Module 1

EE202

Synchronous & Induction Machines

SYLLABUS

Alternators - basic principle, constructional features of salient pole type and cylindrical type alternators, advantages of stationary armature, turbo-alternator.

Armature winding – types of armature winding- single layer, double layer, full pitched and short pitched winding, slot angle, pitch factor and distribution factor – numerical problems.

Effect of pitch factor on harmonics – advantages of short chorded winding,

EMF Equation – numerical problems. Harmonics in generated EMF – suppression of harmonics.

INTRODUCTIO
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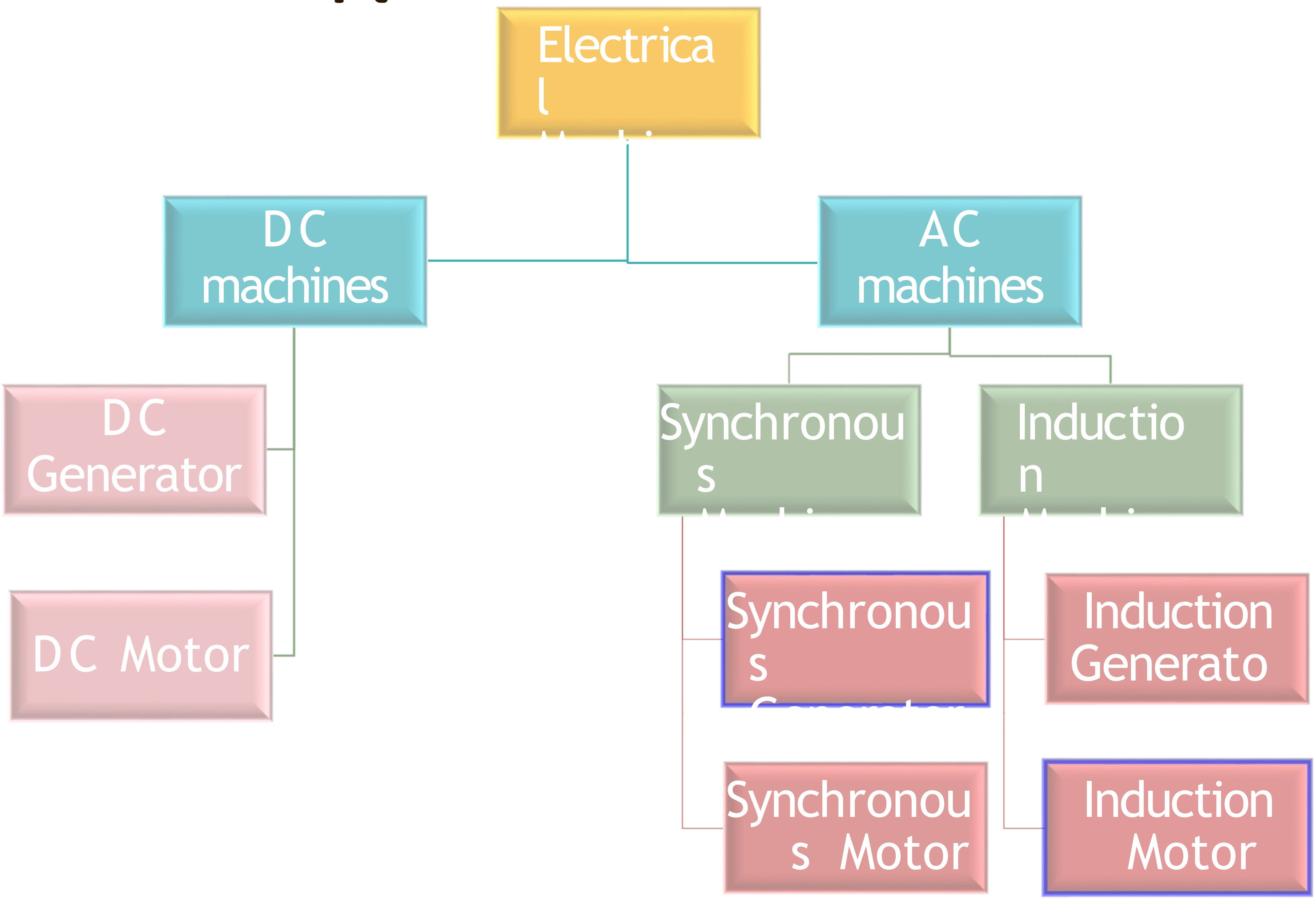
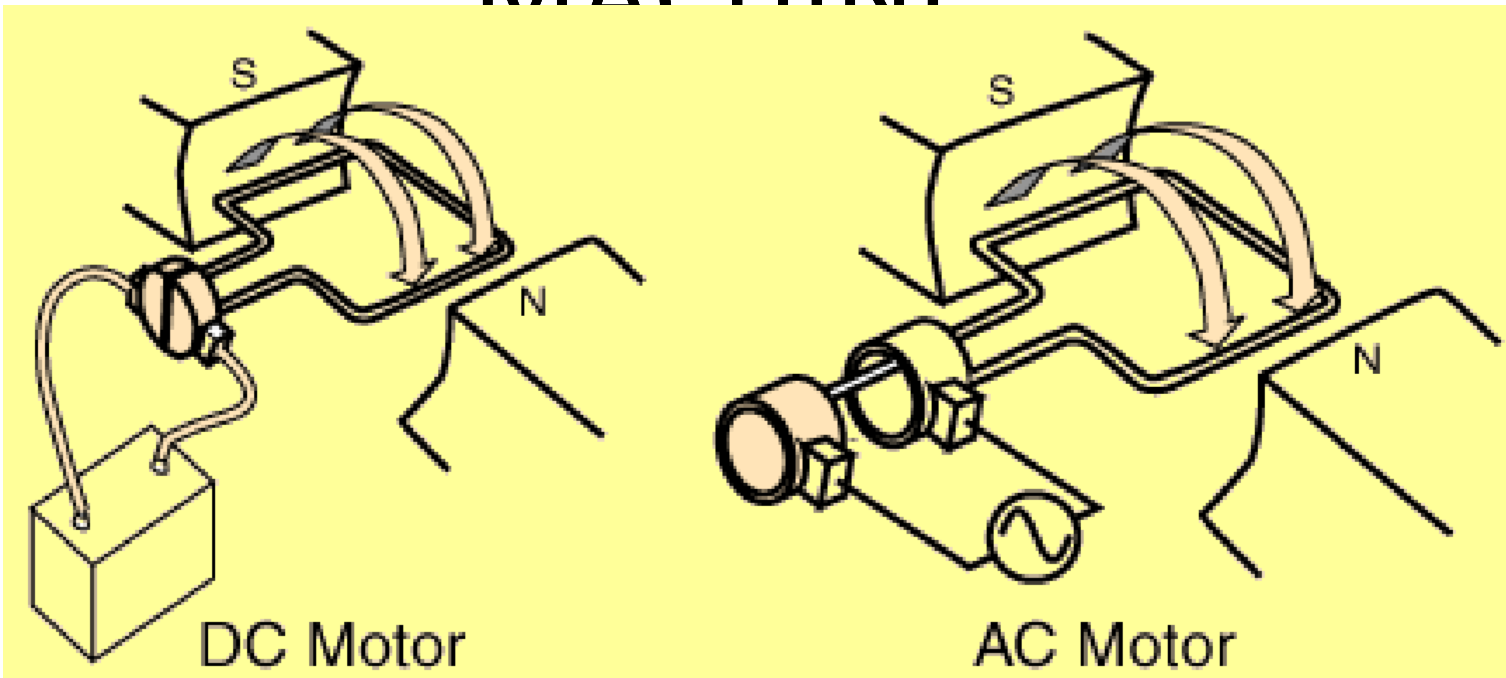


DC MACHINE & AC MACHINE



DC motor - ends of the coil connected to a mechanical rectifier called commutator to 'rectify' the emf produced.

AC motor - No rectification needed- no commutator - split rings are used**.**

AC GENERATOR

- Alternating Current Generator – Alternator

- Alternator – Synchronous Generator (mechanical energy to electrical energy)

- Synchronous Machine converting electrical energy to mechanical energy – Synchronous Motor

PRINCIPLE OF OPERATION

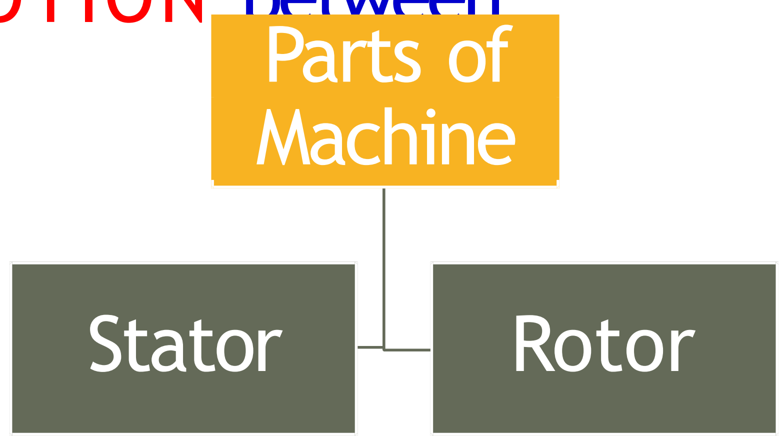
- Faraday's Laws
  - Whenever flux linking a conductor changes an emf is induced in it
  - The induced emf is directly proportional to rate of change of flux linkage
- Lenz's Law
  - The direction of emf is such that the current set by it tends to oppose the change producing it.

$$e = -\frac{dT\phi}{dt}$$

T – no. of Turns
Φ- Flux

CONSTRUCTIONAL REQUIREMENTS

- FIELD System
- System of CONDUCTORS – ARMATURE
- RELATIVE MOTION between Armature the Field and



CONSTRUCTIONAL REQUIREMENTS

- Relative Motion can be achieved by keeping Field as stator and Armature as rotor or vice-versa
  - Stationary Field system
  - Rotating Field system
- Rotor is connected to the external circuit using *slip-rings and brushes*.

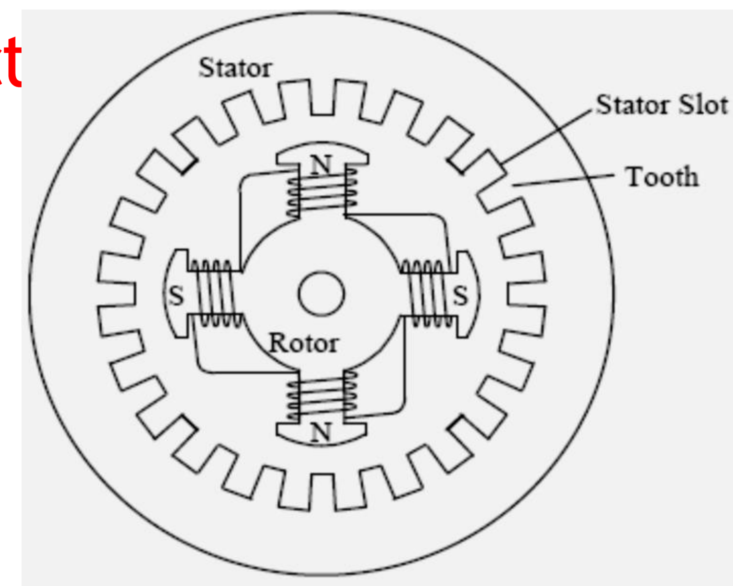
ROTATING FIELD SYSTEM- ADVANTAGES

High power in Stator & Low power in Rotor

1. Field system requires only about 2% Power capacity of the machine – low power easily transferred through slip rings.
2. More space for insulation of high voltage stator. (Insulation depends on kVA rating)
3. Stator insulation is protected against centrifugal forces due to rotation. – No Mechanical

ROTATING FIELD SYSTEM- ADVANTAGES

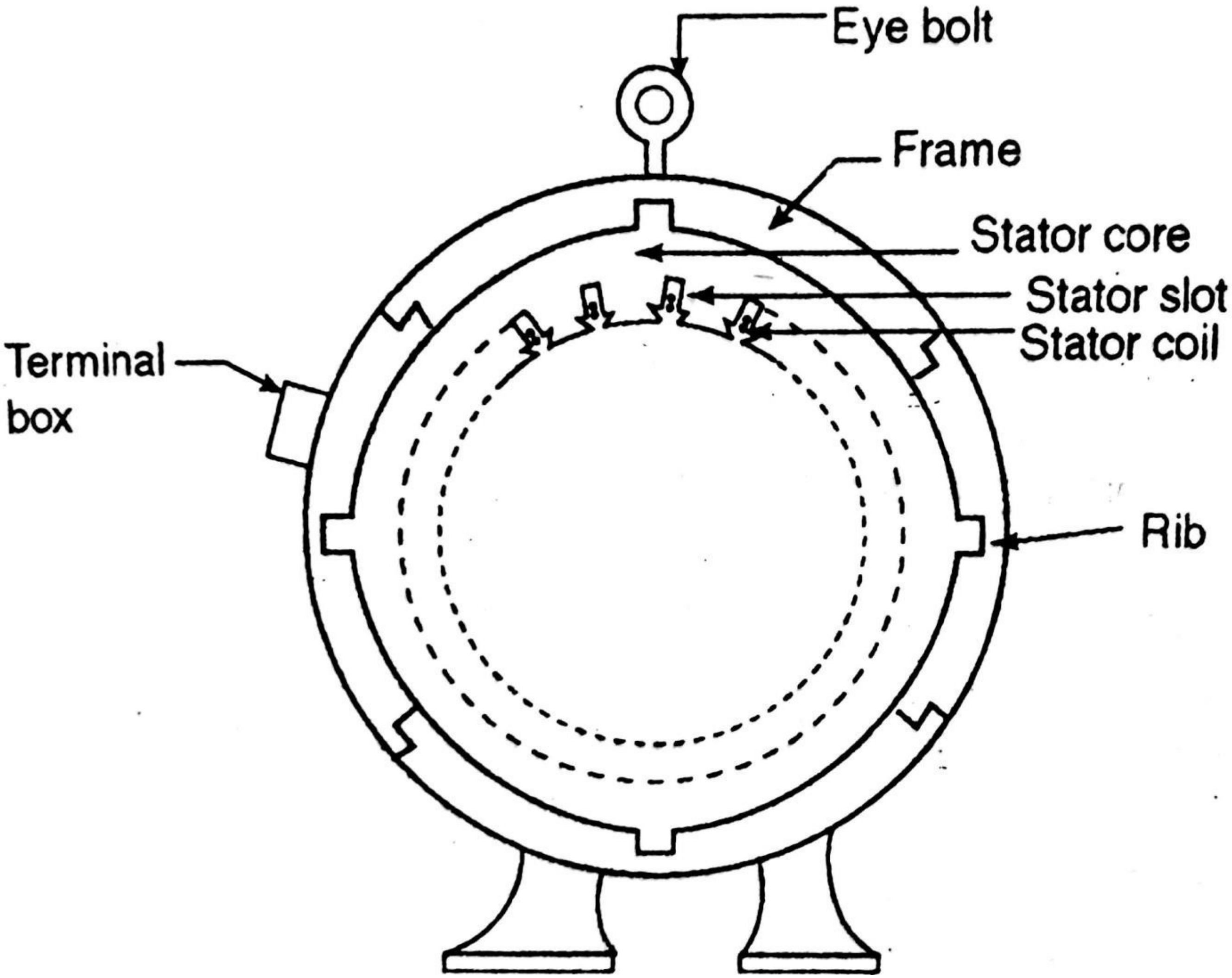
5. Stator conductors can be easily braced against Electromagnetic Stresses from any short circuits
6. Easier cooling to the stationary system.
7. Firm connect … or high kVA rating.



STATOR- ***PARTS***

1. Frame
2. Stator Core
3. Stator Windings
4. Cooling arrangements

STATOR- ***PARTS***



STATOR- ***PARTS***

- **Frame**
  - Gives support and protection to other parts
  - Made of cast iron for smaller machines and welded steel for larger machines
  - Smaller machines- single hollow cylindrical piece
  - Larger machines- Arcs joined together
  - Fins on outer surface increase surface area- heat dissipation
  - Eye-bolt on top – transit purposes

STATOR- ***PARTS***

- **Stator Core**
  - Provides Slots to place winding
    - No. of slots, S = x(3P), x=1,2.. , P = no. of poles
    - Types- open, semi open, closed considering efficiency, noise, heating
  - Path for the magnetic field
  - Made of high grade steel (reduce reluctance) with silicon (reduce hysteresis loss)

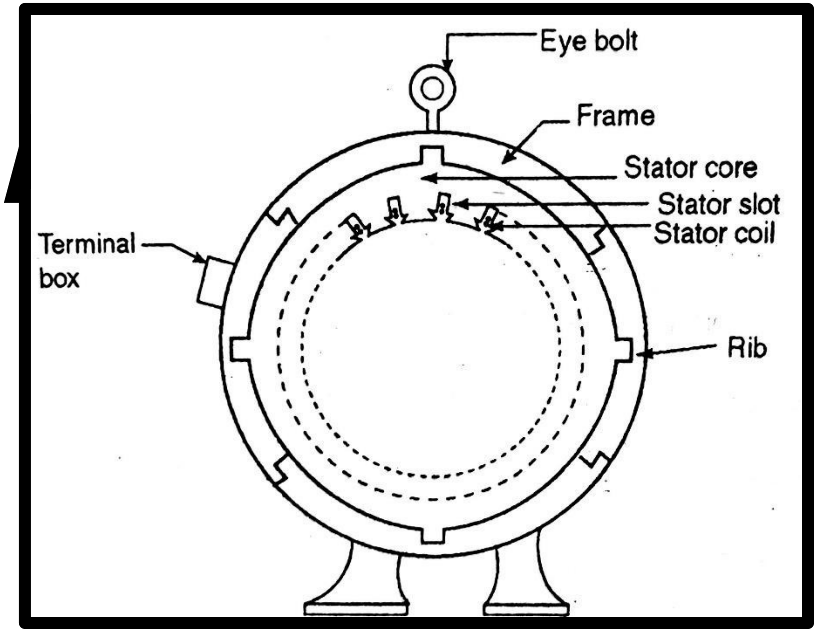
CONSTRUCTION

STATOR- ***PARTS***

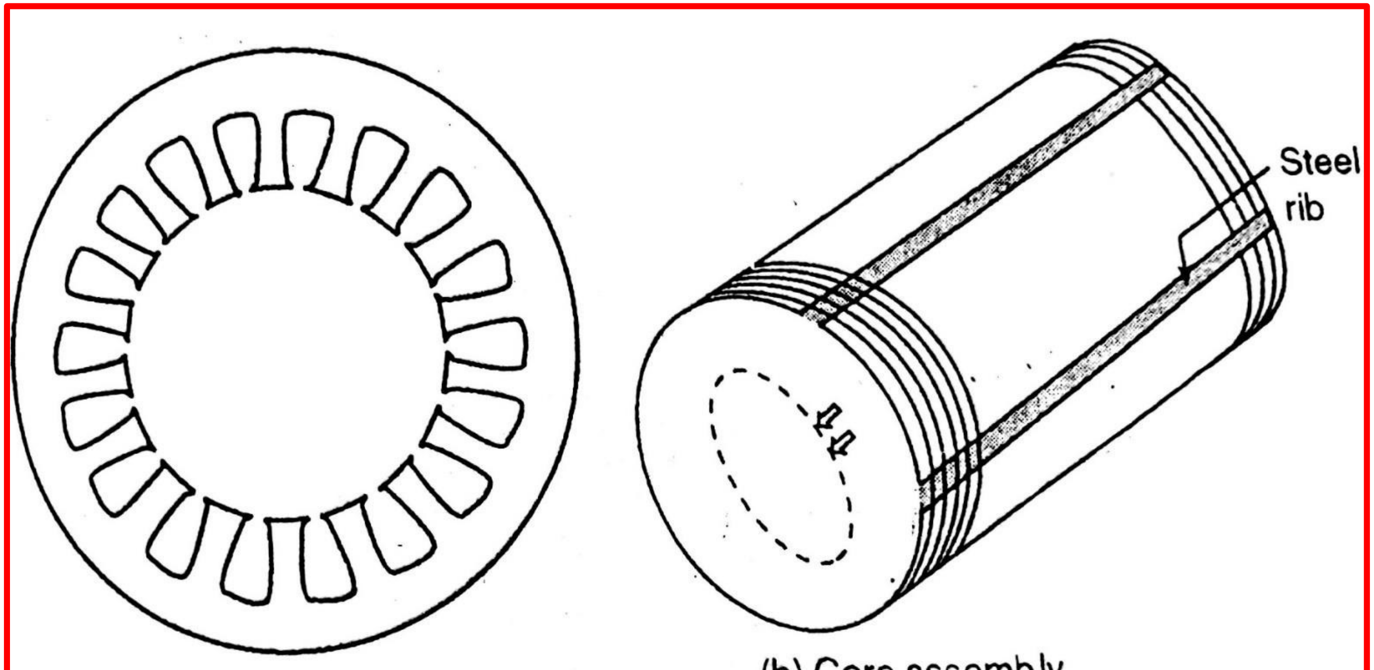
- **Stator Core**
  - Thin sheets (0.5mm thick) are stacked together to form a hollow cylinder to reduce eddy current loss
    - Insulation is provided between the sheets using paper or varnish or other chemical treatment.
    - After every 10 cm a gap for ventilation is provided
    - Held together using thick end plates and insulated bolts.

CONSTRUCTION

STATOR-



- **Stator Core**



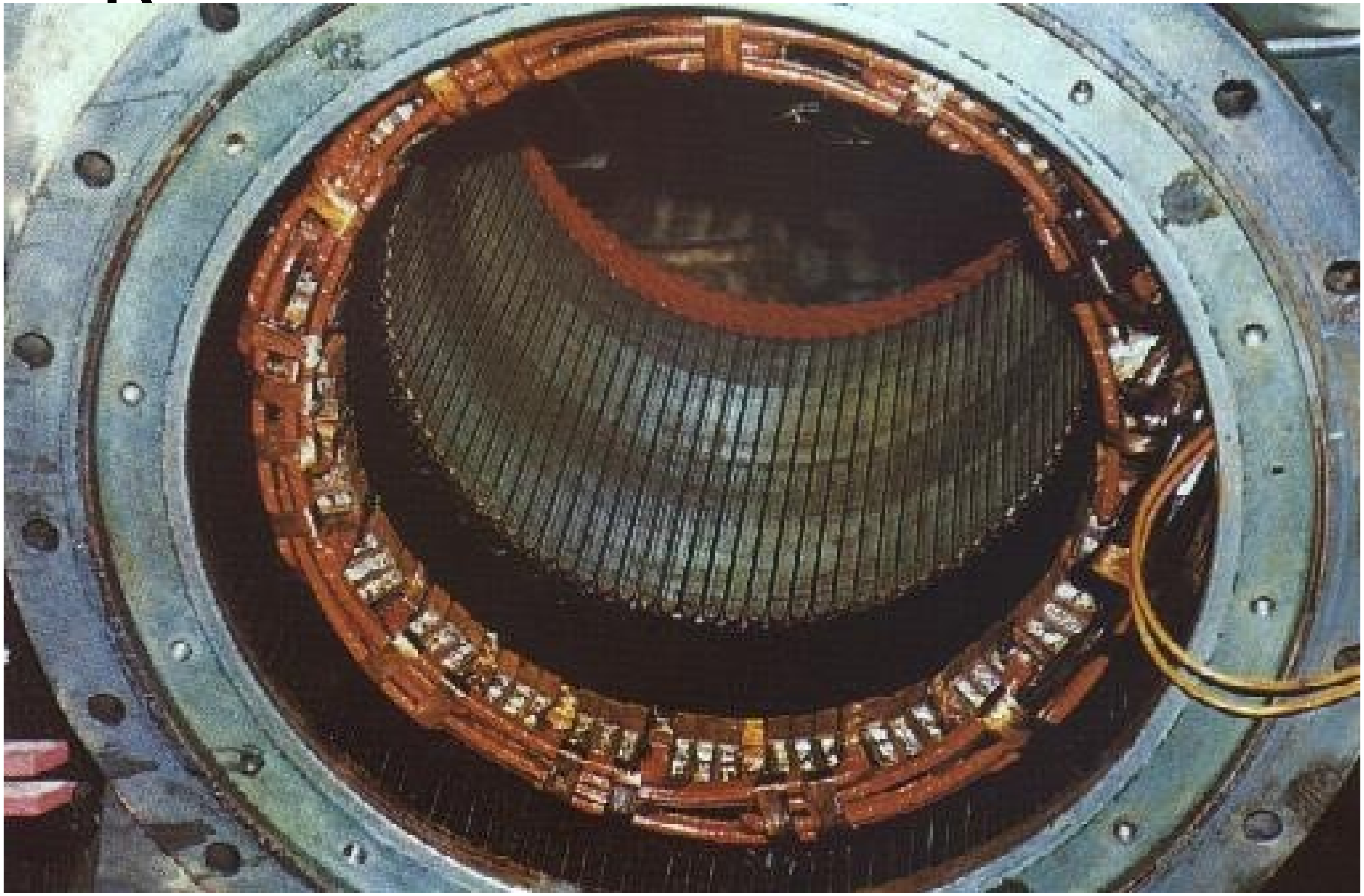
(a) Stator stamping

(b) Core assembly

STATOR- *PARTS*

- **Stator Winding**
  - AC winding (3-Phase)
  - Former wound windings are place in the slots after proper insulation
  - The slots are then closed with wooden wedges
  - Coils belonging to each phase are normally connected in series
  - One starting end and one finishing end are available outside for each phase

STATOR-



ROTOR

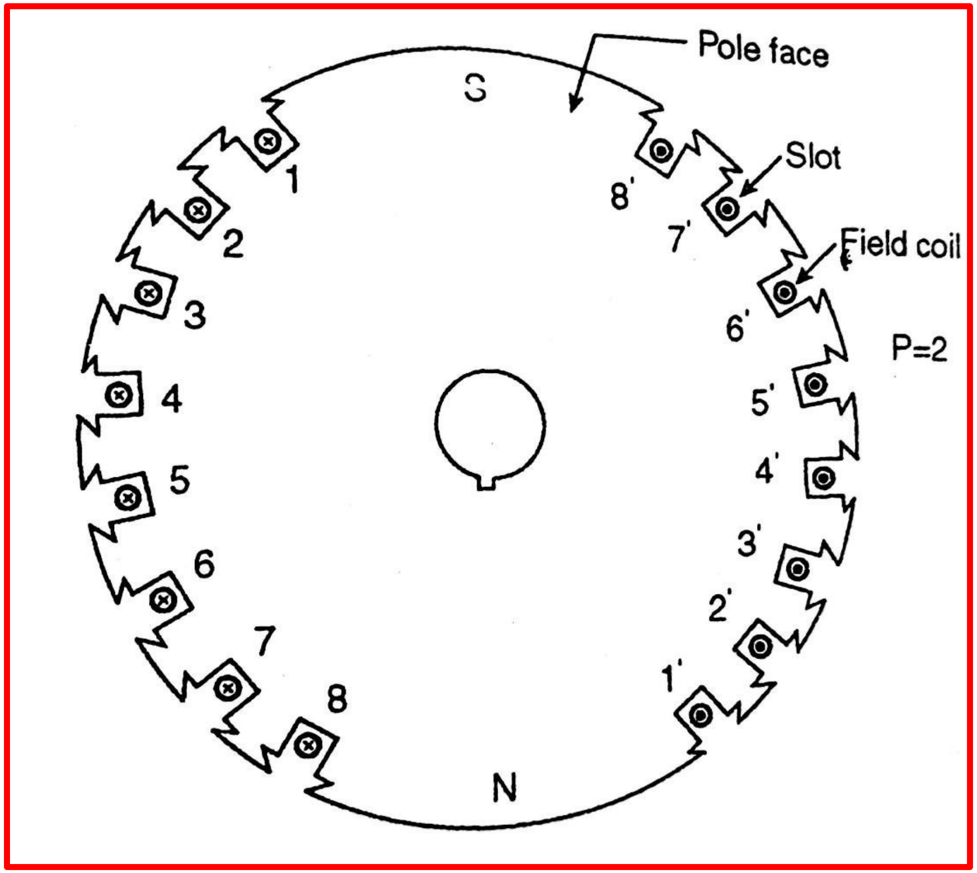
- POLES-
  - Contains even no. of poles
  - Electromagnetic poles for control of generated emf.
  - No. of poles depends on the speed of operation (which depends on the type of turbine or the source of mechanical power)
- Excitation is given by an external source or a built in generator (exciter)
- Excitation is given through slip-rings fixed on the shaft.

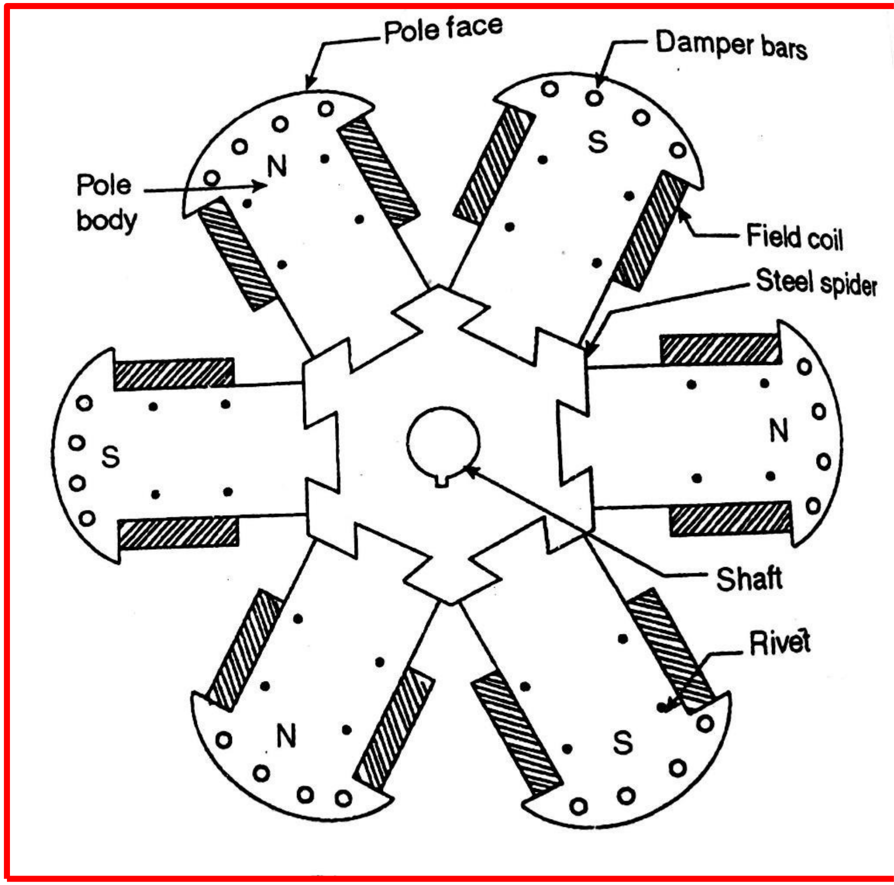
CONSTRUCTION

ROTOR-TYPES

SMOOTH CYLINDRICAL

SALIENT-POLE





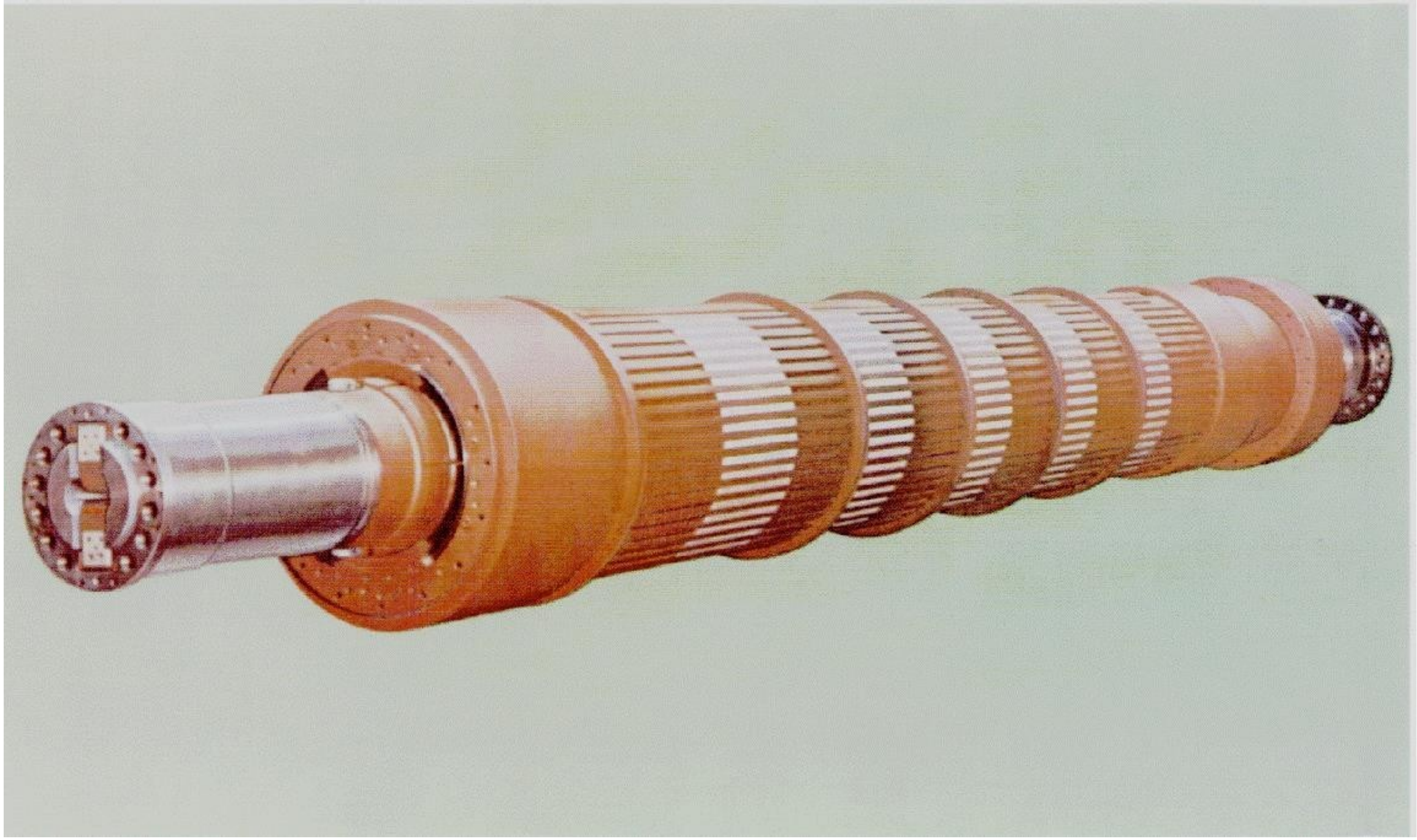
SMOOTH CYLINDRICAL ROTOR

- Smooth outer surface and cylindrical shape
- Material- alloy steel
- Used in high speed application
- For the same kVA rating – smaller diameter and longer axial length
- Outer periphery- slots parallel to the shaft
- All coils are connected in series
- Two sides of the same coil are 180 deg apart
- Some portion is left unslotted to form pole phases

SMOOTH CYLINDRICAL ROTOR

- Forced ventilation for proper cooling
- Flux density is maximum along the pole axis and gradually falls away
- Heavy wedges of non-magnetic steel keep the coils intact inside the slots

SMOOTH CYLINDRICAL ROTOR



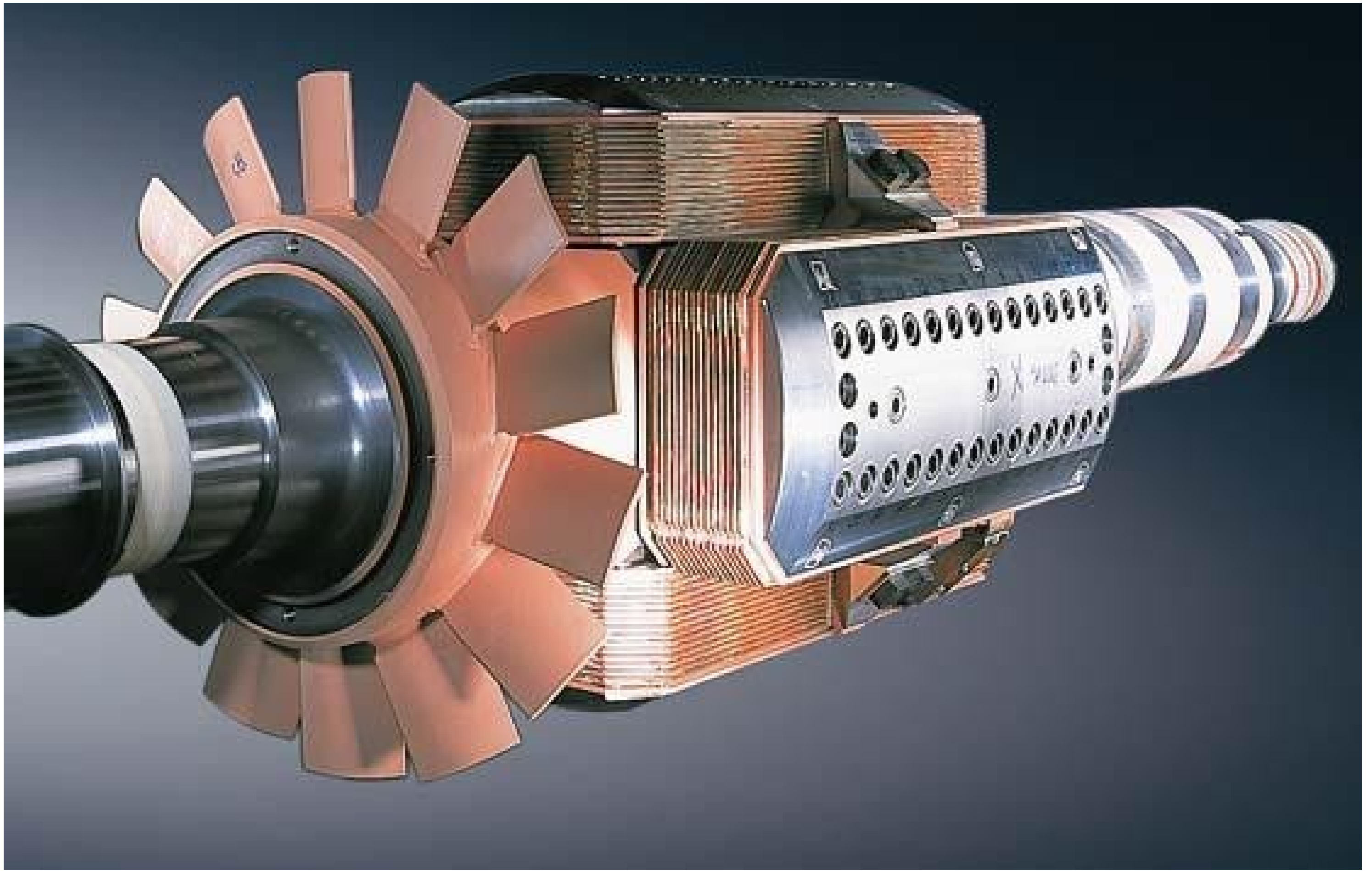
SALIENT POLE ROTOR

- Projected poles
- Medium and small speed operation
- Material of pole body – laminated steel
- Field coils are wound around the pole body
- Poles are fitted together using steel spider
- Pole faces- Shaped for sinusoidal distribute the air gap
  - for generation of sinusoidal emf.
- All coils are connected in series and two end terminals are brought outside to two slip rings on the shaft

SALIENT POLE ROTOR

- Through brushes connections are taken to the terminal box
- When DC supply is given, alternate North and South poles are set up.
- DAMPER WINDINGS-
  - Damps out oscillations when machine is subjected to sudden load changes
  - Copper bars in closed slots in the pole faces

SALIENT POLE ROTOR



SLIP-RINGS AND BRUSHES

ARMATURE INDUCED VOLTAGE

- Frequency of Induced EMF
- Concept of Electrical Degrees and Phase difference
- Constructional Features affecting the induced emf:
  - Armature winding construction – Winding Factor
    - Distribution Factor
    - Pitch Factor
  - Field construction
- dfeger

FREQUENCY OF INDUCED EMF

- P = No. of poles
- N = Speed of rotation (of field) in rpm (rotations per minute)
- n = no. of rotations per second = N/60 rps,
- f = frequency of induced emf in Hz (per second)
- P/2 = no. of pole pairs.
- One cycle of emf : one +ve cycle + one –ve cycle ie when a conductor passes over one pair of poles. For one rotation, the conductor emf goes through P/2 cycles
- No. of cycles of emf per second,

  f = No. of cycles in one rotation * No. of rotations in one second

  = P/2 * n = P/2 * N/60
- Thus, **f = PN/120**

NOTE: WHY 'SYNCHRONOUS MACHINE'

- **Synchronous machine** – Speed of flux (Synchronous speed) = Speed of machine
- **Synchronous generator** – works synchronously with other alternators connected to the Grid
- **Synchronous motor** – Speed of motor is synchronous with speed of flux i.e directly related to frequency of the supply

ELECTRICAL & MECHANICAL ANGLE

- **Mechanical angle:** With Reference to spacial or physical location, one complete rotation = 360 deg. mech.
- **Electrical angle:** With Reference to polarity of Magnetic field, one cycle of flux distribution waveform completes in 360 deg. ele.
- For both:
- **0 deg - Reference point**
- **180 deg - Opposite point**
- **360 deg - Similar point**

ELECTRICAL & MECHANICAL ANGLE IN ELECTRICAL MACHINE

- point same as Mechanical reference)
- 180 deg – Opposite point (Points under two adjacent poles (N and S) are 180 deg apart as flux direction is ecactly opposite under each)
- 360 deg – Similar point

- **Mechanical Angle**
  - 0 deg – Reference point (starting (starting point same as electrical reference)
  - 180 deg – Opposite point (Physically opposite point or direction)
  - 360 deg – Similar point (same as reference)
- **Electrical Angle**
  - 0 deg – Reference point

ELECTRICAL & MECHANICAL ANGLE IN ELECTRICAL MACHINE

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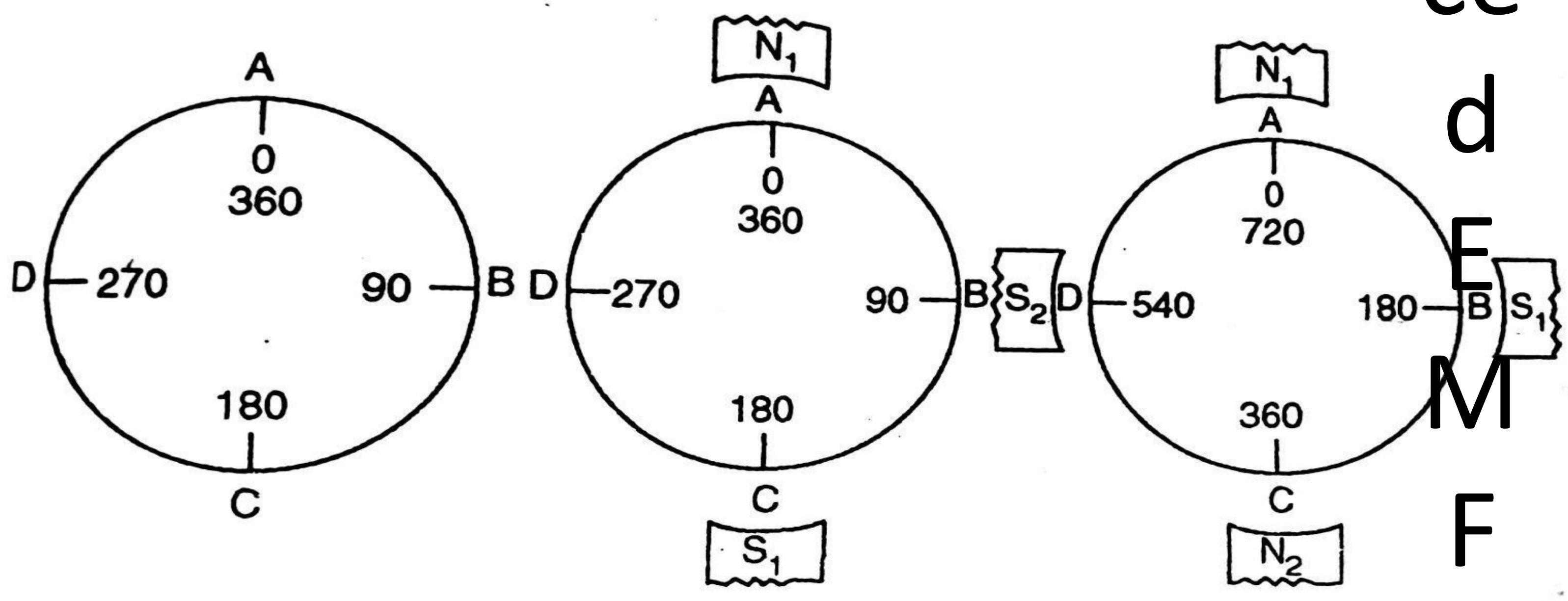


(a) Mechanical degree

(b) Electrical degree -2 pole machine

(c) Electrical degree -4 pole machine

3-PHASE WINDING

- **DC windings** – closed windings, with or without parallel paths
- **AC windings** -
  - open ended
  - no parallel paths
  - 3 identical sets for the 3 phases
  - Two end terminals for each phase
  - The phases can be connected in star or delta externally

SOME TERMS & SYMBOLS

- S – Total No. of slots
- P – No. of poles
- m – No. of slots per pole per phase $= \frac{S}{3P}$
- β – Angle between adjacent slots
- $m\beta$ – phase spread
- C – No. of coils
- Coil side
- u – no. of coil sides per slot

3-PHASE WINDING - TYPES

1. Single Layer & Double layer
2. Integral-slot & Fractional-slot
3. Concentrated & Distributed
4. Full-pitched & Short-pitched
5. Lap,Wave & Concentric

More no. of conductors can produce larger voltage.
Large no. of conductors require more no. of slots, more than a single layer of winding and therefore a distributed winding around the inner periphery of the stator

MODULE II

Performance of Alternator – Causes of voltage drop in Alternator, Synchronous impedance, Phasor diagram of loaded Alternator, Voltage regulation

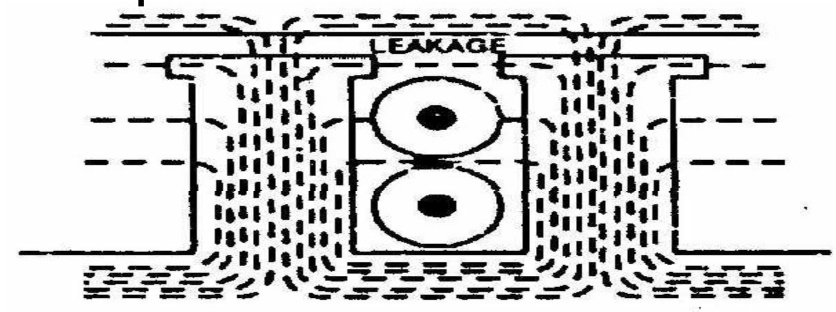
Alternator on load

- When load on the alternator is varied (i.e, armature current is varied), the terminal voltage (V) of the alternator also varies, even if the speed & field excitation kept constant
- The variation in terminal voltage is due to the following reasons
  1. Voltage drop due to armature resistance (IR_a drop)
  2. Voltage drop due to armature leakage reactance (IX_L drop)
  3. Voltage drop due to armature reaction

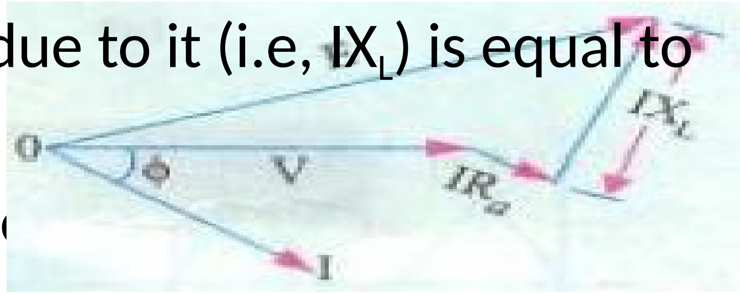
1. ***Armature resistance (R_a)*** – Since the armature (stator) winding has some resistance, there will be an IR_a drop when armature current flows through it
2. ***Armature leakage reactance (X_L)*** - When current flows through the stator winding, flux is set up and a part of it does not cross the air-gap and links the coil sides as shown in figure. This flux is called leakage flux.

   - The leakage flux is proportional to stator current

- The leakage flux alternates with current & produces a self-induced EMF in the stator winding



- This self induced EMF leads stator current by $\pi/2$ & proportional to stator current in magnitude
- Hence armature winding is assumed to possess an armature leakage reactance (X_L) such that the voltage drop due to it (i.e, IX_L) is equal to an EMF set up by leakage flux



- A part of the generated EMF is used to ov reactance drop
- Generated EMF is the phasor sum of terminal voltage, armature resistance drop & leakage reactance drop
- $E = V + IR_a + jIX_L = V + I(R_a+jX_L)$

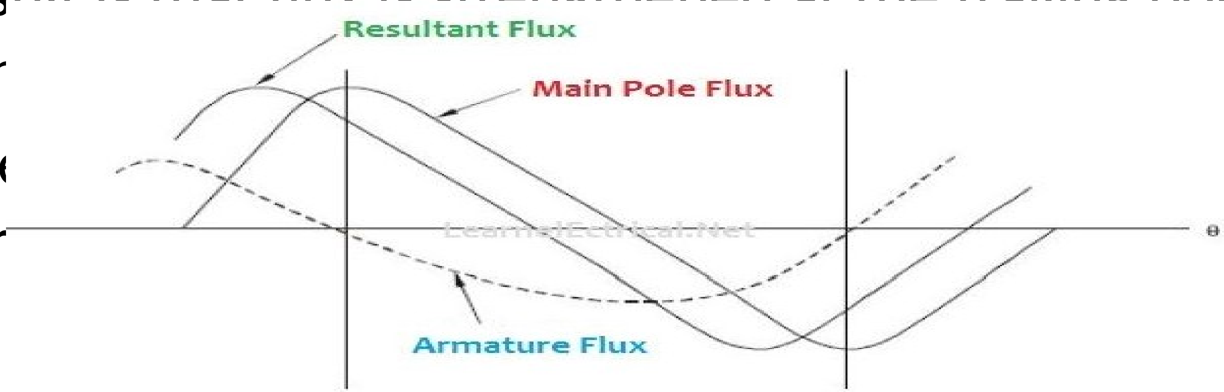
3. Armature reaction

- When an alternator is running at no load, there will be no current flowing through the armature winding.
- The flux produced in the air gap will be only due to the rotor ampere-turns.
- When the alternator is loaded, the three phase stator currents will produce a resultant rotating magnetic field in the air gap.
- Consequently, the air gap flux is changed from the no load condition
- The effect of armature flux on the flux produced by field ampere-turns (main field winding) is called armature reaction
- The armature flux and the flux produced by rotor ampere-turns rotate at the same speed (synchronous speed) in the same direction and, therefore, the two fluxes are fixed in space relative to each other.
- The modification of flux in the air gap due to armature flux depends on the magnitude of stator current and on the power factor of the load.
- It is the load power factor which determines whether the armature flux distorts, opposes or helps the flux produced by rotor ampere-turns
- Under normal operating condition (i.e, power factor = 1), the armature (stator) mmf lags behind the main field mmf by 90° electrical.

Consider the following 3 cases,

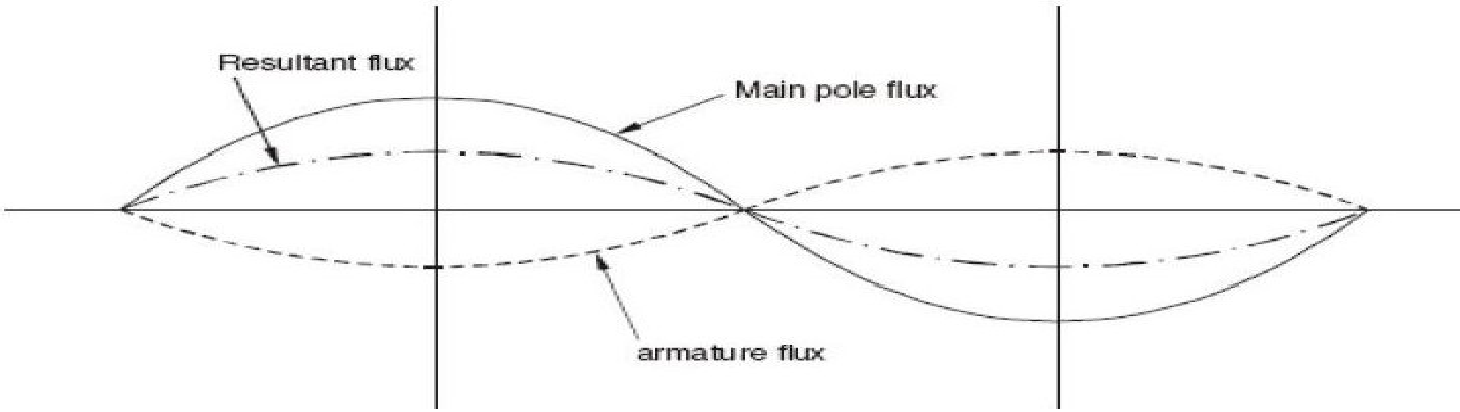
a) When load power factor is unity

- In this case the armature flux is cross magnetizing or distorting in nature
- The armature flux is 90° behind main flux
- The res[...] tips and weaker[...]
- Howeve[...]ains unalter[...]



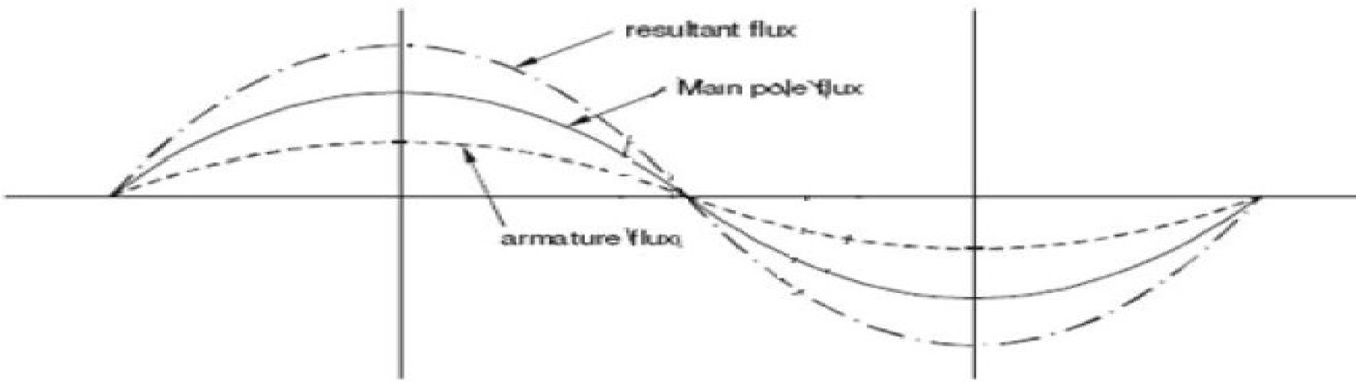
b) <u>At lagging zero power factor</u>

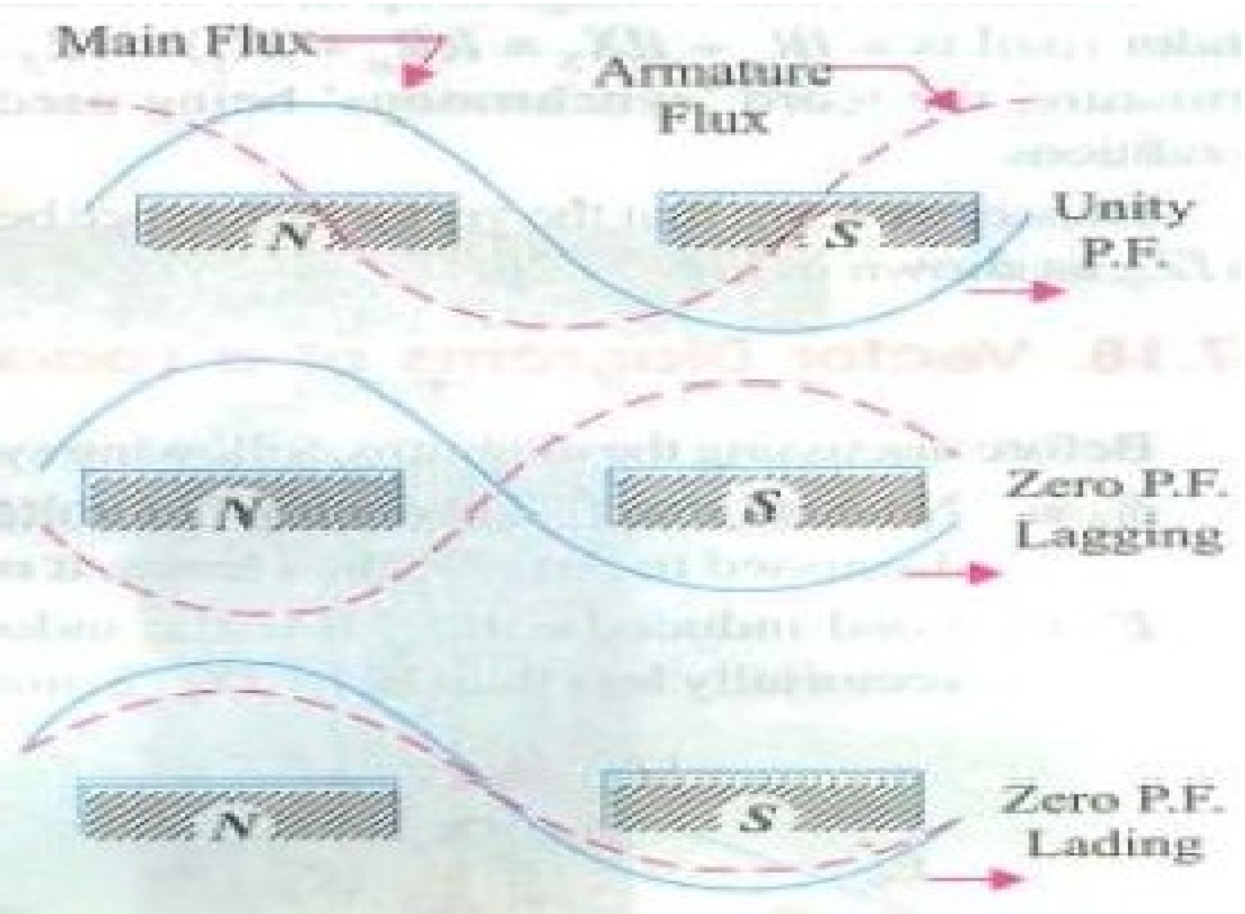
- In this case the effect of armature reaction is demagnetizing in nature
- As a result the flux in the air gap is weakened
- Here due to lagging zero power factor, the armature flux is moved backward through 90° & is in direct opposition to main field flux
- This c MF
- To kee e
  increa



c) **At leading zero power factor**

- In this case the effect of armature reaction is magnetizing in nature
- As a result the flux in the air gap increases
- Here due to leading zero power factor, the armature flux is moved forward through 90° & it aids the main field flux
- This co ed EMF
- To kee o be decrea





Main Flux
Armature Flux
N
S
Unity P.F.
N
S
Zero P.F. Lagging
N
S
Zero P.F. Lading

intermediate power factor

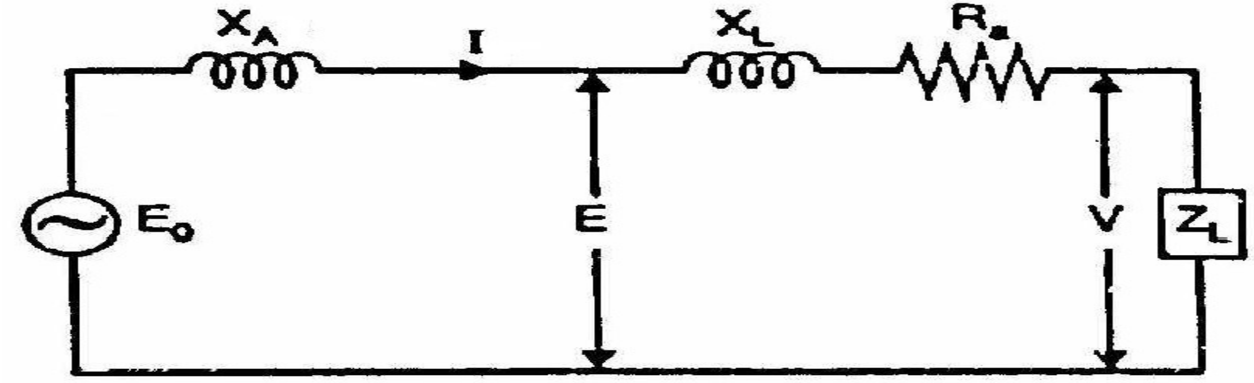
- For intermediate values of load pf, the effect of armature reaction is partly distorting and partly weakening for inductive loads.
- For capacitive loads, the effect is partly distorting and partly strengthening.
- In practice, load on the alternator is generally inductive.

Voltage drop due to armature reaction

- The voltage drop due to armature reaction may be accounted 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

Equivalent circuit of loaded Alternator

- Figure below shows the equivalent circuit of a loaded Alternator for one phase
- All the quantities are per phase values



- Here, E_0 = No load EMF

  E = Induced EMF after allowing armature reaction

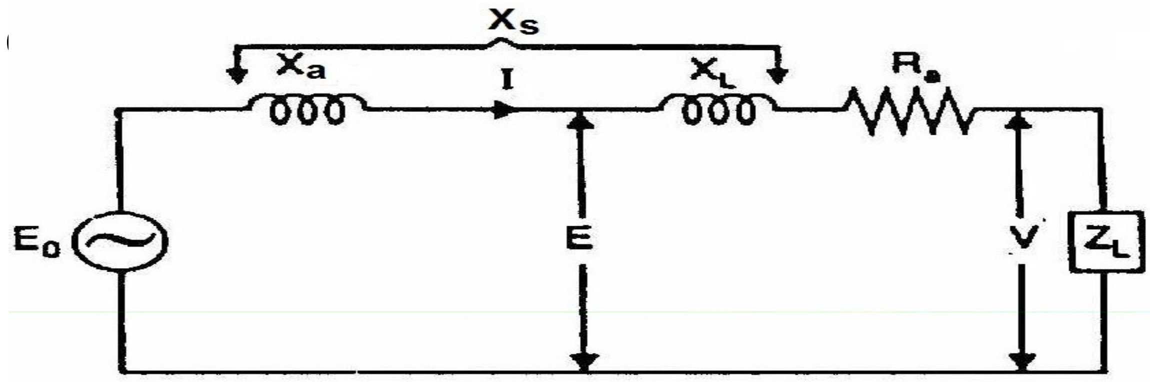
  V = Terminal voltage

- $E = V + I(R_a + jX_L)$

- $E_0 = E + I(jX_a)$

- The sum of armature leakage reactance(X_L) and reactance

i.e, $X_S = X_L + X_a$

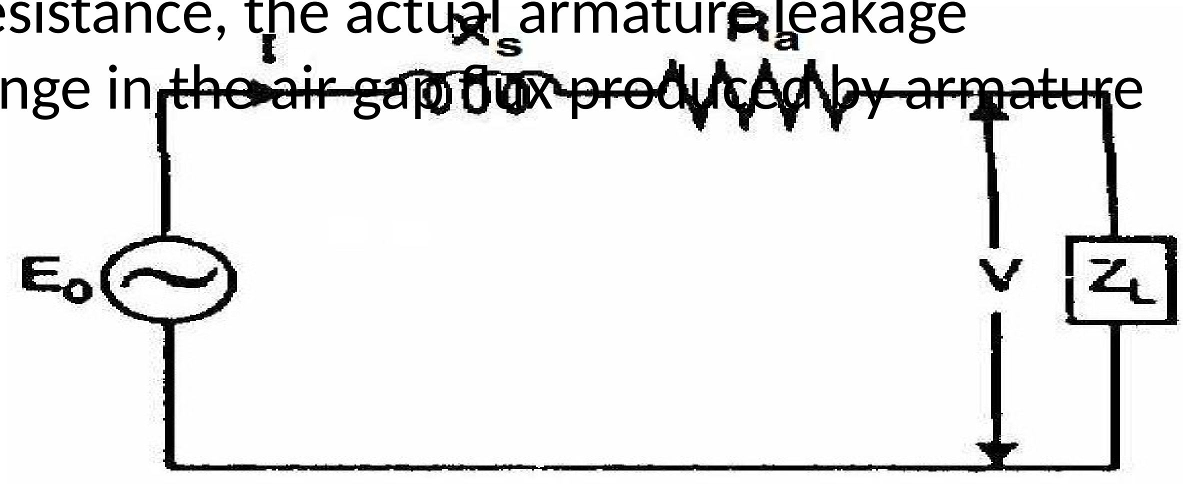


- The synchronous reactance is a fictitious reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and the change in the air gap flux caused by armature reaction

Synchronous Impedance (Z_S)

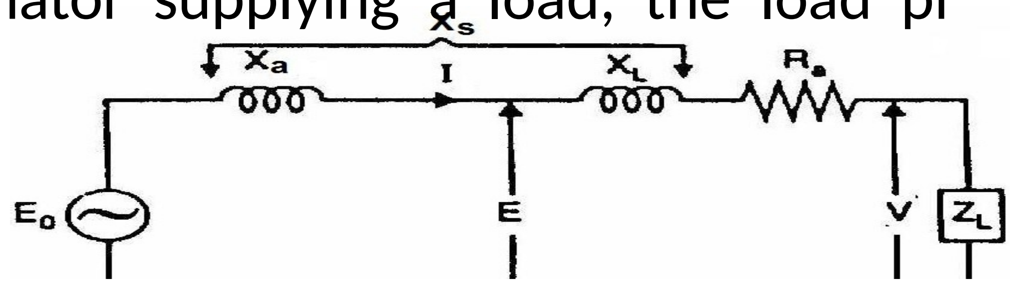
- Synchronous impedance, $Z_S = R_a + j X_S$
- The synchronous impedance is the fictitious impedance employed to account for the voltage effects in the armature circuit produced by the actual armature resistance, the actual armature leakage reactance and the change in the air-gap flux produced by armature reaction.
- $E_0 = V + IZ_S$

  $= V + I(R_a+jX_S)$



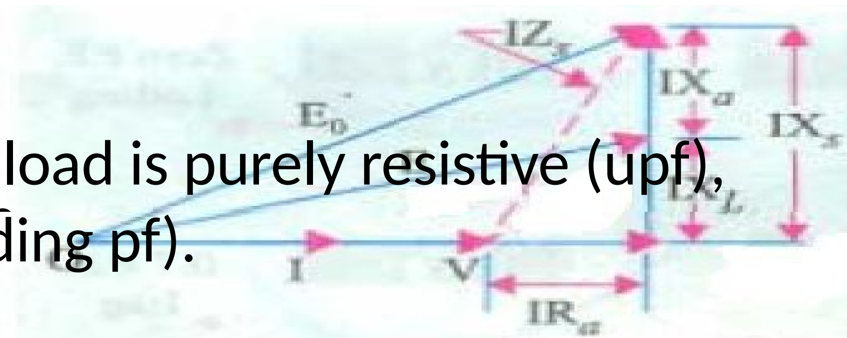
Phasor diagram of a loaded Alternator

- Consider a Y-connected alternator supplying a load, the load pf angle being ‘ϕ’.



- Figure shows the equivalent circuit of the alternator per phase. All quantities are per phase.

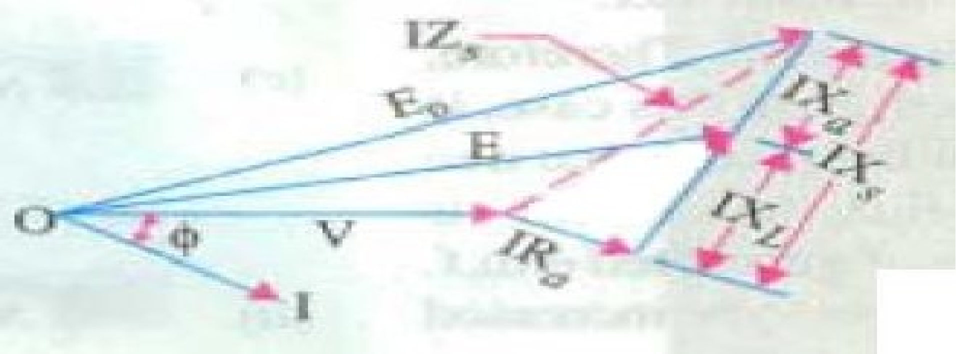
- We have to consider 3 cases. i.e, when load is purely resistive (upf), inductive (lagging pf) & capacitive (leading pf).



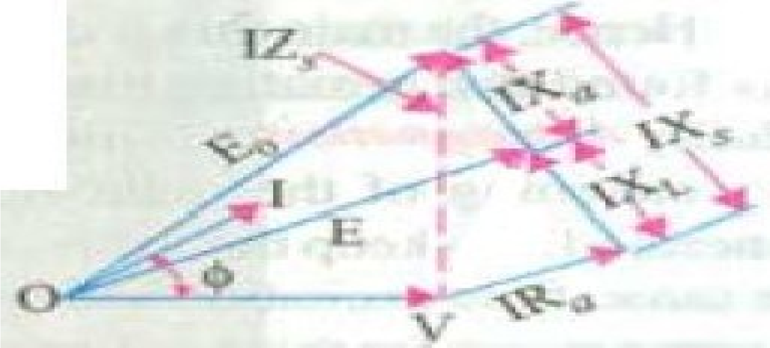
UPF

- The armature current ‘I’ is in phase with the terminal voltage ‘V’
- The phasor sum of ‘V’ and voltage drop IR_a, IX_s will give no load EMF E_0

Lagging pf



- The armature current ‘I’ lags the terminal voltage ‘V’ by pf angle ‘ϕ’
- The phasor sum of ‘V’ and voltage drop IR_a, IX_s will give no load EMF E_0



Leading pf

- The armature current ‘I’ leads the terminal voltage ‘V’ by pf angle ‘ϕ’
- The phasor sum of ‘V’ and voltage drop IR_a, IX_s will give no load EMF E_0

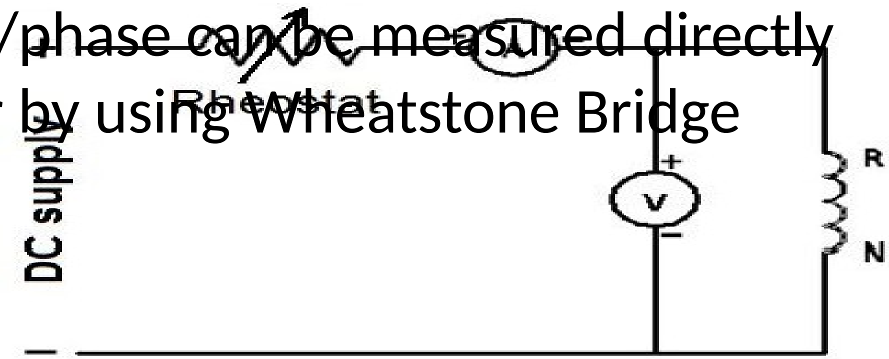
Experimental determination of Synchronous Reactance (X_S)

$$Z_S = \sqrt{R_a^2 + X_S^2}$$

- Synchronous reactance, $X_S = \sqrt{Z_S^2 - R_a^2}$
- If we know synchronous impedance and effective armature resistance, Synchronous impedance can be determined.

Determination of effective armature resistance, R_a

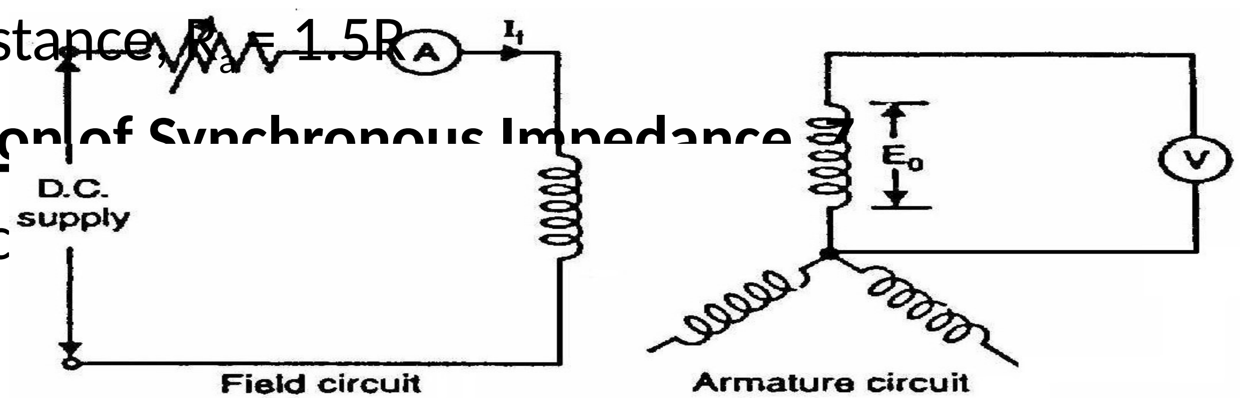
- The effective armature resistance/phase can be measured directly by ammeter – voltmeter method or by using Wheatstone Bridge
- The connection diagram for measuring armature resistance /phase by ammeter – voltmeter method is shown in figure



- The measurement is done by keeping the field circuit open & alternator should be at rest
- The voltmeter reading divided by ammeter reading gives the DC value of resistance/phase, R
- The effective armature resistance is higher than DC resistance due to skin effect in AC
- Effective armature resistance, R_a = 1.5R

<u>Determination of Synchronous Impedance</u>

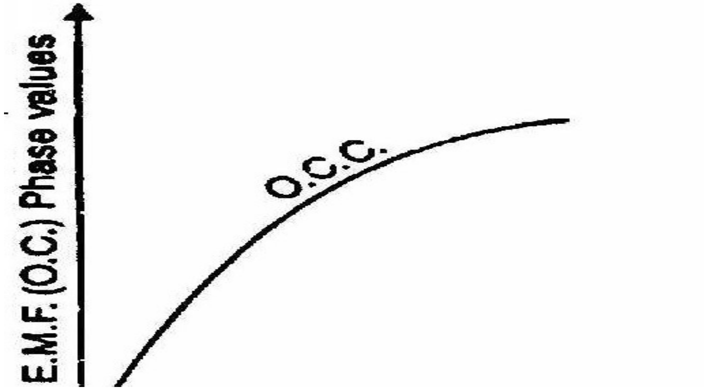
- Synchronous impedanc
  circuit tests



<u>Open circuit test</u>

- The connection diagram for open circuit test is shown in figure.

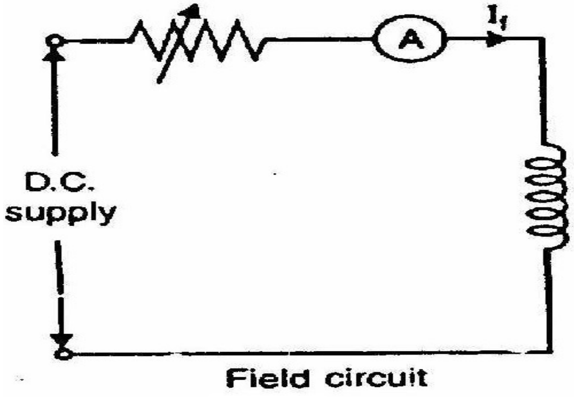
- The alternator is run on no load at the rated speed. The field current I_f is gradually increased from zero (by adjusting field rheostat) until open circuit voltage E_0 (phase value) is about 50% greater than the rated phase voltage.

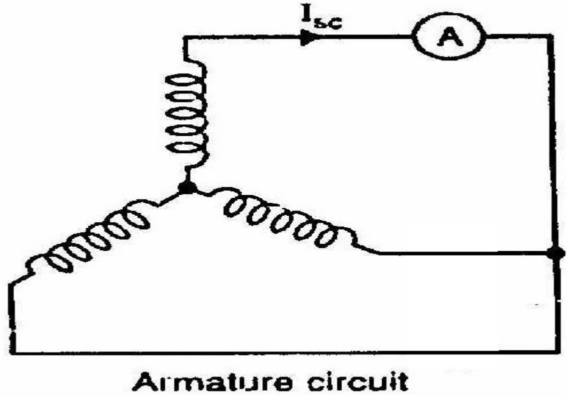


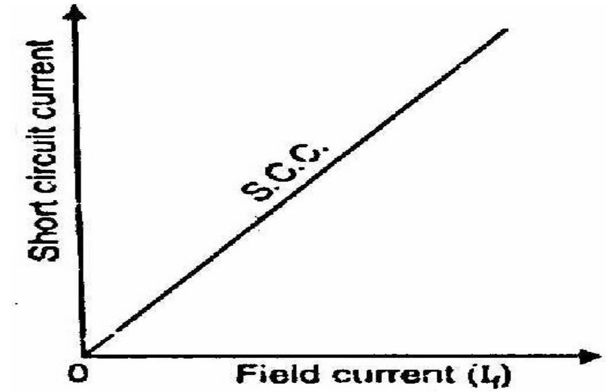
- The graph is drawn between open circuit voltage values and the corresponding values of I_f as shown
- The curve drawn between open circuit voltage and corresponding field current is called Open Circuit Characteristics (OCC)

Short circuit test

- In a short circuit test, the alternator is run at rated speed and the armature terminals are short circuited
- The field current I_f is gradually increased from zero until the short circuit armature current I_{SC} is about the rated current.



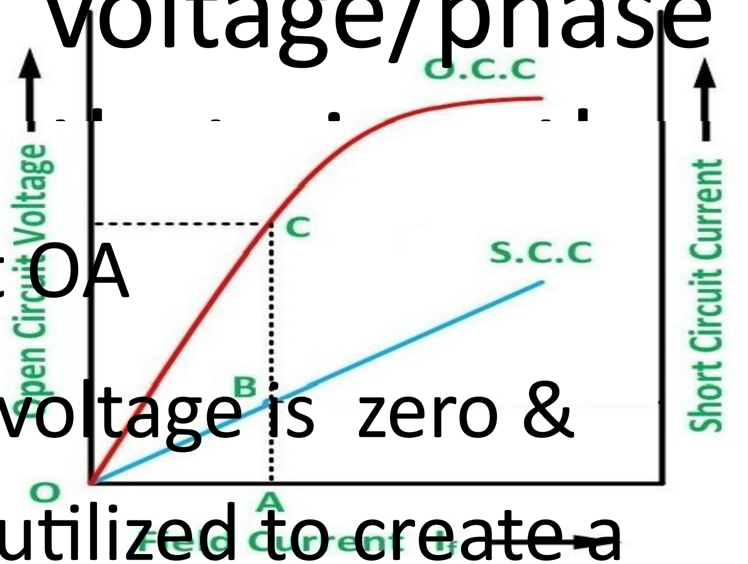




- The graph between short circuit armature current & corresponding field current is called Short Circuit Characteristics (SCC)
- SCC is normally a straight line through origin because the net excitation required is so small as there is no saturation in magnetic circuit

<u>Determination of synchronous impedance from OCC & SCC</u>

- Synchronous impedance can be determined by knowing the value of short circuit current I_{SC} corresponding to a field current that gives rated terminal voltage/phase on open circuit current corresponding to field current which gives rated voltage/phase If OA is the field current



- corresponding to field current OA

AB gives the short circu

- On short circuit, the terminal voltage is zero & the whole of induced EMF is utilized to create a short circuit current (I_{SC}) through synchronous impedance (Z_S)

- Synchronous reactance, $X_S = \sqrt{Z_S^2 - R^2}$

- i.e, $E_0 = I_{SC} Z_S$
- **Synchronous impedance, $Z_S = E_0/I_{SC}$**

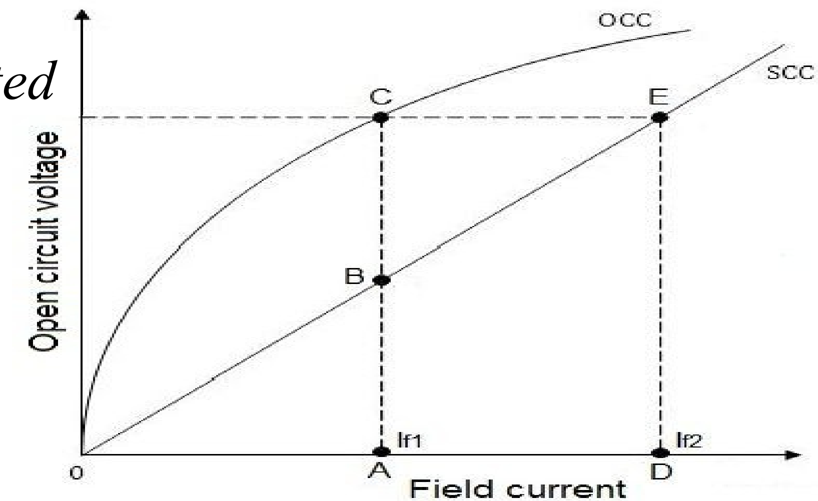
- = AC/AB

Short circuit ratio (SCR)

- The SCR of a synchronous machine is defined as the ratio of field current to produce rated voltage on open circuit to field current required to circulate rated current on short circuit while the machine is driven at synchronous speed

$$SCR = \frac{Field\ Current\ required\ to\ produce\ rated\ Voltage\ on\ open\ circuit}{Field\ current\ required\ to\ produce\ rated}$$

$$SCR = \frac{I_{f1}}{I_{f2}} = \frac{OA}{OD} = \frac{AB}{DE} = \frac{AB}{AC} = \frac{1}{AC/AB}$$



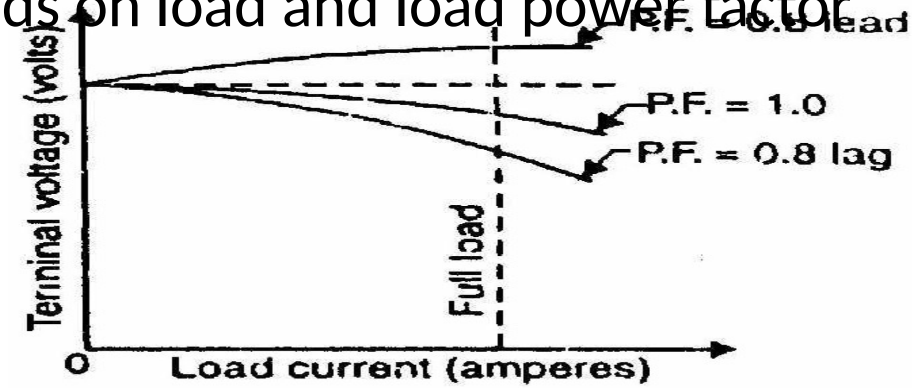
- AC/AB = X_S
- So **SCR = 1/Xs**
- A small value of SCR indicates small value of short circuit current owing to large value of synchronous reactance
- As SCR increases, stability limit increases & voltage regulation improves

Voltage regulation

- Voltage regulation of an alternator is defined as the increase in terminal voltage expressed as the percentage of rated terminal voltage, when load at a given power factor is thrown off with speed & field excitation remains constant

i.e, $$\% \, Voltage \;\; regulation = \frac{E_0 - V}{V} * 100\%$$

- When load on Alternator changes, its terminal voltage also changes
- The magnitude of this change depends on load and load power factor
- The effect of change in load power factor on terminal voltage is shown in figure



- In the case of lagging pf, terminal voltage will rise & in the case of leading pf, terminal voltage will fall with removal of load

Determination of Voltage regulation

a. Direct method

- This method is used to find the regulation of small machines
- Here the Alternator is driven at synchronous speed & field excitation is adjusted to get rated terminal voltage (V)
- Now load is varied to get desired load at desired pf by keeping speed & terminal voltage (V) constant
- Then the entire load is thrown off by keeping the speed & field excitation constant to get no load terminal voltage (E_0)

Now,

$$\%\ Voltage\ Regulation = \frac{E_0 - V}{V} * 100\%$$

- The kVA rating of commercial Alternators are very high & the cost of finding the regulation by direct loading is high
- So voltage regulation of large Alternators are determined by Indirect method

The indirect methods commonly used to find the regulation of an Alternator are

1. EMF method **2. MMF method**

3. ZPF method **4. ASA method**

- All these methods require the following data

i) Armature (stator) resistance

ii) Open Circuit Characteristics (OCC)

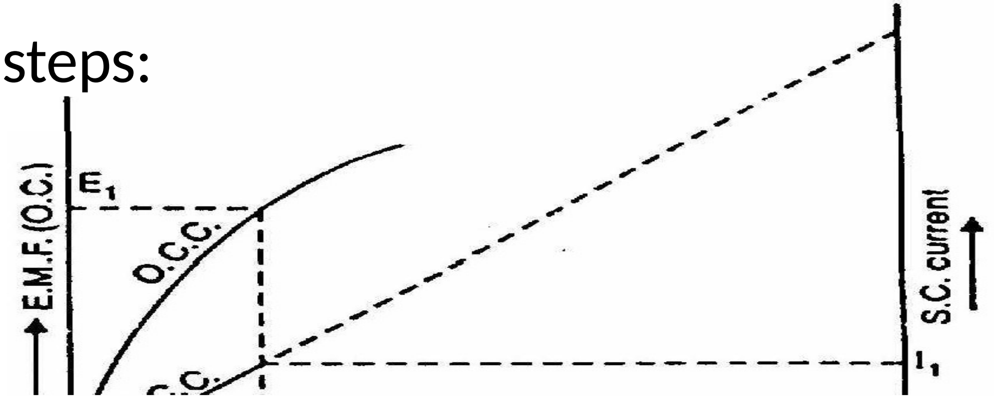
iii) Short Circuit Characteristics (SCC)

1. <u>EMF method or Synchronous impedance method</u>

- In this method of finding the voltage regulation of an alternator, we find the synchronous impedance Z_S (and hence synchronous reactance X_S) of the alternator from the OCC and SCC
- For this reason, it is called synchronous impedance method

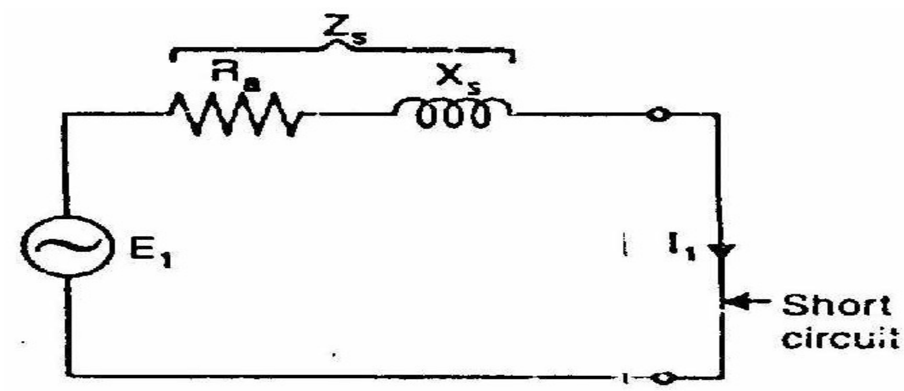
This method involves the following steps:

Step 1 - Plot OCC and SCC using given data



Step 2 - Consider a field current I_f

The open circuit voltage corresponding to this field current is E_1. The short circuit armature current corresponding to field current I_f is I_1. On short circuit p.d. = 0 and voltage E_1 is being used to circulate the short circuit armature current I_1 against the synchronous impedance Z_S.



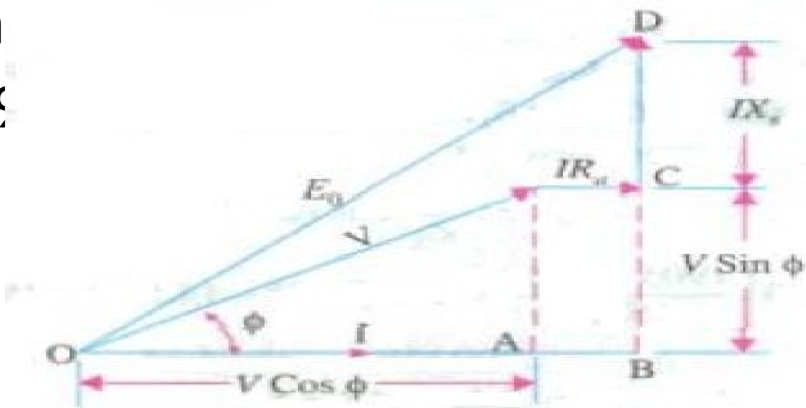
$\therefore$ $E_1 = I_1 Z_S$ or $Z_S = E_1/I_1$

Step 3 – The armature resistance can be found by ammeter-voltmeter method.

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

Step 4 - Once we know R_a and X_S, the phasor diagram can be drawn for any load and any pf.

- The phasor diagram for the inductive load is shown in figure; the load pf being cosϕ lagging. Note that in drawing the phasor diagram, current 'I' has been taken as the referen
  phase with 'I' while IX_s drop leads 'I' by 9
  and IX_s gives the no load EMF E_0



- Consider the triangle OBD.

BD = $V\sin\phi + IX_s$

OD = E_0, $\therefore E_0 = \sqrt{OB^2 + BD^2}$

$$i.e.,\quad E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$$

$$\%\ Voltage\ regulation = \frac{E_0 - V}{V} * 100\%$$

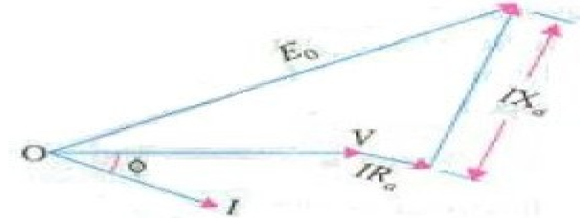
For leading pf, take ϕ as negative & for unity pf take ϕ as zero

- This method is called pessimistic method because the regulation obtained by this method is always higher than actual value
- The reason for error is that here synchronous impedance is assumed to be constant while actually it is not
- Synchronous impedance varies with saturation

2. <u>MMF or Ampere Turn method</u>

- In this method, the armature leakage reactance is considered as an additional armature reaction
- Here it is assumed that the change in terminal voltage on load is entirely due to armature reaction (voltage drop due to armature resistance is neglected)
- The field AT required to produce a voltage at full load is equal to the vector sum of field AT required to produce voltage ‘V’ at no load & field AT required to overcome the effect of armature reaction
- Here EMFs are replaced by MMFs (field MMF = NI_f, N = number of turns in field coil & I_f = field current. Number of turns is a constant & we can consider MMF α I_f)

- This method involves the following steps



Step 1 – Conduct OC & SC test and plot OCC & SCC

Step 2 – Determine R_a

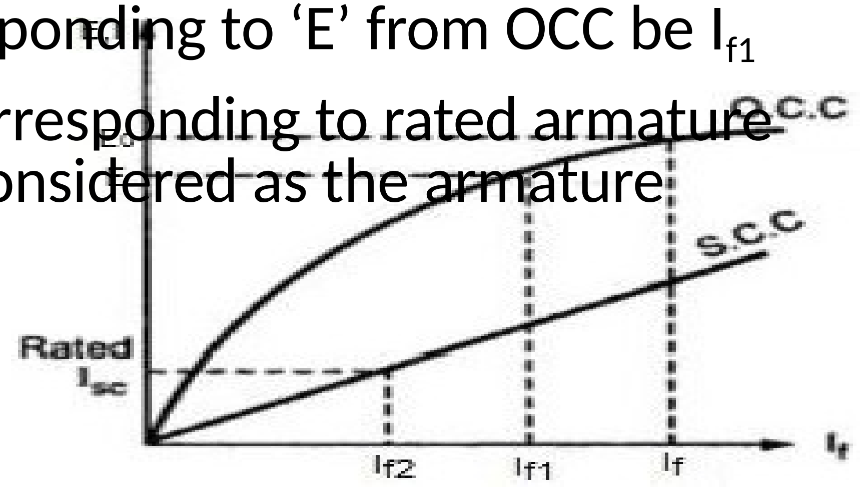
Step 3 – Find the MMF (field current) correspond to V & armature resistance drop (IR_a). The vector sum of V & IR_a is $V+IR_a\cos\phi = E$. The Field current corresponding to 'E' from OCC be I_{f1}

Step 4 – Find the MMF (field current) corresponding to rated armature current from SCC. Let it be I_{f2}. This is considered as the armature reaction MMF

Step 5 – Find the vector sum of I_{f1} & I_{f2} to get total field current I_f (total MMF) according to the power factor

Step 6 – From OCC find the open circuit voltage corresponding to field current I_f to to get E_0

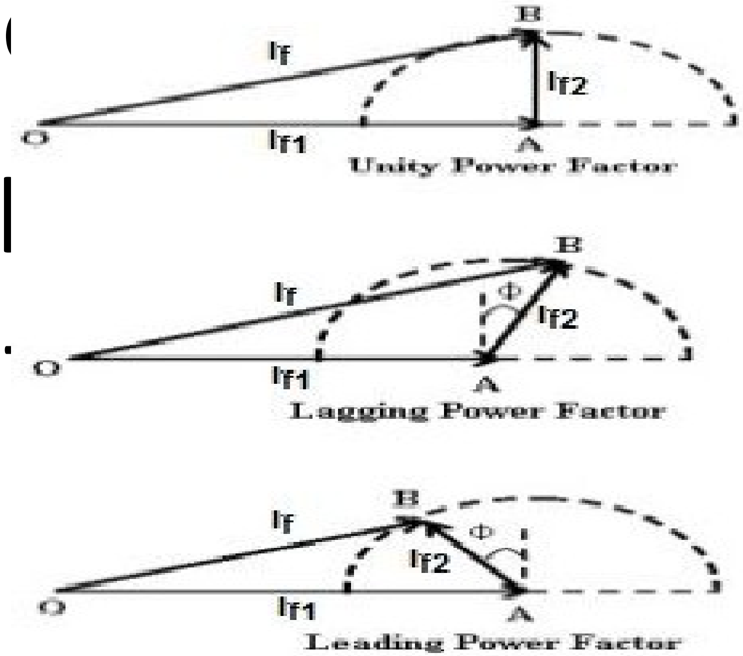
Step 7 – By knowing the value of E_0 & V, can find the voltage regulation



- The determination of ... MMF under various p... are shown in ...

- In general for lagging pf, resultant field current is given by

$$I_f = \sqrt{I_{f1}^2 + I_{f2}^2 + 2 I_{f1} I_{f2} Sin\phi}$$



- For UPF, ϕ = 0 and for leading pf, take ϕ as negative

- The value of regulation obtained by this method is always less than the actual value. For this reason, this method is also known as optimistic method.

- The reason for decrease in regulation value is that, the field current required to overcome armature reaction is determined on unsaturated part of the OCC

3. Zero Power Factor (ZPF) or Potier Method

- The voltage regulation obtained by EMF & MMF methods is based on the total synchronous reactance
- This method is based on the separation of reactance into leakage reactance & reactance due to armature reaction. Therefore this method is more accurate

i) OCC ii) effective armature resistance iii) magnitude of field current required to circulate full load current in stator iv) Zero Power Factor (ZPF) full load voltage characteristics

Plotting ZPF curve

- This is the curve between terminal voltage & field current, when the alternator is delivering full load current to a zero pf (lagging) load
- The test is carried out by running the alternator at synchronous speed & connecting a purely inductive 3ϕ load to its terminals
- There is no need of plotting the full curve, only points A & B are sufficient.
- Point ‘B’ corresponds to the field current which gives rated terminal voltage, when the machine is delivering full load current at zero pf

- Point ‘A’ corresponds to the field current required to circulate rated current on short circuit (from short circuit test. Since armature resistance is very small, during short circuit, the circuit can be considered as purely inductive)

Procedure for Potier method

Step 1 - Plot OCC

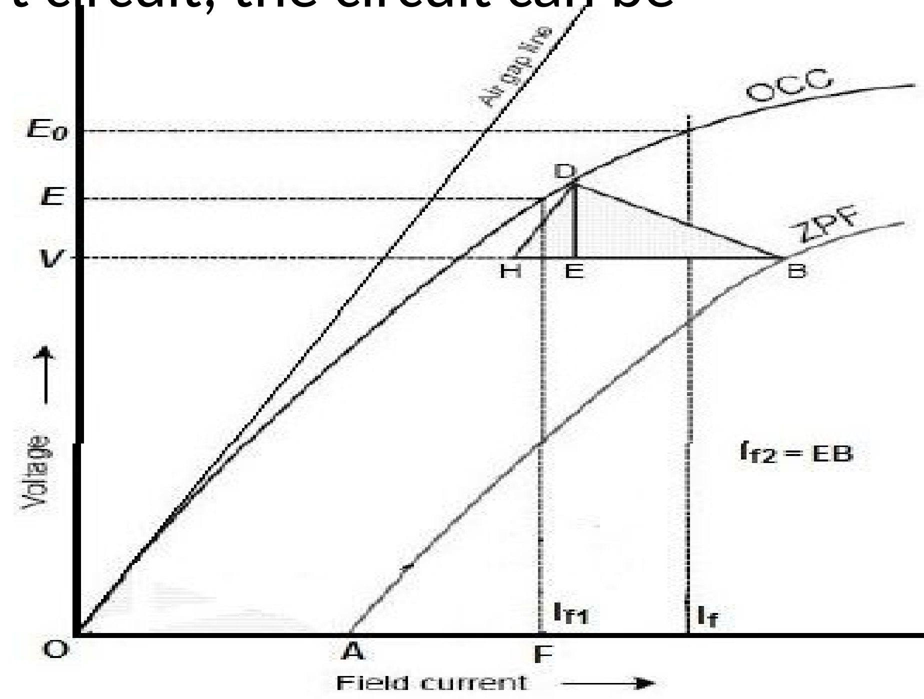
Step 2 – Find armature resistance (R_a)

Step 3 – Plot ZPF curve

Step 4 – Draw a line tangent to OCC, which is known as air gap line

Step 5 – Find the point corresponding to V (rated terminal voltage) on ZPF curve (i.e, point B)

Step 6 – Draw the triangle BHD such that BH = OA & HD parallel to air gap line, D is the point on OCC



draw the line DE perpendicular to BH. The ***triangle BED is known as Potier triangle***

- ***The length DE represents IX_L drop & HE represents field current corresponding to leakage reactance drop.***
- ***EB represents field current corresponding to armature reaction drop***

Step 7 - Find 'E', which is the vector sum of V, IR_a & leakage reactance drop (IX_L) by using the equation $E = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi \pm IX_L)^2}$

(Take ϕ as +ve for lagging pf, -ve for leading pf)

Step 8 – From OCC find the field current (I_{f1}) corresponding to E

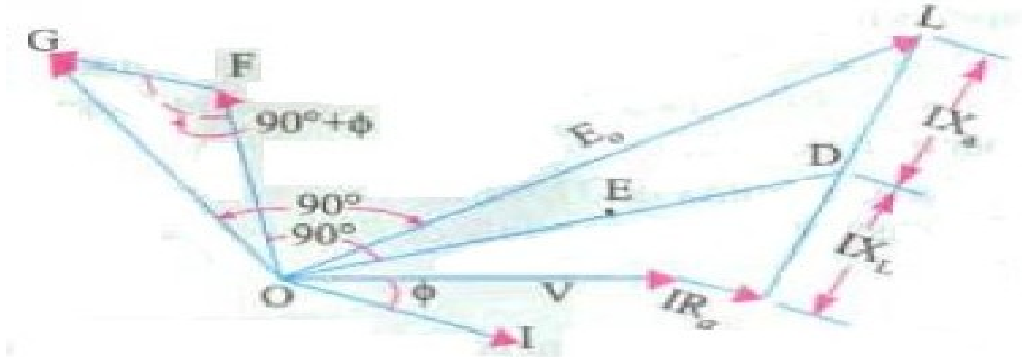
Step 9 – Find the field current (I_{f2}) corresponding to armature reaction from Potier triangle

using the equation

(Take ϕ as +ve for lagging pf, -ve for leading pf)

Step 11 – From OCC find the voltage (E_0), corresponding to field current (I_f) & find voltage regulation

The phasor diagram for EM
metho … own

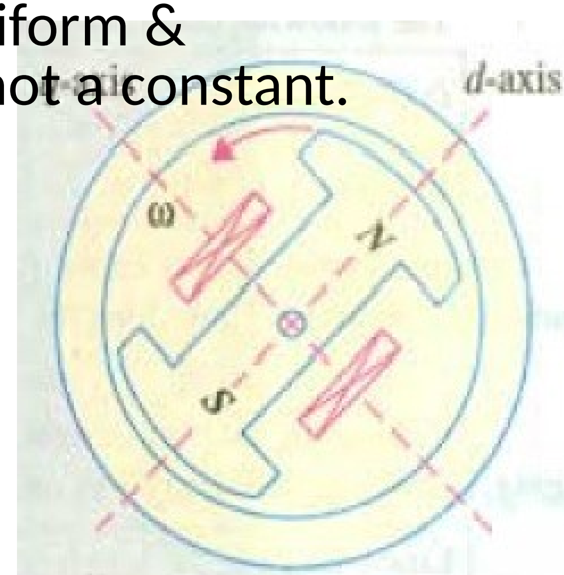


MODULE III

Theory of Salient pole machine – Blondel's two reaction theory, phasor diagram, Slip test
Parallel operation of Alternators – necessity, methods of synchronization
Effect of changing excitation of Alternators, load sharing of two Alternators in parallel

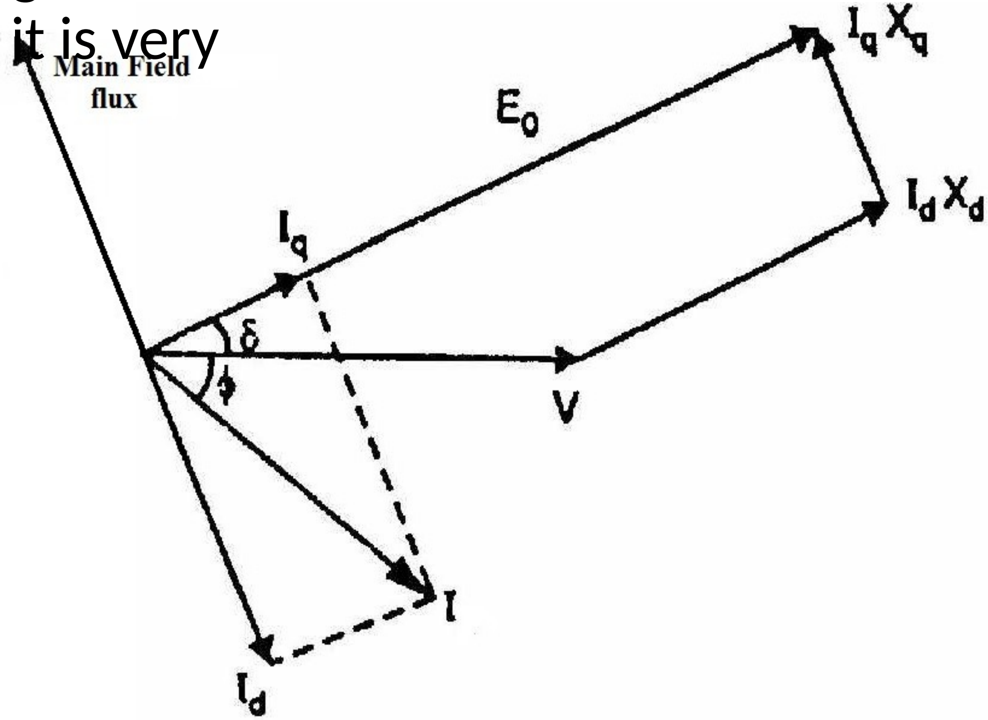
Blondel’s two reaction theory

- In a cylindrical rotor machine, air gap is uniform & therefore air gap reactance (reluctance) remains same irrespective of rotor position
- The effect of armature reaction, fluxes & voltage induced can therefore be treated in a simple way with concept of synchronous reactance. It is taken as constant for all positions of field poles
- In a salient pole machine, the air gap is not uniform & therefore reactance (reluctance) of air gap is not a constant.
- It has a minimum value along the pole axis & a maximum value along the axis midway between the poles
- The pole axis is called direct axis & axis midway between the poles is called quadrature axis
- Due to non uniformity in the air gap reluctance, the armature mmf is divided into two components namely direct axis component & quadrature axis component
- Since armature mmf has two components, the armature reaction has also two components



- Similarly armature current has also two components I_d & I_q
- Synchronous reactance also has two components X_d & X_q
- Assume that the armature leakage reactance (X_L) be constant along both axis
- Direct axis synchronous reactance, $X_d = X_{ad} + X_L$

  Quadrature axis synchronous reactance, $X_q = X_{aq} + X_L$
- The per phase phasor diagram of a salient pole machine based on two reactance concept is given below. Here the armature resistance is neglected since it is very small.



- The *voltage equation* is $E_0 = V + I_d X_d + I_q X_q$
- In a salient pole machine, X_q = 0.6 to 0.7 times X_d whereas in cylindrical rotor machine, $X_d = X$

- From phasor diagram, $I_d = I\ Sin(\delta+\phi)$ ..... (1)

$I_q = I\ Cos(\delta+\phi)$ ..... (2)

$E_0 = V\ Cos\delta + I_dX_d$ ..... (3)

$I_qX_q = V\ Sin\delta$ ..... (4)

(3) => $I_d = \frac{E_0 - VCos\delta}{X_d}$ ..... (5)

(4) => $I_q = \frac{VSin\delta}{X_q}$ ..... (6)

Power developed in a Salient pole Synchronous Generator

- The per phase power output of an Alternator is given by, $P_{out} = VICos\phi$

$ICos\phi = I_dSin\delta + I_qCos\delta$ (proof given as note) i.e, $P_{out} = V(I_dSin\delta + I_qCos\delta)$ ..... (7)

Substituting (5) & (6) in (7),

$$P_{out} = V\left[\frac{E_0 - VCos\delta}{X_d}Sin\delta + \frac{VSin\delta}{X_q}Cos\delta\right] = \frac{E_0V}{X_d}Sin\delta + V^2\left[\frac{Sin\delta Cos\delta}{X_q} - \frac{Sin\delta Cos\delta}{X_d}\right]$$

$$P_{out} = \frac{E_0V}{X_d}Sin\delta + \frac{V^2 Sin2\delta}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right] \quad ..... (8)$$

developed per phase. Total power developed is three times per phase power.

- In a non-salient pole machine, $X_d = X_q$

$$\therefore \quad P_{out} = \frac{E_0 V}{X_d} Sin\delta$$

- The second term in equation (8) introduces the effect of salient

This term represents *reluctance power or power due to saliency* (The power obtained with zero excitation is called reluctance power)

<u>Expression for load angle δ</u>

- Substituting equation (2) in (4),

$$VSin\delta = IX_q Cos(\delta + \phi) = IX_q \left(Cos\delta\, Cos\phi - Sin\delta\, Sin\phi \right)$$

$$i.e, \quad V = IX_q \,(Cot\delta\, Cos\phi - Sin\phi)$$

$$Cot\delta = \frac{V + IX_q Sin\phi}{IX_q Cos\phi}$$

$$Tan\delta = \frac{IX_q Cos\phi}{V + IX_q Sin\phi} \qquad \text{..... (9)}$$

regulation of a Salient pole Alternator

Step 1 – Determine X_d & X_q by conducting slip test   Step 2 – Determine V, I & ϕ value from given data   Step 3 – Determine load angle δ using (9)

Step 4 – Determine E_0 by using equation (3)

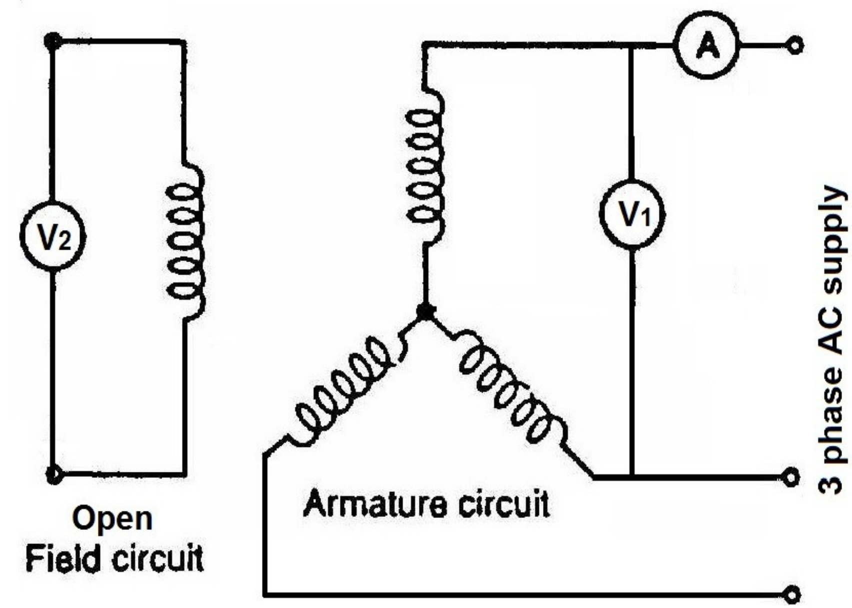
Step 5 – Now find % regulation by using the equation

$$\%\ Regulation = \frac{E_0 - V}{V} * 100\%$$

Determination of X_d & X_q - Slip Test

- X_d & X_q can be determined by applying a balanced reduced external AC voltage to an unexcited machine at running at a speed slightly less than synchronous speed (slip < 1%)
- Applied voltage to armature, armature current & induced voltage in field winding are measured by connecting voltmeters & ammeter
- Connection diagram is shown in figure
- Due to voltage applied to armature terminals, a current flows through armature & a rotating magnetic field is produced in armature

across field winding
The voltmeter & ammeter



- Adjust the speed of Alternator, so that the meter shows an oscillation with maximum amplitude
- Note down the maximum & minimum values of oscillation in voltmeter & ammeter
- Now, $X_d = \dfrac{Maximum\ \ Voltage}{Minimum\ \ Current}$ & $X_q = \dfrac{Minimum\ \ Voltage}{Maximum\ \ Current}$

value to minimum value

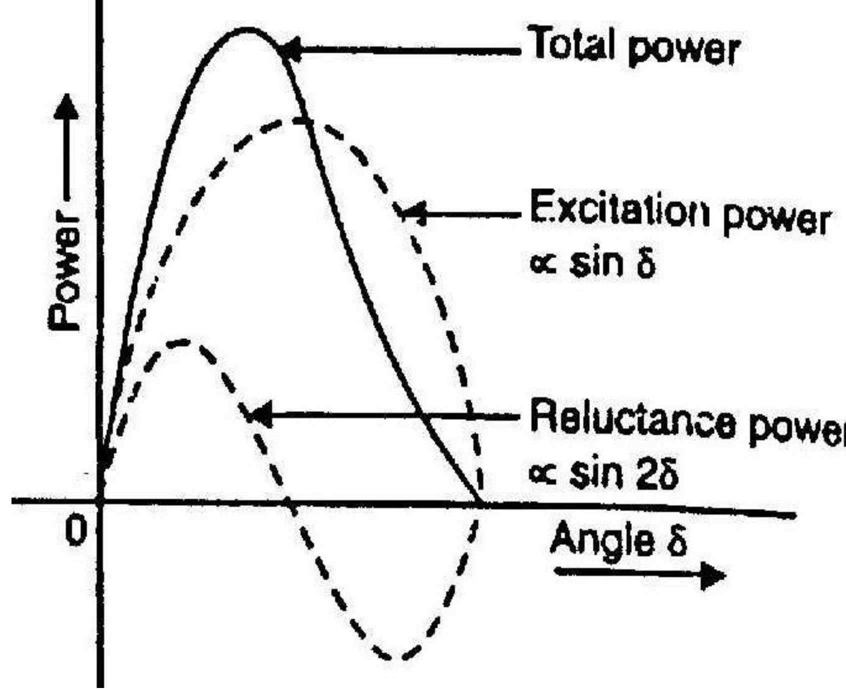
[When stator poles & rotor poles (d-axis) coincide, reluctance is minimum, reactance is maximum. So armature draws minimum current to maintain flux in the airgap. When stator poles coincide with q-axis, reluctance is maximum, reactance is minimum. So armature draws maximum current]

Power Angle Characteristics

- The power output is given by

$$P_{out} = \frac{E_0 V}{X_d} Sin\delta + \frac{V^2 Sin2\delta}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]$$

- Total power output = Excitation power + Reluctance power
- The power angle characteristics is shown in figure



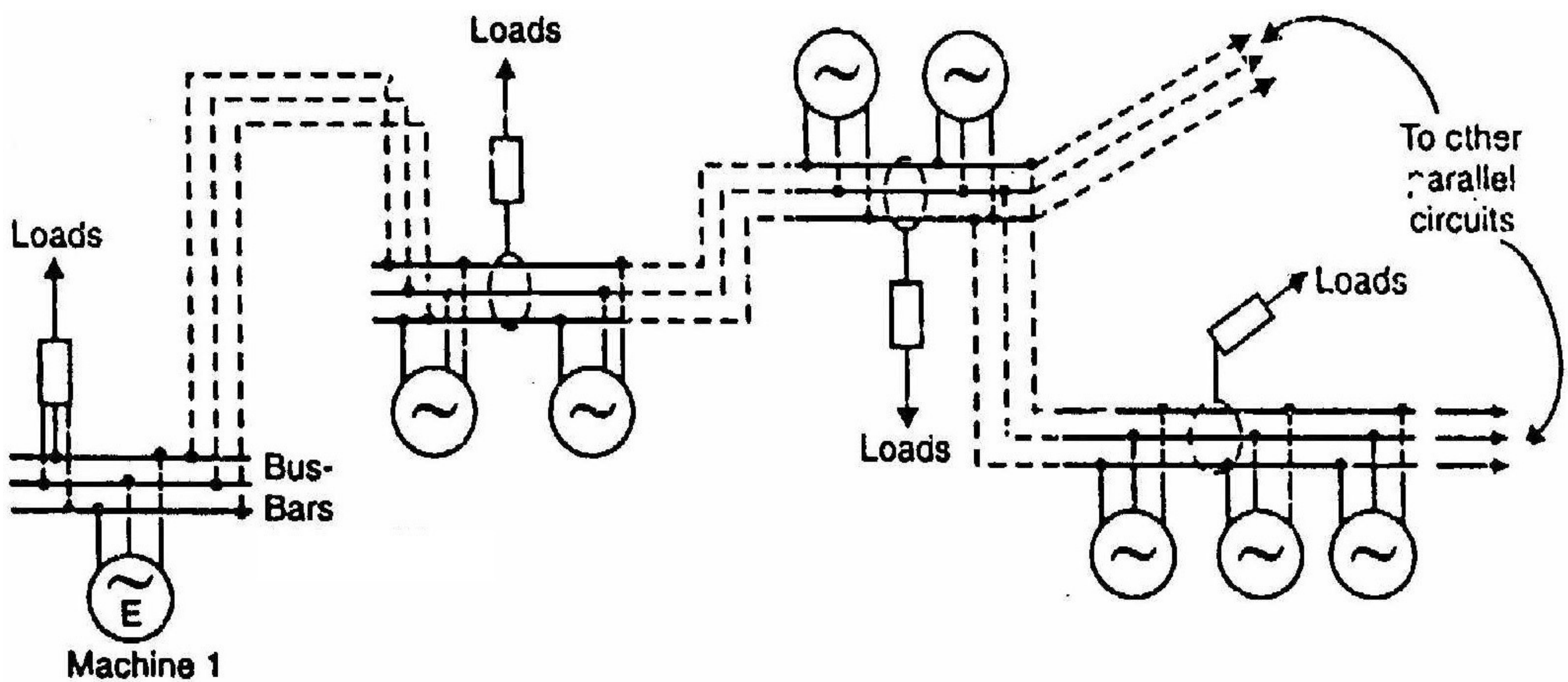
- It is clear that reluctance power varies with δ at twice the rate of the excitation power.

Parallel operation of Alternators

- In power stations, electrical power is generated by Alternators (normally) & Alternators in different power stations are connected in parallel to the national grid
- The total capacity of national grid is very high (thousands of MW) compared to the capacity of a single Alternator connected

single Alternator may not affect the voltage & frequency of the whole system

- An Alternator connected to such a system is said to be connected to infinite busbars
- The method of connecting an incoming Alternator safely to busbar is called synchronizing
- A typical infinite bus system is shown in figure



Advantages of parallel operation of Alternators

1. *Continuity of service* - The continuity of service is one of the important requirements of any electrical system. If one alternator fails, the continuity of supply can be maintained through the other healthy units. This will ensure uninterrupted supply to the consumers.

2. *Efficiency* - Alternators give maximum efficiency when delivering full- load power output. The load on the power system varies during the whole day, being maximum during peak hours (6 pm to 10 pm) & minimum during off peak hours (10 pm to 6 am). So to get maximum efficiency, units can be added or put off depending upon the load requirement. This permits the efficient operation of the power system.

3. *Maintenance & repair* - Alternators require routine maintenance & repair. During maintenance & repair, continuity of supply can be ensured from other units

4. *Load growth* - The load demand is increasing day by day due to the increased use of electrical power. The load growth can be met by adding more units in parallel, without disturbing the original installation.

Conditions for paralleling an Alternator to infinite bus bar

- The method of connecting an incoming Alternator safely to busbar is called synchronizing
- For synchronizing an Alternator to an infinite busbar, the following conditions are to be satisfied

1. *The terminal voltage (r.m.s. value) of the incoming alternator must be the same as busbars voltage.*
2. *The frequency of the generated voltage of the incoming alternator must be equal to the busbars frequency.*
3. *The phase of the incoming alternator voltage must be identical with the phase of the busbars voltage. In other words, the two voltages must be in phase with each other.*
4. *The phase sequence (RYB or RBY) of the voltage of the incoming alternator should be the same as that of the busbars.*

- The condition 1 is indicated by a voltmeter, conditions 2&3 are indicated by a synchronizing lamp arrangement or a synchroscope. The condition 4 is indicated by a phase sequence indicator

Methods of synchronization

- *The equality of voltage between incoming Alternator & busbar can be checked by using a voltmeter*. If they are different, then terminal voltage of Alternator is made equal to busbar voltage by varying its field excitation
- *The phase sequence of the alternator & the busbars can be checked by a phase sequence indicator*. If they are different, change phase sequence of Alternator so that both are having same phase sequence
- *The difference in frequency & phase of the voltages of the incoming alternator & busbars* can be checked by one of the following two methods:

  (i) By using a synchronizing Lamp arrangement

  (ii) By using a synchroscope

(i) By using a synchronizing Lamp arrangement

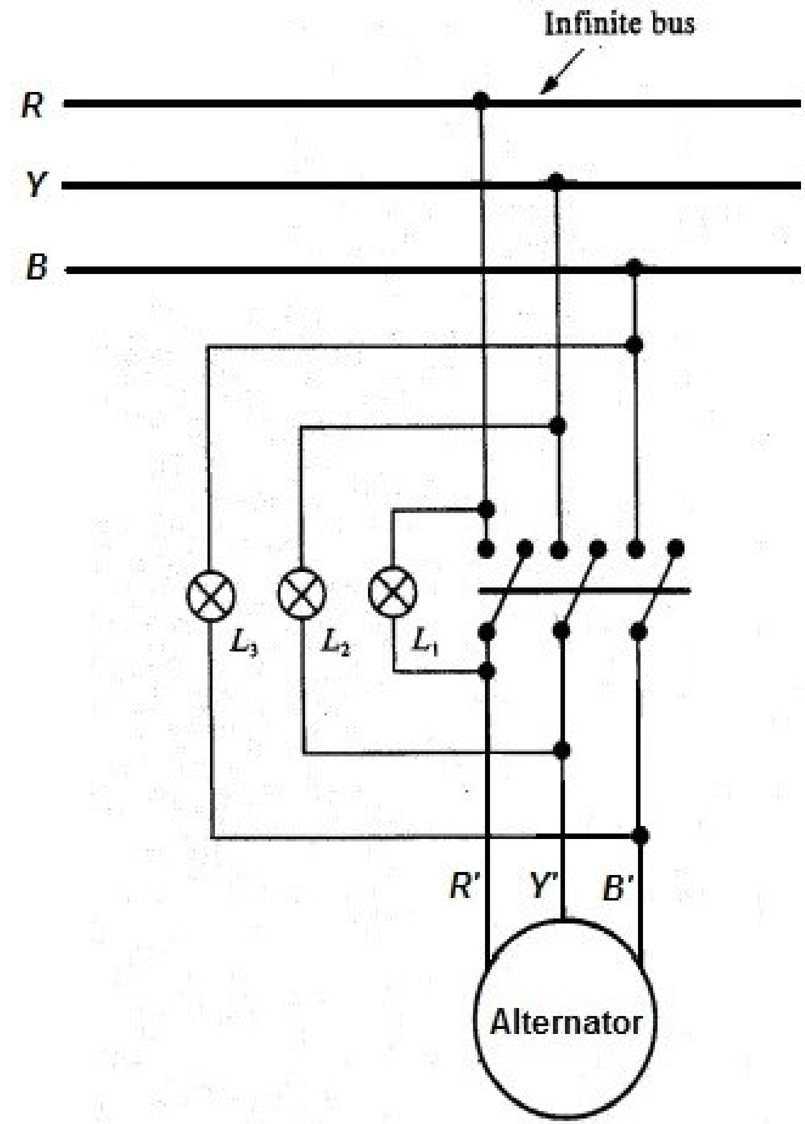
- There are 2 type of synchronizing lamp arrangement

  1. 3 dark lamp method or dark lamp method

  2. 2 bright & 1 dark lamp method or bright lamp method

1. Three dark lamp method

- Figure shows the connection of lamps for dark lamp method
- The prime mover of incoming Alternator is started and brought up close to rated speed
- The Alternator is then excited and its voltage is raised to bus bar voltage by increasing the excitation
- Now the lamps are watched closely. If the incoming Alternator is properly connected, all the three lamps should become bright and dim together.
- If they bright and dim in sequence, it shows that the incoming Alternator is not properly connected and phase sequence



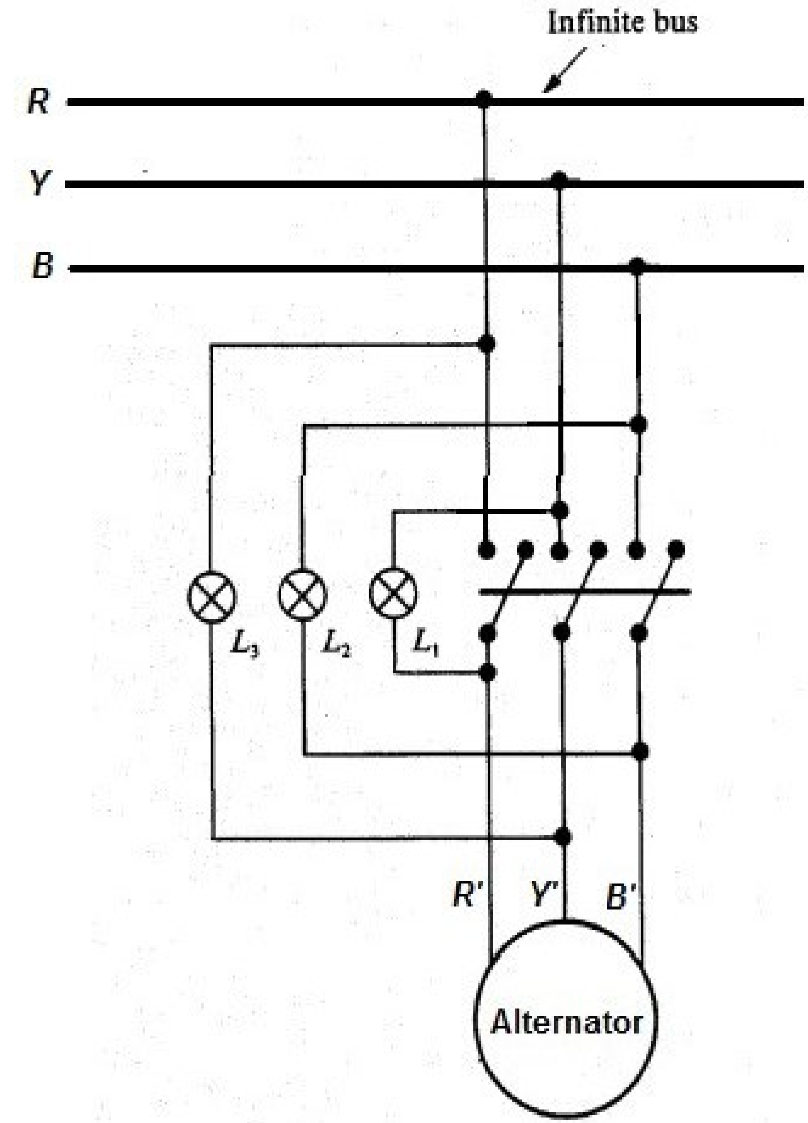
- The speed of the prime mover of incoming machine is further adjusted until the lamps flicker at a very low rate (less than one dark period per second)
- The voltage of incoming machine is again adjusted and the paralleling switch is closed at the instant all the three lamps are dark

Disadvantage of this method

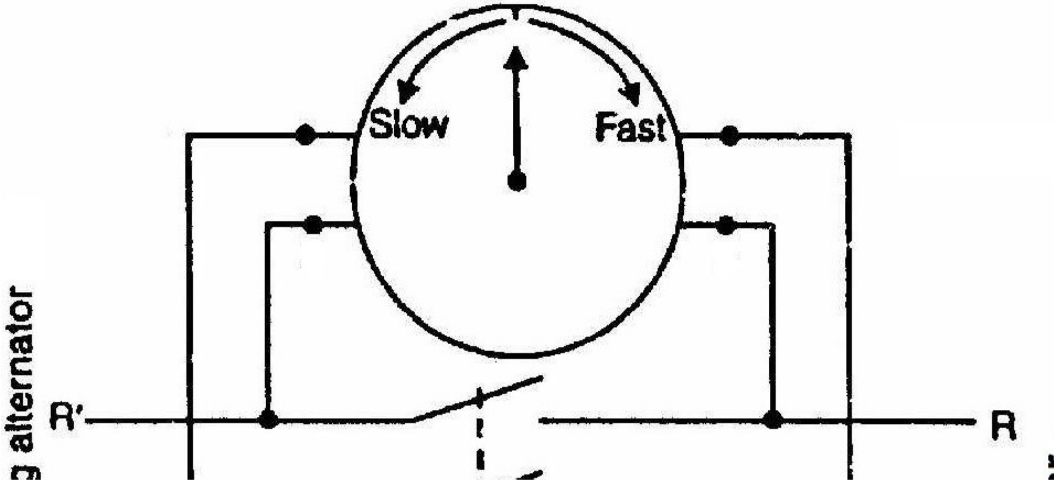
- The lamps go dark at somewhat less than half their rated voltage and so the paralleling switch might be closed when there is a considerable voltage exists across the switch & this may damage the machines.
- Another disadvantage is that the lamp filaments might burn out.
- Third disadvantage is that the flicker of lamps does not indicate whether the incoming machine is slow or fast
- These difficulties are eliminated in two bright and one dark lamp method.

2. Two bright & one dark lamp method

- Figure shows the connection of lamps for 2 bright & 1 dark lamp method
- Here when the incoming Alternator is in synchronism with bus bar, lamps L_1 and L_3 are bright and L_2 is dark
- When the three lamps are placed in a ring, a light wave travelling in counter clockwise direction indicates that the incoming machine is slow and light wave travelling in clockwise direction indicates that the incoming machine is fast
- So by observing the sequence of brightness of lamps,



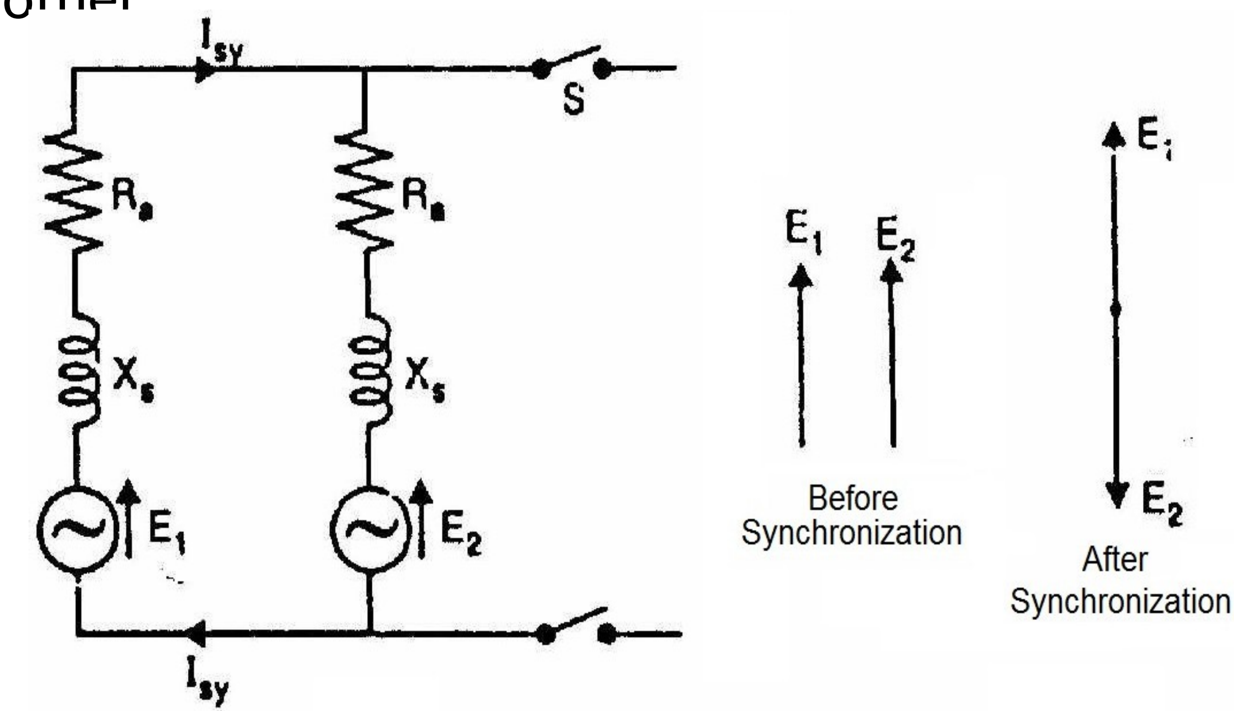
ii) By using a synchroscope



- If the phase sequence is known to be correct, the best method of synchronization is by means of a Synchroscope.
- The synchroscope is an instrument for indicating difference of phase and frequency between two voltages
- It is essentially a split phase motor which produces a torque when there is difference in frequency between the voltages in two phase windings
- Voltages from corresponding phases of the incoming Alternator & bus bar are applied to synchroscope.
- A pointer, which is attached to the rotating part of the instrument moves over a dial in either a clockwise or counter clockwise direction, depending on whether the incoming machine is fast or slow
- When the frequencies of the two Alternators are equal, no torque is exerted on the rotating part of the instrument & so the pointer stops
- When the pointer stops in vertical position, the frequencies are equal, the voltages are in phase & the paralleling switch may be closed

Synchronizing action

- Once an Alternator is put in synchronism with another Alternator or bus bar, after that the system will maintain the synchronism even if one of the Alternator tries to fall out of synchronism
- Consider two Alternators connected in parallel as shown in figure
- Before connecting them in parallel, $E_1 = E_2$ in magnitude & they are in phase
- After synchronizing, they are having same magnitude but they oppose each other

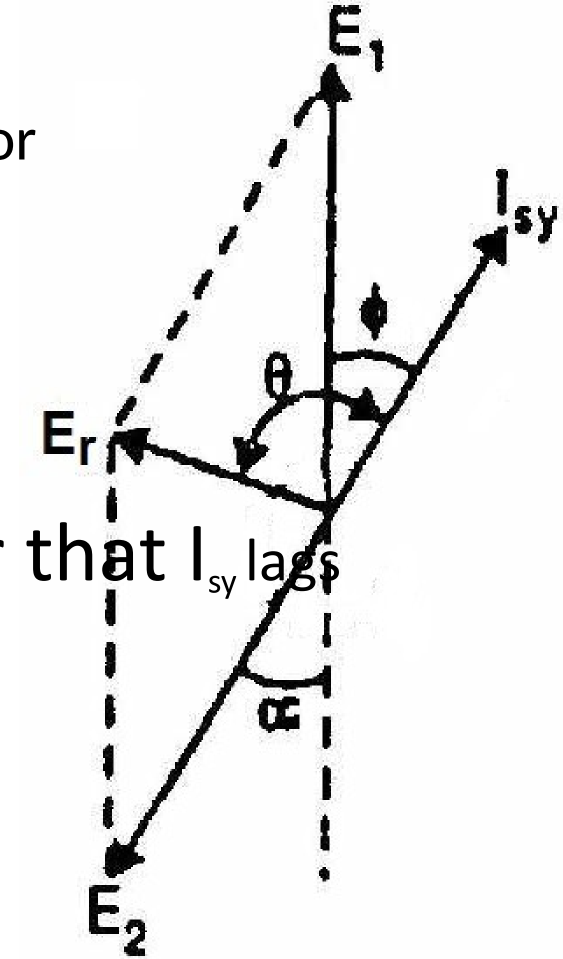


change in speed

- Suppose due to any reason, speed of Alternator 2 decreases
- Now E_2 falls back by α° & there exists a resultant voltage E_r
- E_r will circulate a current between Alternator 1 & Alternator 2, this current is called *Synchronizing current* (I_{sy})

$$I_{sy} = \frac{E_r}{2Z_s} \cong \frac{E_r}{2X_s} \quad (R_a \text{ is very small})$$

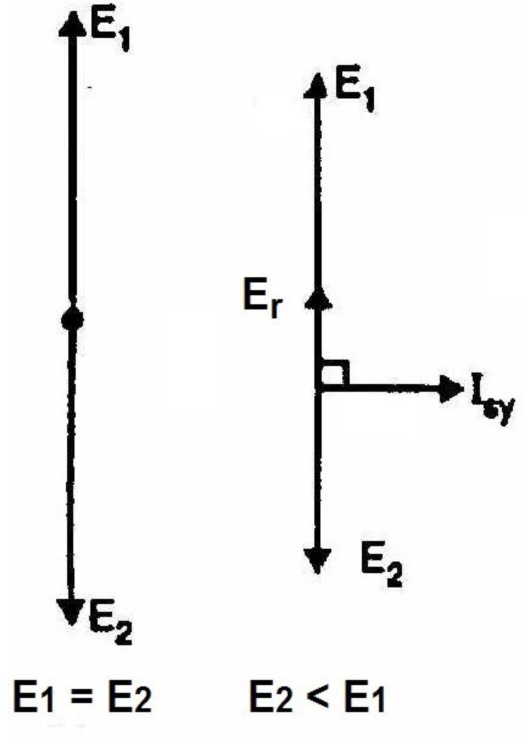
-
- From above equation it is clear that I_{sy} lags behind E_r by $\theta \cong 90^\circ$



- From phasor diagram, I_{sy} is almost in phase with E_1 & out of phase with E_2
- Therefore, Alternator 1 is generating & Alternator 2 is motoring
- Now due to motoring action, speed of Alternator 2 will increase to maintain synchronism

b) Effect of change in voltage

- Suppose due to any reason, EMF of Alternator 2 (E_2) decreases
- Now there exists a resultant voltage E_r
- This E_r causes a current I_{sy} to circulate between Alternator 1 & Alternator 2
- I_{sy} lags E_r by 90∘
- Also, I_{sy} lags E_1 by 90 ∘ & leads E_2 by 90 ∘
- Therefore, I_{sy} causes a demagnetizing armature
  reaction in Alternator 1 & magnetizing armature reaction in Alternator 2
- As a result, terminal voltage of Alternator 1 decreases & terminal voltage of Alternator 2 increases to maintain the synchronism



Synchronizing power

- Consider two Alternators connected in parallel
- Suppose due to any reason, speed or EMF produced by Alternator 2 decreases
- Now a resultant voltage E_r exists between the terminals of two Alternators & this causes a synchronizing current I_{sy}
- I_{sy} flows from Alternator 1 to Alternator 2
- The power supplied by Alternator 1 to maintain Alternator 2 in synchronism is called Synchronizing power
- $P_{sy} = E_1 I_{sy} Cos\phi$

  $= E_1 I_{sy}$ .... (1) (Since $\phi = \alpha$, which is very small, $Cos\ \alpha \approx 1$) $E_1 = E_2 = E$ .... (2)

  $I_{sy} = E_r/(2X_s)$ .... (3)

$$E_r = \sqrt{E_1^2 + E_2^2 + 2E_1 E_2 Cos(180-\alpha)} = \sqrt{E^2 + E^2 + 2E^2 Cos(180-\alpha)}$$

$$= \sqrt{2E^2(1+Cos(180-\alpha))} = \sqrt{2E^2 \cdot 2Cos^2\left(\frac{180-\alpha}{2}\right)} = 2E\,Cos\left(90-\frac{\alpha}{2}\right) = 2E\,Sin\frac{\alpha}{2}$$

i.e, $E_r = 2E\ Sin\frac{\alpha}{2} = 2E\frac{\alpha}{2} = \alpha E$

very small, Sin(α/2) = α/2)

Sub (4) in (3) => $I_{sy} = \alpha E/(2X_s)$ .... (5)

Sub (2) & (4) in (1) => $P_{sy} = \frac{\alpha E^2}{2X_s}$ .... (6)

Equation (6) gives per phase synchronizing

power. Three phase Synchronizing power = 3 P_{sy}

Synchronizing Torque

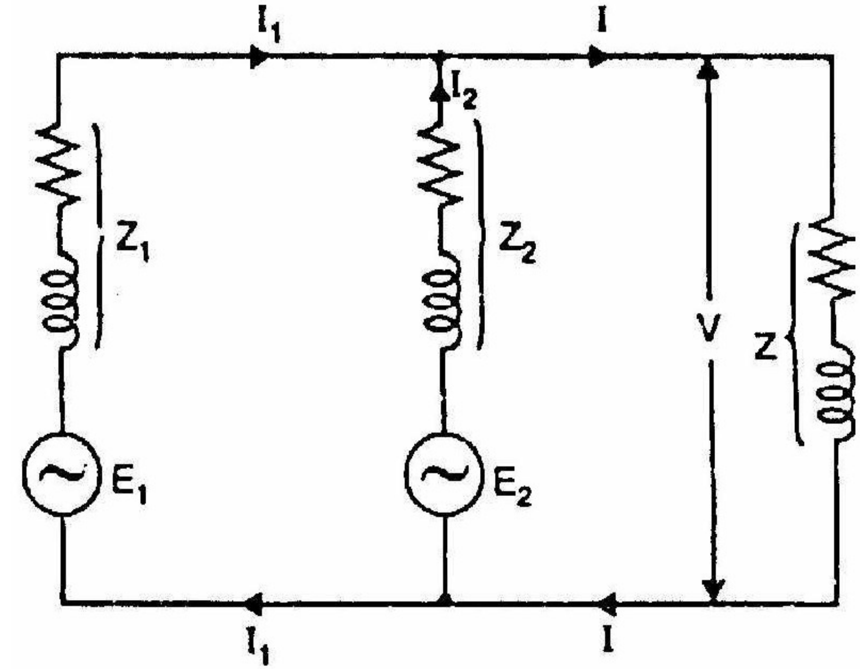
3 phase synchronizing power,

$$3P_{sy} = \frac{2\pi N_s T_{sy}}{60}$$

Synchronizing torque,

$$T_{sy} = \frac{3P_{sy}\,60}{2\pi N_s}$$

Load sharing between two Alternators in parallel



- Consider two identical alternators connected in parallel
- Let E_1, E_2 = Induced EMFs per phase

  Z_1, Z_2 = Synchronous impedance per phase

  Z = load impedance per phase

  I_1, I_2 = current supplied by two Alternators

  V = terminal voltage per phase

  from figure, $V = E_1 – I_1Z_1 = E_2 – I_2Z_2$

$$I_1 = \frac{E_1 - V}{Z_1}, \quad I_2 = \frac{E_2 - V}{Z_2}$$

$$I = I_1 + I_2 = \frac{E_1 - V}{Z_1} + \frac{E_2 - V}{Z_2}$$

- $V = (I_1+I_2)Z =$

IZ

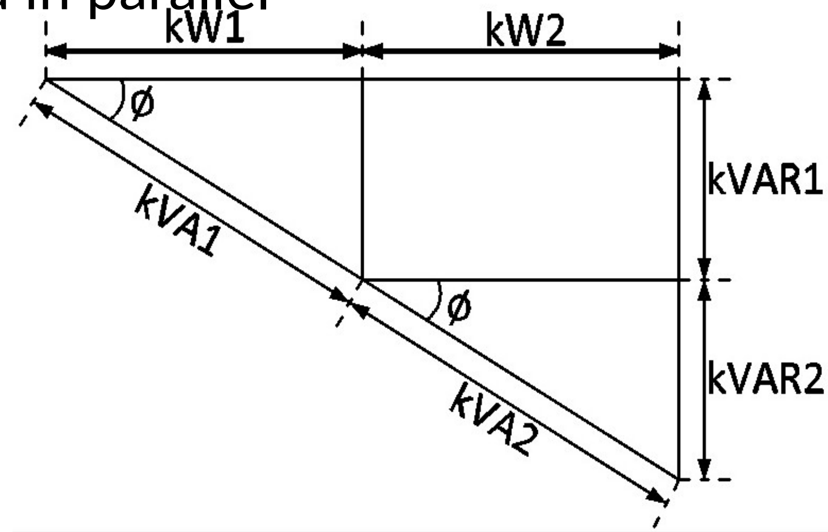
Alternator on infinite busbars

When an Alternator is synchronised to an infinite busbar,

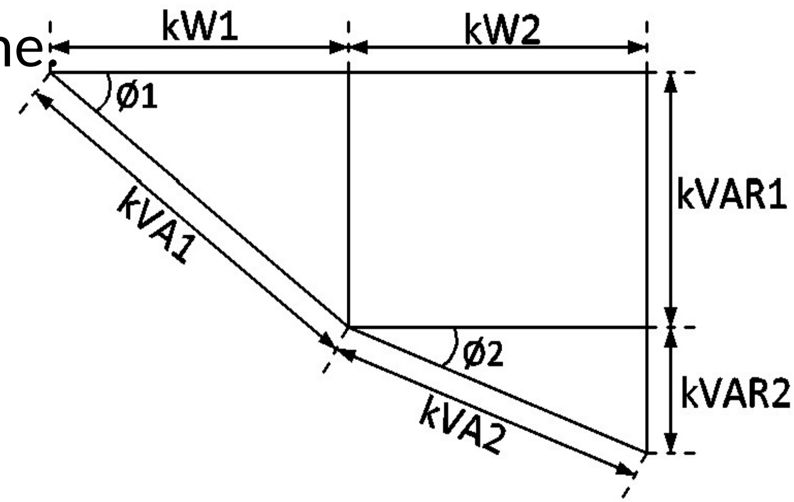
- Any change in operating conditions of Alternator will not change the terminal voltage & frequency of system
- Any change (increase/decrease) in mechanical power input to Alternator cause a change in the kW output of the Alternator
- Any change (increase/decrease) in excitation of Alternator causes a change in kVAR output of the Alternator

<u>Effect of change of excitation of an Alternator</u>

- Consider two Alternators connected in parallel
- Assume that they are identical & shares one half of active (kW) & reactive (kVAR) power
- Now power factor of Alternators being same as load power factor (Cosϕ)



- Now let excitation of Alternator 1 increased, so that $E_1 > E_2$
- It results in a resultant voltage & causes a circulating current (I_{sy})
- When excitation of an Alternator increases, its terminal voltage increases, the power factor deceases. i.e, it delivers a current that is more lagging the voltage
- This lagging current causes a demagnetizing armature reaction & effect of increase in excitation (over excitation) is cancelled
- i.e, Power factor of Alternator 1 decreases (ϕ increases to ϕ_1).
- Since mechanical power input to the Alternators remain same, kW shared by Alternators remain same; But kVAR shared by Alternator changes as shown in figure



- Similarly if excitation is reduced (under excitation), terminal voltage decreases
- Now the Alternator delivers a leading current, so that it causes a magnetizing armature reaction & effect of under excitation is

MODULE IV

Synchronous motor – Construction, Principle of operation, Effect of excitation on armature current & power factor, V & inverted V curve, Phasor diagram, Losses & efficiency

Three phase induction motor – Constructional features, Types, Theory, Slip, Mechanical power & torque developed, Torque slip characteristics, Equivalent circuit

Synchronous motor

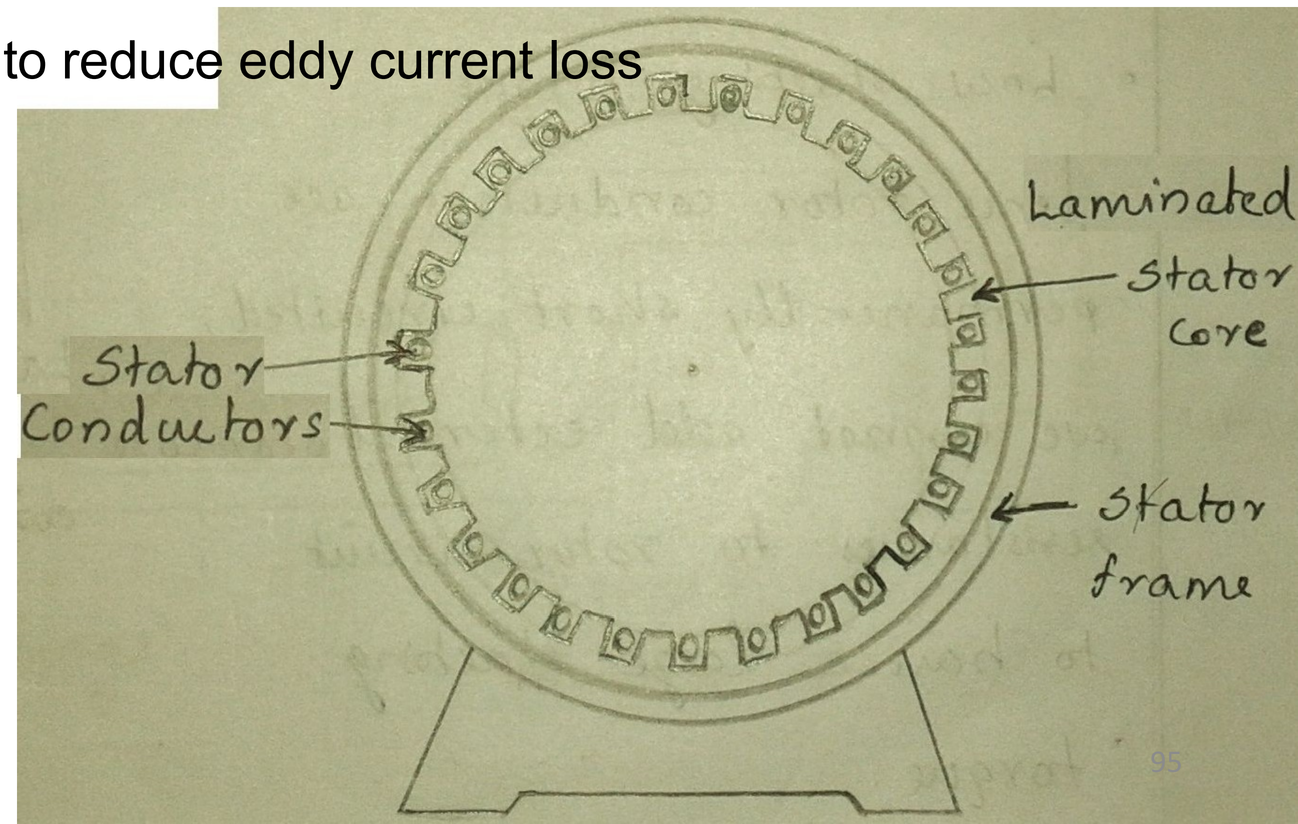
- A synchronous motor is an electrical machine which converts AC electrical energy into mechanical energy
- A synchronous motor runs at synchronous speed, Ns = (120f)/P

Construction of Synchronous motor

- It has mainly 2 parts
    1. Stator
    2. Rotor

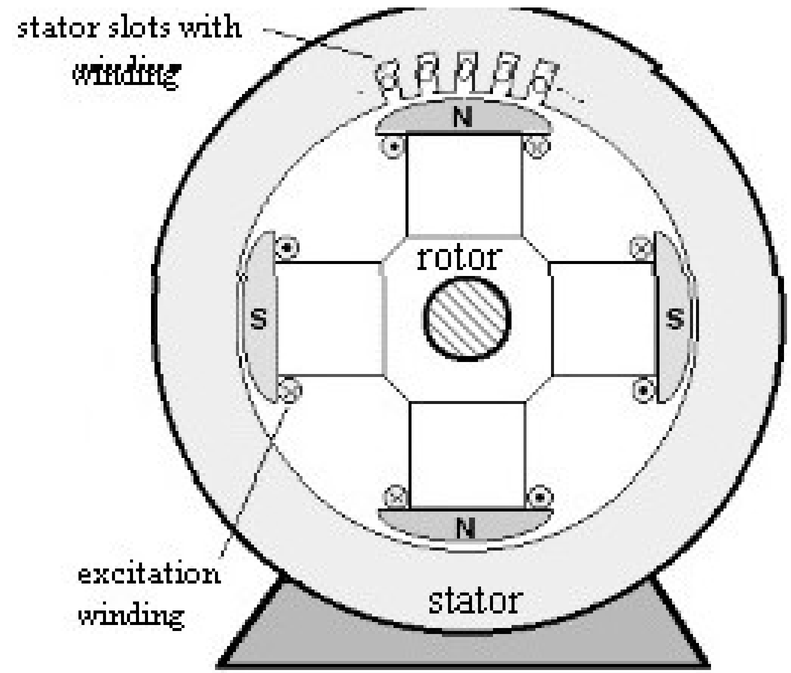
1. Stator or Armature

- stationary part
- ***Stator core*** contain an iron ring made of silicon steel laminations
- Slots are cut on the inner periphery of the stator core, in which stator conductors are placed
- Stator core is laminated to reduce eddy current loss
- ventilating ducts to provide efficient cooling
- Slots can be open, semi closed or totally closed
- Open slots



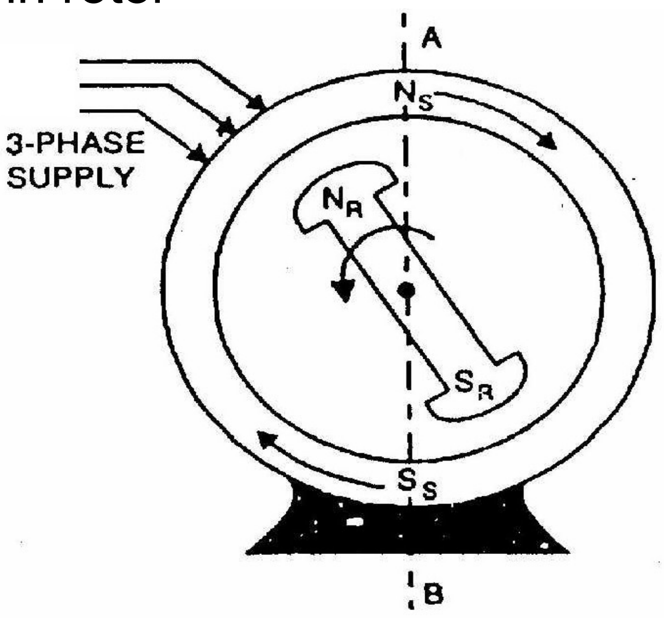
b) Rotor or Field magnet system

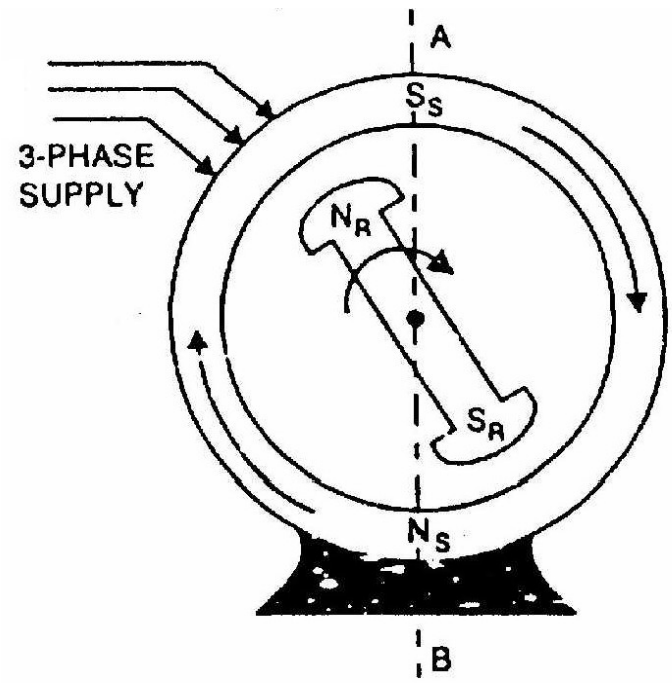
- It is the rotating part of the machine
- Rotor contain Field magnets & are supplied with DC voltage
- For this external DC sources are used & exciting current is supplied to rotor through slip rings & brushes



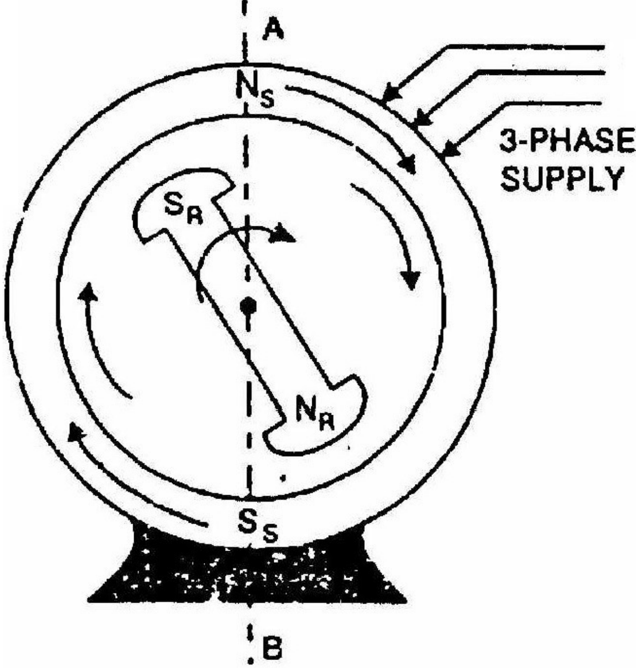
Principle of operation

- When a 3 phase supply is given to the stator, a rotating magnetic field is produced which rotates at synchronous speed
- When a DC supply is given to field windings, stationary N & S poles are created in rotor
- Now we got a revolving magnetic field poles in stator & stationary poles in rotor

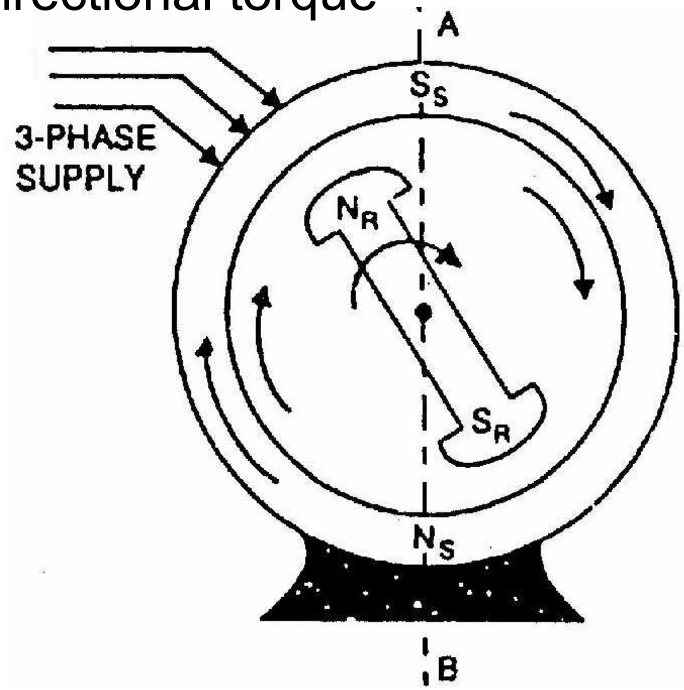




UNIDIRECTIONAL TORQUE



- If rotor is rotated by some external means at a speed near synchronous speed, in the same direction of stator magnetic field, then rotor will experience a unidirectional torque



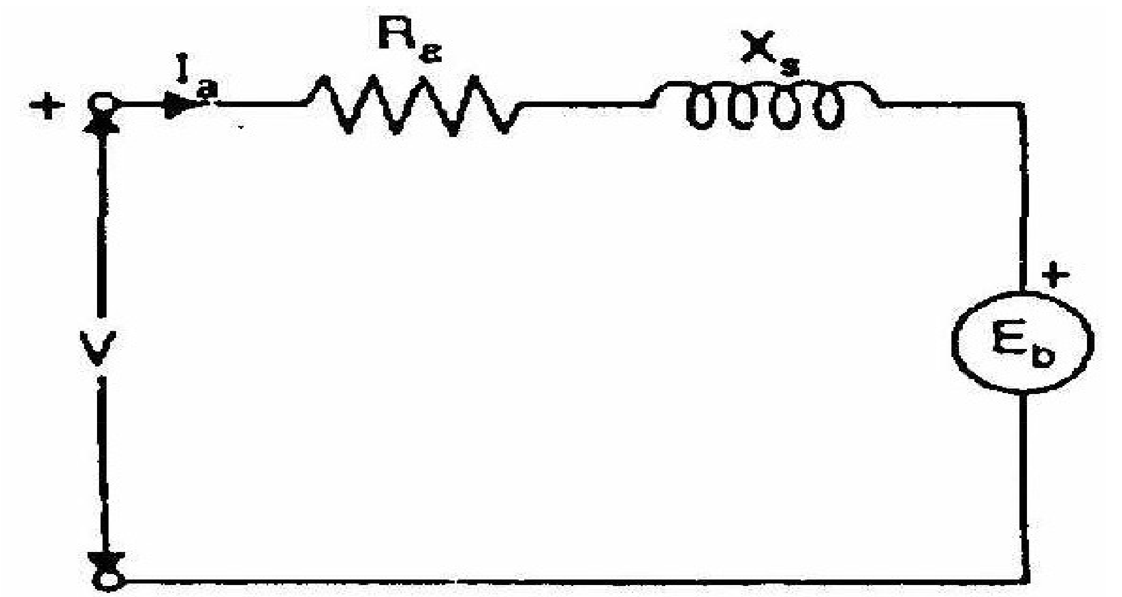
EQUIVALENT CIRCUIT OF A SYNCHRONOUS MOTOR

- In a synchronous motor we are giving two supply, DC supply to rotor & 3 phase AC supply to stator
- When AC supply is given to stator, a current flows through stator windings
- Stator windings have resistance (R_a) & synchronous reactance (X_s)
- Also when a DC supply is given to rotor, a magnetic field is produced & it links stator conductors,
- As rotor rotates, flux linked with stator conductors changes & an EMF induces in stator windings. This is called back EMF (E_b) or counter EMF
- The back EMF opposes the stator supply voltage

- From equivalent circuit,

- net voltage per phase in stator winding is given as $E_r = V – E_b$
- Armature current/phase

  $I_a = E_r/Z_s$



STARTING METHODS OF SYNCHRONOUS MOTOR

- Synchronous motor has no self starting torque
- ***1. From DC source***
- If a DC supply & a DC motor (shunt/compound) is available, the Synchronous motor is coupled to DC motor & is started using DC motor

2. By using an AC motor

- a small AC induction motor is used for starting the Synchronous motor

3. By providing damper windings

- Synchronous motor can be made self starting by providing a special winding on rotor poles known as damper winding or squirrel cage winding
- Damper winding consist of short circuited copper bars placed in rotor poles
- When AC supply is given to stator, the synchronous motor will start as an Induction motor & rotates at a speed near synchronous speed

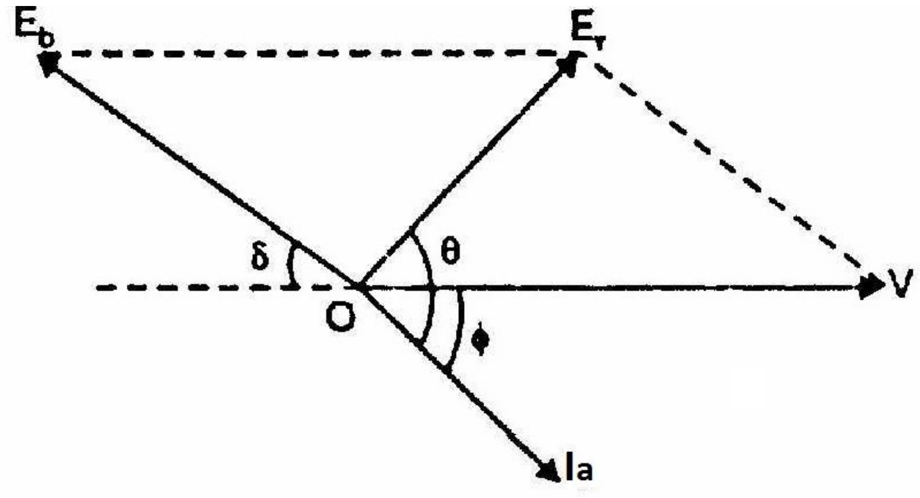
Phasor diagram of a Synchronous motor

- Consider a Synchronous motor. Let, V = stator supply voltage/phase E_b = Back EMF/phase

  Z_s = Synchronous impedance/phase

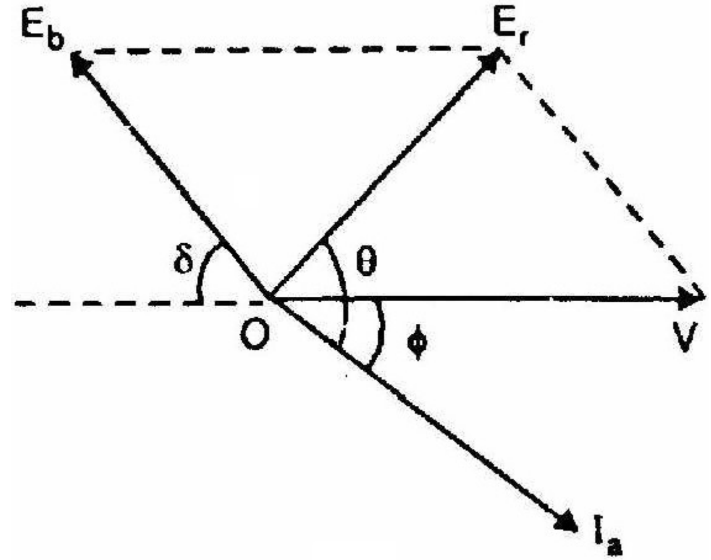
Motor on no load **–**

- On no load, load angle(δ) is small
- E_b falls back V by a small angle δ
- Net voltage/phase = E_r
- Armature current, Ia = E_r/Z_s
- I_a lags behind E_r by an angle ≈ 90◦



on load

- When load increases, δ increases
- Power input/phase, $P_i = VI_a Cos\phi$



Effect of varying excitation on Armature current & Power factor

- Consider a Synchronous motor having a fixed stator supply voltage & driving a constant mechanical load
- Since mechanical load & speed are constant, power input to motor ($VIaCos\phi$) remains constant
- If field excitation changes, back EMF changes
- This results in a change of position of Er & Ia. Hence power factor ($cos\phi$) changes
- The phasor diagram of Synchronous motor for different values of field excitation (Under, normal & over) are shown in figure

Under excitation

- Motor is said to be under excited if $E_b < V$

Normal excitation

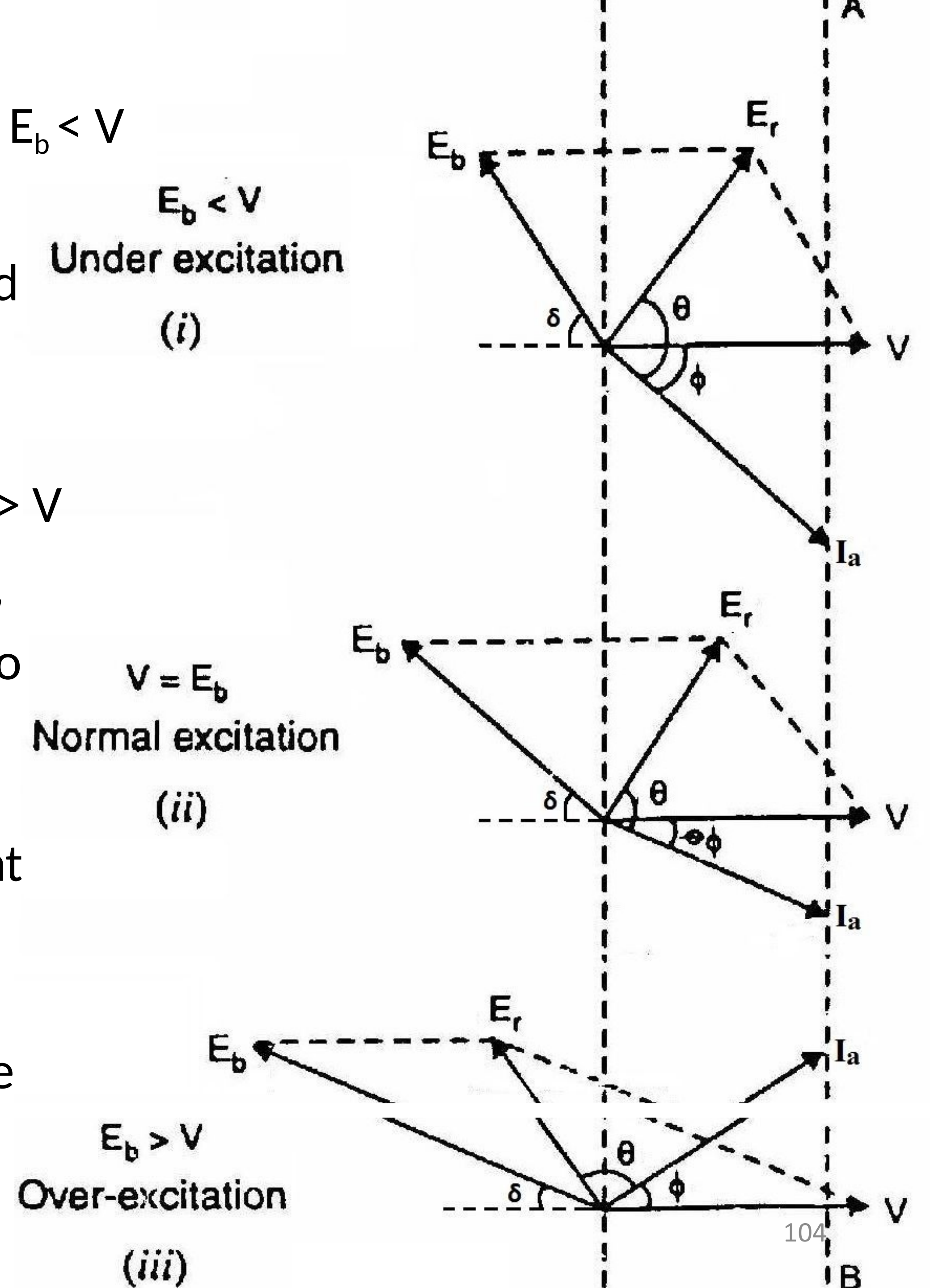
- Motor is said to be normally excited if $E_b = V$

Over excitation

-Motor is said to be over excited if $E_b > V$

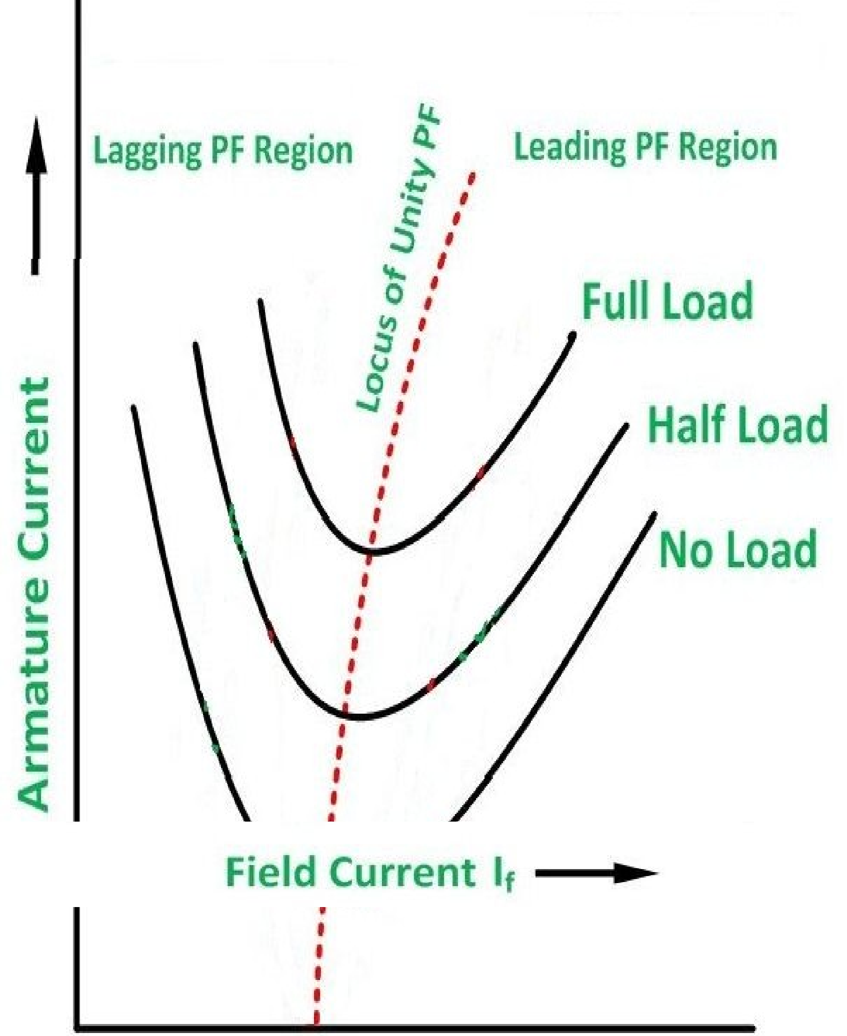
From phasor diagram, it is clear that,

- As excitation changes from under to over excitation, power factor changes from lagging to leading
- Also magnitude of armature current changes with excitation
- I_a is minimum at upf & increases in magnitude as power factor become

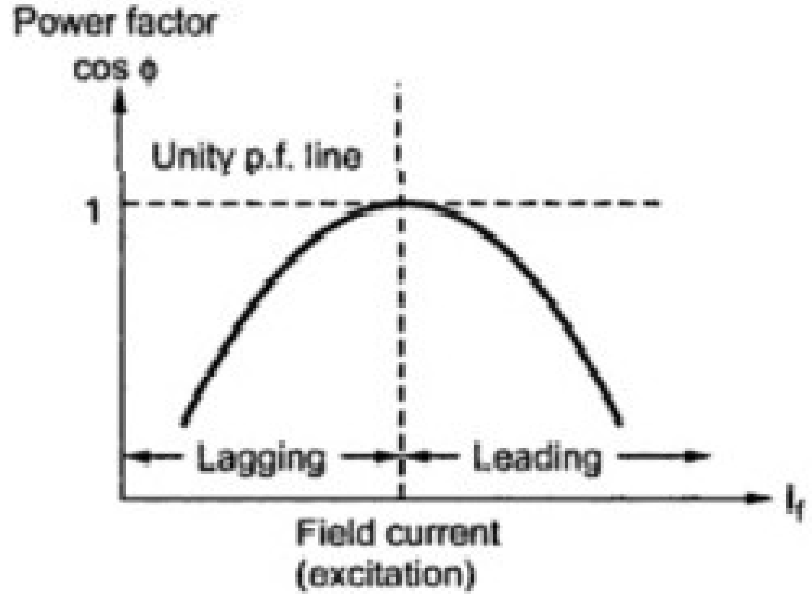


V curve

- V - curve of a Synchronous motor is the graph between armature current (I_a) and field current(I_f) at constant load
- I_a is minimum at upf & increases in magnitude as power factor decreases in lag & lead directions
- Since it is a V-shaped curve, it is called V-curve

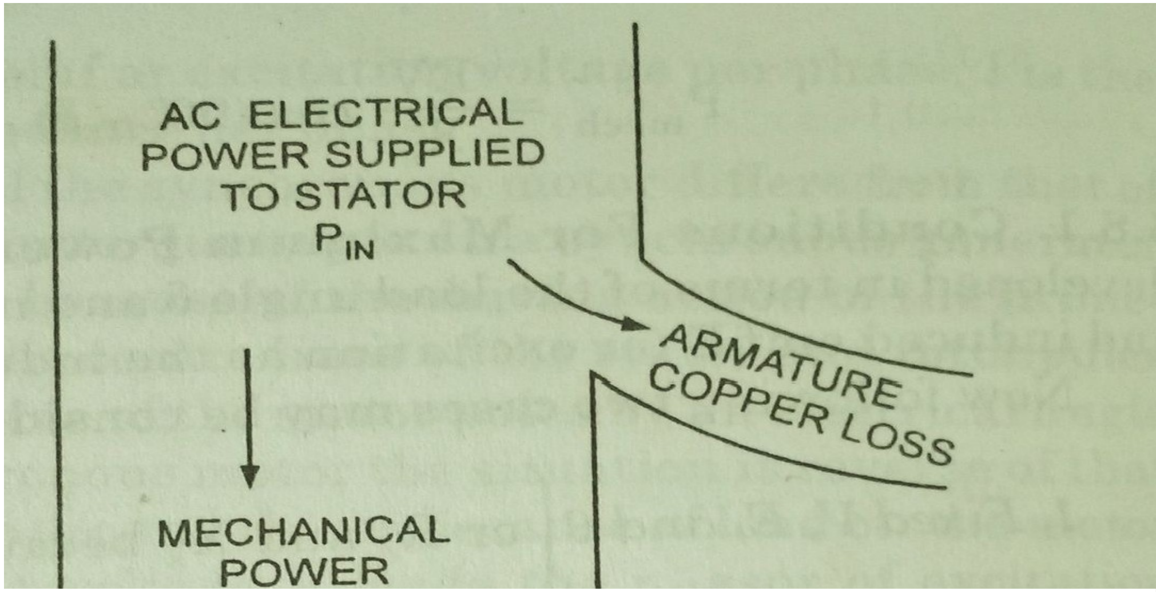


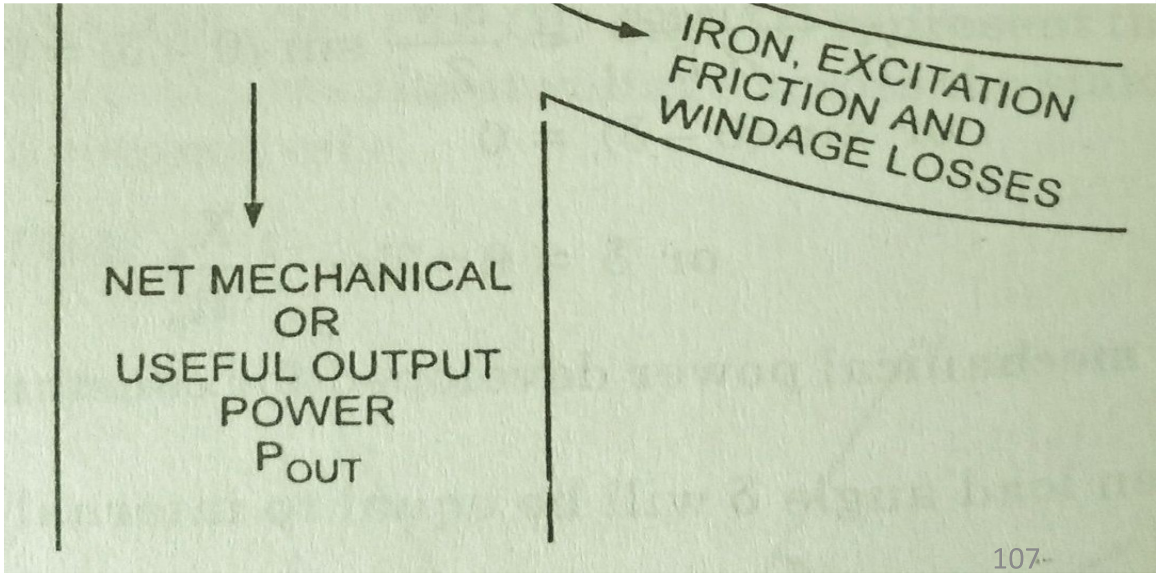
Inverted V – curve



- It is the graph between field current(I_f) & power factor
- As field excitation changes, power factor also changes
- When motor is under excited, power factor is lagging
- As excitation increases, power factor increases to reach UPF
- When motor is over excited, power factor increases in leading direction

Power flow in a Synchronous motor





Losses & Efficiency of Synchronous motor

Losses in synchronous motor may be divided into two,

a) **Load losses**

Armature Cu loss

b) **Open Circuit losses** – These losses present at no load condition. The open circuit losses are,

1. Frictional losses – losses occurring in the machine due to friction.
2. Windage loss – Losses due to air friction on rotor
3. Iron losses – These are Hysteresis & Eddy current losses in stator & rotor cores due to varying magnetic flux in the machine

$$Efficiency = \frac{Mechanical\ Power\ Output\ of\ Motor}{Electrical\ Power\ Input\ to\ Stator} * 100\%$$

$$Efficiency = \frac{Electrical\ Power\ Input\ to\ Stator - Losses}{Electrical\ Power\ Input\ to\ Stator} * 100\%$$

Different Torques in Synchronous motor

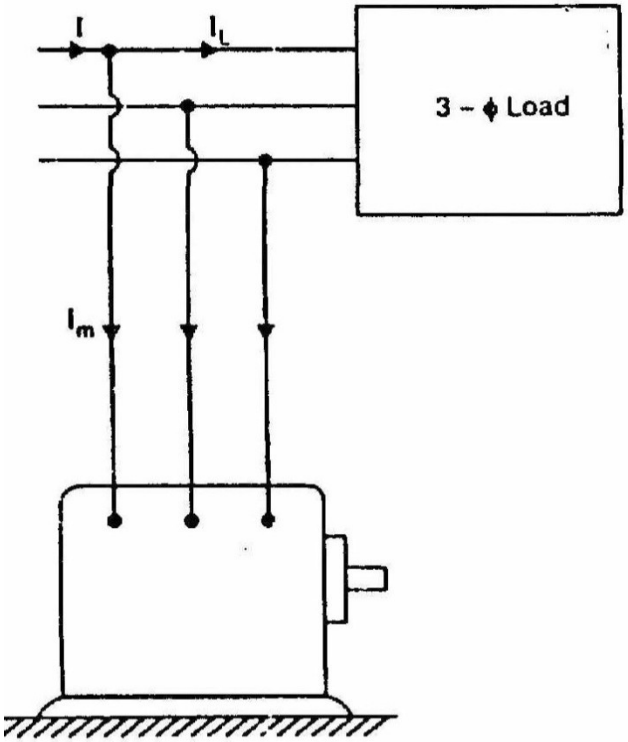
1. *Starting torque* – This is the torque produced in the motor during starting.
2. *Running torque* – Torque produced by motor during running condition
3. *Pull in torque* – This is the torque produced when motor is pulled into synchronism when changing from induction to synchronous motor operation
4. *Pull out torque* – Maximum load torque above which motor will be pulled out of synchronism is called pull out torque

Synchronous Condenser

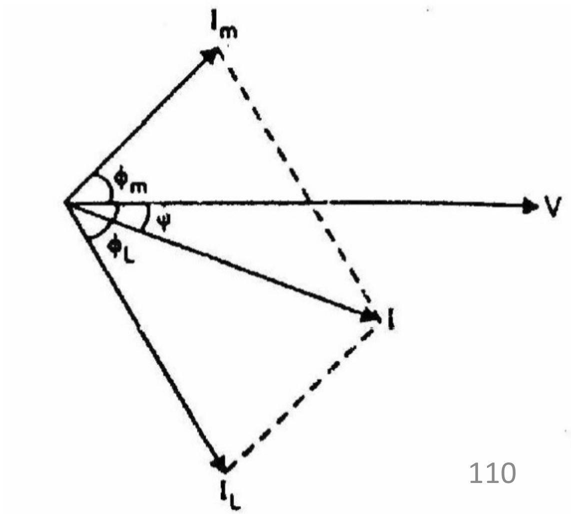
- An over excited synchronous motor running at no load is called Synchronous condenser

- Under this condition, motor will draw a leading current from supply & it can be used for power factor correction

- By connecting a Synchronous condenser in parallel to loads, over all power factor can be improved



3 – ϕ synchronous motor



Three Phase Induction motors

- Three-phase induction motors are the most common machines in industry.
- Three phase Induction motors are having following ***advantages***
  - simple design, rugged, low-price, easy maintenance
  - wide range of power ratings: fractional horsepower to 10 MW
  - run essentially at constant speed from no-load to full load
  - It has high efficiency and reasonably good power factor
  - It has self starting torque
- ***Disadvantages*** of 3 phase Induction motors are
  - Speed control is difficult & requires a variable frequency power electronic drive for accurate speed control
  - Starting torque is inferior to DC shunt motor

<u>Construction of 3 Phase Induction Motor</u>

An induction motor has two main parts

1. *<u>Stator</u>* - stationary part
2. *<u>Rotor</u>* – rotating part

- Stator is separated from rotor by a small air gap ranges from 0.4mm to 4mm, depending on the power rating of motor

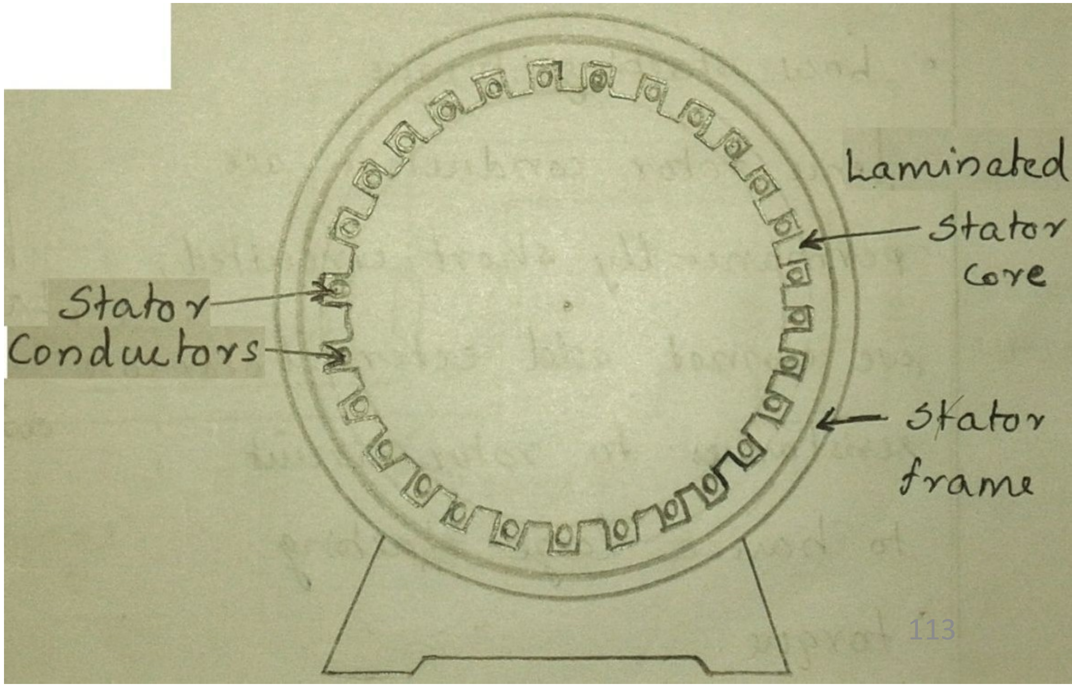
There are two type of 3 phase Induction motor based on the construction of rotor.

a) *Squirrel Cage Induction Motor (SCIM)* b) *Slip Ring Induction Motor (SRIM)*

-

- 1. ***Stator*** –

- steel frame that supports a hollow, cylindrical core
- Core is made of thin laminations of silicon steel Insulated 3 phase stator windings are provided in these slots
- Windings can be star or delta connected

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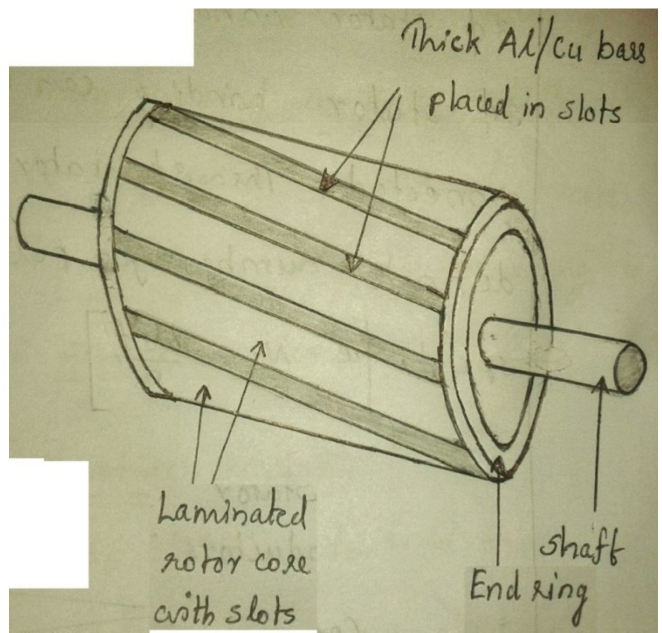
2. ***Rotor*** – rotating part

Depending on the construction, there are two type of rotor

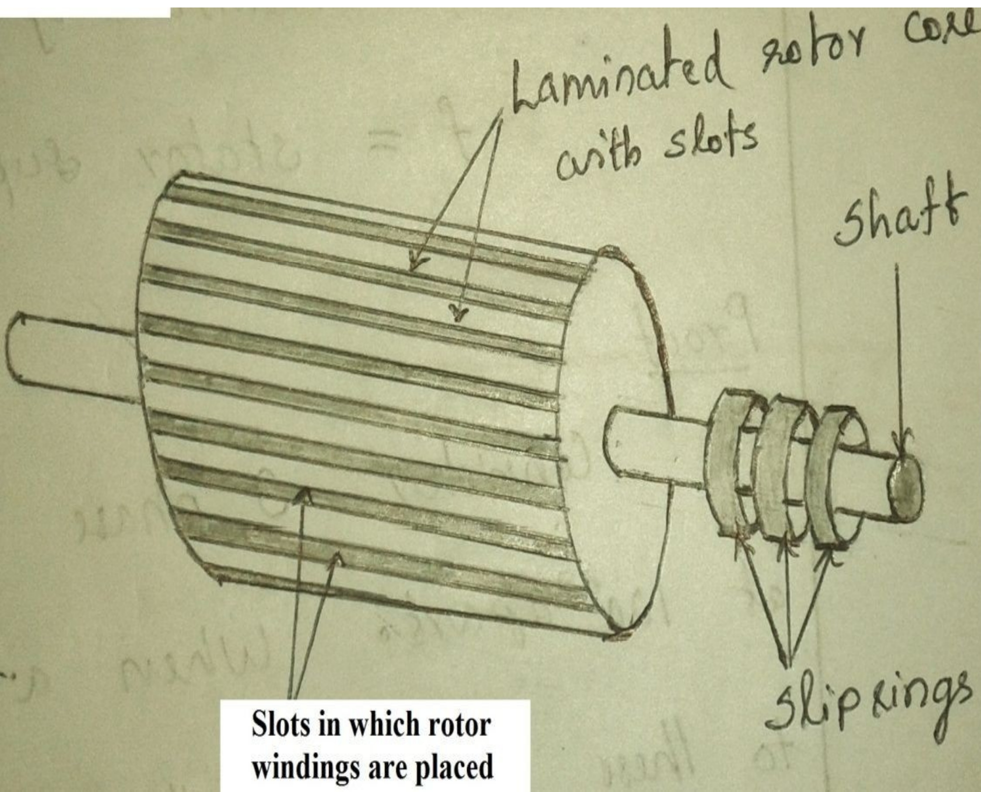
a) Squirrel cage rotor

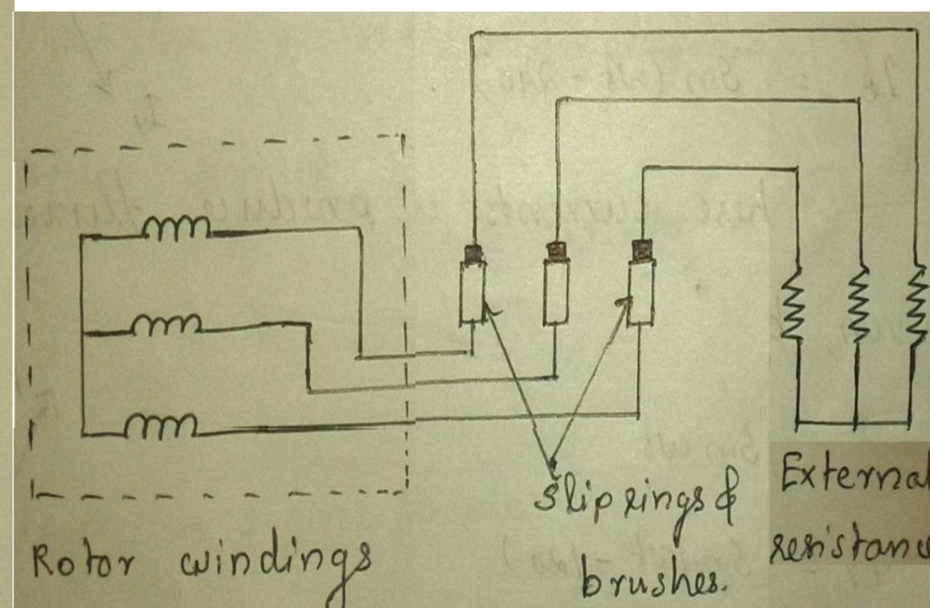
- It consist of laminated cylindrical core having slots on the outer periphery
- Thick copper or aluminium bars are placed in these slots
- All these bars are joined together at both ends by using metal rings called end rings

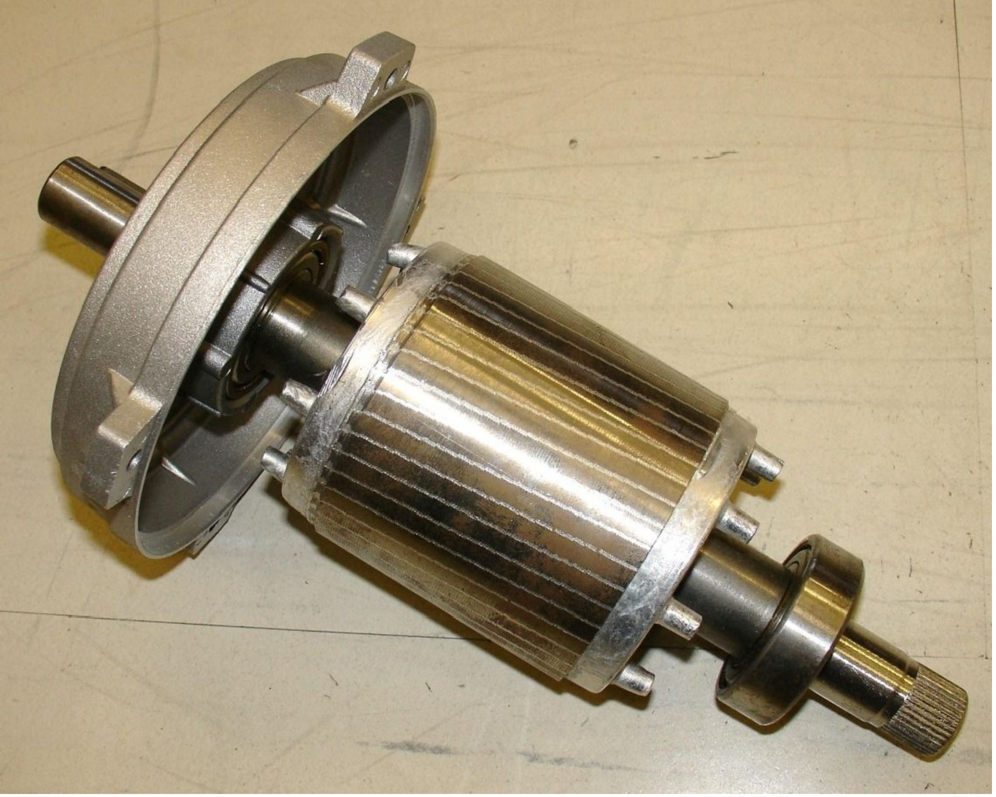


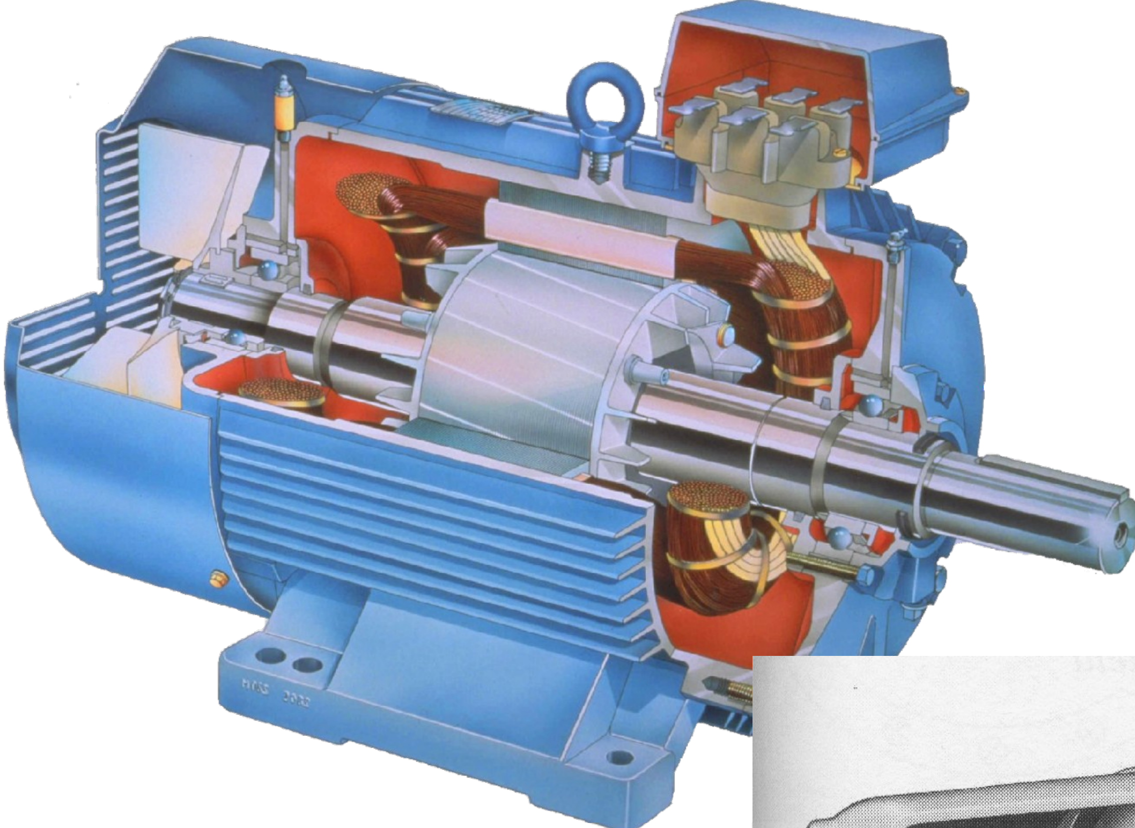
b. Wound rotor

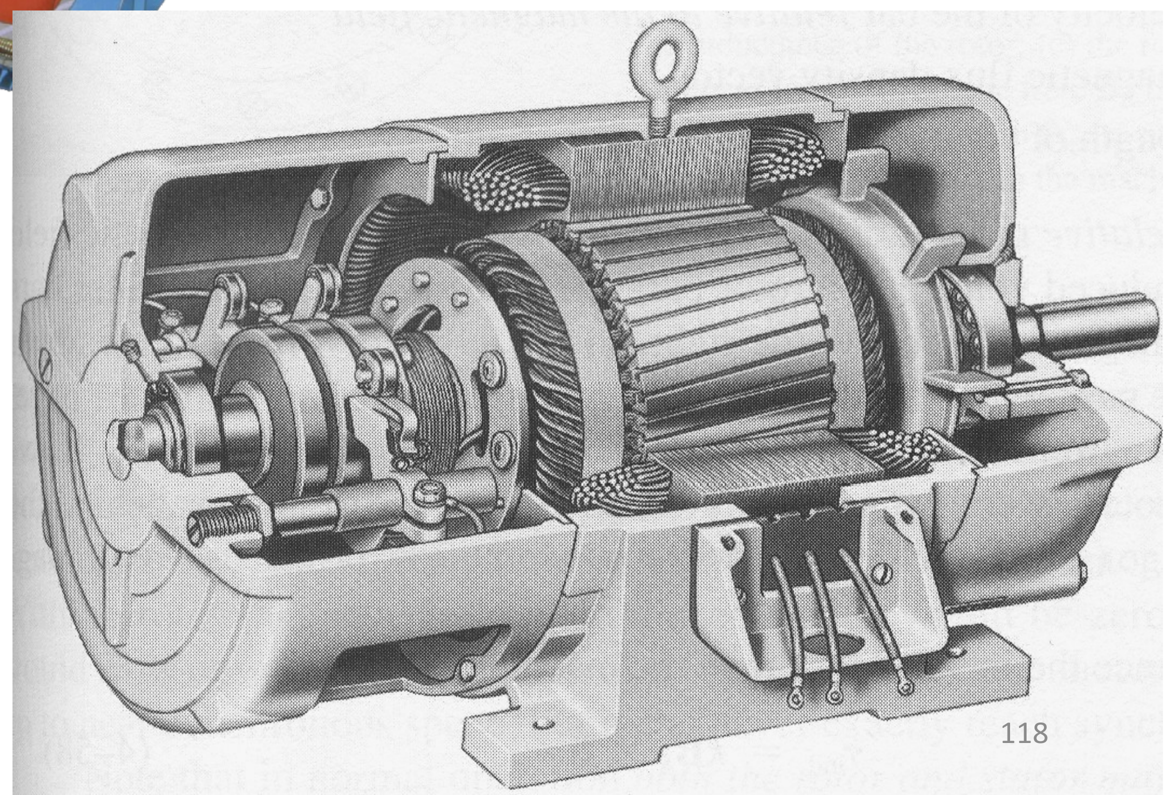
- It consist of laminated cylindrical core having slots on the outer periphery
- One terminal of each rotor phase winding is brought out and connected to 3 slip rings mounted on the rotor shaft.
- By using brushes, external resistances can be connected to rotor windings to increase starting torque.











SCIM	SRIM
Construction is **simple and rugged.**	Construction is **complicated.**
Cheap	**Costly**
Rotor consists of **bars of conductors shorted at the end by end rings.**	Rotor consists of **3 phase winding** similar to stator winding.
External resistance cannot be added	**External resistance can be added** to increase the starting torque.
Used for **constant speed operation**.	Used where **high starting torque** is required.
Requires **less conductor material**	Requires **more conductor material**
Brushes and slip rings are absent.	**Slip rings and brushes are present to add external resistance.**
Less Maintenance	Due to brushes, **frequent maintenance** is required.

SC IM	SRIM
Moderate starting torque and cannot be controlled.	**High starting torque with low starting current**.
Rotor resistance starter cannot be used.	**Rotor resistance starter** can be used.
Rotor copper loss is low. So **efficiency is high.**	**Rotor copper loss is high**. So **efficiency is low.**
Rotor automatically adjust itself for same no. of stator poles.	**Rotor is also wound for same no. of poles as that of stator.**
95% of IM in industry are SCIM	**Only 5%** of IM in industry are SRIM
Used in •**Fans** •**Blowers** •**Drilling & Printing machines** •**Pumps**	Used in • **Lifts** •**Cranes** •**Compressors** •**Elevators**

Production of 3 phase Rotational Magnetic Field

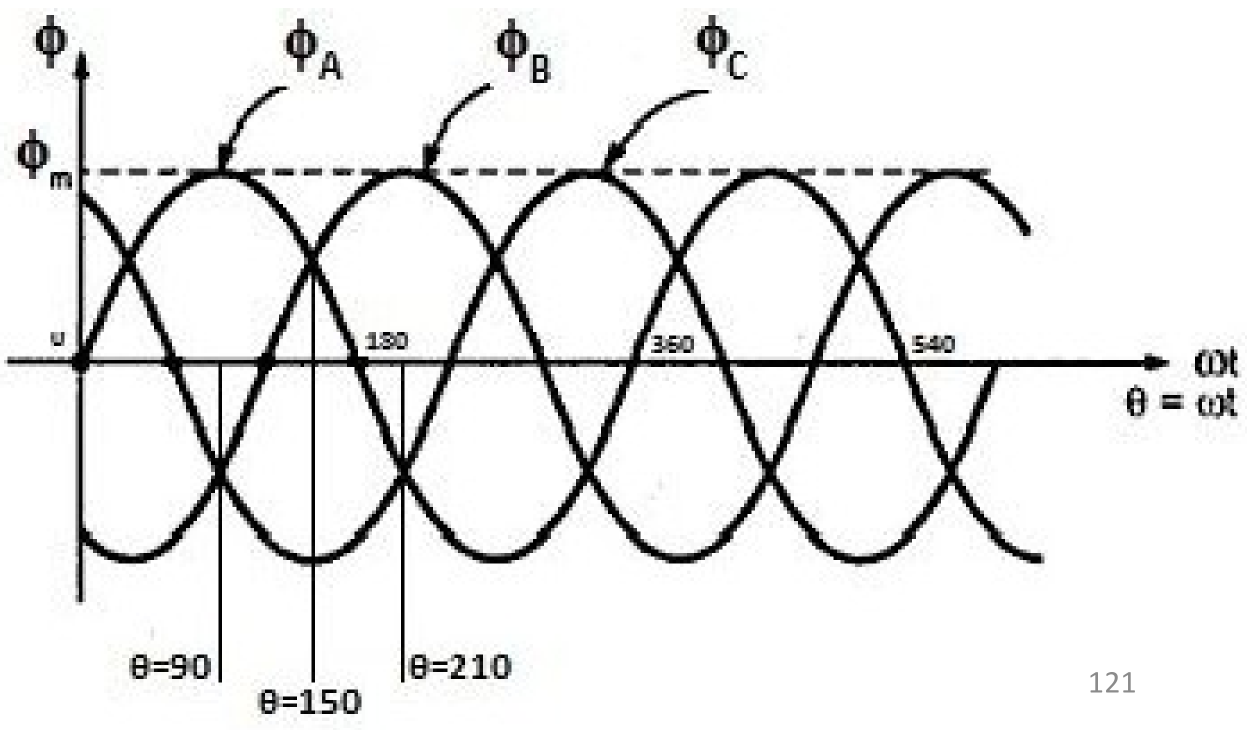
- Consider 3 coils A, B & C placed 120°(elec) apart in space
- When a 3 phase AC supply is given to these coils, currents I_A, I_B & I_C flows through these windings
- These currents will produce fluxes ϕ_A, ϕ_B & ϕ_C

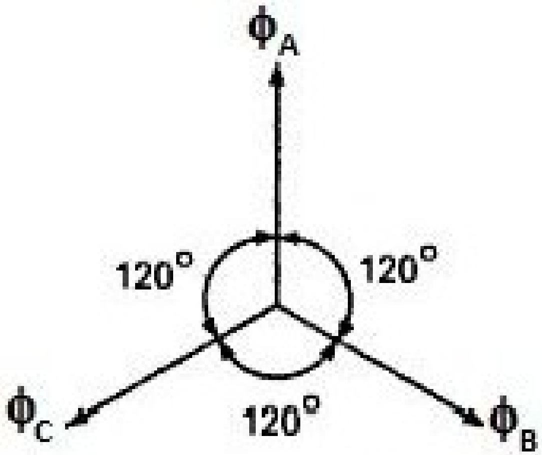
$\phi_A = \phi_m Sin\omega t$

$\phi_B = \phi_m Sin(\omega t-120)$

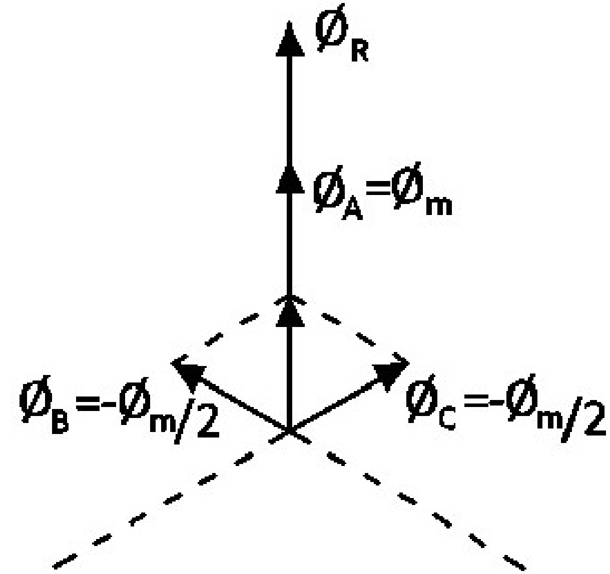
$\phi_C = \phi_m Sin(\omega t-240)$

- The flux waves are shown in figure

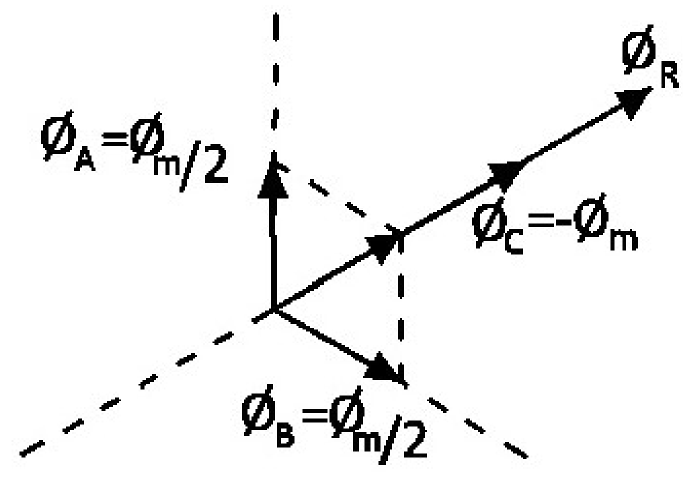




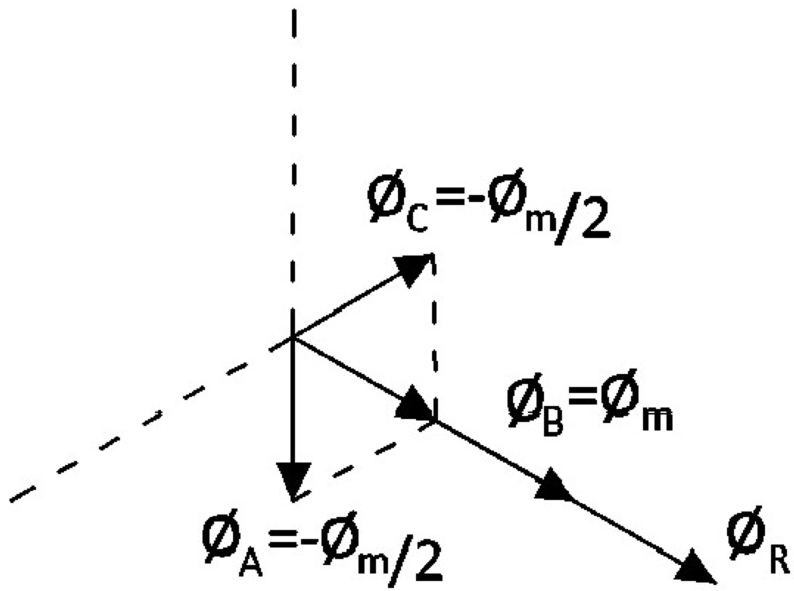
Assumed positive directions



Case 1



Case 2



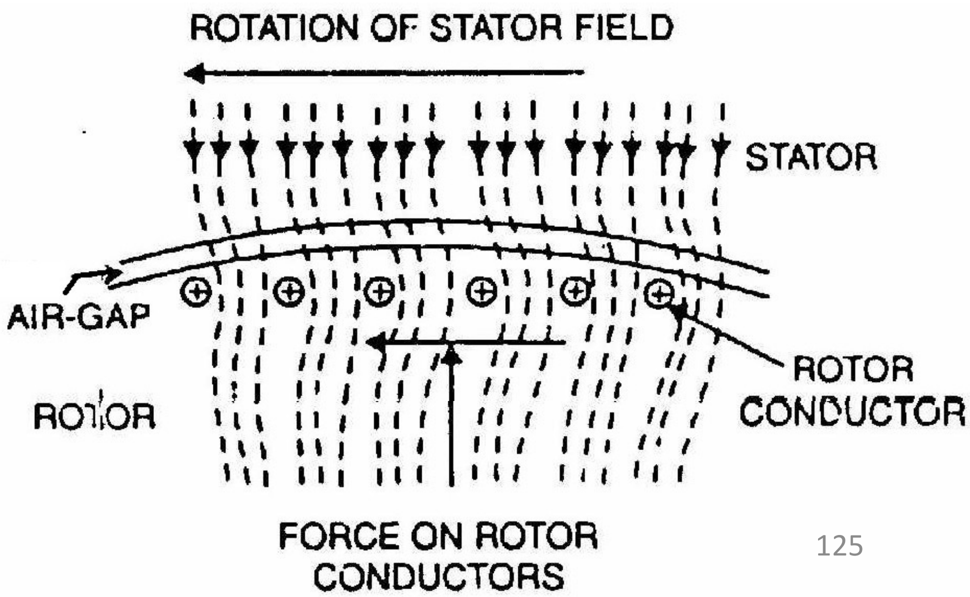
Case 3

Rotating Magnetic Field

Number of poles	Synchronous speed, Ns (For a supply frequency of
2	3000 rpm
4	1500 rpm
6	1000 rpm
8	750 rpm
10	600 rpm

Principle of operation

- *a current carrying conductor placed in a magnetic field*
- The current carrying conductor placed in a magnetic field experiences a mechanical force/torque
- Thus rotor conductors experiences a force/torque, and it tends to rotate the rotor in the same direction of rotating magnetic field (Lenz's Law)
- i.e, the direction of rotor current will be such as to oppose the cause producing it .



Slip

- The difference between the synchronous speed(N_s) and the actual speed of rotor(N) is called slip(S)

- Expressed as the % of synchronous speed

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

- if the rotor is stationary, $S = 1$

- ***Rotor current Frequency***

- The frequency of the voltage/current induced in the rotor is given by

$$f_r = \frac{N_{slip} P}{120} = s\ f$$

i.e, rotor current frequency = slip * stator supply frequency

$S = (N_s - N)/N_s \Rightarrow SN_s = N_s - N$

.... (1) $N_s = (120f)/P \Rightarrow f = (N_s P/120)$

.... (2)

Rotor current frequency, $f_r = \frac{(N_s - N)P}{120} = \frac{sN_s P}{120}$ (from eqn. 1)

i.e, $\mathbf{f_r = Sf}$ (Sub. Eqn. 2)

- When motor is at stationary, $S = 1$, $\therefore f_r = f$
- When motor picks up speed, S decreases. Consequently f_r decreases

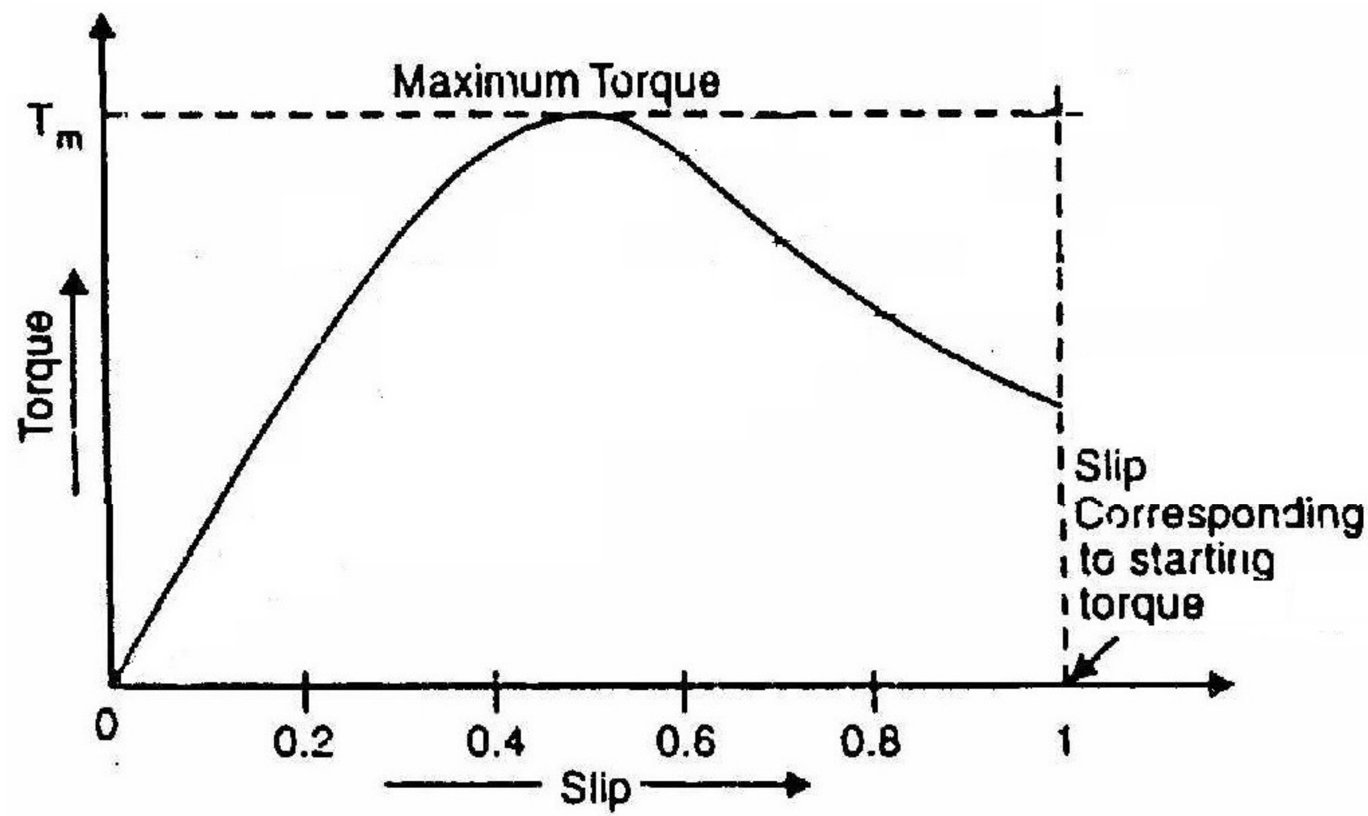
Effect of Slip on rotor circuit

- Rotor induced EMF/phase = SE_2
- Rotor frequency = Sf
- Rotor reactance/phase = SX_2

Torque – Slip & Torque – Speed characteristICS

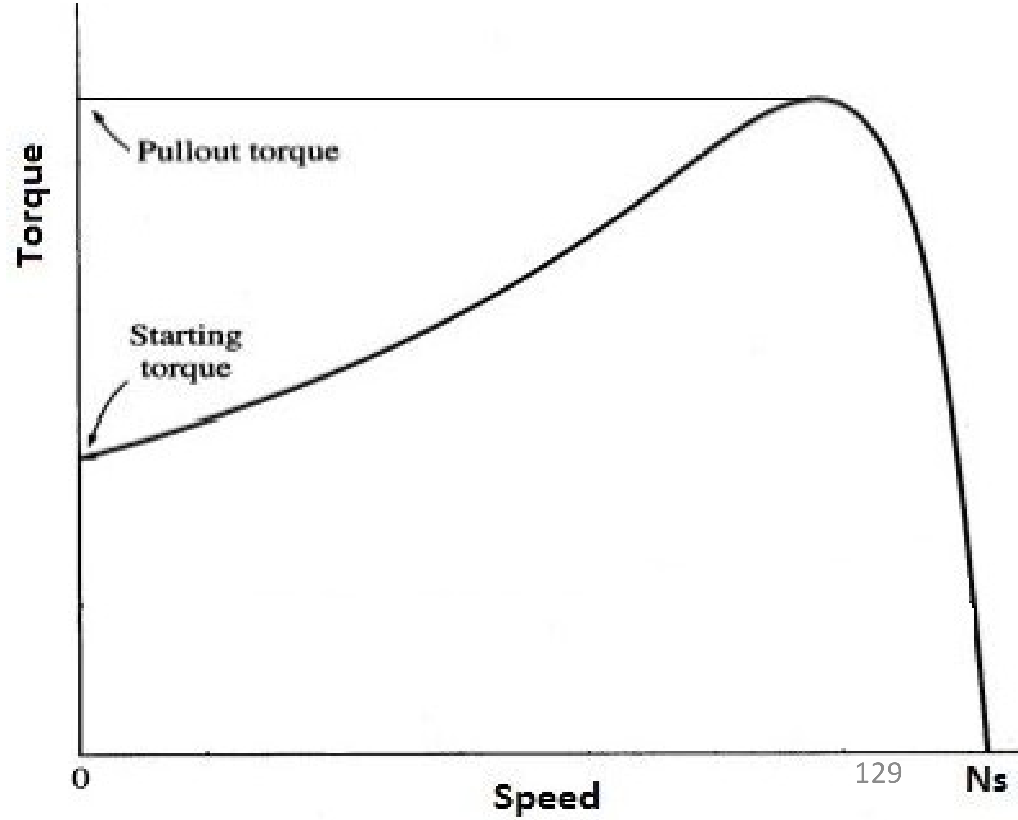
- Torque produced by an Induction motor is given by,

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



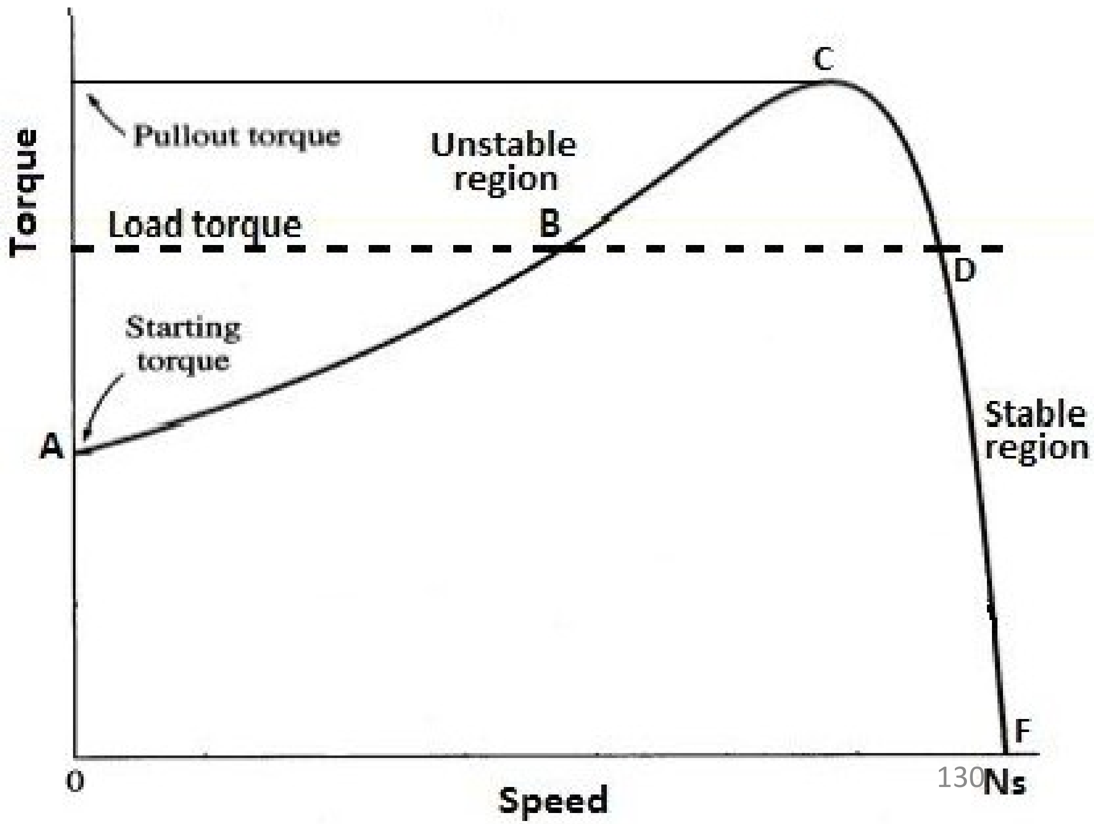
- As slip increases, speed decreases & torque increases. Torque reaches maximum value at $s = (R_2/X_2)$. Maximum torque is known as breakdown torque or pullout torque
- With further increase in slip, torque decreases, motor slows down & stops
- With higher value of slip, R_2 become negligible compared to sX_2 & $T \alpha (s/(sX_2)^2) \alpha (1/s)$, i.e, curve is a hyperbola

- ***The T-Speed characteristics of an Induction motor is shown in figure***



Torque-Speed curve & operating region

- At point B, the operation is unstable So in point B, the operation is unstable
- Now consider point D. At this point if there is a tendency of speed rise, the developed torque decreases than load torque causing a decrease in speed & motor is bring back to point D.



Power stages in an Induction motor

1. ***Fixed losses***

   a) Stator iron losses

   b) Friction & windage losses

   - Rotor iron losses are negligible

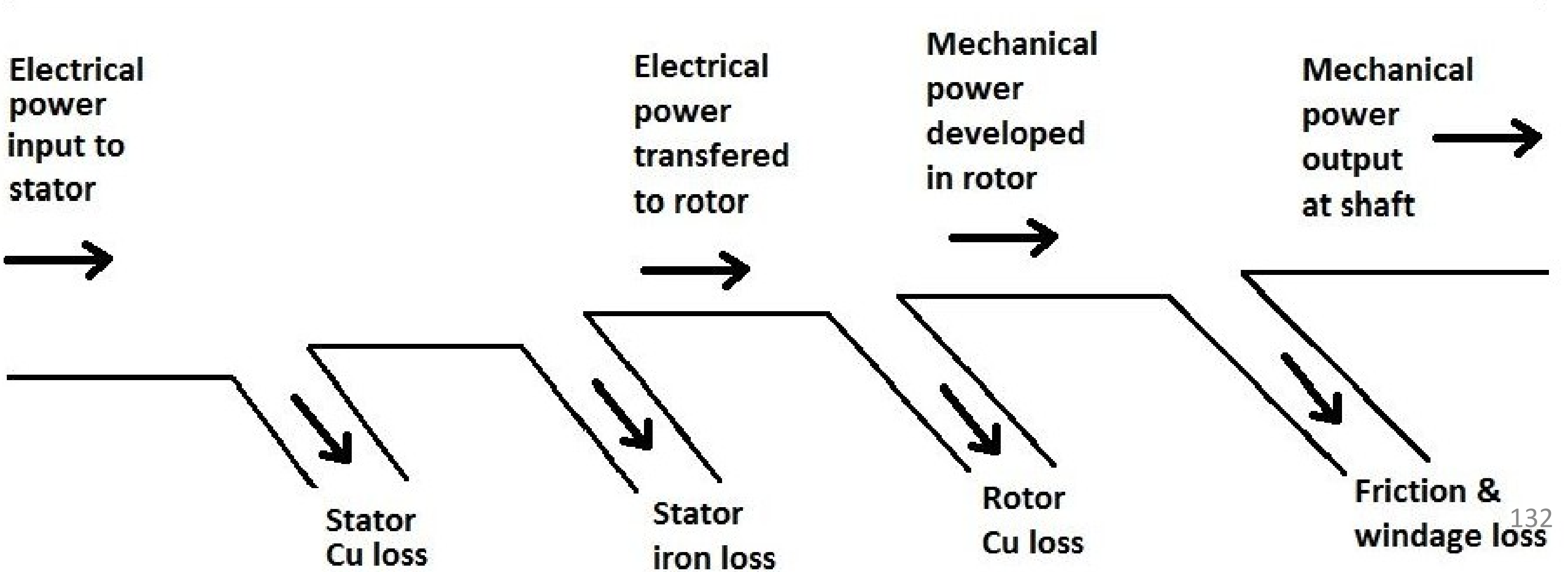
2. ***Variable losses***

   a) Stator Cu loss

   b) Rotor Cu loss

- Power flow diagram is shown in next slide

Power flow



Electrical power input to stator
Electrical power transfered to rotor
Mechanical power developed in rotor
Mechanical power output at shaft
Stator Cu loss
Stator iron loss
Rotor Cu loss
Friction & windage loss

Equivalent circuit of an Induction motor

- equivalent circuit of transformer can be represented by using a transformer equivalent circuit
- Let K be the transformation ratio
- The per phase equivalent circuit of induction motor w.r.to stator is shown in figure
- V_1 = stator supply voltage/phase

  R_1, X_1 = stator resistance & reactance/phase R_2,

  X_2 = rotor resistance & reactance/phase R_0, X_m =

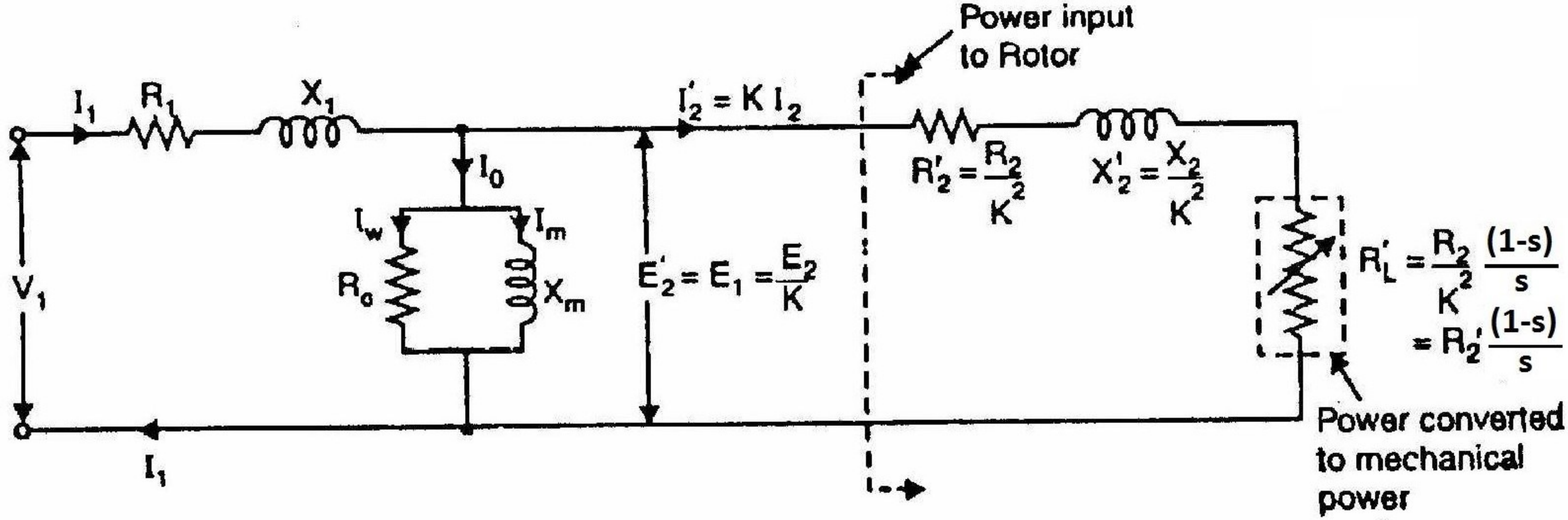
  No load resistance & reactance/phase

R_L = per phase Electrical equivalent of mechanical power developed in rotor

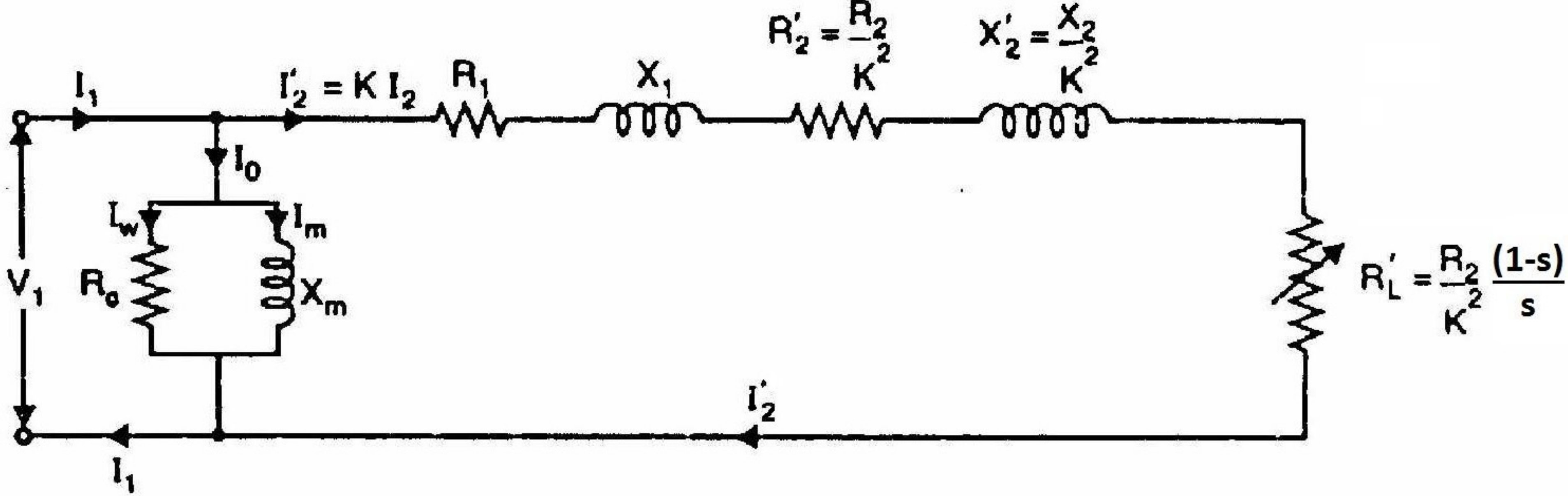
I_1 = Stator current/phase

I_2 = rotor current/phase

I_0 = No load



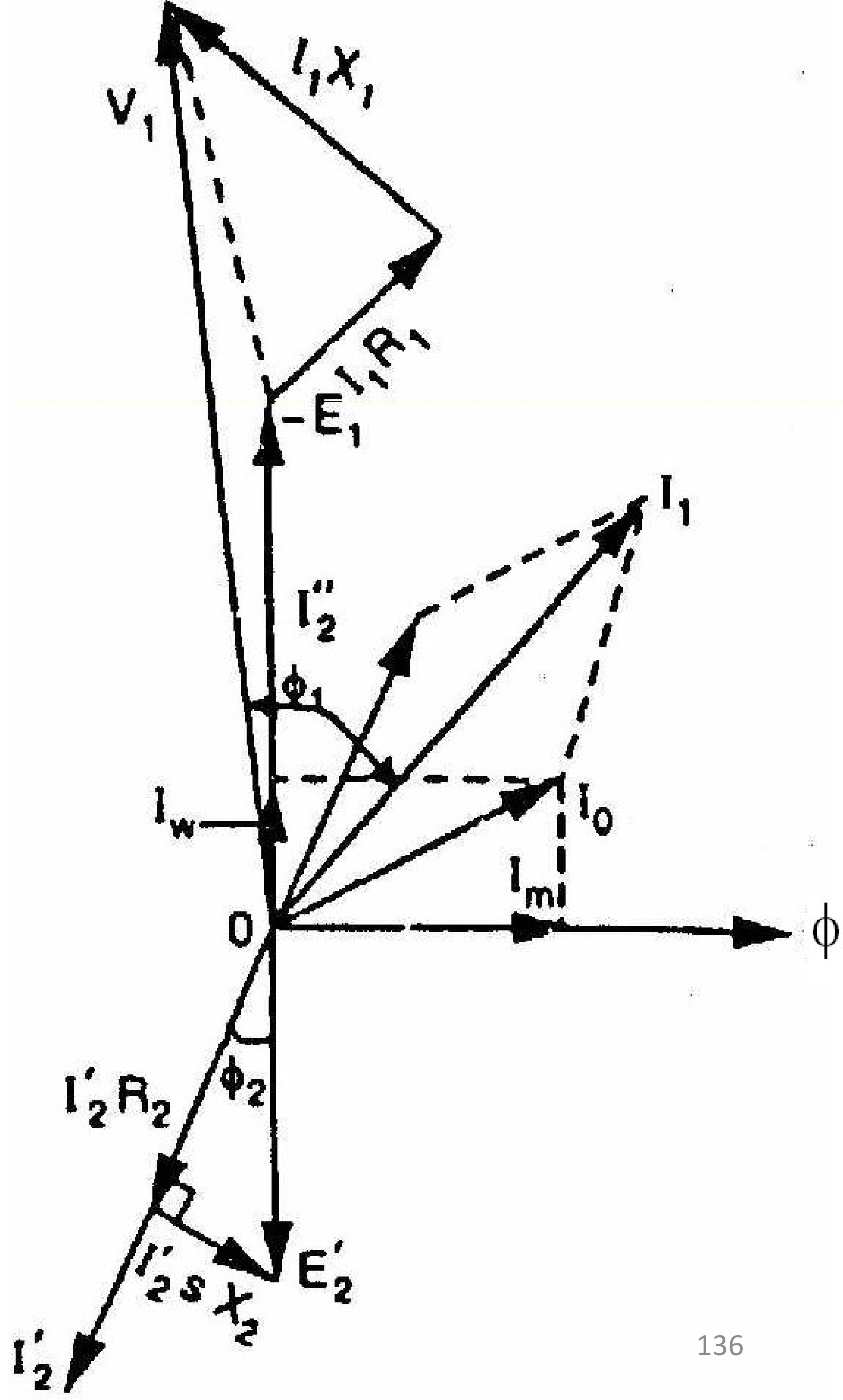
- The equivalent circuit can be simplified by transferring the no load branch to supply terminals as shown



I1
I'2 = K I2
R1
X1
R'2 = R2/K2
X'2 = X2/K2
I0
Iw
Im
V1
Ro
Xm
R'L = R2/K2 (1-s)/s
I'2
I1

Phasor diagram of Induction motor

- Phasor diagram can be drawn based on the equivalent circuit if Induction motor



MODULE
V

Tests on Induction motor, Circle diagram, Cogging & Crawling, Double cage Induction motor.
Starting of Induction motors – DOL starter, Autotransformer starter, Star-delta starter, Rotor resistance starter.

Braking of Induction motor – Plugging, Dynamic braking, Regenerative braking.

Speed control – Stator voltage control, V/F control, Rotor resistance control

Tests on 3 phase Induction Motor

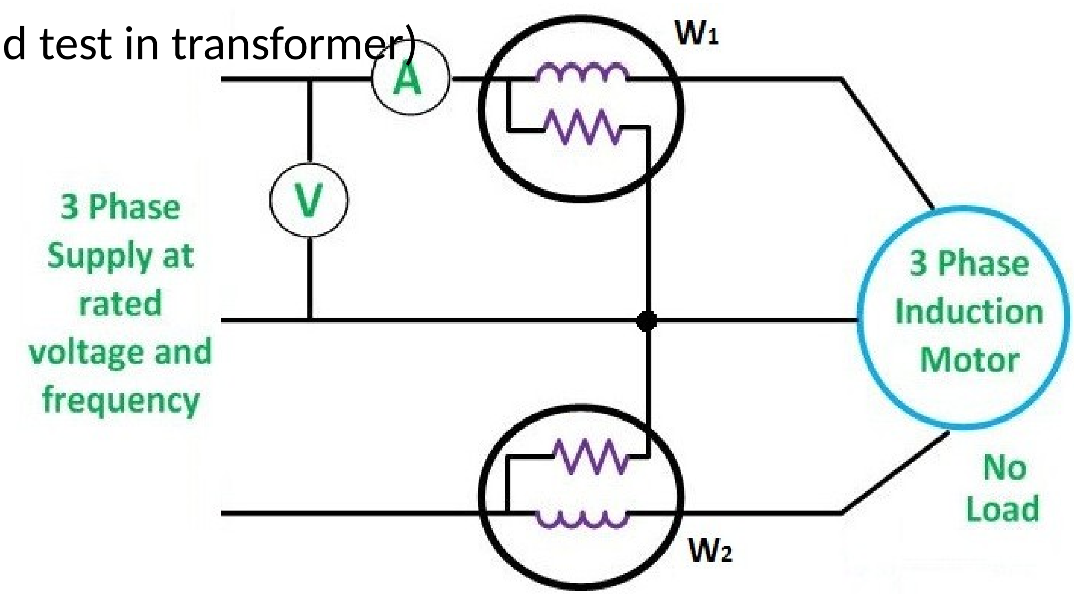
Assume that, the motor stator is star connected

1. Stator resistance measurement

- A DC voltage is applied across any two phase terminals & resistance is measured using ammeter-voltmeter method. The measured resistance value is given by Voltmeter reading/Ammeter reading
- Now stator resistance/phase, R_{DC}/ph = Measured resistance value/2
- R_{AC}/ph = R_{DC}/ph*1.25

2. No load test (Equivalent to No load test in transformer)

- During this test, Induction motor is made to run at no load by applying rated voltage & frequency supply
- The connection diagram is shown in figure



Voltmeter reading = V_{OL} = No load line voltage Ammeter

reading = I_{OL} = No load line current

Wattmeter reading, W_1+W_2 = 3 phase power input at no

load = P_O No load voltage/phase = $V_{OPH} = V_{OL}/(\sqrt{3})$

No load current/phase = $I_{OPH} = I_{OL}$

No load power input = $P_O = 3V_{OPH}I_{OPH}Cos\phi_0$

$$Cos\phi_0 = No\ load\ \ p.f = \frac{P_0}{3V_{OPH} I_{OPH}}$$

$I_{MPH} = I_{OPH}Sin\phi_0$

$I_{WPH} = I_{OPH}Cos\phi_0$

R_O =

V_{OPH}/I_{WPH}

X_O =

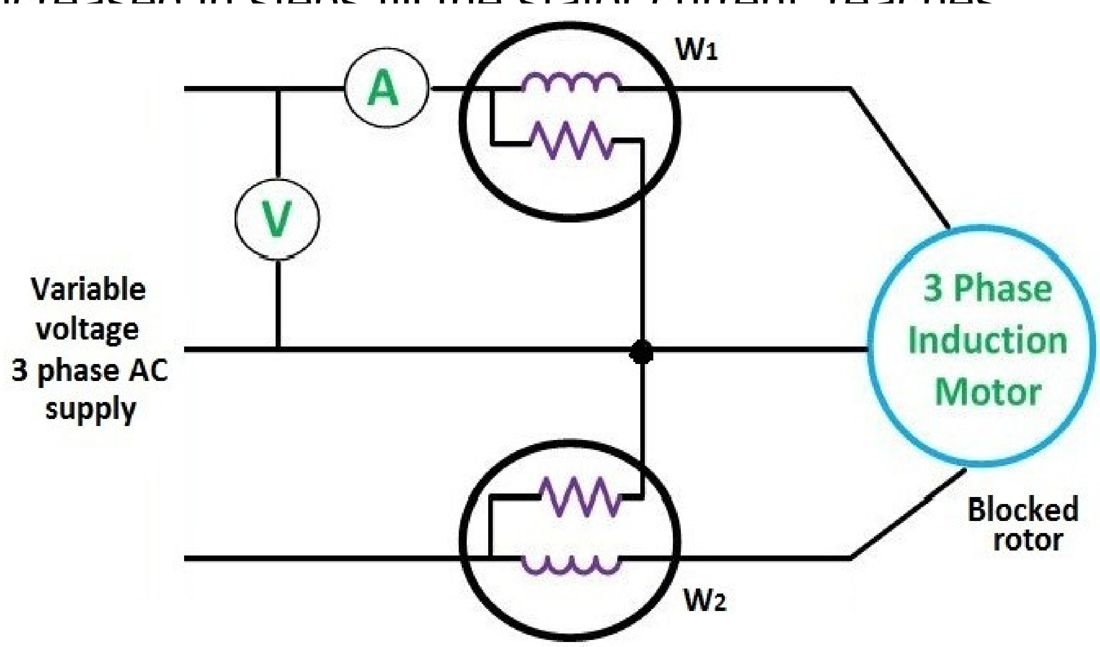
V_{OPH}/I_{MPH}

- From No load test values, the parameters for equivalent circuit &

3. Blocked rotor test

(Equivalent to Short circuit test in transformer)

- During this test, rotor is blocked from rotation by using hand or by using a brake drum & belt arrangement
- Now the stator is supplied from a variable voltage supply
- The stator applied voltage is increased in steps till the stator current reaches rated value
- Now the meter readings are taken
- The connection diagram is shown in figure



Voltmeter reading = V_{SCL} = Blocked rotor/Short circuit line voltage

Ammeter reading = I_{SCL} = Short circuit line current

Wattmeter reading, W_1+W_2 = 3 phase power input at short circuit = P_{SC}. Short circuit voltage/phase = V_{SCPH} = $V_{SCL}/(\sqrt{3})$

Short circuit current/phase = $I_{SCPH} = I_{SCL}$

Short circuit power input = $P_{SC} = 3V_{SCPH}I_{SCPH}Cos\phi_{SC} = 3I_{SCPH}^2 R_{01}$

$$Cos\phi_{SC} = Short\ Circuit\ p.f = \frac{P_{SC}}{3V_{SCPH}\,I_{SCPH}} \qquad R_{01} = \frac{P_{SC}}{3I_{SCPH}^2}$$

$Z_{01} = V_{SCPH}/I_{SCPH}$, $\quad X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$X_{01} = X_1 + X_2'$. Normally stator & rotor reactance/phase is assumed to be constant. i.e, $X_1 = X_2 = X_{01}/2$

$R_{01} = R_1 + R_2'$. Stator resistance/phase is measured by Ammeter- Voltmeter method.

Rotor resistance/phase, $R_2' = R_{01} - R_1$

- From Blocked rotor test values, the parameters for equivalent circuit & parameters for drawing Circle diagram are obtained

Circle diagram

- In a series RL circuit containing a constant reactance (X_L) & variable resistance (R), the locus of current in the circuit is a circle of diameter V/X_L
- From equivalent circuit of Induction motor, it is clear that it can be considered as a series RL circuit with constant reactance ($X_{01} = X_1+X_2'$) & a variable resistance (R_{01} is constant but load resistance $R_L' = (R_2/K^2)*((1-s)/s)$ varies with slip)
- So locus of current I_1' is a circle of radius V/X_{01}

Construction of Circle diagram

- Data required for construction of circle diagram is obtained from No load test, Blocked rotor test & Stator resistance measurement test
- Different steps involved in construction of circle diagram & calculations are given below
- Assume that the stator is star connected

calculate No load current/phase (I_{0ph}) load power factor angle (ϕ_0) & No

- $I_{0ph} = I_{0L}$

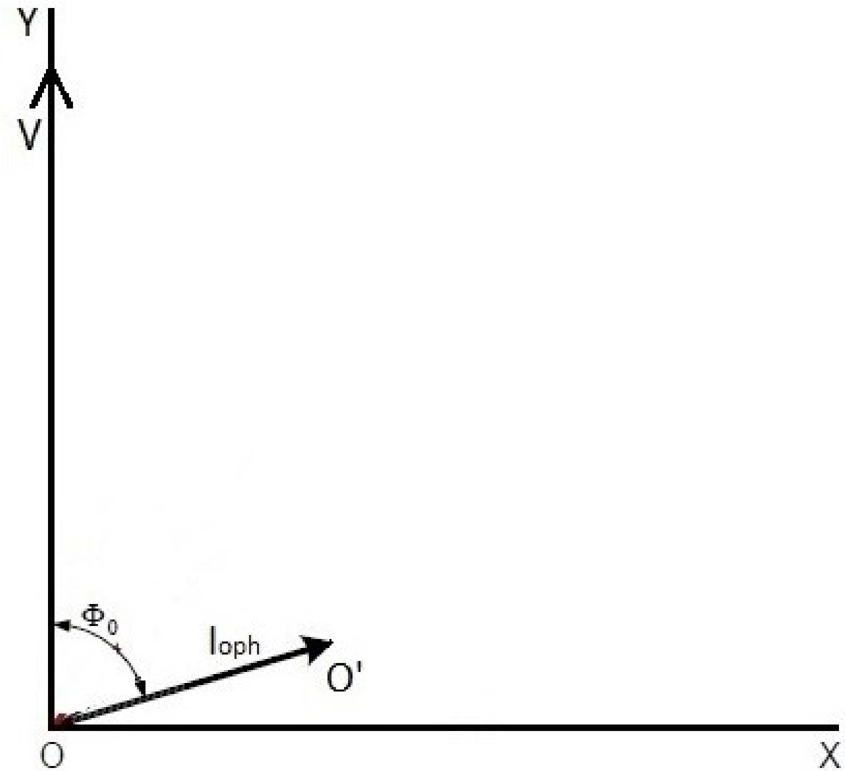
$$\phi_0 = Cos^{-1}\left(\frac{P_0}{\sqrt{3}\,V_{oph}\,I_{oph}}\right)$$

- From Blocked rotor test, calculate short circuit power factor angle (ϕ_{sc}) & short circuit stator current/phase (I_{SN}) when rated voltage is applied

$$\phi_{sc} = Cos^{-1}\left(\frac{P_{sc}}{\sqrt{3}\,V_{scph}\,I_{scph}}\right) \qquad I_{SN} = I_{scph}\,\frac{V_{Ratedph}}{V_{scph}}$$

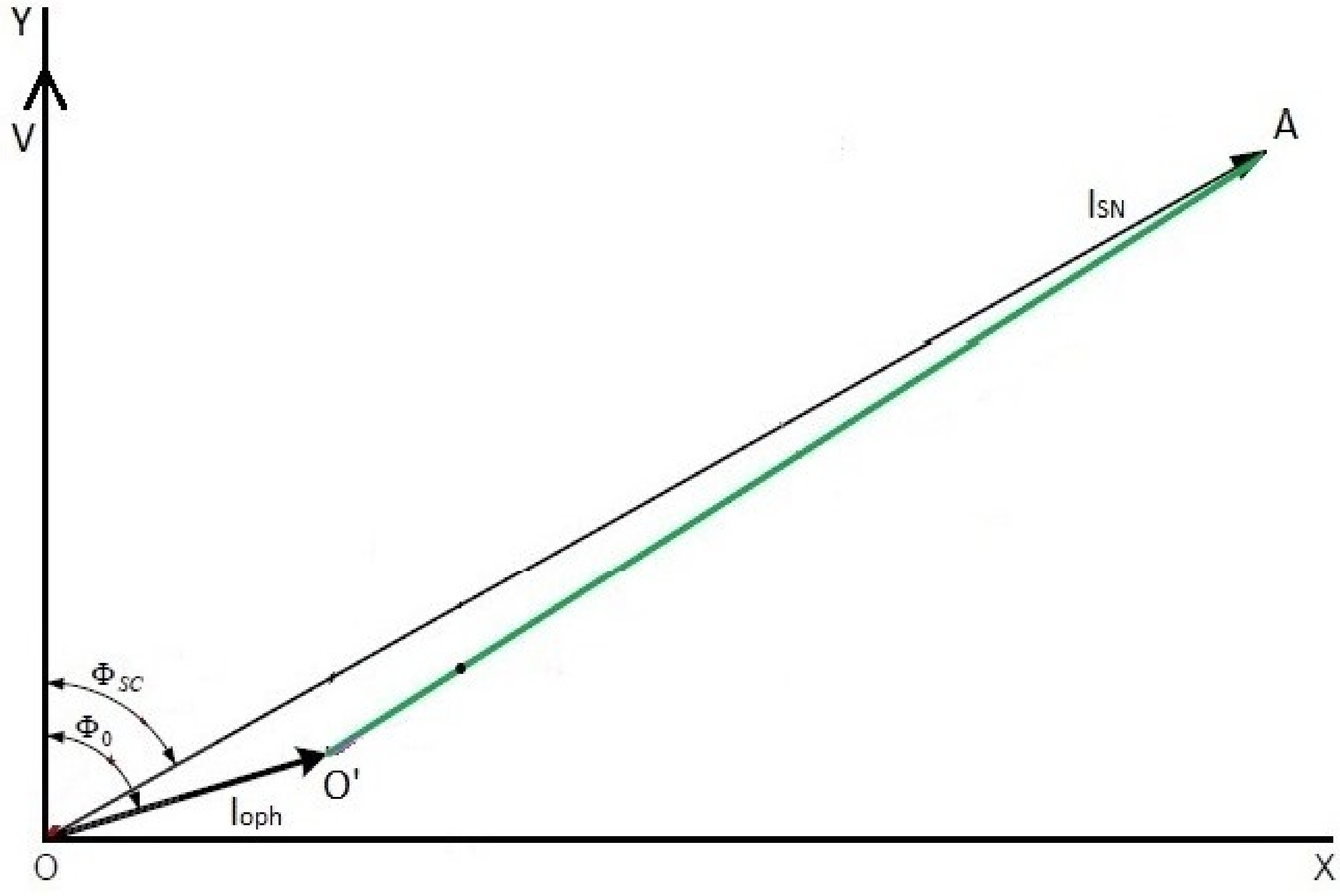
Step 2 - Draw the horizontal axis OX & vertical axis OY

- The Voltage phasor V is taken as reference phasor & is drawn along Y-axis
- With suitable scale (1cm = x A), draw phasor OO' with length corresponding to I_{0ph} at an angle ϕ_0 from the vertical axis.



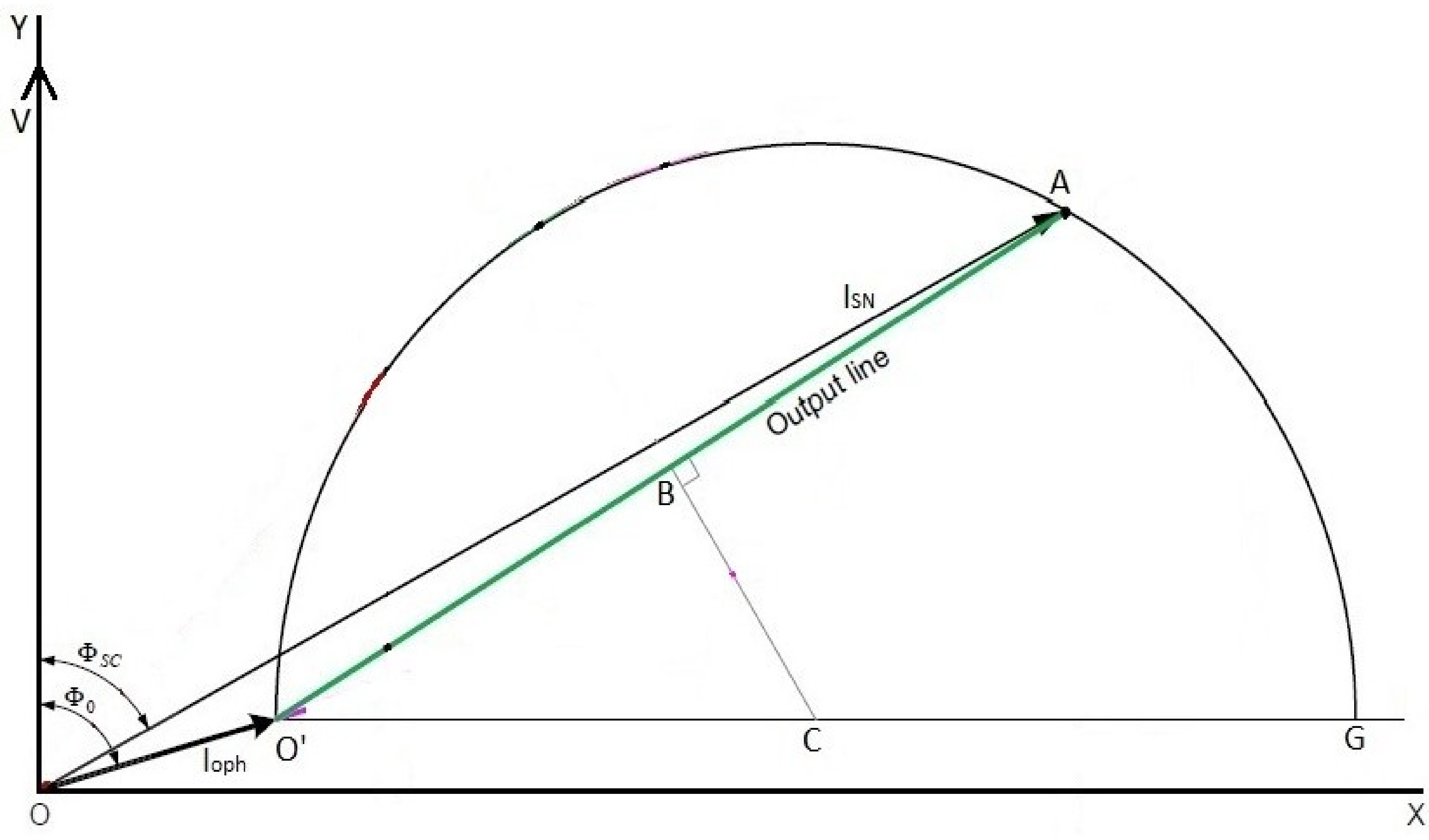
Step 3

- Draw OA equal to I_{SN} at an angle ϕ_{SC} and join O'A
- O'A represents the rotor current (I_1') referred to stator



Step 4

- To determine the centre of circle, line O’G is drawn parallel to OY
- Draw the perpendicular bisector to O’A to meet the horizontal line O’G at C
- With C as centre, draw a semi circle passing through O’ & G. This forms the circle diagram which is the locus of the input current

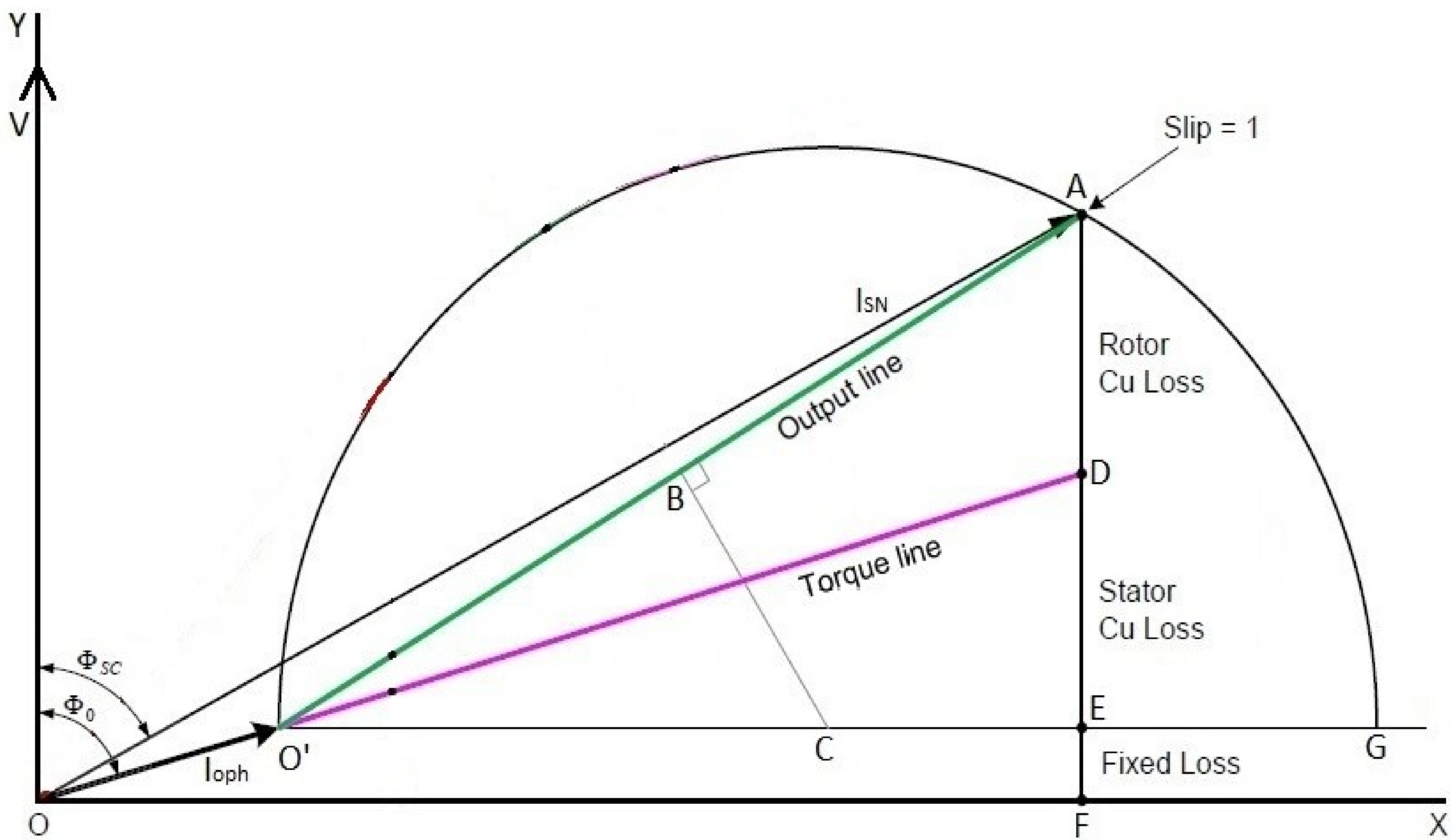


ep 5

- From point A, draw a vertical line AF to meet the line OY
- AF represents the power input to motor when rotor is blocked (s =1)
- This power input to motor meets the core losses & stator and rotor Cu losses
- EF represents core losses (constant losses)
- AE represents stator & rotor Cu losses
- Line AE is divided by D into two segments such that

$$\frac{AD}{DE} = \frac{\text{Rotor Cu loss}}{\text{Stator Cu loss}} = \frac{R_2}{R_1}$$

- The line joining O’ & D is drawn
- Line O’D is known as Torque line or Rotor input line
- Line O’A is known as Output line or Mechanical power developed line



Y
V
Slip = 1
A
I_{SN}
Rotor
Cu Loss
Output line
D
B
Torque line
Stator
Cu Loss
Φ_{SC}
Φ_0
E
I_{oph}
O'
C
G
Fixed Loss
O
F
X

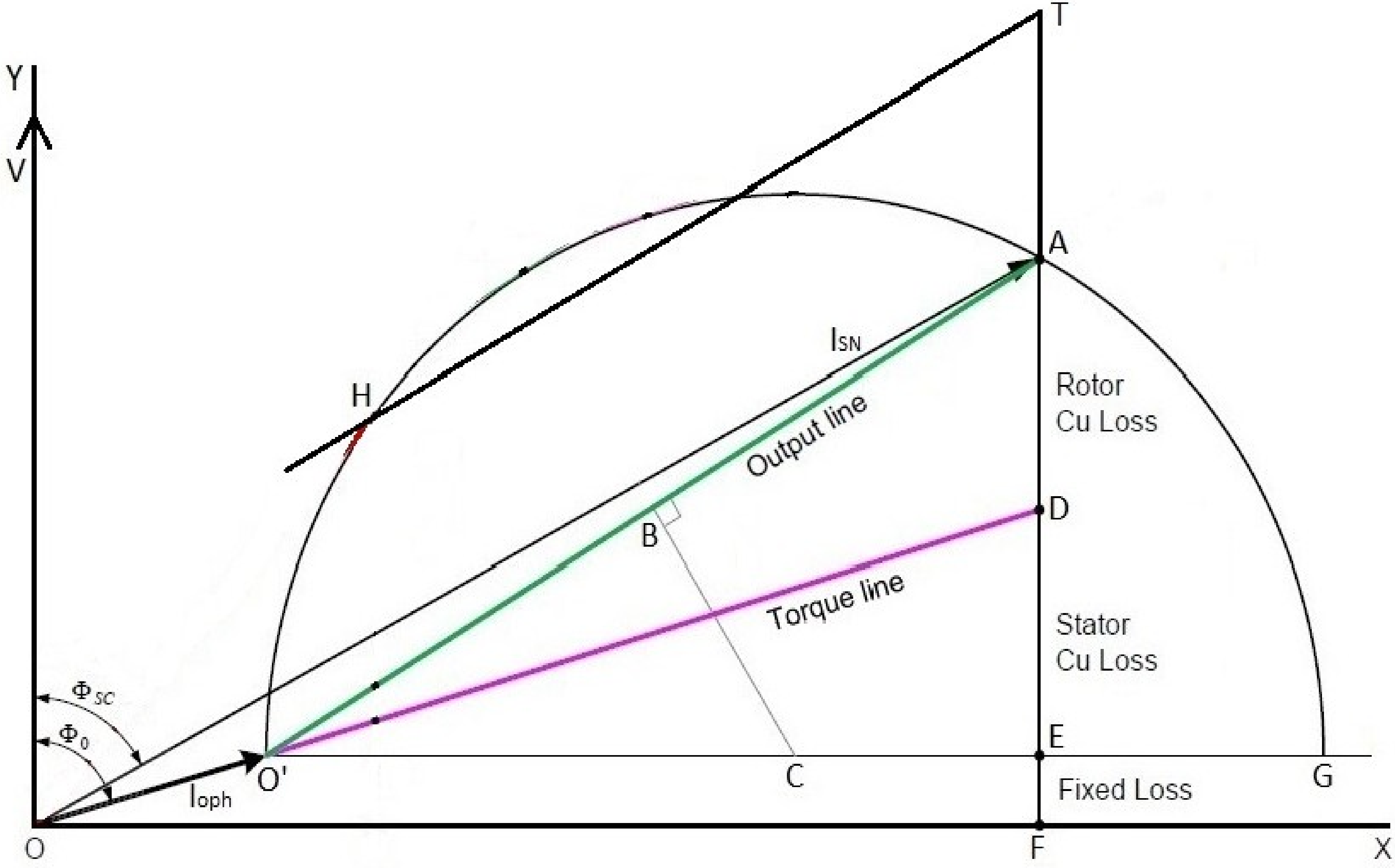
Step 6

To find motor parameters corresponding to a particular output power (eg. Full load or half load etc.)

- Assume that we have to find motor parameters corresponding to a load condition. The load condition will be given in W/kW or in Amperes of current.
- Set the Power scale as *1cm = 3*V_{ph} ** Current scale* Watts

a) *Method of finding the operating point 'H' when load condition is given in W/kW/MW*

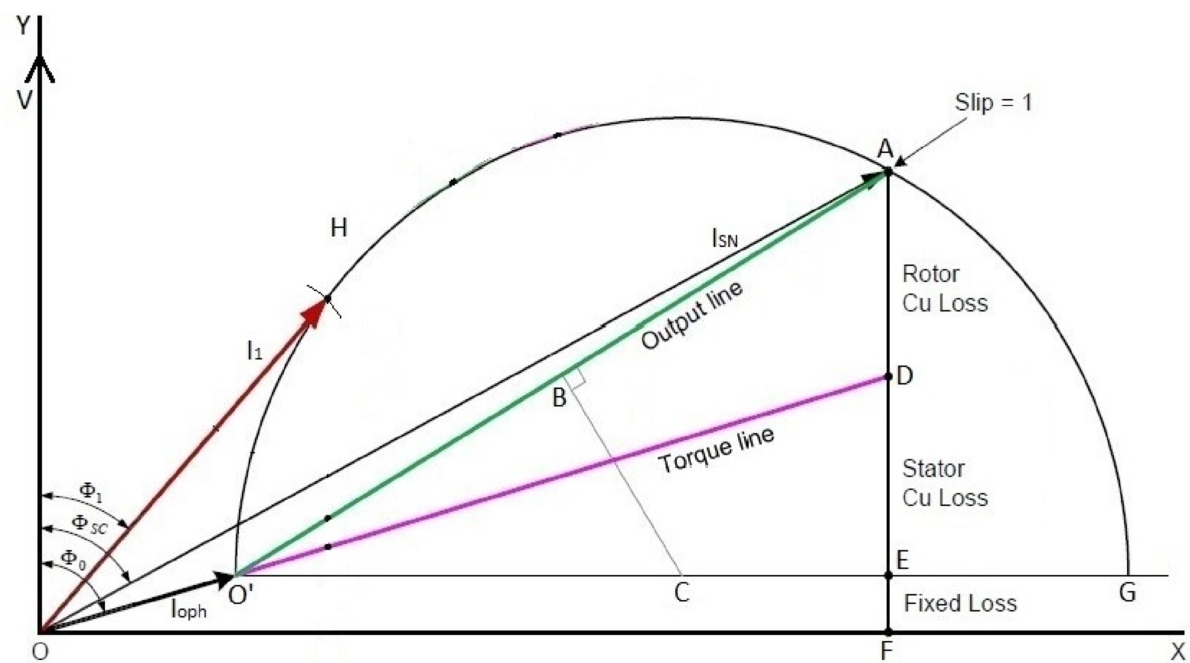
- Represent the output power in circle diagram by drawing the line 'AT' as shown in next figure
- The length 'AT' in cm = (Output power in Watts/Power scale)
- From point 'T', draw a line parallel to output line & it crosses the circle at point 'H'.
- Now point 'H' is the operating point.



T
Y
V
A
I_{SN}
Rotor
Cu Loss
H
Output line
D
B
Torque line
Stator
Cu Loss
Φ_{SC}
Φ_0
E
O'
I_{oph}
C
G
Fixed Loss
O
F
X

b) Method of finding the operating point 'H' when load condition is given in Amperes of current

- To represent the load current in circle diagram, draw an arc to cut the circle at 'H' using compass with 'o' as centre & *radius = Load current/Current scale*
- Now 'H' is the operating point & Line OA represents the current

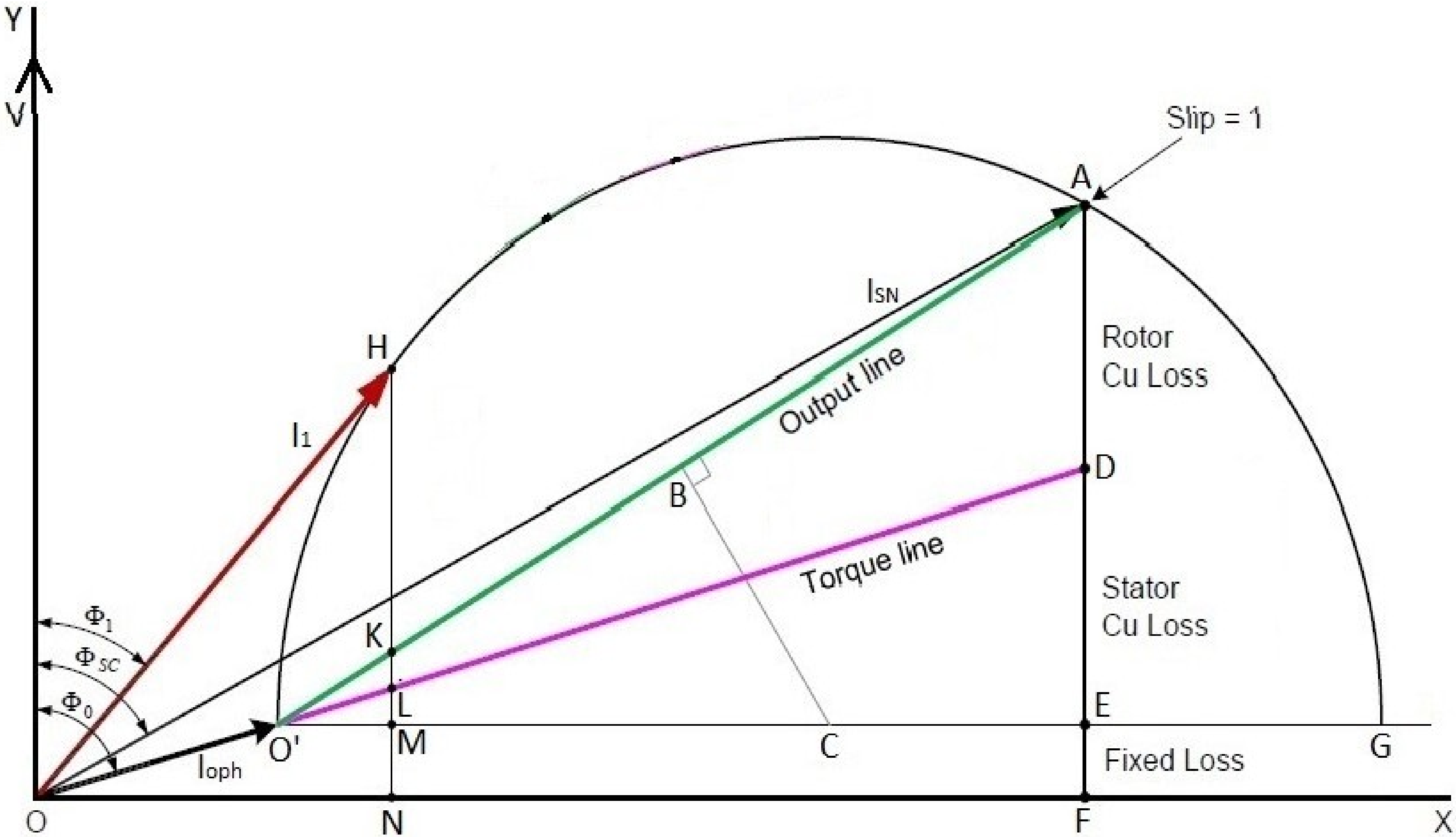


ep 7

To find desired parameters at an operating point 'H'

(Refer figure in next slide)

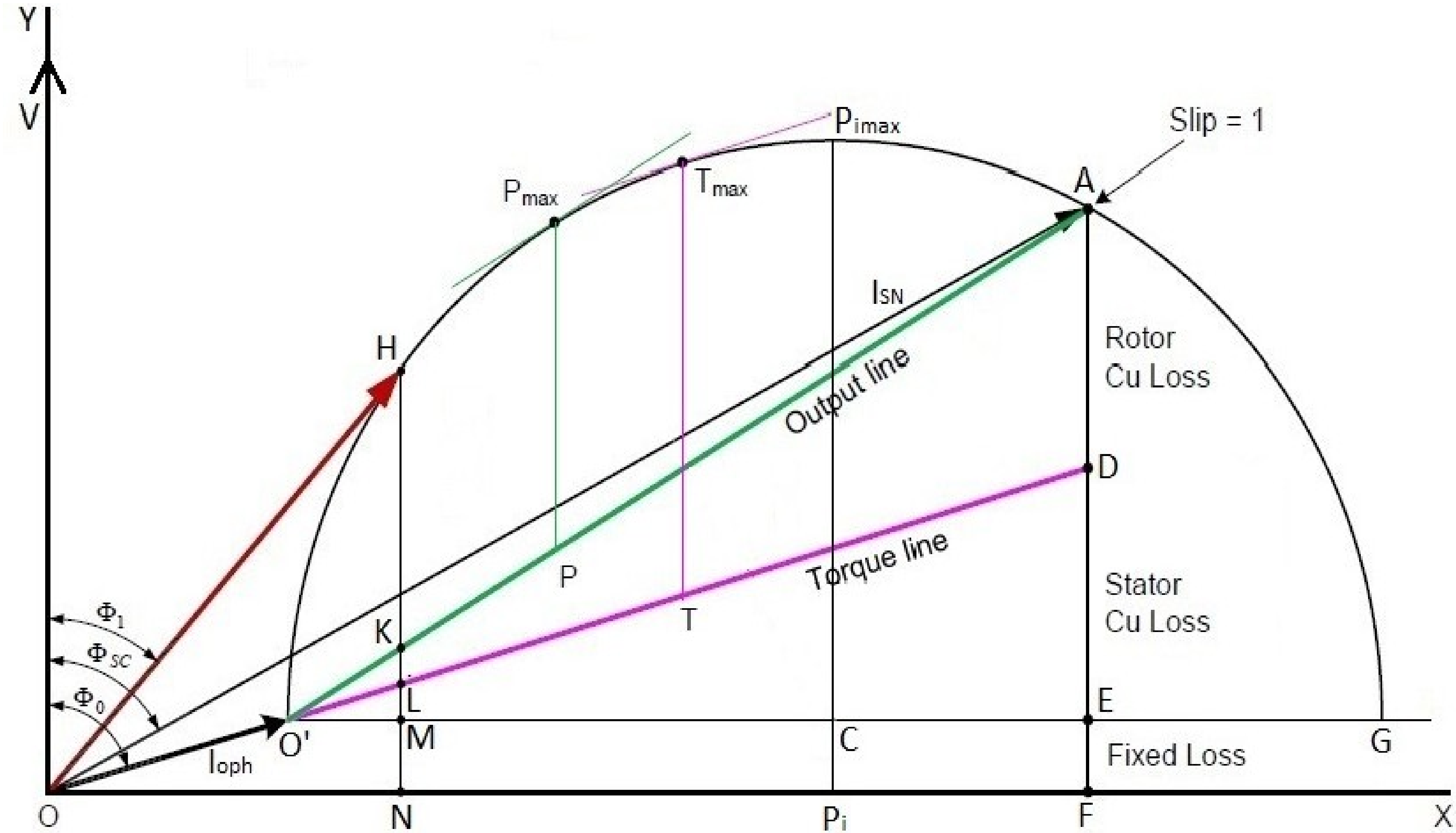
- For a given operating point H, draw a vertical line HN as shown.
- Then, Input power = HN * Power scale
- Output power = HK * Power scale
- Rotor copper loss = KL * Power scale
- Stator copper loss = LM * Power scale
- Constant loss (Iron loss + Mechanical loss) = MN * Power scale
- Efficiency of the machine at the operating point H, η = (HK/HN)*100%
- Power factor of the machine at operating point H = $\cos\phi_1$
- Slip of the machine at the operating point H, s = KL/HL
- Torque at the point H = HL* Power scale (Sync. Watts)
- Starting torque at rated voltage (in syn. watts) = AD* Power scale
- Load current at point H = OH * Current scale


Y
V
Slip = 1
A
I_{SN}
H
Rotor
Cu Loss
Output line
I_1
D
B
Torque line
Stator
Cu Loss
Φ_1
Φ_{SC}
Φ_0
K
L
E
O'
M
C
G
I_{oph}
Fixed Loss
O
N
F
X

ep
8

To find maximum values *(Refer diagram in next slide)*

- To find the operating points corresponding to Maximum power output & Maximum torque, draw tangents to the circle diagram parallel to the Output line and Torque line respectively.
- The points at which these tangents touch the circle are respectively the maximum power point (P_{max}) and maximum torque point (T_{max})
- To find the point corresponds to maximum input, draw a line parallel to x-axis & tangent to the circle at the point P_{imax}
- Now, Maximum power output = PP_{max}* Power scale
- Maximum torque = TT_{max}* Power scale
- Maximum power input = P_iP_{imax}*Power scale



Y
V
P_{imax}
Slip = 1
T_{max}
P_{max}
A
I_{SN}
H
Rotor
Cu Loss
Output line
D
Torque line
P
Stator
Cu Loss
T
K
Φ_1
Φ_{SC}
Φ_0
L
E
O'
M
C
G
I_{oph}
Fixed Loss
O
N
P_i
F
X

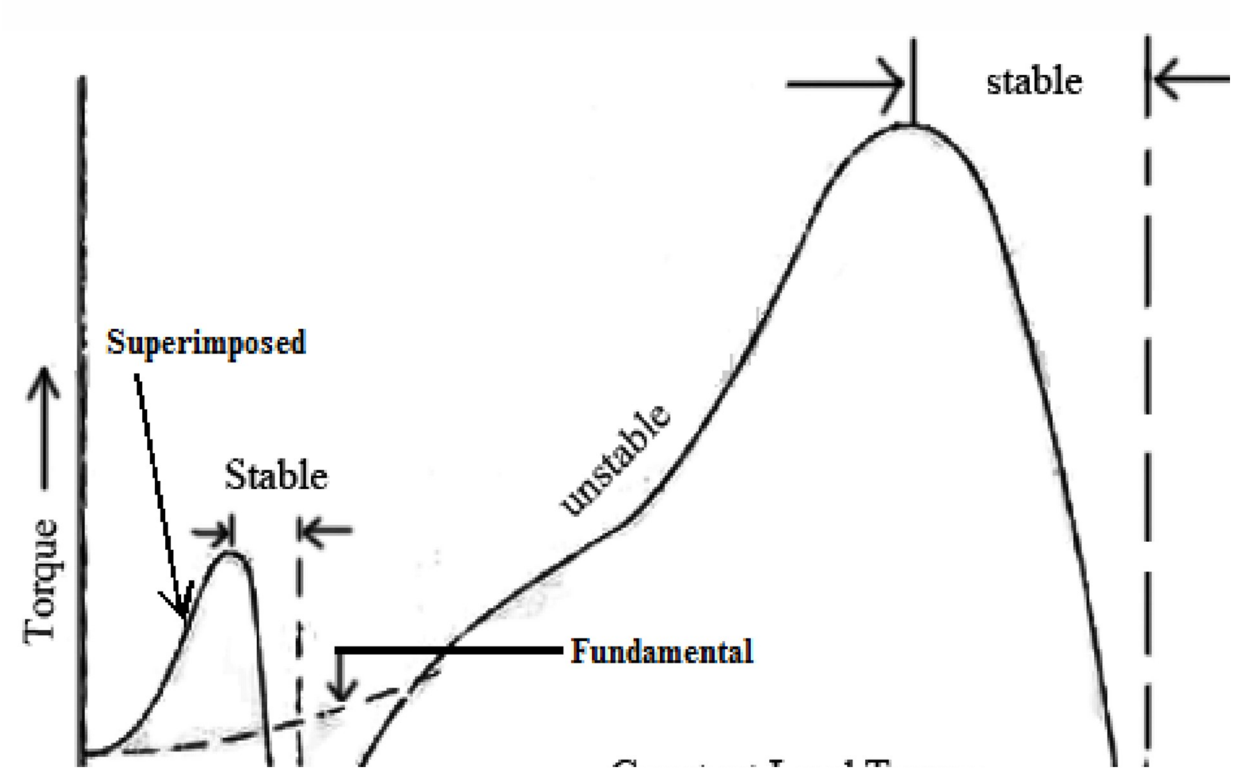
Coggin g

- At certain times, even when full voltage is applied to stator winding, the Squirrel Cage Induction motors refuses to start & pick up speed
- This phenomenon is called cogging or teeth locking
- Cogging is due to magnetic locking between stator & rotor teeth
- Cogging occur when number of stator slots (S_1) is an integral multiple of number of rotor slots (S_2)
- This mainly occur in squirrel cage induction motor because in slip ring induction motor, starting torque is high
- Cogging can be avoided by making $S_1 \neq S_2$ & also by skewing the rotor

Crawling

- 3 phase induction motors, especially cage motors exhibit a tendency to run stably at a sub-synchronous speed (1/7th of synchronous speed) & is unable to pickup its normal speed
- This unusual phenomenon is called crawling
- If voltage applied to stator winding contain harmonics, the airgap flux won't be sinusoidal

- Each harmonic voltages produce its own flux & torque causing vibration & noise
- The major harmonics are 3rd, 5th & 7th
- Even harmonics are absent due to half wave symmetry
- Since motor is a balanced 3 phase load, 3rd harmonics are absent
- So total flux contain, $\phi = \phi_1 - \phi_5 + \phi_7$
- These fluxes



- 1st & 7th produce motoring torque
- Torque produced by 1st & 7th superimposes to get net Torque – speed characteristics of motor as shown in figure
- The load torque line intercepts Torque – Speed curve at points M & N
- At ‘M’ motor is able to provide stable operation at speed $N_S/7$

Methods to avoid crawling

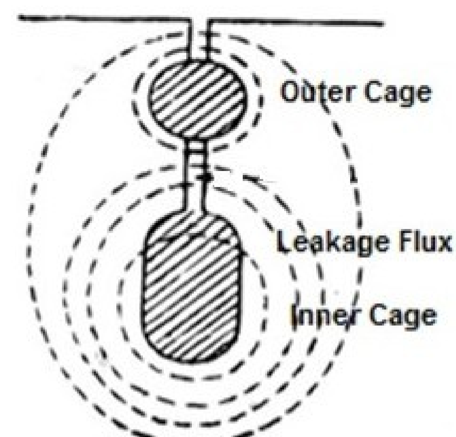
- Number of stator slots, S1 $\neq$ Number of rotor slots,S2
- Difference between S1 & S2 should be $\pm$P, $\pm$2P or $\pm$5P
- Difference between S1 & S2 should not be 1, 2, (P$\pm$1) or (P$\pm$2) to avoid noise & vibration
- Reduce 5th & 7th harmonics by short pitching the windings

High torque Cage motors

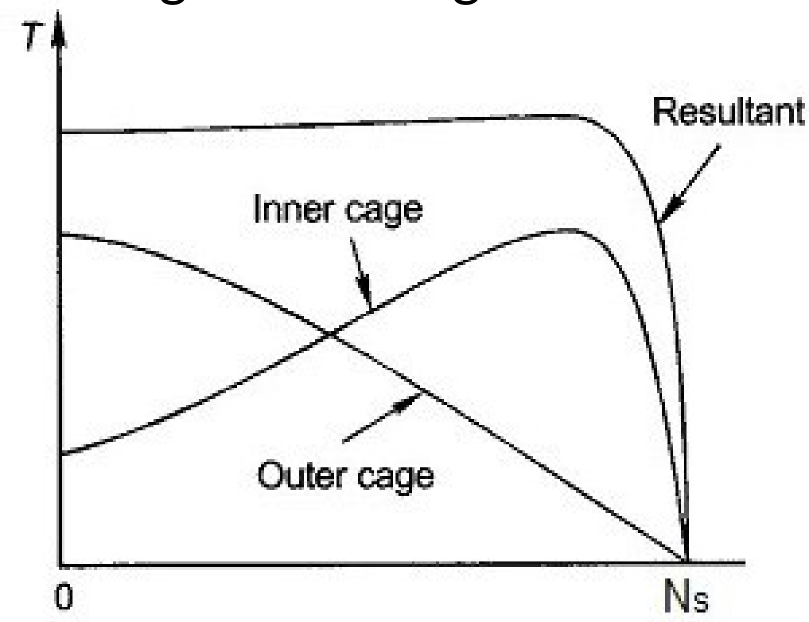
- SCIM has high efficiency, low cost, low maintenance etc.
- But it is having low starting torque, low p.f & high starting current
- A SRIM is having high starting torque, low starting current & high p.f due to high rotor resistance value
- So our requirement is high rotor resistance during starting to get more torque & low rotor resistance under normal operation
- It can be achieved by 2 methods
  1. Double cage Induction motor
  2. Deep bar Induction motor

Double cage Induction motor

- The stator remains same as normal SCIM
- Rotor carry 2 set of squirrel cage winding
  * Inner cage winding – with low resistance & high reactance value made of Cu
  * Outer cage winding – with high resistance & low reactance value made of Manganese Brass



- Inner cage winding has higher cross sectional area than that of outer cage winding in order to have a resistance of $(1/4)^{th}$ of outer cage winding. End rings may be separate or combined
- During starting, $f_r = f$ & X_L of inner cage winding is high
- So impedance of outer cage winding is low compared to inner cage & most of current flows through outer high resistance cage to get more starting torque
- At normal speed, Slip decreases & reactance of inner cage decreases
- Now current divides between two windings according to their resistance value
- Because of low resistance, inner cage carry more current & produce desired running torque
- Torque – speed characteristics of individual cages & resultant are shown in graph



Need of starter

- In the case of an Induction motor at starting, when motor is standstill, the squirrel cage rotor is like a short circuited secondary of a transformer
- Therefore if full supply voltage is applied during stating, current in rotor circuit will be very high & consequently stator also draw a high current from supply
- Magnitude of this current depends on electrical design of motor & is usually 5 to 7 times rated full load current
- To limit the current within safe value starter is used

Functions of starter

- Limit the starting current within safe limit
- Provide protection against overload & under voltage
- In SRIM, starter helps to improve starting torque

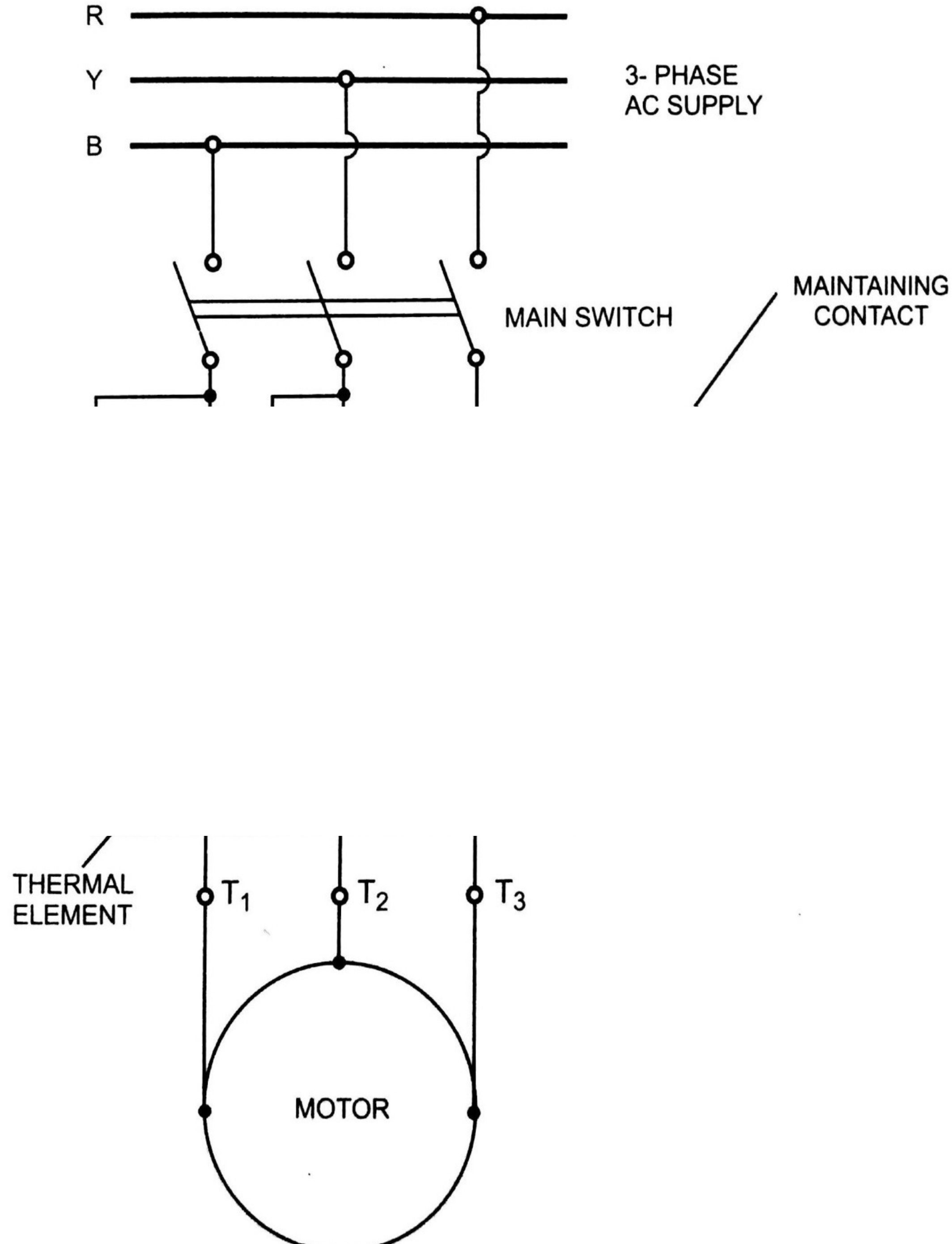
Starting of Squirrel cage induction motor

- Different type of starters used in SCIM are

1. DOL (Direct On Line) starter or Full voltage starter

- This is the most economical method of starting
- DOL starter is used based on following factors
  * Power rating & design of motor
  * Type of application
  * Location of motor in distributed system
  * Capacity of power system
- This method involves direct switching of poly phase SCIM to supply as shown in figure
- It consist of start & stop button, a contactor, overload & under voltage protection devices
- Start button is a normally open switch & Stop button is normally closed switch
- For starting the motor, main switch is closed
- Now start button is pressed & operating coil of contactor gets energized

- Now the main contactor closes & connects the motor to supply
- At the same time an auxiliary/maintainin g contactor also closes & acts as a parallel circuit to start button. So now start button can be released
- When stop button is pressed, operating coil gets de-energized & all contactors get open & motor stops
- If supply fails or supply voltage falls below certain value, main contactor &

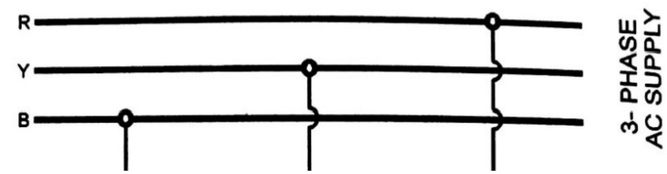


- When motor is overloaded, overload relay acts & operating coil gets de-energized

- Now motor is disconnected from supply by opening the contactors

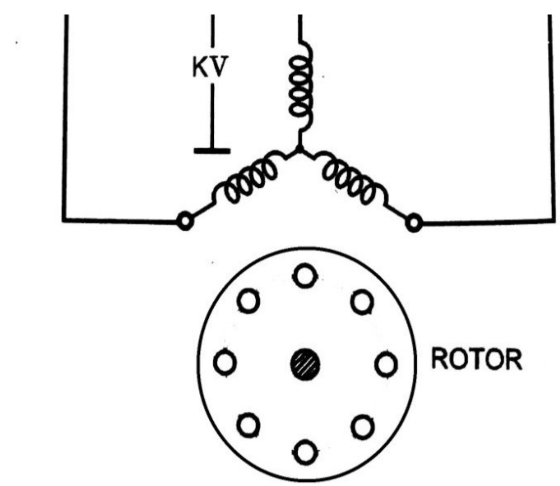
- In DOL starter, Starting torque,

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



2. Auto transformer starter

- Here the motor is supplied from an Auto transformer
- During starting, a low voltage is applied & as motor gains speed, auto transformer is adjusted to give rated voltage
- Auto transformer is adjusted manually or magnetically
- Met the motor be started by an auto transformer having turns ratio 'k', then $T_{st} = T_f k^2 \left(\frac{I_{sc}}{I_f}\right)^2 S_f$

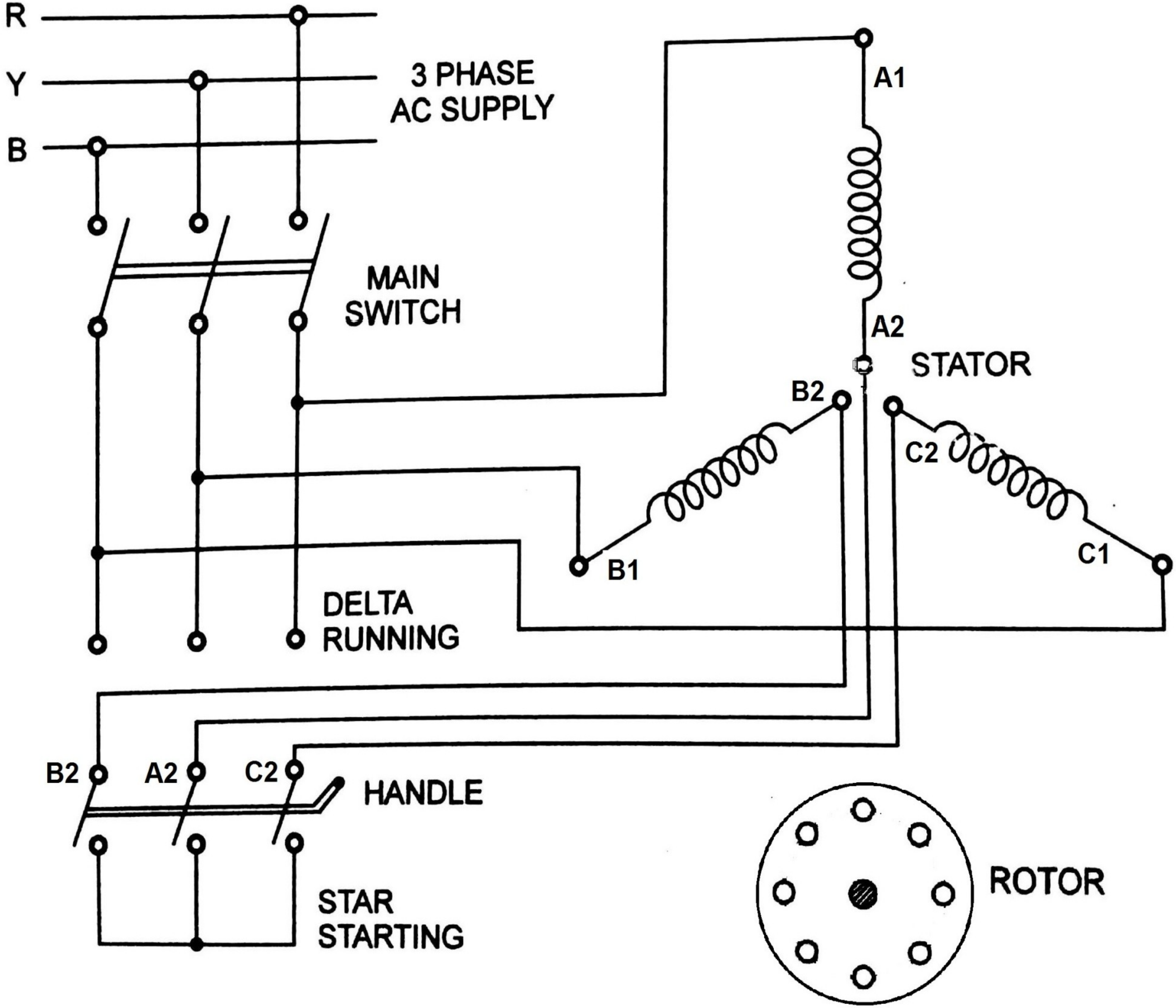


- i.e Starting torque = (1/K2) * Starting torque with DOL starter

3. Star – Delta starter

- This method of starting is based on the principle that, when 3 phase windings are connected in star, voltage across each winding is (1/√3) times line voltage
- Where as when windings are delta connected, voltage across each winding is the full line voltage
- Here during starting, stator windings are star connected & when motor attains speed, same winding is connected in delta through a change over switch operated by a handle
- The connection diagram is shown in figure

- Starting torque, $T_{st} = \frac{1}{3} T_f \left(\frac{I_{sc}}{I_f} \right)^2 S_f$ = (1/3) * Starting torque with DOL starter



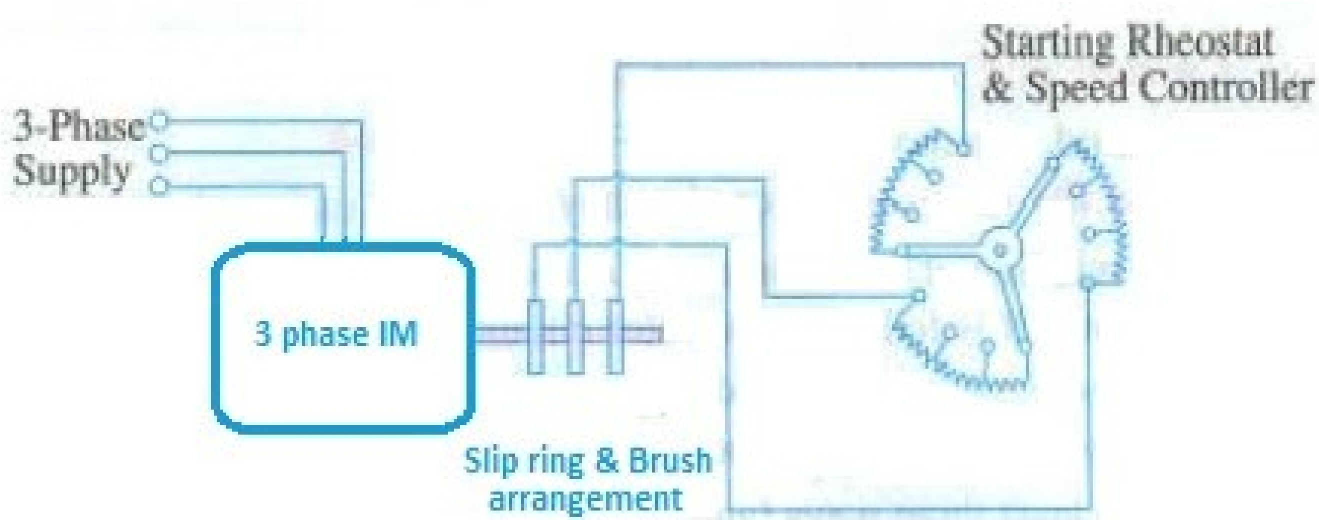
R
Y
B
3 PHASE
AC SUPPLY
MAIN
SWITCH
DELTA
RUNNING
A1
A2
STATOR
B2
B1
C2
C1
B2
A2
C2
HANDLE
STAR
STARTING
ROTOR

Starting of SRIM

- The 3 types of starter already mentioned can be used in SRIM. But commonly used method is by using Rotor resistance starter

Rotor Resistance Starter

- SRIM is started by applying full rated voltage in stator & introducing variable resistance in each phase of rotor circuit
- The external resistance added in rotor circuit help to reduce starting current & also helps to improve starting torque
- During starting, rotor resistance is kept at maximum value & as motor gains speed, resistance value is decreased in steps & finally completely removed from circuit as motor attains rated speed
- The connection diagram for rotor resistance starter is shown in figure



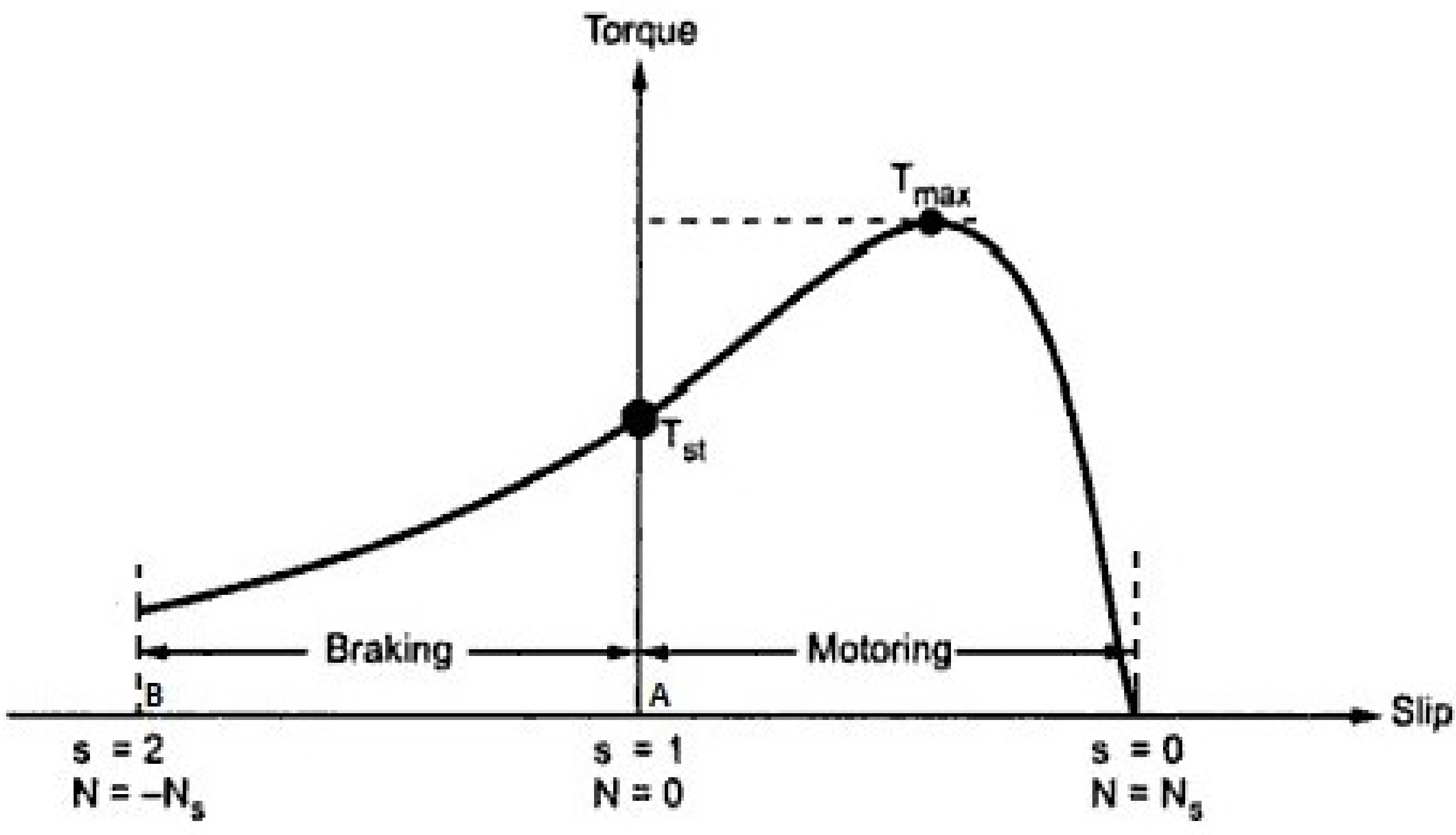
Braking of Induction motor

- The simplest method of stopping of an Induction motor is to disconnect the motor from supply mains
- Now motor automatically stops due to combined effect of rotor & load (Kinetic energy in rotating parts gets dissipated as heat due to friction)
- When rapid stopping required, mechanical or electrical braking is employed
- There are mainly three methods of Electrical braking

1. ***Plugging or Counter current braking***

- Plugging can be achieved in an Induction motor by interchanging connections of any two phases of stator w.r.to supply terminals
- This causes a reversal of the direction of rotational magnetic field & direction of torque produced by the motor
- The torque produced by motor under braking condition acts as a braking torque & speed of motor decreases
- During braking, motor runs in the opposite direction of rotational magnetic field & a large voltage induces in rotor windings. So rotor windings should be provided with additional insulation to withstand this high voltage

- During plugging, motor acts as a brake & absorbs kinetic energy from rotor causing its speed to fall
- The associated power is dissipated as heat in motor
- The condition for braking an induction motor can be studied by considering the Torque-Slip curve of the motor when extended beyond the point of slip = 1



represents the torque at the instant of plugging & we can see that the torque increases gradually as motor speed approaches

- *If supply line is not disconnected at zero speed, motor accelerates in the reverse direction*
- From T-S characteristics we can see that the braking torque is very small compared to maximum torque
- The braking torque & rotor current during braking are given by

$$T_b = \frac{KsR_2E_2^2}{R_2^2 + (sX_2)^2} \qquad I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

Advantage

- It is the quickest braking method

Drawbacks

- During braking power is wasted as heat & causes heating up of machine
- Due to large heat production, this braking can't apply frequently

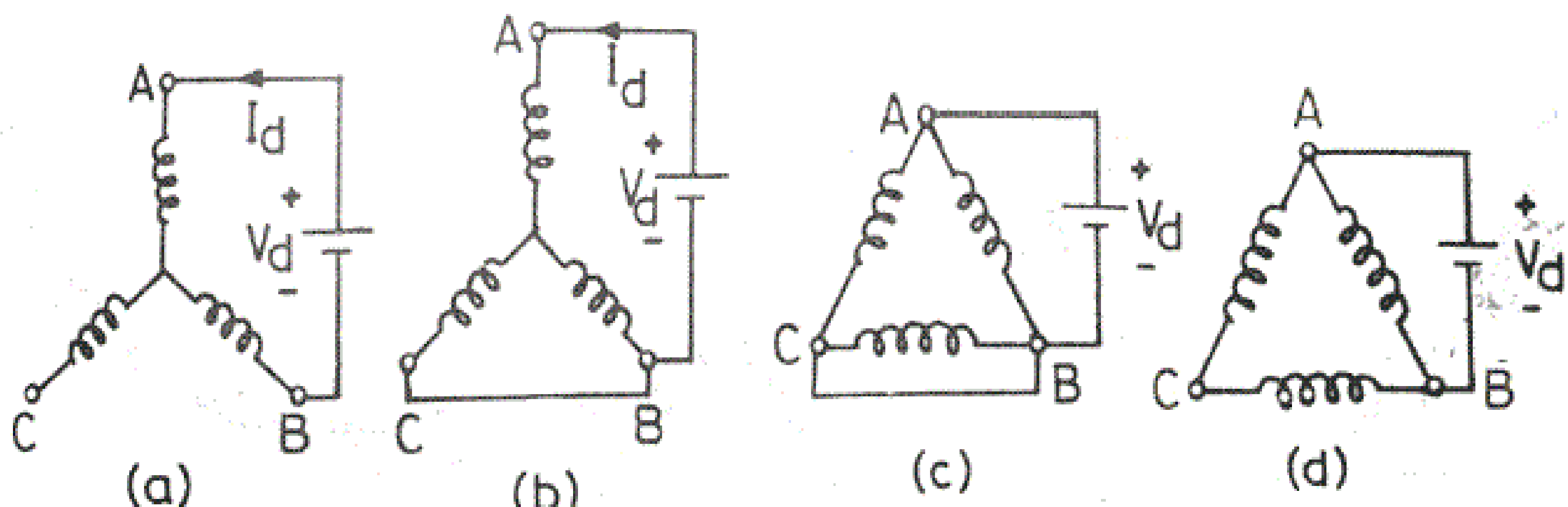
2. *Dynamic or Rheostatic braking*

- Here during braking the stator windings are disconnected from AC supply & is connected to a DC source
- Now a stationary DC field is produced in stator & act as field excitation of a DC motor
- The rotor windings of Induction motor acts as armature winding
- In SRIM, external resistances can be inserted into rotor circuit
- When stator windings are disconnected from AC supply & excited with DC, the magnetic field produced will be stationary & rotor will be rotating
- Now current induces in rotor conductors & torque is produced by motoring action
- The direction of torque produced is in opposite direction to that corresponding to normal motoring operation
- This produces a braking torque & motor speed reduces
- The magnitude of braking torque developed depends upon the DC excitation, rotor resistance & speed of motor

- Normally the braking torque is controlled either by varying DC excitation or by varying rotor resistance
- Various methods for connecting the stator windings to DC source are shown in figure
- The DC excitation can be given either by using an independent DC source or from a rectifier

Advantages

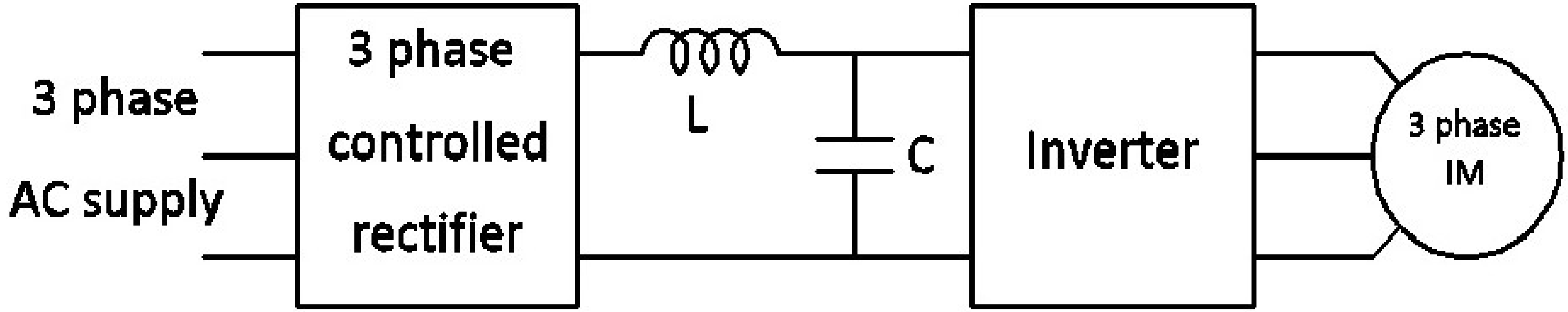
- Less heat is produced as compared to plugging
- Provides smooth braking
- Here there is no tendency of machine to run backwards



3. *Regenerative Braking*

- During regenerative braking, Induction motor works as a generator & electrical power generated is fed back to the supply
- This generator action produces the required braking torque
- When speed of an Induction motor increases above synchronous speed, it acts as an Induction generator
- The Induction motor can be made to operate at speed above synchronous speed by any of the following method
  * Switching over to a low frequency supply in frequency controlled induction motor drives
  * Switching over to a large number of poles operation from a smaller one in multi speed squirrel cage motors
- During braking, slip & torque become negative & machine acts as a generator receiving mechanical energy & giving back electrical energy to supply
- The torque – speed characteristics of an Induction motor under regenerative braking operation is shown in figure

Induction motor drive equipped with regenerative

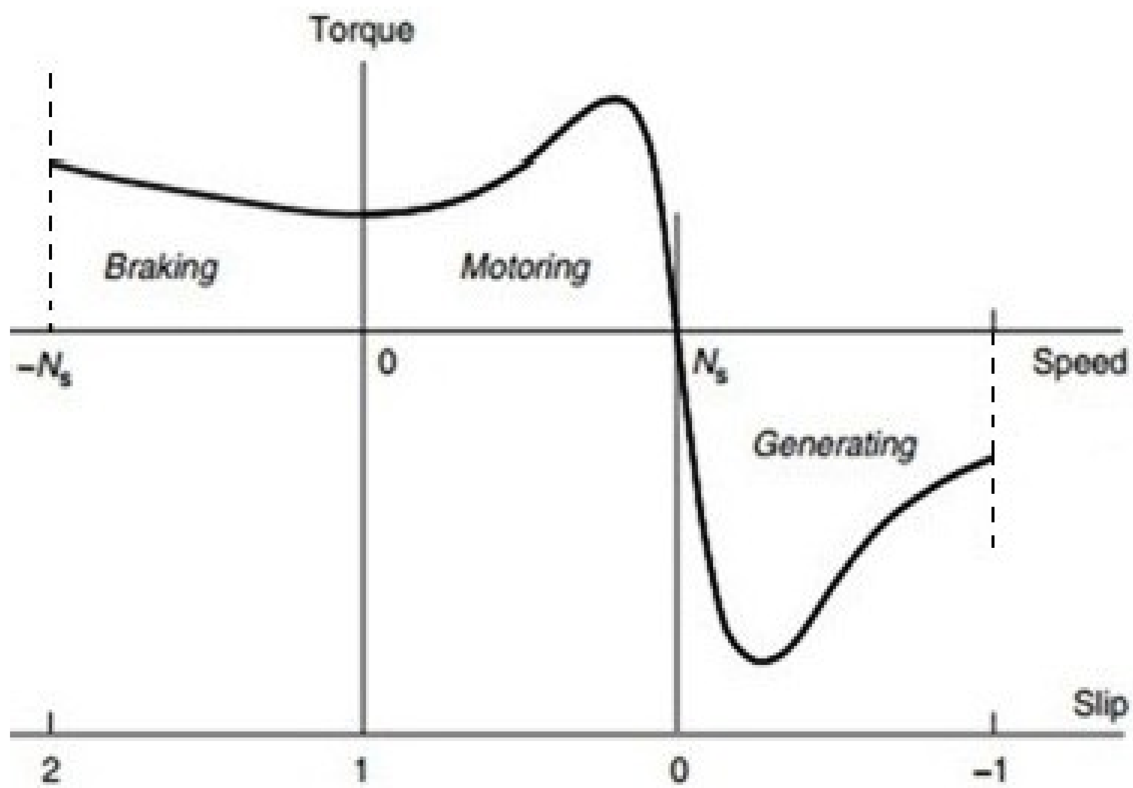


Advantage

- The generated power is fully used

Drawback

- The motor should be supplied from a variable frequency supply



Speed control of Induction motor

- 3 phase Induction motors are practically a constant speed motor like a DC shunt motor
- A DC shunt motor can be made to run at any speed within limits to obtain required performance by armature & field control

  But in Induction motor speed control, it is not that easy
- In Induction motor, as speed changes, efficiency & performance changes
- In an Induction motor, speed is given by $N = N_S\ (1\text{-}S)$

$$\text{i.e, } N = (120f/p)*(1\text{-}S)$$

- So speed of an Induction motor can be varied by varying Supply frequency(f), Number of poles in stator(P) or slip(S)
- Speed control of Induction motor is mainly classified into 2

  1) Speed control from stator side (Applicable to SCIM & SRIM)

     i) Speed control by varying Stator supply voltage

     ii) Speed control by varying Stator supply frequency

     iii) Speed control by varying Stator number of poles

rotor side (Applicable to SRIM)

i) Rotor resistance control

ii) Cascade operation

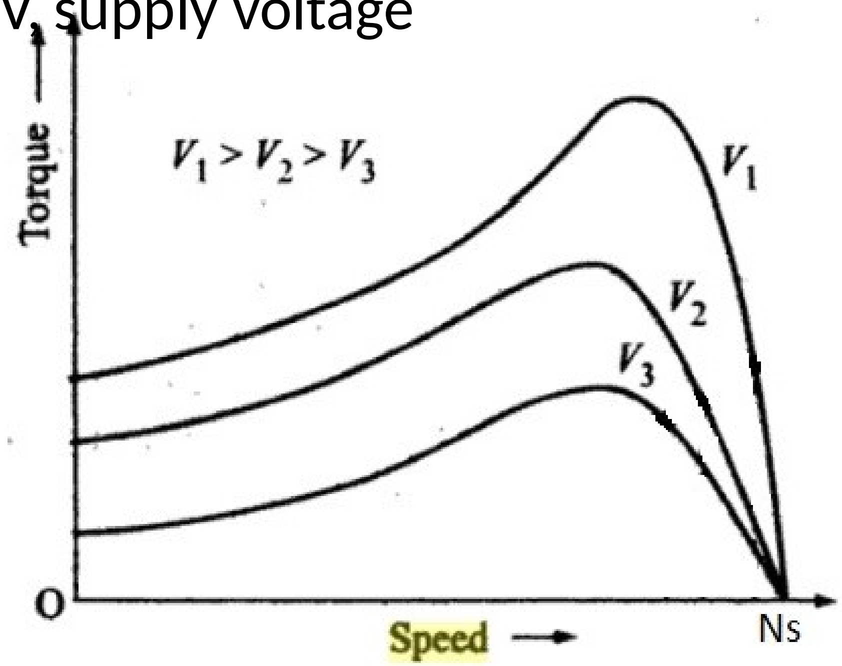
iii) By injecting an external voltage to rotor circuit

a) Stator voltage control

- Here the slip is controlled to control the speed of motor
- Motor is supplied from a variable voltage constant frequency supply
- In an Induction motor, T α E_2^2 & E_2 α V, supply voltage

  i.e, T α V^2

- So by varying stator voltage, T & hence slip can be controlled
- T – Slip characteristics of an Induction motor with variation in supply voltage is shown in figure



- Applied voltage can be varied by using a 3 phase autotransformer or tap changing transformer

Advantage- Simple, low cost

Drawbacks

- Voltage can’t be increased above rated value. So speed control below rated speed is only possible
- A large change in voltage is required to get a small change in speed
- The torque developed changes with change in supply voltage

b) V/f control

- Speed of Induction motor can be varied by varying supply frequency
- But from EMF equation of Induction motor, α (1/f)
- So when we decrease frequency to reduce speed, flux increases & causes saturation of core. The core losses also increases
- If frequency is increased to increase speed, flux reduces & torque produced by motor reduces

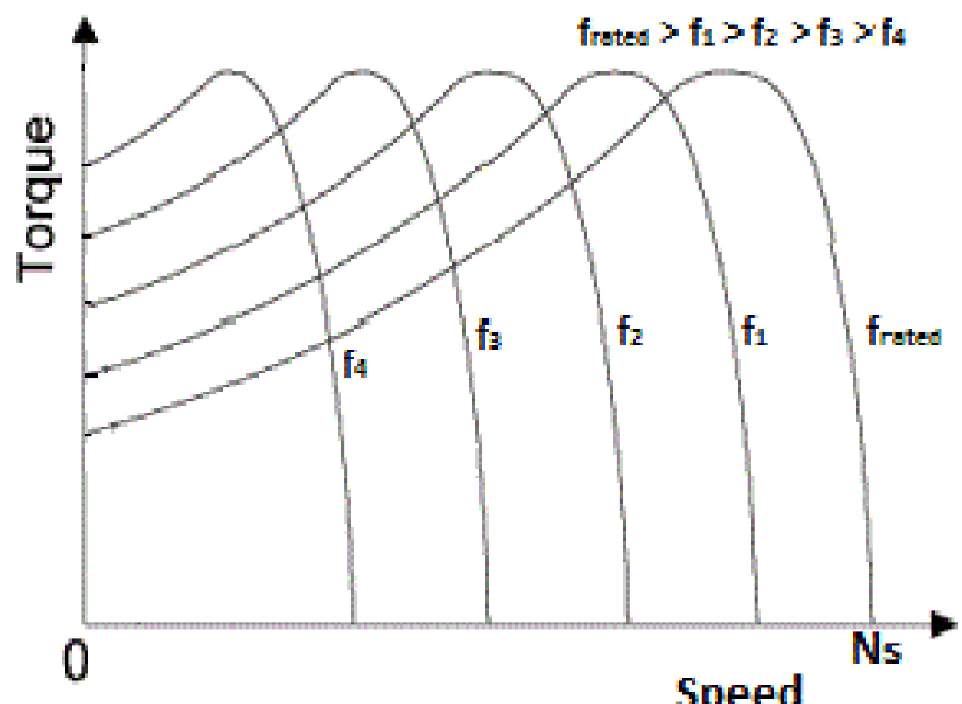
- From EMF equation, $\phi \alpha (V/f)$
- By keeping V/f ratio constant, we can keep flux constant
- So instead of controlling frequency alone, V & f are varied simultaneously to keep V/f ratio constant
- Here motor is supplied from a variable frequency variable voltage supply
- T – speed characteristics of Induction motor with V/f control is shown in figure

Advantages

- Smooth speed control is possible
- Speed control above & below rated speed is possible

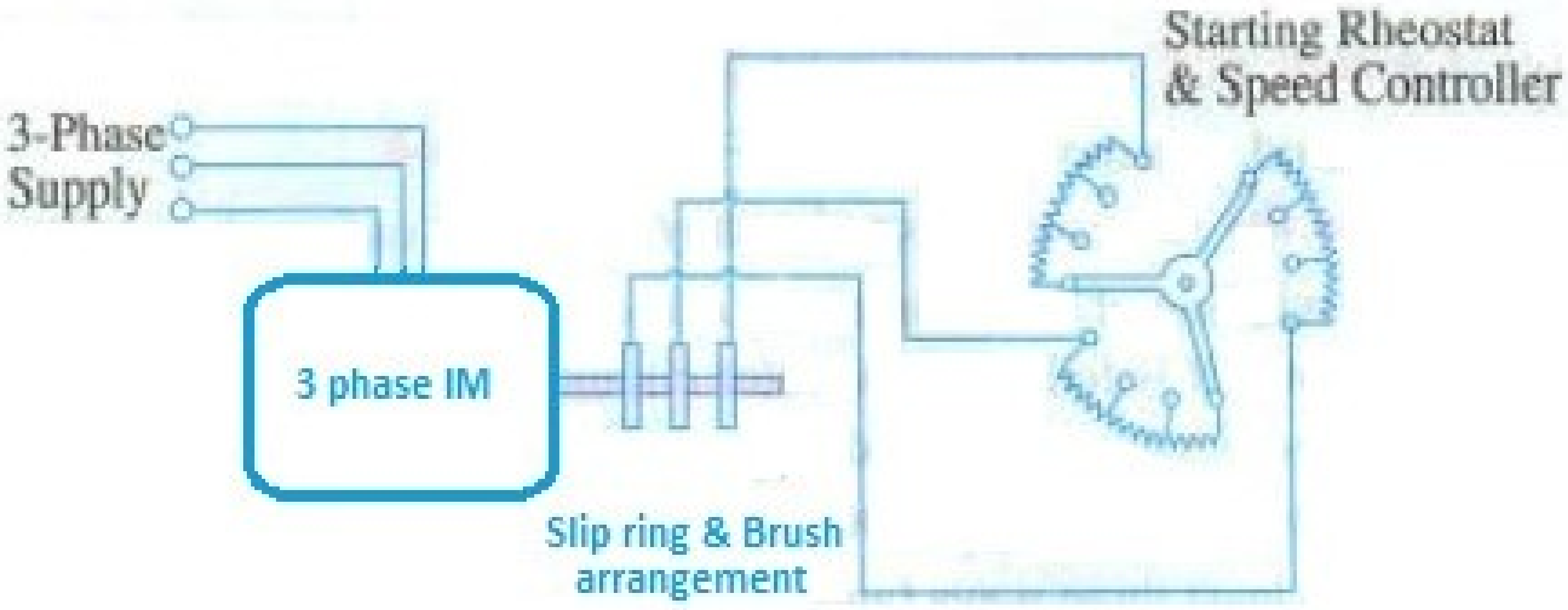
Drawbacks

- A variable voltage variable frequency supply is required
- Costly & complicated



c) Rotor resistance control

- This method is applicable to SRIM alone
- Here slip is varied to vary speed of motor
- We have, $T = \dfrac{K s R_2 E_2^2}{R_2^2 + (s X_2)^2}$
- When slip is small, T α (s/R_2)
- i.e, for a given torque, slip can be varied by varying R_2, rotor resistance
- For varying rotor resistance, an external resistance is introduced in rotor circuit through slip rings & brush arrangement. It is shown in figure
- The method is similar to armature voltage control of shunt motor *Advantages* - Simple, low cost, possible to get high starting torque *Drawbacks*



Starting Rheostat
& Speed Controller
3-Phase
Supply
3 phase IM
Slip ring & Brush
arrangement

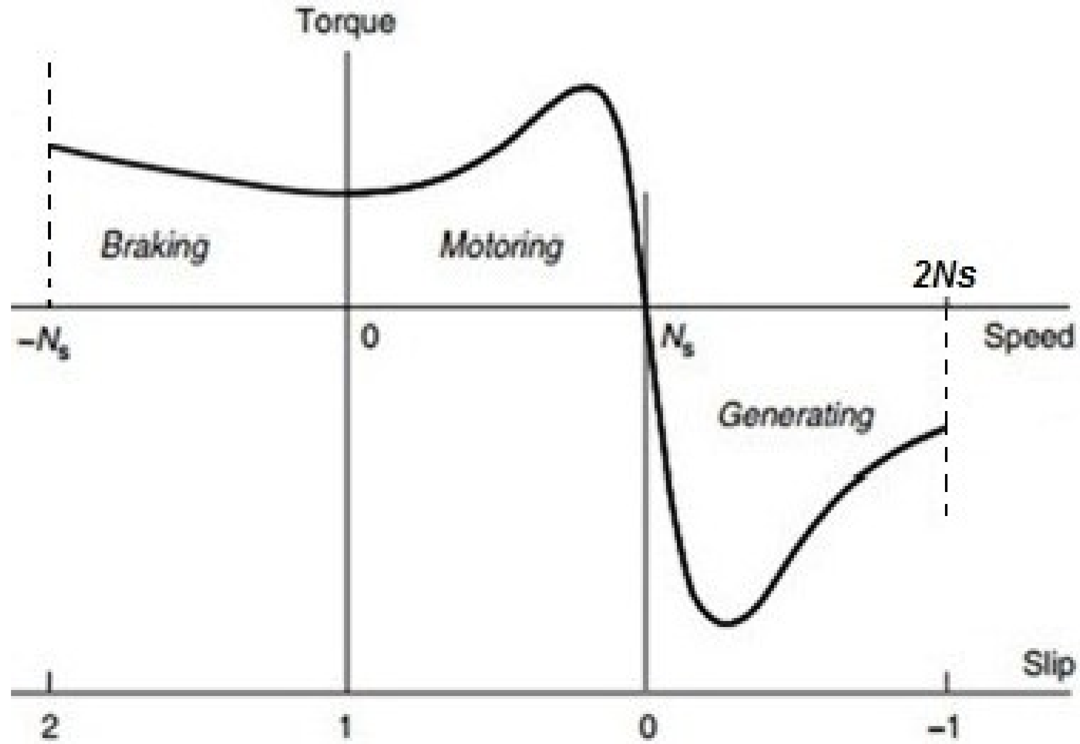
MODULE - VI

- Induction Generator – Principle, Grid connected & Self excited operation, Comparison of Induction generator & Synchronous generator,
- Synchronous Induction motor – Principle,
- Single phase Induction motor – Double field revolving theory, Equivalent circuit, Torque – Slip Curve, Types of Single phase Induction motor – Split phase, Capacitor start, Capacitor start & run type, Shaded pole Induction motor – Principle, applications

Induction Generator

- An Induction Generator is a poly phase Induction machine working as a generator
- When an Induction machine is connected to 3 phase AC supply, it will work as a motor drawing power from supply
- The motor speed will be less than synchronous speed & slip is positive
- If the induction motor is coupled to a prime mover (whose speed can be controlled), the speed of Induction motor can be increased above synchronous speed
- Now slip is negative & direction of current, power & torque reverses
- i.e, Machine works as a generator & produces electrical energy
- The produced electrical energy is fed back to supply
- The Torque – Speed characteristics of Induction generator is shown in figure
- The Induction generator takes the required reactive power from supply to produce the magnetic field in machine. So it is not a self excited machine

- In an Induction generator, the magnitude of voltage & frequency of generated AC voltage depends on the magnitude of voltage & frequency of stator supply

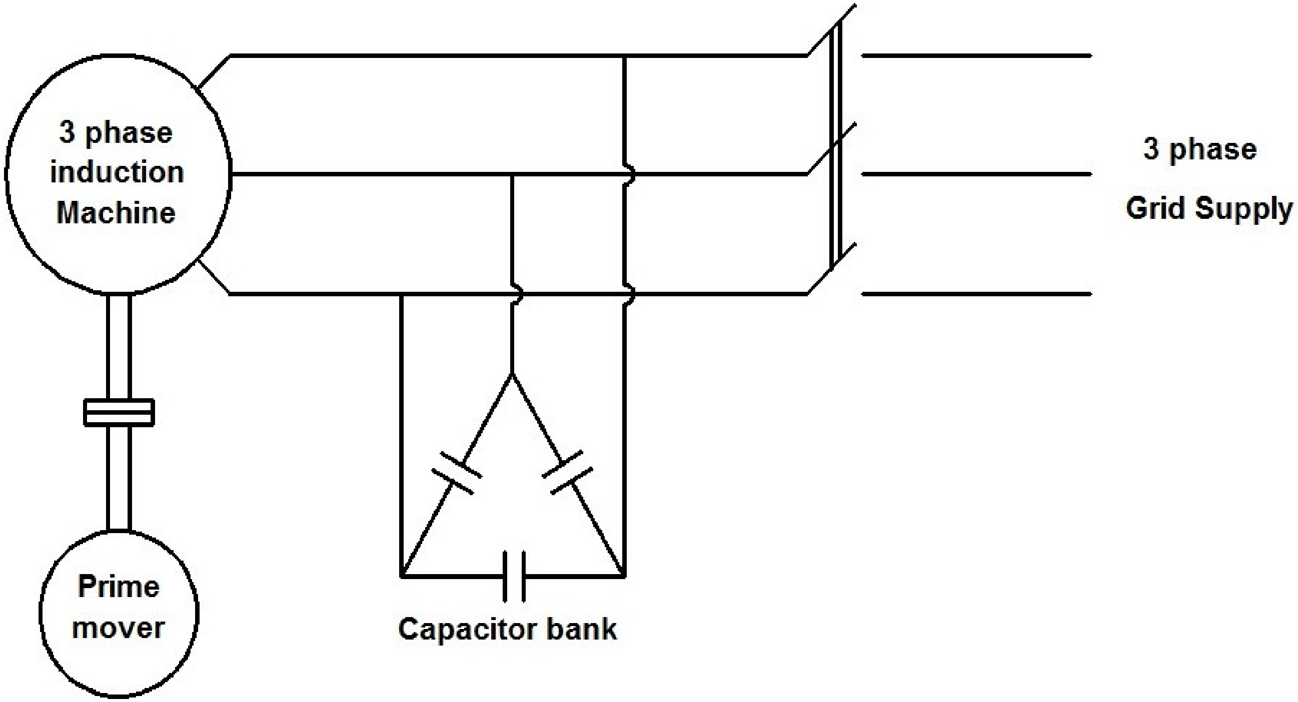


- An Induction generator has 2 modes of operation,

1. <u>Grid connected operation</u>

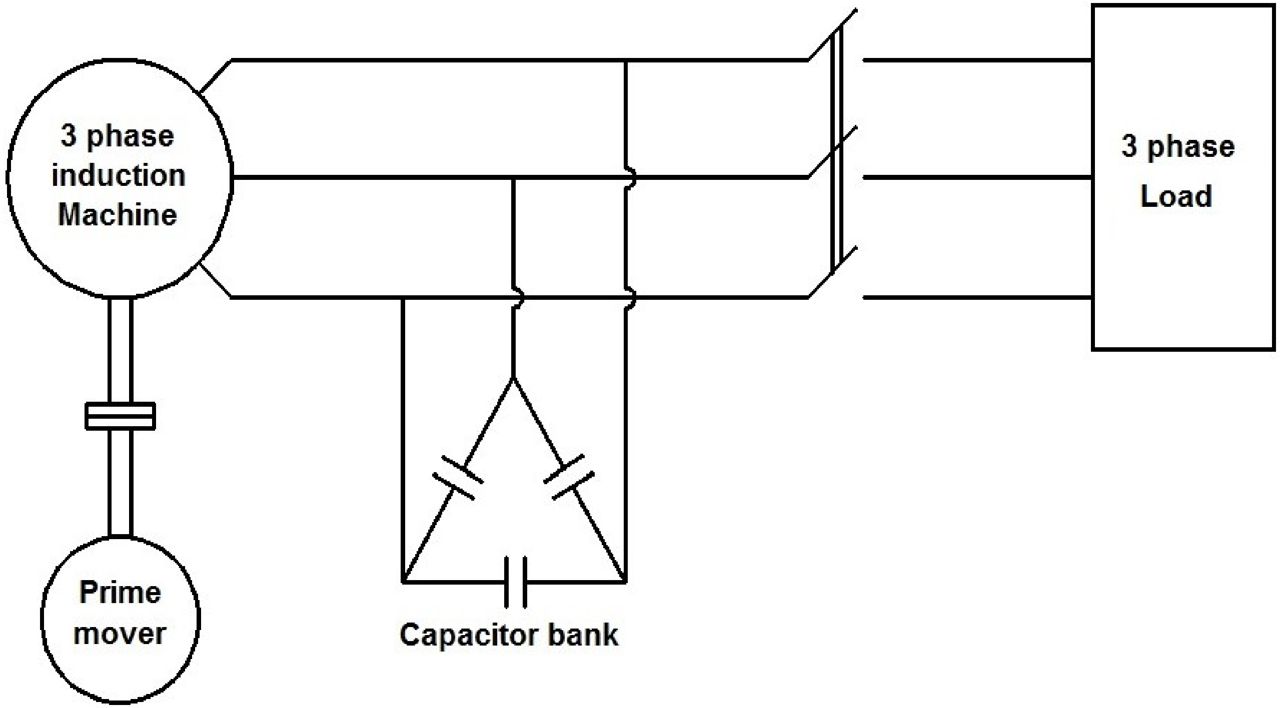
- Here the Induction generator is directly connected to grid as shown in figure
- The reactive power required for machine to produce magnetic field is drawn from grid supply
- The generator is started as an Induction motor & then speed is increased above synchronous speed by using the prime mover to work as a generator

To avoid drawing of reactive
power from supply, usually a
d as



2. Self excited/Stand alone operation

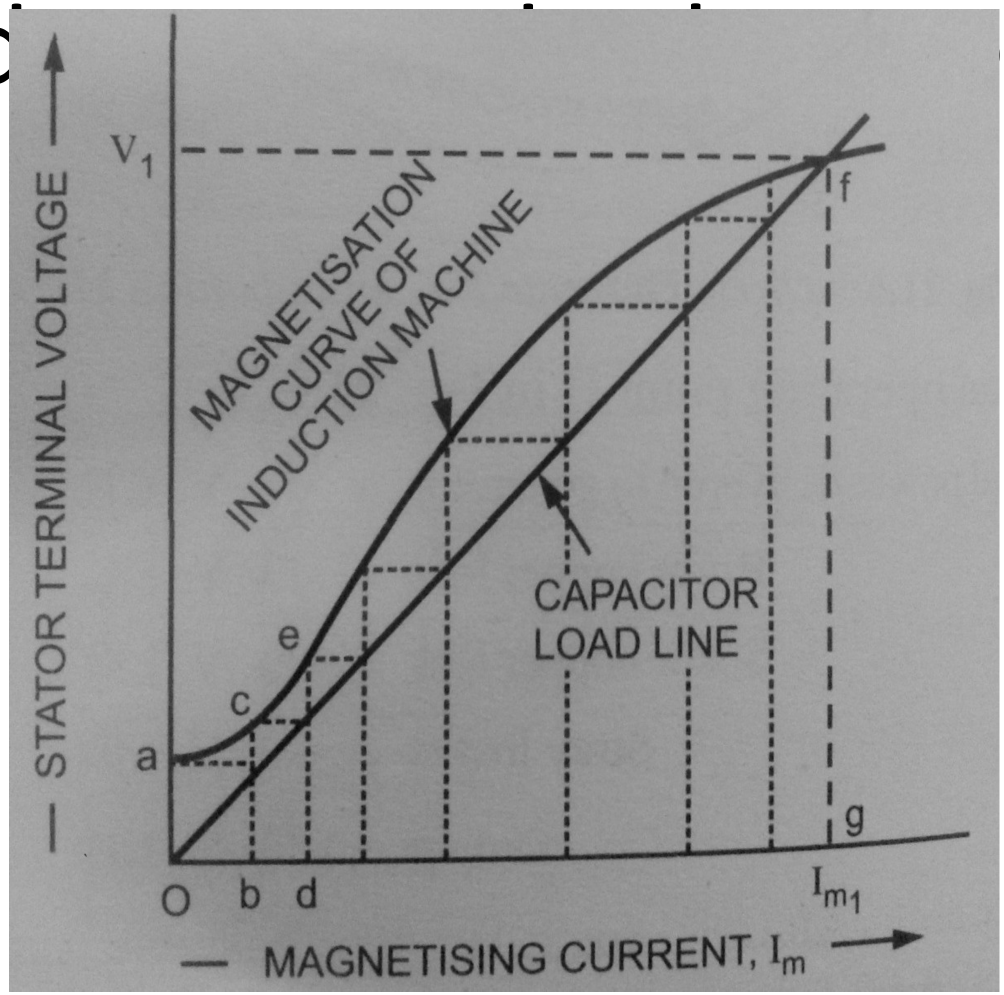
- Here Induction generator does not require an existing AC supply for obtaining reactive power to produce magnetic field
- In self excited system, a capacitor bank is connected across the Induction machine stator terminals as shown in figure



- When Induction generator is rotated at synchronous speed, due to residual magnetism in rotor circuit, a small voltage induces in stator
- This voltage produces a capacitor current. This capacitor current flows to stator & produces a flux in the stator which aids the residual flux
- As a result total flux increases & stator induced voltage also increases
- Now capacitor bank produces much larger current as a result of

saturation curve of Induction generator intersects capacitor load line, at the point ‘p’, thus giving no load … f V_1 for

- Here higher the value of capacitor, greater will be the voltage build up



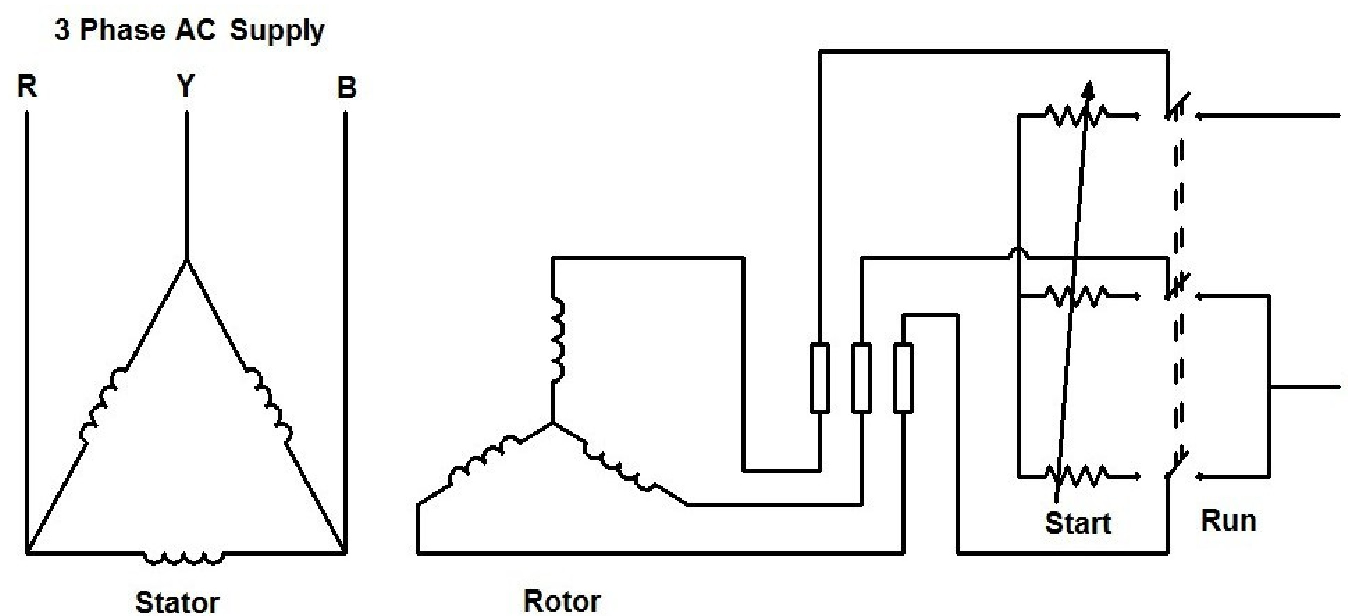
Comparison of Induction generator & Synchronous generator

Induction Generator	Synchronous Generator
Does not require DC excitation	Require DC excitation
Frequency of generated AC voltage depends on frequency of stator supply	Frequency of generated AC voltage depends on speed of Alternator
Magnitude of generated AC voltage depends on Magnitude of stator supply voltage	Magnitude of generated AC voltage depends on field excitation
No synchronization is required	Synchronization is required
Power factor of output power is Power factor can be varied by always leading due to presence of varying field excitation capacitor bank	
In grid connected operation, an An existing AC supply is not existing AC supply is required required	

Induction Generator	Synchronous Generator
Hunting & falling out of synchronism are absent	Hunting & falling out of synchronism are absent.
Simple, rugged, cheaper in cost & low maintenance	Complicated, costly, frequent maintenance Induction generator
Used in power plants where prime mover speed is not constant	Can't be used with a prime mover having variable speed characteristics
Application – Wind mills	Application – Hydro electric power plants

Synchronous Induction motor

- A Synchronous Induction motor as its name indicates is a motor which can work as an Induction motor & as a Synchronous motor
- It will work as an Induction motor during starting & during running, it will work as a synchronous motor
- Construction is same as that of a SRIM
- Provisions are provided to add external resistance in rotor circuit during induction motor operation & to apply DC excitation during Synchronous motor operation
- The connection diagram is shown in figure



- During starting, the switch is put to start position
- Now stator supply is given & machine is started as SRIM
- When machine is running at near synchronous speed, switch is put to run position
- Now a DC voltage is given to rotor & fixed magnetic poles are created in rotor
- Since the motor is running near synchronous speed, the rotor magnetic poles gets locked with stator rotating magnetic field poles & starts running as a synchronous motor
- This motor got the advantages of SRIM during starting (good starting torque & low starting current) & advantages of a Synchronous motor during running (Constant speed & adjustable power factor)
- It is used where high starting torque & constant speed is required

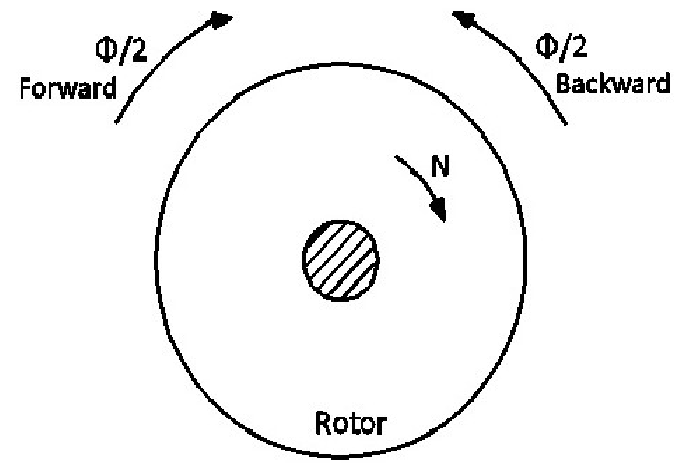
Single phase Induction motor

- A Single phase Induction motor operates on 1 phase AC supply
- Used in homes, offices etc. where 1 phase AC supply is available
- Construction of 1 phase Induction motor is almost same as that of a 3 phase SCIM
- The main difference is that, stator contains only a 1 phase winding. Rotor is a squirrel cage rotor
- Unlike a 3 phase Induction motor, 1 phase Induction motor is not self starting & requires some starting means
- When a 1 phase AC supply is given to stator winding, an alternating (pulsating) magnetic field is produced in stator & it links the rotor
- An EMF induces in rotor & a current flows through the rotor conductors
- Now the rotor conductors are like a current carrying conductor placed in a magnetic field & it experiences a torque
- The torque produced in rotor is also pulsating in nature. So net torque is zero & 1 phase Induction motor is not self starting
- If rotor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation
- So 1 phase Induction motor require some starting means due to lack of starting torque

This strange behavior of 1 phase Induction motor can be explained on the basis of Double field revolving theory

Double field revolving theory

- This theory is based on the idea that the pulsating magnetic produced in stator can be resolved into 2 components rotating in opposite directions at synchronous speed with half of its amplitude
- Under stationary condition, the torque produced by these magnetic fields are having equal magnitude & are rotating in opposite direction
- So resultant torque is zero
- If rotor is rotated by some external means in forward direction with speed 'N', then the slip of rotor w.r.to forward rotating field , $S_f = (N_s - N)/N_s = S$



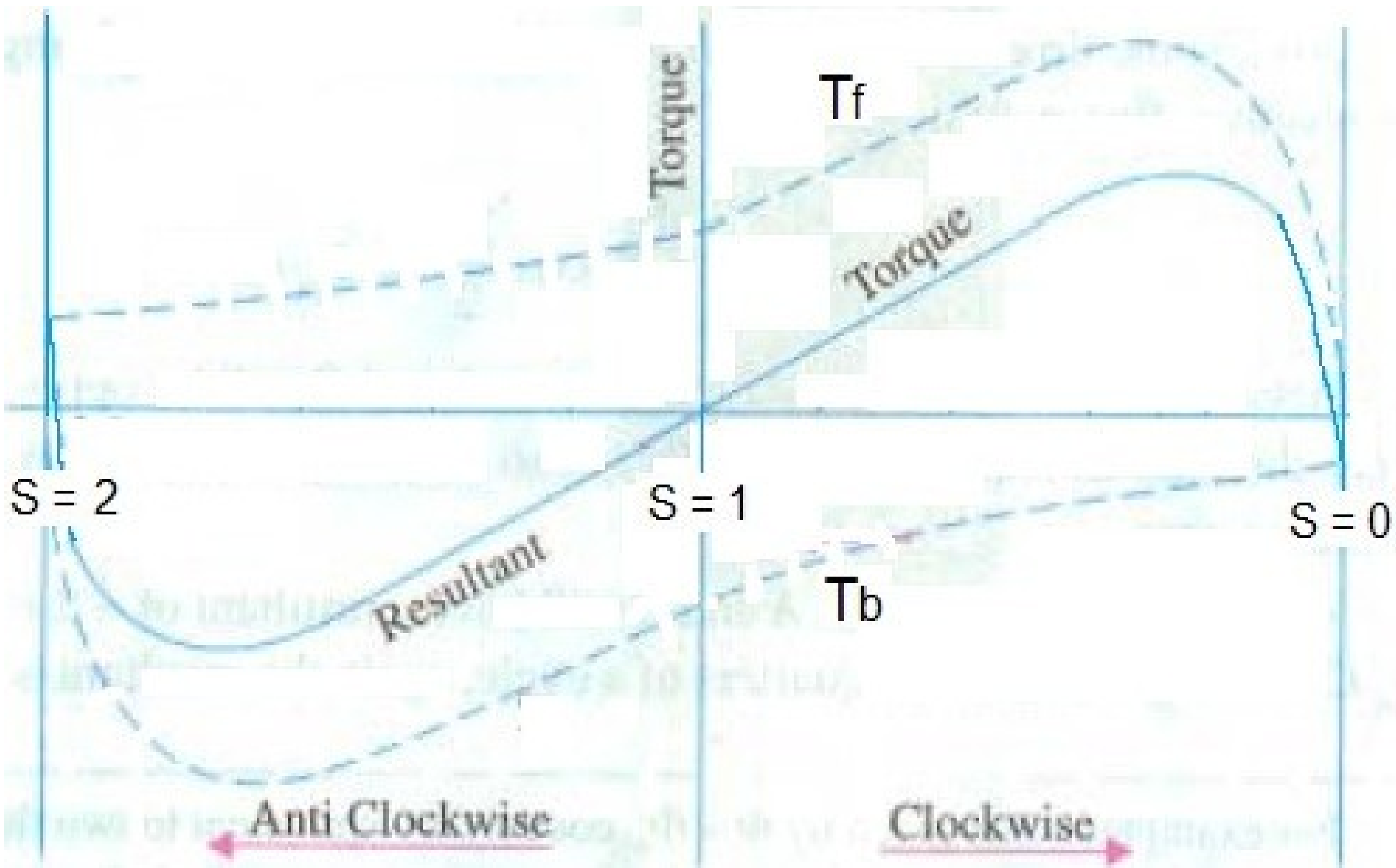
- Similarly slip of rotor w.r.to backward rotating field,

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

i.e, $S_b = \frac{2N_s - (N_s - N)}{N_s} = 2 - S$

- For normal operation, (2-s)>s
- So the current induced by backward rotating field is much larger & power factor is low
- This current induces an EMF in stator & produces a MMF which opposes backward rotating field & its magnitude decreases
- On the other hand, current induced by forward rotating field is low & power factor is high
- This low current produces an a low value MMF which opposes the forward rotating field
- Now the magnitude of forward field is higher compared to magnitude of backward field
- This will continue as speed increases in forward direction
- At near synchronous speed, forward field may be several times the backward field. As a result there is a net running torque
- The T-Speed characteristics of 1 phase motor is the resultant of T- Speed characteristics of forward & backward rotating fields
- It is shown in figure
- When S = 1, resultant torque is zero
- For other values of slip, motor produces a net torque

- The resultant maximum torque is less than in a 3 phase Induction motor
- The resultant torque become zero at a speed slightly below synchronous speed
- At synchronous speed, torque is negative



Equivalent circuit of 1 phase induction motor

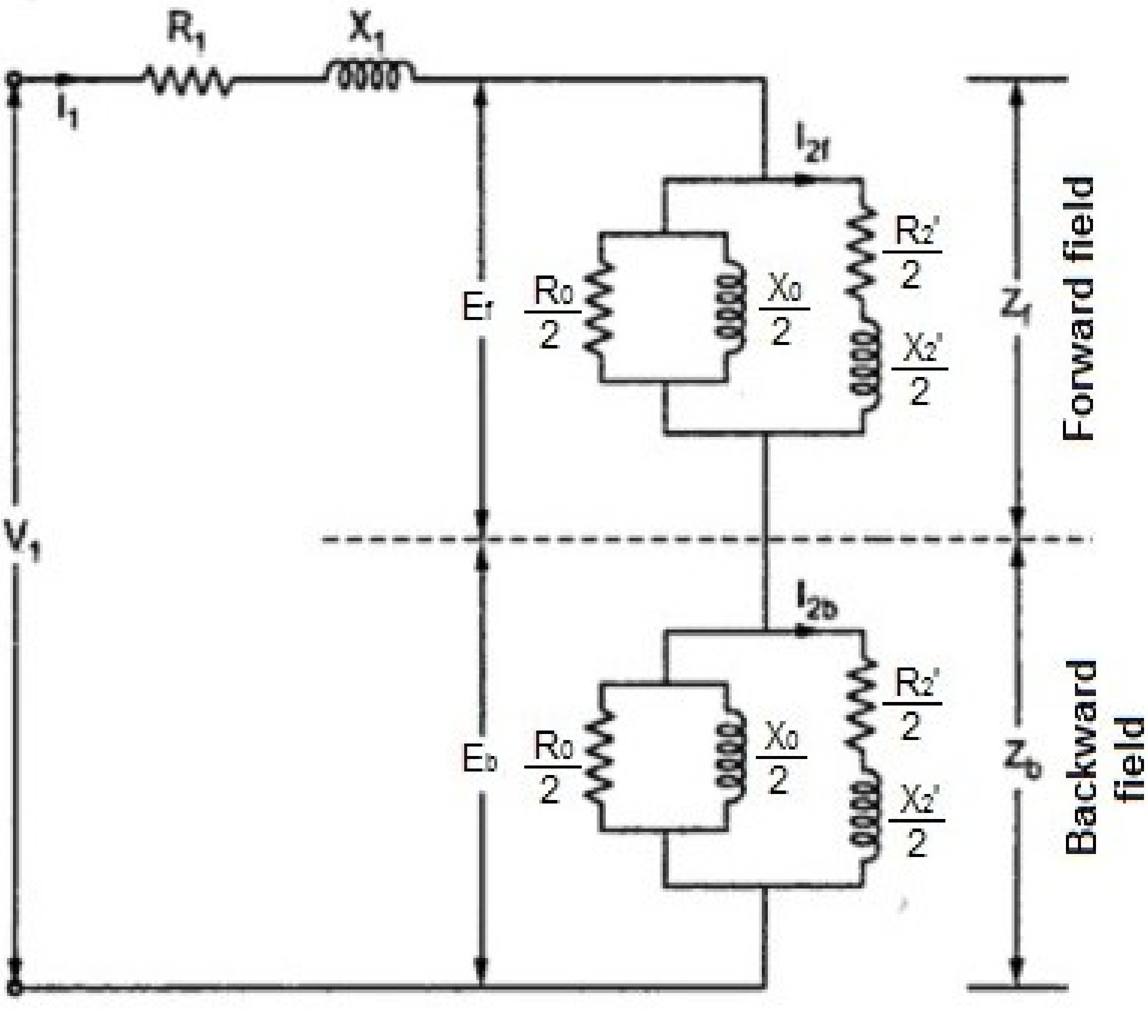
- When the stator of a single-phase induction motor is connected to single-phase supply, the stator current produces a pulsating flux
- According to Double-field revolving theory, this flux can be resolved into 2 flux components having same magnitude & revolving in opposite directions at the synchronous speed
- Each of these fluxes induces currents in the rotor circuit and produces induction motor action similar to that in a 3-phase induction motor
- Therefore, a single-phase induction motor can to imagined to be consisting of two motors, having a common stator winding but with their respective rotors revolving in opposite directions
- Each rotor has resistance and reactance half the actual rotor values
- Let R_1 = resistance of stator winding

  X_1 = leakage reactance of stator winding X_0 = total magnetizing reactance

  R_0 = total resistance equivalent to core losses

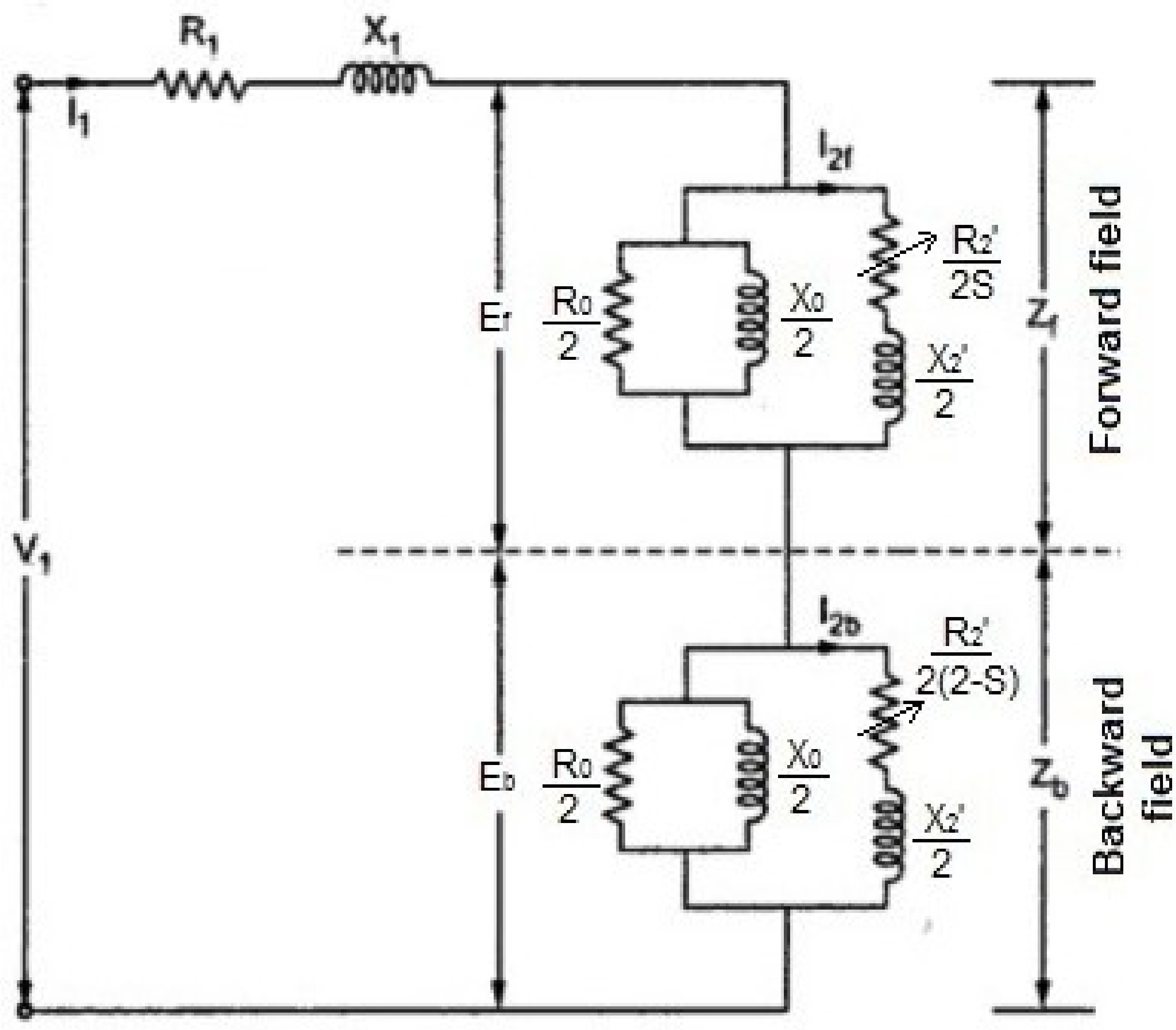
At standstill

- At standstill, the motor is simply a transformer with its secondary short circuited.
- Therefore, the equivalent circuit of single phase motor at standstill will be as shown in Figure



Rotor running

- Now consider that the motor is pinning at some speed in the direction of the forward revolving field, the slip being s.
- The equivalent circuit under this situation is shown in figure



Making 1 phase Induction motor self starting

- 1 phase Induction motor is not self starting & if the rotor is rotated in one direction by some external means, it will continue to run in the direction of rotation
- This method of starting is undesirable & require some method for creating a rotational magnetic field & make the motor self starting
- This can be achieved by converting 1 phase supply into 2 phase supply by providing an additional winding called auxiliary/starting winding
- Once the motor has achieved sufficient speed, the additional windings can be disconnected & the motor will continue to rotate
- Depending on the method employed for making the motor self starting, 1 phase Induction motors are classified into

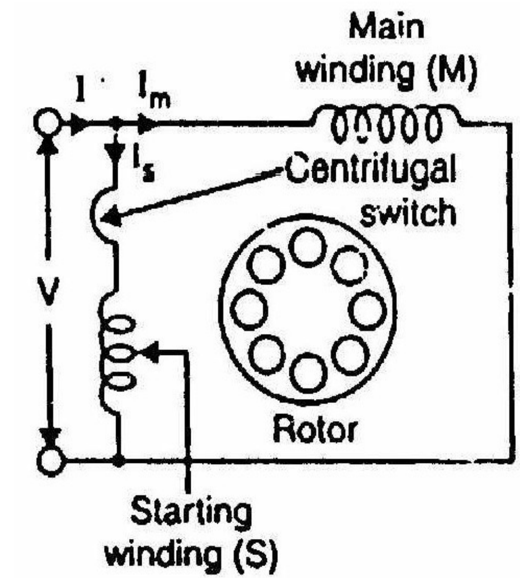
a) Split phase motor – started by 2 phase motor action through the use of a starting winding

b) Capacitor motor - started by two-phase motor action through the use of an auxiliary winding and a capacitor

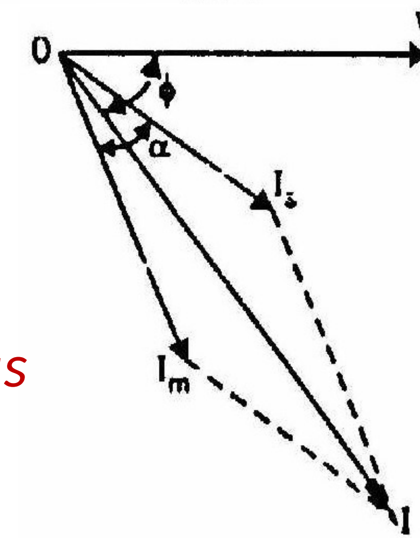
c) Shaded pole motor - started by the motion of the magnetic field produced by means of a shading coil around a portion of the pole structure

a) Split phase Induction motor

- It is provided with two windings – *main or running winding* (M) *and auxiliary or starting winding* (S)



- The main winding is permanently connected to the supply and the starting winding is placed 90° electrical from main winding and is connected to the supply *only during starting through a centrifugal switch.*



- The *main winding has low resistance and high reactance* and the *auxiliary winding has high resistance and low reactance*
- So the *current flowing through these windings has a phase difference α (25° to 30°)* and the flux produced by these currents also has a phase

- *The resultant flux will be rotating one*.
- *Starting torque is proportional to Sinα*
- Split phase induction motor is having moderate starting torque and are used in washing machines, blowers, grinders etc.

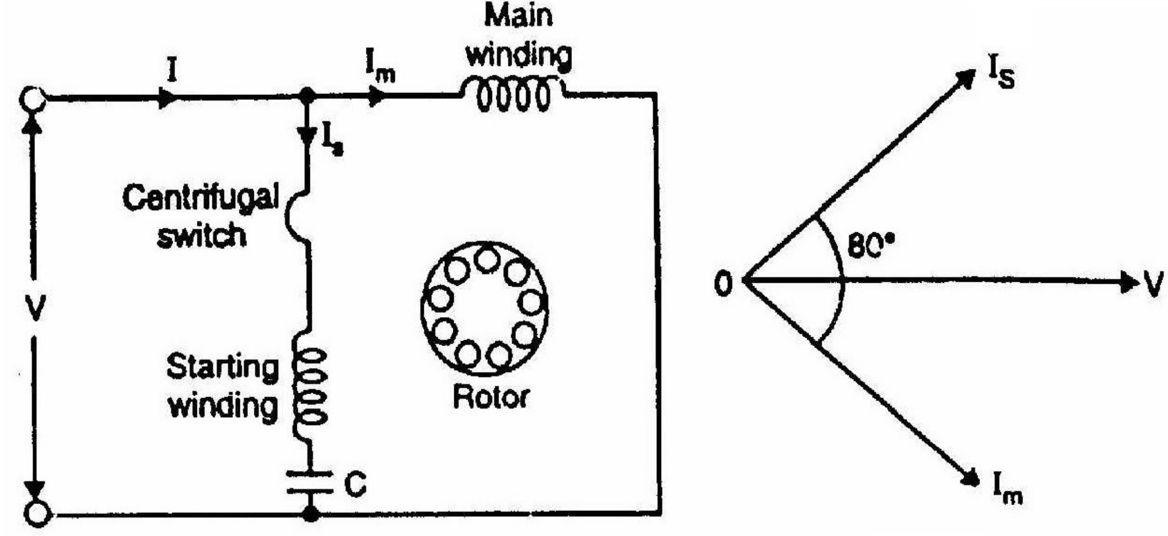
b) Capacitor motor

- In split phase motor, the maximum phase difference between starting and running winding current is 30°
- To improve starting torque (by increasing the angle), a capacitor is included in the staring winding circuit.
- Depending on the connection of capacitor, these motors are classified into

i) Capacitor start motor

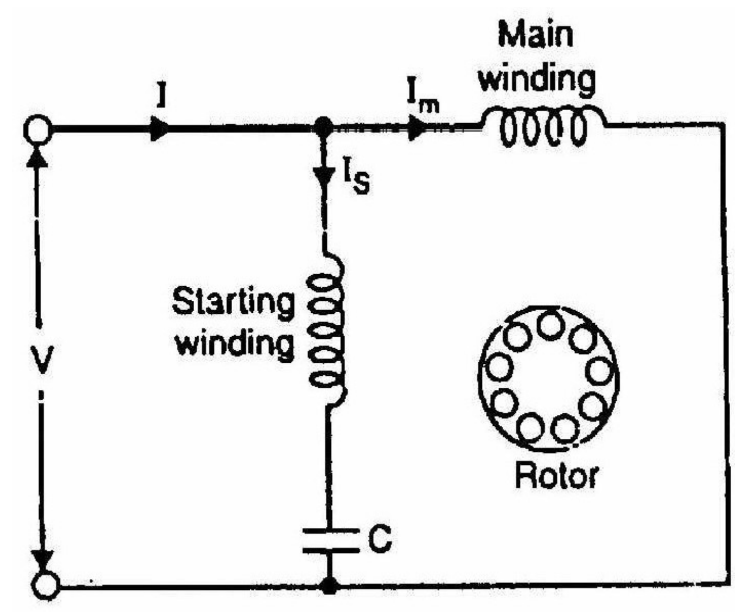
- Here in addition to split phase motor, a capacitor is connected in series with the starting winding
- The value of capacitor is chosen such that the phase difference 'α' is about 80°

- Used in applications requiring high starting torque like refrigerator, air conditioner, compressors etc



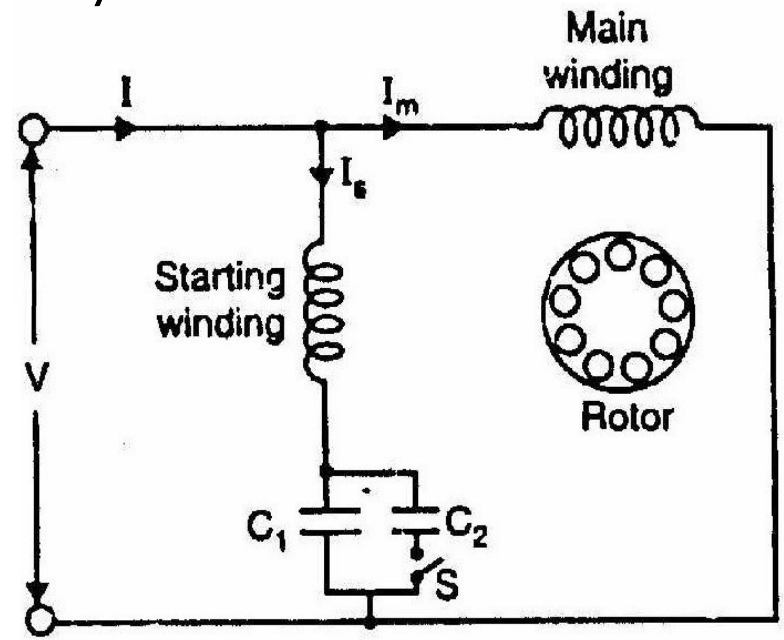
ii) <u>Capacitor start capacitor run motor</u>

- This motor is identical to Capacitor start motor
- The only difference is that both starting and running winding remain connected to supply during starting and running



- No need of centrifugal switch
- Got improved power factor and efficiency

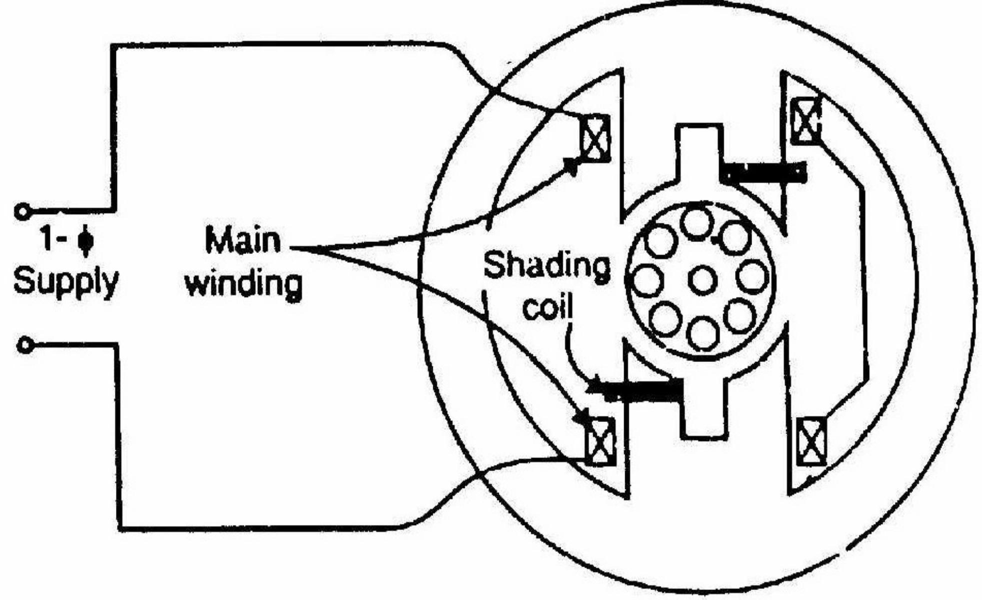
Design 2



- Here two capacitors C_1 and C_2 are connected in series with starting winding.
- The smaller capacitor C_1 required for optimum running condition is permanently connected in series with starting winding.
- The larger capacitor C_2 act as starting capacitor and is connected in parallel to C_1 through a centrifugal switch.
- This motor produces a constant torque
- These motors are mostly used in hospitals, studios and in other places where silence is important.

c) Shaded pole motor

- The shaded-pole motor has a cage rotor with salient poles in the stator.
- On one side of each pole a slot is cut and a copper shading ring is embedded in the slot.



- The stator supply current produces an alternating flux which induces a current in shading ring

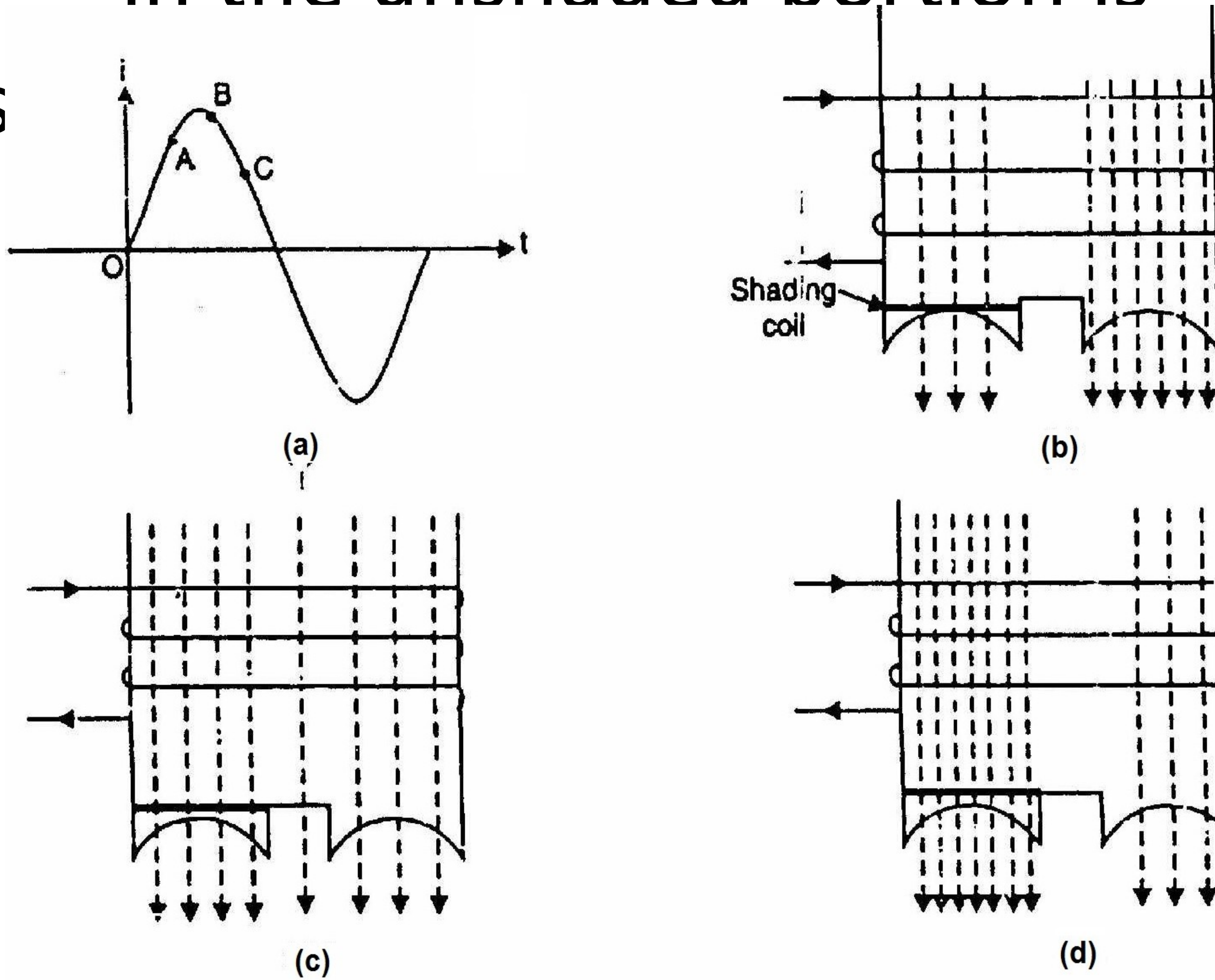
Working

- The operation of the motor can be understood by considering one pole of stator with shading ring as shown in figure

i) During the portion OA of the alternating-current cycle [See Fig. (a)], the flux begins to increase and an EMF is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux.

of the pole is weakened while that in the unshaded portion is

s).



ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See Fig. (c)] since no current is flowing in the shading coil

iii) As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in Fig. (d)

- This shifting flux is like a rotating weak field moving in the direction from unshaded portion to the shaded portion of the pole.
- The rotor is of the squirrel-cage type and is under the influence of this moving field.
- Consequently, a small starting torque is developed.
- As soon as this torque starts to revolve the rotor, additional torque is produced by single phase induction motor action.
- The motor accelerates to a speed slightly below the synchronous speed and runs as a single phase induction motor

- The salient features of this motor are extremely simple construction and absence of centrifugal switch.
- Since starting torque, efficiency and power factor are very low, these motors are only suitable for low power applications e.g., to drive: (a) small fans (b) toys (c) hair driers (d) desk fans etc.
- The power rating of such motors is upto about 30 W.