armature conductors will depend on the ***positions of the short-circuited brushes***.
- If brush axis is colinear with magnetic axis of the main poles, the directions of the induced currents (shown by dots and arrows) will be as indicated in Fig. (*a*).
- As a result, the armature will become an electromagnet with a *N*-pole on its top, directly under the main *N*-pole and with a *S*-pole at the bottom, directly over the main *S*-pole.
- Because of this face-to- face positioning of the main and induced magnetic poles, no torque will be developed. The two forces of repulsion on top and bottom act along *Y Y*' in direct opposition to each other.
- If brushes are shifted through 90^0 to the position shown in Fig. (*b*) So that the brush axis is at right angles to the magnetic axis of the main poles, the directions of the induced voltages at any time in the respective armature conductors are exactly the same as they were for the brush position of Fig. (*a*).
- However, with brush positions of Fig. (*b*), the voltages induced in the armature conductors in each path between the brush terminals will neutralize each other, hence there will be no net voltage across brushes to produce armature current. If there is no armature current, obviously, no torque will be developed.
- If the brushes are set in position shown in Fig. so that the brush axis is neither in line with nor 90º from the magnetic axis *Y Y*' of the main poles, a net voltage will be induced between the brush terminals which will produce armature current.
- The armature will again act as an electromagnet and develop its own *N*-and *S*-poles which, in this case, will not directly face the respective main poles.



- As shown in Fig., the armature poles lie along *AA*' making an angle of α with *Y Y*'.
- Hence, *rotor N*-pole will be repelled by the main *N*-pole and the rotor *S*-pole will, similarly, be repelled by the ***main*** *S*-pole.
- Consequently, the rotor will rotate in clockwise direction. Since the forces are those of ***repulsion***, it is appropriate to call the motor as repulsion motor.
- If the brushes are shifted counter-clockwise from *YY'*, rotation will also be counter-clockwise.
- Direction of rotation of the motor is determined by the position of brushes with respect to the main magnetic axis.
- The value of starting torque developed will depend on the ***amount*** of brush-shift whereas direction of rotation will depend on the ***direction*** of shift.
- Maximum starting torque is developed at some position where brush axis makes, an angle lying between 0º and 45º with the

magnetic axis of main poles.

- Motor speed can also be controlled by means of brush shift. Variation of starting torque of a repulsion motor with brush-shift is shown in Fig.

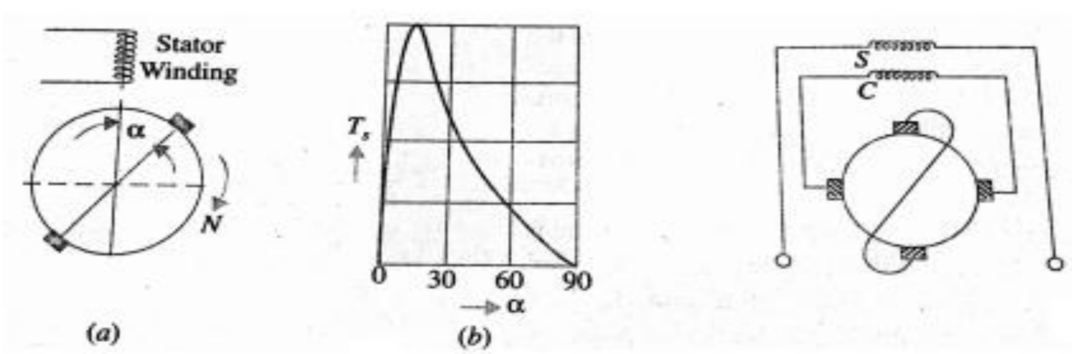
A straight repulsion type motor has high starting torque (about 350 per cent) and moderate starting current (about 3 to 4 times full-load value).

Principal shortcomings of such a motor are:

1. speed varies with changing load, becoming dangerously high at no load.
2. low power factor, except at high speeds.
3. tendency to spark at brushes.

Compensated repulsion motor

- In this type of motor an additional stator winding called compensation winding is provided. This is the modified form of the basic repulsion motor.
- The compensation winding serves for two purposes: ·
    - To Improve the Power factor ·
    - For better speed regulation
- This type of motor is used whenever there is a need for motor to run at constant speed and at higher power factor so an additional stator winding called compensating winding is used.
- The additional winding which is connected in series with the armature, is smaller than stator winding and wounded to the inner slots of main pole.
- It also consists of additional set of brushes which are placed mid way between the short circuited brushes.
- Such a type of modification reduces the quadrature drop and improves the power factor. And speed regulation also improves due to this compensation.
- Quadrature drop occurs in salient pole types due to non-uniform air gap length. Due to quadrature drop crossmagnetizing effect occurs which opposes the mmf waves.
- By providing such a type of compensation, this effect can be reduced which increases power factor. Further the leakage between armature and field is reduced



Repulsion start induction run motors

- As the name suggests this motor starts as a repulsion motor and runs as an Induction motor.
- This type of motor starts as a normal Repulsion motor and after achieving three-fourths of its full speed, it runs as an Induction motor.
- For this purpose a centrifugal force-operated device is used. This centrifugal device short circuits the commutator segments and this aids in running the motor as a squirrel cage motor.
- As soon as the commutator is short circuited, the brushes present do not carry any current.
- So the brushes can be removed to avoid the wear and tear.
- The advantage in running the motor as a squirrel cage one is that, it provides high starting torque, 350 percent without excessive current. Also constant speed is ensured for wide range of torque.
- There are two different designs in repulsion start motors:

BRUSH LIFTING TYPE- In this type the brush is lifted as soon as the commutator is short circuited to avoid unnecessary wear and tear and losses due to friction. So in this type the brush is present only when the motor is started as a repulsion one.

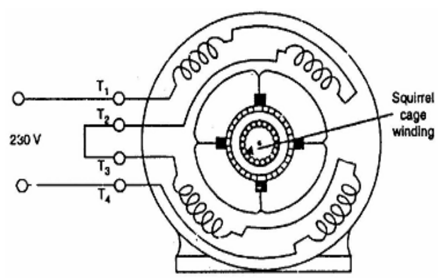
BRUSH RIDING TYPE- In this type of motors the brushes ride along with the commutator at all times. So the brushes are present even after the commutator is short circuited.

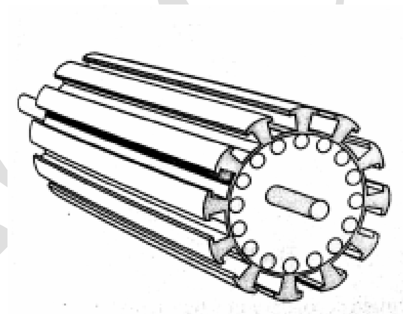
Applications

Compressors, Hoists, Pumps, Machine tools, Floor-polishing

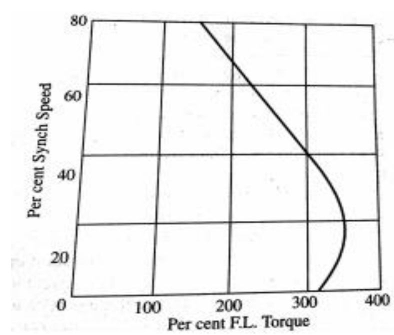
Repulsion induction motor

- This type of motor is a combination of repulsion motor and induction motor. It is also referred as ***squirrel cage repulsion motor***.
- This motor possesses the characteristic of both induction motor and repulsion motor. It combines the desirable starting characteristics of repulsion motor and constant speed characteristics of an induction motor.
- Here the stator winding is same as every other repulsion motor but there are two separate rotor windings
    - A squirrel cage winding ·
    - A Commutator winding
- The commutator winding lies on the outer slots while the squirrel cage winding is located in the inner slots. Both the windings operate during the entire period of operation of motors. The brushes are in contact with the commutator all the time.





- The biggest advantage in such type of motors is that they don't need a separate centrifugal short-circuit system as in Repulsion-start Induction-run motors.
- As soon as the motor is started, the squirrel cage winding is practically inactive for a small period of time due to high reluctance.
- Only the commutator winding supplies most of the torque.
- But during normal running condition, the squirrel cage winding supplies most of the torque and commutator winding supplies relatively lower torque when compared to Squirrel cage winding.
- So the squirrel cage winding takes up most of the load as the rotor accelerates
- The starting torque is very high, 300 percent with better speed regulation.



Applications

Petrol pumps, Compressors, Refrigerators, Mixing machines, Lifts and Hoists

LINEAR INDUCTION MOTOR

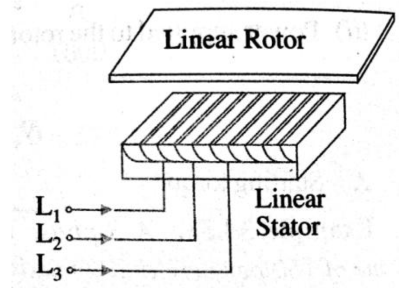
- If the stator is laid out flat and a flat squirrel cage winding is brought near to it, we get a linear induction motor.
- In practice, instead of a flat squirrel cage winding, an aluminium or copper or iron plate is used as a 'rotor'.
- The flat stator produces a flux that moves in a straight line from its one end to the other at a linear synchronous speed given by

$$v_s = 2.w.f$$

where v_s = linear synchronous speed (m/s)

w = width of one pole pitch (m)

f = supply frequency (Hz)



- The speed does not depend on the number of poles, but only on the pole pitch and stator supply frequency.
- As the flux moves linearly, it drags the rotor plate along with it in the same direction.
- In practical applications, the 'rotor' is stationary, while the stator moves.
- For example, in high speed trains, which utilize magnetic levitation, the rotor is composed of thick aluminium plate that is fixed to the ground and extends over the full length of the track.
- The linear stator is bolted to the undercarriage of the train.

Properties of a Linear Induction Motor

1. Synchronous speed, $v_s = 2.w.f$
2. Slip, s = $(v_s - v) / v_s$ where v is the actual speed
3. Thrust or Force, F = P_2 / v_s where P_2 is the active power supplied to the rotor.
4. Active power flow (i) $P_{cr} = sP_2$ (ii) $P_m = (1-s) P_2$

SERVOMOTORS

This is nothing but a simple electrical motor, controlled with the help of servomechanism. If the motor as controlled device, associated with servomechanism is DC motor, then it is commonly known as DC servo motor. If the controlled motor is operated by AC, it is called AC servo motor.

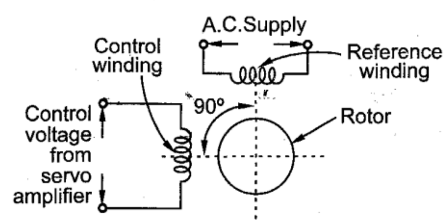
Requirements of Good Servomotor

i) Linear relationship between electrical control signal and the rotor speed over a wide range.
ii) Inertia of rotor should be as low as possible. A servomotor must stop running without any time delay, if control signal to it is removed.
iii) Its response should be as fast as possible.
iv) It should be easily reversible.
v) It should have linear torque - speed characteristics.
vi) Its operation should be stable without any oscillations or overshoots.

Servo motor is a special type of motor which is automatically operated up to certain limit for a given command with help of error-sensing feedback to correct the performance.

A.C. Servomotor

Most of the servomotors used in low power servomechanisms are a.c.servomotors. The a.c. servomotor is basically two phase induction motor. The output power of a.c. servomotor varies from fraction of watt to few hundred watts. The operating frequency is 50 Hz to 400 Hz.



Stator of A.C. servomotor

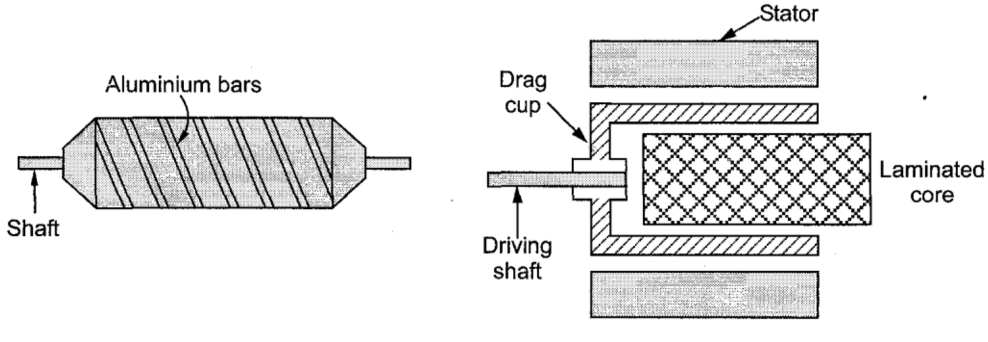
Construction

- It is mainly divided into two parts namely stator and rotor.
- The stator carries two windings, uniformly distributed and displaced by 90°, in space.
- One winding is called main winding or fixed winding or reference winding. This is excited by a constant voltage a.c. supply.
- The other winding is called control winding. It is excited by variable control voltage, which is obtained from a servo amplifier. This voltage is 90° out of phase with respect to the voltage applied to the reference winding. This is necessary to obtain rotating magnetic field.

Rotor

- The rotor is generally of two types. The one is usual squirrel cage rotor. This has small diameter and large length. Aluminium conductors are used to keep weight small. Its resistance is very high to keep torque speed characteristics as linear as possible. Air gap is kept very small which reduces magnetising current. This cage type of rotor is shown with skewed bars in the Fig. (a).

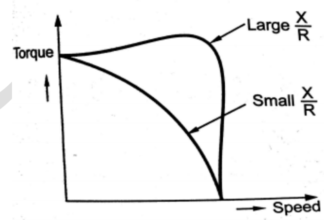
- The other type of rotor is drag cup type. There are two air gaps in such construction. Such a construction reduces inertia considerably and hence such type of rotor is used in very low power applications. The aluminium is used for the cup construction. The construction is shown in the Fig. (b).



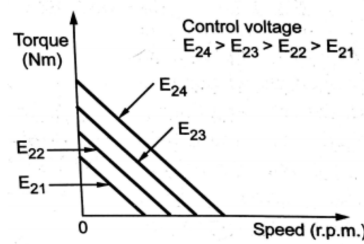
(a) Squirrel cage rotor **(b) Drag cup type rotor**

<u>Torque-Speed Characteristics</u>

- The torque-speed characteristics of a two phase induction motor, mainly depends on the ratio of reactance to resistance. For small X to R ratio i.e. high resistance low reactance motor, the characteristics is much more linear while it is nonlinear for large X to R ratio as shown in the Fig.



- In practice, design of the motor is so as to get almost linear torque-speed characteristics. The Fig. shows the torque-speed characteristics for various control voltages.
- The torque varies almost linearly with speed. All the characteristics are equally spaced for equal increments of control voltage. It is generally operated with low speeds.



<u>Features of A.C. Servomotor</u>

i) Light in weight ii) Robust construction iii) Reliable and stable operation iv) Smooth and noise free operation v) Large torque to weight ratio vi) Large R to X ratio i.e. small X to R ratio vii) No brushes or slip rings hence maintenance free viii) Simple driving circuits.

<u>Applications</u>

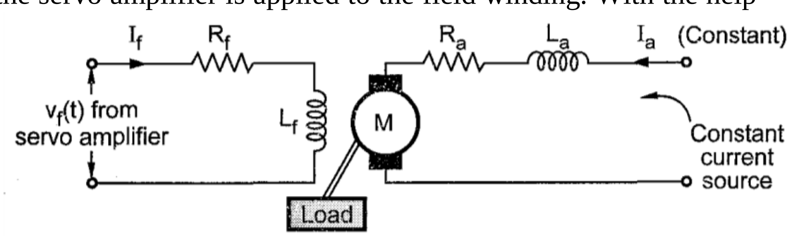
Due to the above features it is widely used in instrument servomechanisms, remote positioning devices, process control systems, self balancing recorders, computers, tracking and guidaice systems, robotics, machine tools etc.

<u>D.C. Servomotor</u>

- Basically d.c. servomotor is more or less same as normal d.c.motor. There are some minor differences between the two.
- All d.c. servomotors are essentially separately excited type. This ensures linear torque-speed characteristics.
- The control of d.c. servomotor can be from field side or from armature side.
- Depending upon this, these are classified as field controlled d.c. servomotor and armature controlled d.c. servomotor.

<u>Field Controlled D.C. Servomotor</u>

- In this motor, the controlled signal obtained from the servo amplifier is applied to the field winding. With the help of constant current source, the armature current is maintained constant. The arrangement is shown in the Fig.



- This type of motor has large L_f / R_f ratio where L_f is reactance and R_f is resistance of field winding.
- Due to this the time constant of the motor is

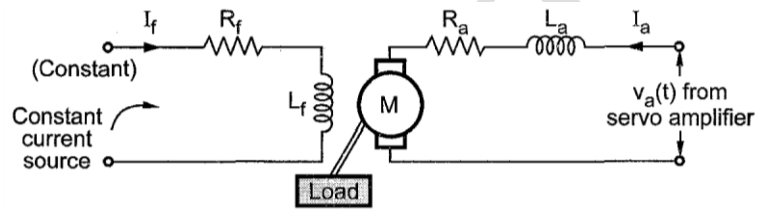
high. This means it cannot give rapid response to the quick changing control signals hence this is uncommon in practice.

Features of Field Controlled D.C. Servomotor

i) Preferred for small rated motors.
ii) It has large time constant.
iii) It is open loop system. This means any change in output has no effect on the input.
iv) Control circuit is simple to design.

Armature Controlled D.C. Servomotor

- In this type of motor, the input voltage 'V_a' is applied to the armature with a resistance of R_a and inductance L_a.
- The field winding is supplied with constant current I_f.
- Thus armature input voltage controls the motor shaft output. The arrangement is shown in figure.
- The constant field can be supplied with the help of permanent magnets. In such case no field coils are necessary.

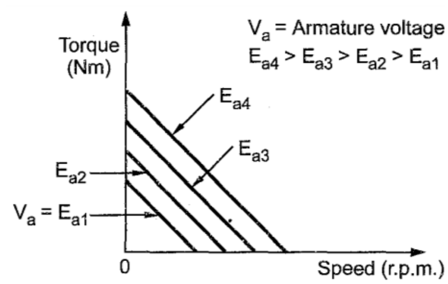


Features of Armature controlled DC Servomotor

(i) Suitable for large rated motors.
(ii) It has small time constant hence its response is fast to the control signal.
(iii) It is a closed loop system.
(iv) The back e.m.f. provides internal damping which makes motor operation more stable.
(v) The efficiency and overall performance is better than field controlled motor.

Characteristics of D.C. Servomotors

The characteristics of d.c. servomotors are mainly similar to the torque-speed characteristics of a.c. servomotor. The characteristics are shown in the Fig.



Applications of D.C. Servomotor

These are widely used in air craft control systems, electromechanical actuators, process controllers, robotics, machine tools etc.

STEPPER MOTORS

- These motors are also called stepping motors or step motors. The name stepper is used because this motor rotates through a fixed angular step in response to each input current pulse received by its controller.
- Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.
- The unique feature of a stepper motor is that its output shaft rotates in a series of discrete angular intervals or steps, one step being taken each time a command pulse is received.
- When a definite number of pulses are supplied, the shaft turns through a definite known angle. This fact makes the motor well-suited for open-loop position control because no feedback need be taken from the output shaft.
- Such motors develop torques ranging from 1 μN-m (in a tiny wrist watch motor of 3 mm diameter) upto 40 N-m in a motor of 15 cm diameter suitable for machine tool applications.
- Their power output ranges from about 1 W to a maximum of 2500 W. The only moving part in a stepping motor is its rotor which has no windings, commutator or brushes.
- This feature makes the motor quite robust and reliable.

Step Angle

- The angle through which the motor shaft rotates for each command pulse is called the step angle β.
- Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained.

Step angle $\beta = \frac{N_s - N_r}{N_s N_r} \times 360^0$ where N_s = No. of stator poles (teeth), N_r = No. of rotor poles (teeth)

Or $\beta = \frac{360^0}{m\ N_r} = \frac{360^0}{\text{No.of stator phases x No.of rotor teeth}}$

Resolution

Resolution is given by the number of steps needed to complete one revolution of the rotor shaft. Higher the resolution, greater the accuracy of positioning of objects by the motor

∴ Resolution = No. of steps / revolution = $360^o / \beta$

Slewing

When the pulse rate is high, the shaft rotation seems continuous. Operation at high speeds is called 'slewing'. When in the slewing range, the motor generally emits an audible whine having a fundamental frequency equal to the stepping rate. If f is the stepping frequency (or pulse rate) in pulses per second (pps) and β is the step angle, then motor shaft speed is given by

$$n = \beta \times f / 360 \text{ rps} = \text{pulse frequency resolution}$$

Applications:

- Such motors are used for operation control in computer peripherals, textile industry, IC fabrications and robotics etc.
- Applications requiring incremental motion are typewriters, line printers, tape drives, floppy disk drives, numerically-controlled machine tools, process control systems and *X -Y* plotters.
- Stepper motors also perform countless tasks outside the computer industry. It includes commercial, military and medical applications where these motors perform such functions as mixing, cutting, striking, metering, blending and purging.
- They also take part in the manufacture of packed food stuffs, commercial end-products

Types of Stepper Motors

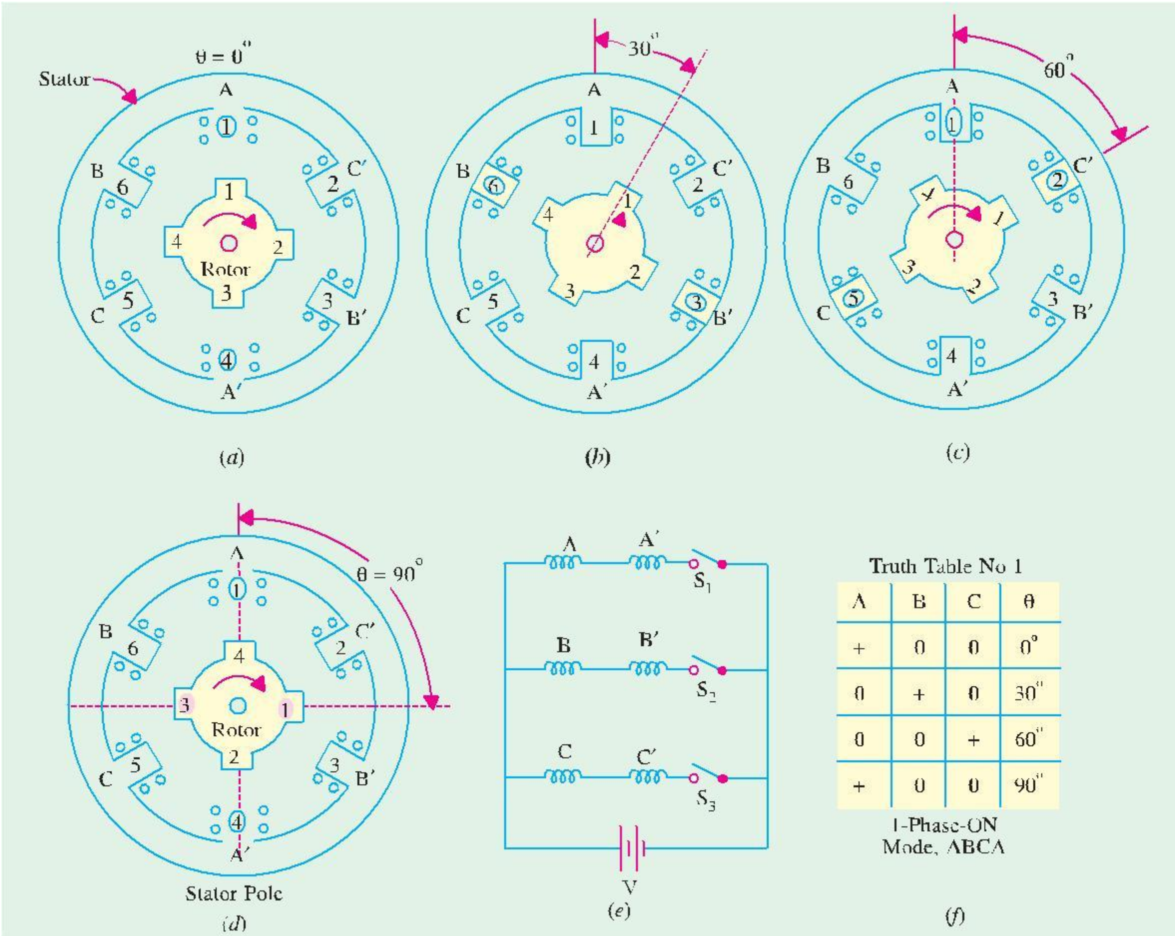
(i) Variable Reluctance Stepper Motor
(ii) Permanent Magnet Stepper Motor
(iii) Hybrid Stepper Motor

Variable Reluctance Stepper Motors

Construction:

- A variable-reluctance motor is constructed from ferromagnetic material with salient poles as shown in Fig.
- The stator is made from a stack of steel laminations and has six equally-spaced projecting poles (or teeth) each wound with an exciting coil.
- The rotor which may be solid or laminated has four projecting teeth of the same width as the stator teeth.
- There are three independent stator circuits or phases *A*, *B* and *C* and each one can be energised by a direct current pulse from the drive circuit.
- A simple circuit arrangement for supplying current to the stator coils in proper sequence is shown in Fig. (*e*).
- The six stator coils are connected in 2-coil groups to form three separate circuits called phases. Each phase has its own independent switch.
- Diametrically opposite pairs of stator coils are connected in series such that when one tooth becomes a *N*-pole, the other one becomes a *S*-pole.
- When there is no current in the stator coils, the rotor is completely free to rotate.
- Energising one or more stator coils causes the rotor to step forward (or backward) to a position that forms a path of least reluctance with the magnetized stator teeth.
- The step angle of this three-phase, four rotor teeth motor is $\beta = 360/ 4 \times 3 = 30^o$.

Working. The motor has following modes of operation:



(*a*) 1-phase-ON or Full-step Operation

- Fig. (*a*) shows the position of the rotor when switch S_1 has been closed for energising phase *A* .
- A magnetic field with its axis along the stator poles of phase *A* is created. The rotor is therefore, attracted into a position of minimum reluctance with diametrically opposite rotor teeth 1 and 3 lining up with stator teeth 1 and 4 respectively.
- Closing S_2 and opening S_1 energizes phase *B* causing rotor teeth 2 and 4 to align with stator teeth 3 and 6 respectively as shown in Fig. (*b*). The rotor rotates through full-step of 30º in the clockwise (CW) direction.
- Similarly, when S_3 is closed after opening S_2, phase *C* is energized which causes rotor teeth 1 and 3 to line up with stator teeth 2 and 5 respectively as shown in Fig. (*c*). The rotor rotates through an additional angle of 30º in the clockwise (CW) direction.
- Next if S_3 is opened and S_1 is closed again, the rotor teeth 2 and 4 will align with stator teeth 4 and 1 respectively thereby making the rotor turn through a further angle of 30º as shown in Fig. (*d*).
- By now the total angle turned is 90º. As each switch is closed and the preceding one opened, the rotor each time rotates through an angle of 30º.
- By repetitively closing the switches in the sequence 1-2-3-1 and thus energizing stator phases in sequence *A B C A* etc., the rotor will rotate clockwise in 30º steps.
- If the switch sequence is made 3-2-1-3 which makes phase sequence *CBAC* (or *ACB*), the rotor will rotate anticlockwise. This mode of operation is known as 1-phase-ON mode or full-step operation and is the simplest and widely-used way of making the motor step.
- The stator phase switching truth table is shown in Fig. (*f*). It may be noted that the direction of the stator magnetizing current is not significant because a stator pole of either magnetic polarity will always attract the rotor pole by inducing opposite polarity.

(*b*) 2-phase-ON Mode

- In this mode of operation, two stator phases are excited simultaneously.
- When phases *A* and *B* are energized together, the rotor experiences torques from both phases and comes to rest at a point mid-way between the two adjacent full-step positions.
- If the stator phases are switched in the sequence *A B*, *BC*, *C A*, *A B* etc., the motor will take full steps of 30º each (as in the 1-phase-*ON* mode) but its equilibrium positions will be interleaved between the full-step positions. The phase switching truth table for this mode is shown in Fig. (*a*).
- The 2-phase-ON mode provides greater holding torque and a much better damped single-stack response than the 1-phase-ON mode of operation.

Truth Table No. 2

A	B	C	θ
+	+	0	15°
0	+	+	45°
+	0	+	75°
+	+	0	105°

2 Phase-ON Mode
AB, BC, CA, AB

Truth Table No. 3

	A	B	C	θ	
A	+	0	0	0°	
	+	+	0	15°	AB
B	0	+	0	30°	
	0	+	+	45°	BC
C	0	0	+	65°	
	+	0	+	75°	CA
A	+	0	0	90°	

Half-Stepping Alternate
1-Phase-On &
2-Phase-on Mode
A, AB, B, BC, C, CA, A

(*c*) Half-step Operation

Half-step operation or 'half-stepping' can be obtained by exciting the three phases in the sequence *A*, *AB*, *B*, *BC*, *C* etc. *i.e*. alternately in the 1-phase-ON and 2-phase-ON modes. It is sometime known as 'wave' excitation and it causes the rotor to advance in steps of 15º *i.e*. half the full-step angle. The truth table for the phase pulsing sequence in half-stepping is shown in Fig. (*b*).

(*d*) Microstepping

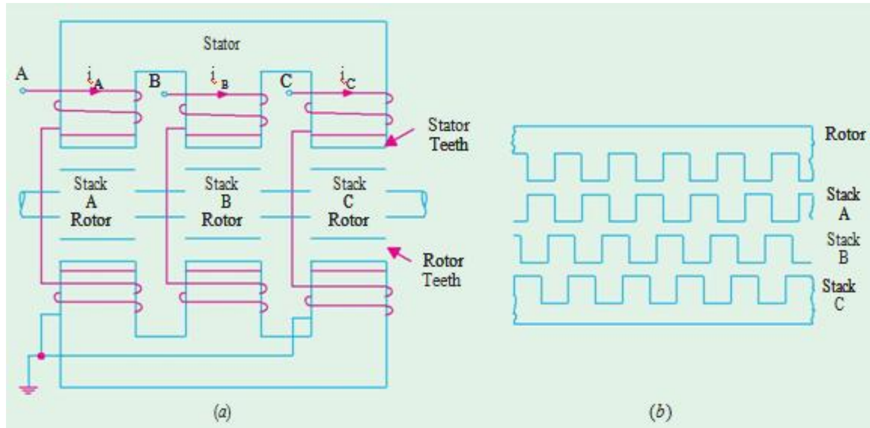
- It is also known as mini-stepping. It utilizes two phases simultaneously as in 2-phase-*ON* mode but with the two currents deliberately made unequal (unlike in half-stepping where the two phase currents have to be kept equal).
- The current in phase *A* is held constant while that in phase *B* is increased in very small increments until maximum current is reached. The current in phase *A* is then reduced to zero using the same very small increments.
- In this way, the resultant step becomes very small and is called a microstep.
- For example, a *VR* stepper motor with a resolution of 200 steps / rev (β = 1.8º) can with microstepping have a resolution of 20,000 steps / rev (β = 0.018º).
- Stepper motors employing microstepping technique are used in printing and phototypesetting where very fine resolution is called for.
- Microstepping provides smooth low-speed operation and high resolution.

Torque. If I_a is the d.c. current pulse passing through phase *A*, the torque produced by it is given by $T = (1/2)\, I_a^2\, dL/d\theta$. *VR* stepper motors have a high (torque / inertia) ratio giving high rates of acceleration and fast response.

A possible disadvantage is the absence of detent torque which is necessary to retain the rotor at the step position in the event of a power failure.

Multi-stack VR Stepper Motor

- Multi-stack motors provide smaller step angles.
- The multi-stack motor is divided along its axial length into a number of magnetically-isolated sections or stacks which can be excited by a separate winding or phase.
- Both stator and rotor have the same number of poles.
- The stators have a common frame while rotors have a common shaft as shown in Fig. (*a*) which represents a three-stack *VR* motor.
- The teeth of all the rotors are perfectly aligned with respect to themselves but the stator teeth of various stacks have a progressive angular displacement as shown in the developed diagram of Fig. (*b*) for phase excitation.



- Three-stack motors are most common although motors with upto seven stacks and phases are available.
- They have step angles in the range of 2º to 15º. For example, in a six-stack *V R* motor having 20 rotor teeth, the step angle β = 360º / 6 x 20 = 3º.

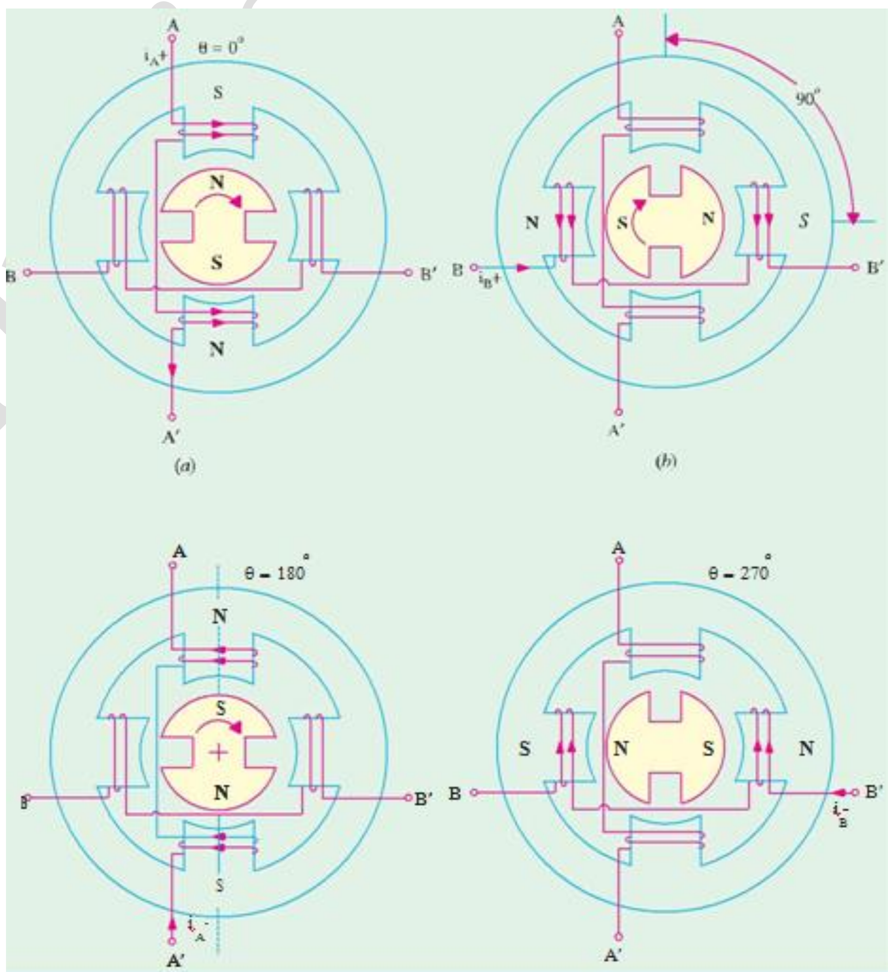
Permanent Magnet Stepper Motor

Construction

- Its construction is similar to that of the single stack VR motor except the rotor is made of a permanent magnet material like magnetically hard ferrite.
- The stator has projecting poles but the rotor is cylindrical and has radially magnetized permanent magnets.
- The operating principle is explained with fig. (a) where the rotor has two poles and stator has four poles.
- Since stator poles are energized by one winding, the motor has two windings or phases marked A and B.
- The step angle $\beta = 360^0 / mN_r = 360^0 / 2 \times 2 = 90^0$ or $\beta = (4 - 2) / 360^0 / 2 \times 4 = 90^0$.

Working.

- When a particular stator phase is energized, the rotor magnetic poles move into alignment with the excited stator poles. The stator windings *A* and *B* can be excited with either polarity current (A^+ refers to positive current i_{A+} in the phase A and A^- to negative current i_{A-}).
- The fig. (a) shows the condition when phase A is excited with positive current i_{A+}. Here $\theta = 0^0$.



- If excitation is now switched to phase *B* as in Fig. (*b*), the rotor rotates by a full step of 90º in the clockwise direction.
- Next, when phase *A* is excited with negative current i_A^-, the rotor turns through another 90º in *C W* direction as shown in Fig. (*c*).
- Similarly, excitation of phase *B* with i_B- further turns the rotor through another 90º in the same direction as shown in Fig. (*d*).
- After this, excitation of phase *A* with i_A+ makes the rotor turn through one complete revolution of 360º.

Truth Table No. 1

A	B	θ
+	0	0°
0	+	90°
–	0	180°
0	–	270°
+	0	0°

1-Phase-ON Mode

Truth Table No. 2

A	B	θ
+	+	45°
–	+	135°
–	–	225°
+	–	315°
+	+	45°

1-Phase-ON Mode

Truth Table No. 3

A	B	θ
+	0	0°
+	+	45°
0	+	90°
–	+	135°
–	0	180°
–	–	225°
0	–	270°
+	–	315°
+	0	0°

Alternate 1-Phase-On & 2-Phase-On Modes

- Table No.1 applies when only one phase is energized at a time in 1-phase-*ON* mode giving step size of 90º.
- Table No.2 represents 2-phase-*ON* mode when two phases are energised simultaneously. The resulting steps are of the same size but the effective rotor pole positions are midway between the two adjacent full-step positions.
- Table No.3 represents half-stepping when 1-phase-*ON* and 2-phase-*ON* modes are used alternately. In this case, the step size becomes half of the normal step or one-fourth of the pole-pitch (*i.e*. 90º / 2 = 45º or 180º / 4 = 45º). Microstepping can also be employed which will give further reduced step sizes thereby increasing the resolution.

Advantages and Disadvantages.

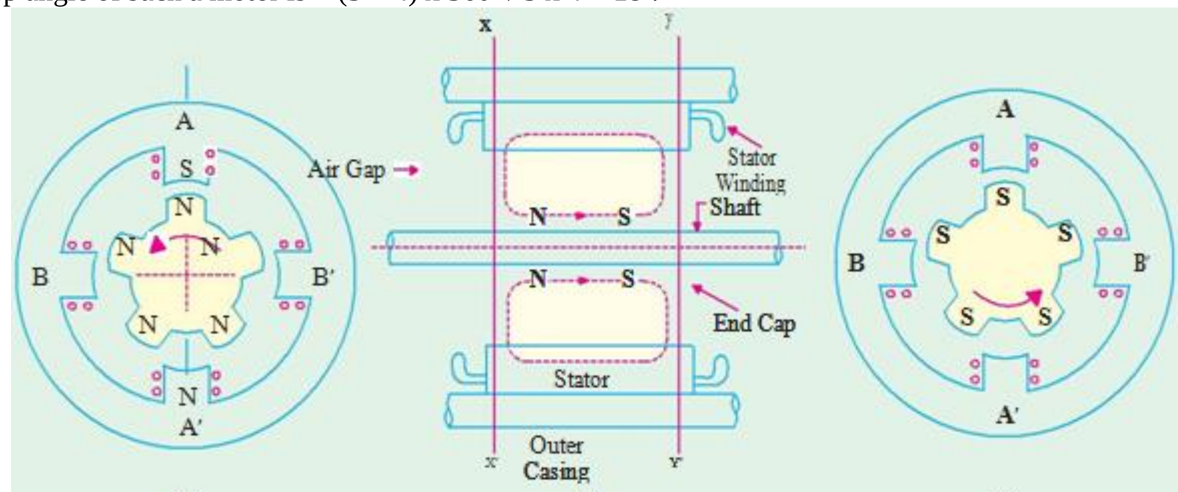
- Since the permanent magnets of the motor do not require external exciting current, it has a low power requirement but possesses a high detent torque as compared to a *VR* stepper motor.
- This motor has higher inertia and hence slower acceleration.
- However, it produces more torque per ampere stator current than a *VR* motor.
- Since it is difficult to manufacture a small permanent-magnet rotor with large number of poles, the step size in such motors is relatively large ranging from 30º to 90º.

Hybrid Stepper Motor

Construction.

- It combines the features of the variable reluctance and permanent-magnet stepper motors.
- The rotor consists of a permanent-magnet that is magnetized axially to create a pair of poles marked *N* and *S* in Fig. (*b*).
- Two end-caps are fitted at both ends of this axial magnet. These end-caps consist of equal number of teeth which are magnetized by the respective polarities of the axial magnet.

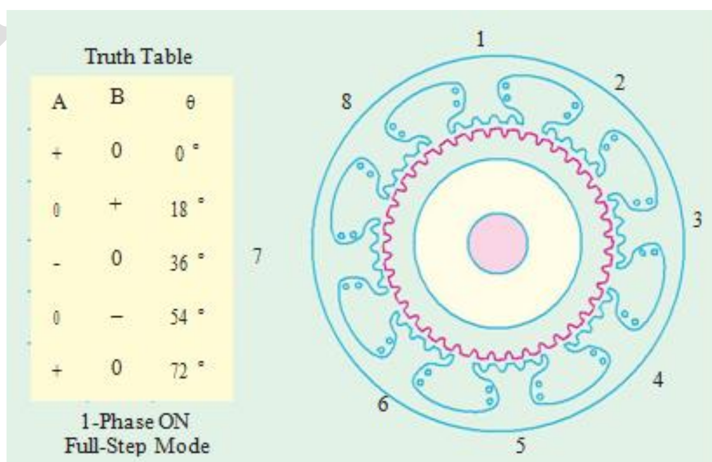
- The rotor teeth of one end-cap are offset by a half tooth pitch so that a tooth at one end-cap coincides with a slot at the other. The cross-sectional views perpendicular to the shaft along X -*X ′* and *Y* -*Y ′* axes are shown in Fig. (*a*) and (*c*) respectively.
- As seen, the stator consists of four stator poles which are excited by two stator windings in pairs. The rotor has five *N*-poles at one end and five *S*-poles at the other end of the axial magnet.
- The step angle of such a motor is = (5 − 4) x 360º / 5 x 4 = 18º.



(*a*) (*b*) (*c*)

Working.

- In Fig. (*a*), phase *A* is shown excited such that the top stator pole is a *S*-pole so that it attracts the top *N*-pole of the rotor and brings it in line with the *A* -*A ′* axis.
- To turn the rotor, phase *A* is denergized and phase *B* is excited positively. The rotor will turn in the CCW direction by a full step of 18º.
- Next, phase *A* and *B* are energized negatively one after the other to produce further rotations of 18º each in the same direction. The truth table is shown in Fig. (*a*).
- For producing clockwise rotation, the phase sequence should be A^+; B^-; A^-; B^+; A^+ etc.
- In order to give high resolution, hybrid stepping motors are built with more rotor poles.
- Hence, the stator poles are often slotted or castleated to increase the number of stator teeth.
- As shown in Fig. (*b*), each of the eight stator poles has been alloted or castleated into five smaller poles making N_s = 8 x 5 = 40º.
- If rotor has 50 teeth, then step angle = (50 − 40) x 360º / 50 x 40 = 1.8º.
- Step angle can also be decreased (and hence resolution increased) by having more than two stacks on the rotor.



A	B	θ
+	0	0 °
0	+	18 °
-	0	36 °
0	–	54 °
+	0	72 °

1-Phase ON
Full-Step Mode

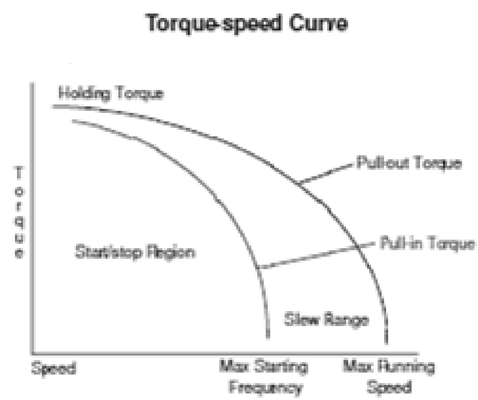
(*a*) (*b*)

- This motor achieves small step sizes easily and with a simpler magnet structure whereas a purely *PM* motor requires a multiple permanent-magnet.
- As compared to *VR* motor, hybrid motor requires less excitation to achieve a given torque.
- However, like a *PM* motor, this motor also develops good detent torque provided by the permanent-magnet flux. This torque holds the rotor stationary while the power is switched off.
- This fact is quite helpful because the motor can be left overnight without fear of its being accidentally moved to a new position.

Summary of Stepper Motors

- A stepper motor can be looked upon as a digital electromagnetic device where each pulse input results in a discrete output *i.e*. a definite angle of shaft rotation. It is ideally-suited for open-loop operation because by keeping a count of the number of input pulses, it is possible to know the exact position of the rotor shaft.
- In a *VR* motor, excitation of the stator phases gives rise to a torque in a direction which minimizes the magnetic circuit reluctance. The reluctance torque depends on the square of the phase current and its direction is independent of the polarity of the phase current. A *VR* motor can be a single-stack or multi-stack motor. The step angle $\beta = 360^o / m\,N_r$ where N_r is the number of rotor teeth and m is the number of phases in the single-stack motor or the number of stacks in the multi-stack motor.
- A permanent-magnet stepper motor has a permanently-magnetized cylindrical rotor. The direction of the torque produced depends on the polarity of the stator current.
- A hybrid motor combines the features of *VR* and *PM* stepper motors. The direction of its torque also depends on the polarity of the stator current. Its step angle $\beta = 360^o / m\,N_r$.
- In the 1-phase *ON* mode of excitation, the rotor moves by one full-step for each change of excitation. In the 2-phase-*ON* mode, the rotor moves in full steps although it comes to rest at a point midway between the two adjacent full step positions.
- Half-stepping can be achieved by alternating between the 1-phase-*ON* and 2-phase-*ON* modes. Step angle is reduced by half.
- Microstepping is obtained by deliberately making two phase currents unequal in the 2-phase-*ON* mode.

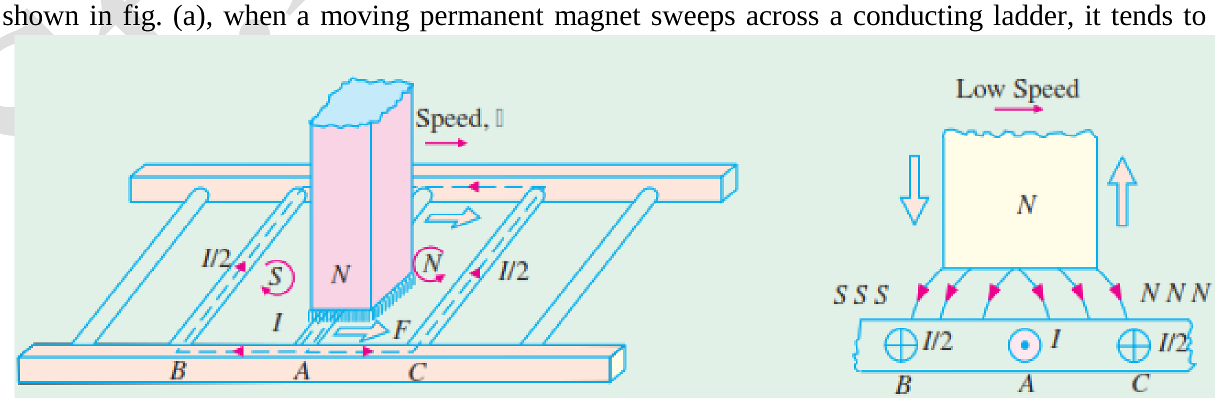
Important Definitions



Holding Torque - amount of torque that the motor produces when it has rated current flowing through the windings but the motor is at rest.
Detent Torque - amount of torque that the motor produces when it is not energized. No current is flowing through the windings.
Pull-in Torque Curve - Shows the maximum value of torque at given speeds that the motor can start, stop or reverse in synchronism with the input pulses. The motor cannot start at a speed that is beyond this curve. It also cannot instantly reverse or stop with any accuracy at a point beyond this curve.
Stop / Start Region - area on and underneath the pull-in curve. For any load value in this region, the motor can start, stop, or reverse "instantly" (no ramping required) at the corresponding speed value.
Pull-out Torque Curve - Shows the maximum value of torque at given speeds that the motor can generate while running in synchronism. If the motor is run outside of this curve, it will stall.
Slew Range - the area between the pull-in and the pull-out curves, where to maintain synchronism, the motor speed must be ramped (adjusted gradually).

INTRODUCTION TO MAGNETIC LEVITATION SYSTEMS

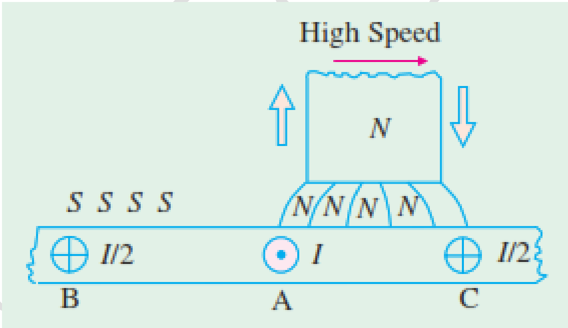
- As shown in fig. (a), when a moving permanent magnet sweeps across a conducting ladder, it tends to drag the



(*a*) (*b*) Gateway

ladder along with, because it applies a horizontal tractive force F = BI*l* .

- This horizontal force will be accompanied by a vertical force, which tends to push the magnet away from the ladder in the upward direction.
- A portion of the conducting ladder of fig. (a) has been shown in fig. (b). the voltage induced in conductor A is maximum because flux is greatest at the centre of the N pole.
- If the magnet speed is very low, the induced current reaches its maximum value in A at virtually the same time (because delay due conductor inductance is negligible).
- As this current flows via conductors B and C, it produces induced SSS and NNN poles.
- Consequently, the front half of the magnet is pushed upwards while the rear half is pulled downwards.
- Since the distribution of SSS and NNN pole is symmetrical with respect to the centre of the magnet, the vertical forces of attraction and repulsion, being equal and opposite, cancel each other out, leaving behind only horizontal tractive force.
- Consider the case, when the magnet sweeps over the conductor A with a very high speed.



- Due to conductor inductance, current A reaches its maximum value a fraction of a second (Δt) after voltage reaches its maximum value.
- Hence, by the time I in conductor A reaches its maximum valu, the centre of the magnet is already ahead by a distance = $v.\Delta t$ where v is the magnet velocity.
- The induced poles SSS and NNN are produced as before, by the currents returning via conductors B and C respectively.
- But, by now, the N pole of the permanent magnet lies over the induced NNN pole, which pushes it upwards with a strong vertical force. This forms the basis of magnetic levitation which literally means 'floating in air'.
- Magnetic levitation is being used in ultra high speed trains (upto 300 km/h) which float in the air about 100mm to 300mm above the metallic track.
- They do not have any wheels and do not require the traditional steel rail.
- A powerful electromagnet fixed underneath the train moves across the conducting rail, thereby inducing current in the rail. This gives raise to vertical force called force of levitation, which keeps the train pushed up in the air above the track.
- Linear motors are used to propel the train.