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SCHOOL OF ELECTRICAL & ELECTRONICS ENGINEERING
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT - I

AC Machines – SEEA1303

I SYNCHRONOUSGENERATORS

Constructional features - EMF Equation - Armature Reaction - Synchronous Reactance - Voltage Regulation -Synchronous Impedance Method - MMF and Potier Methods - Synchronising & Parallel Operation - Two Reaction Theory - Determination of Xd and Xq (Slip test).

ALTERNATORS

- **An electrical machine which converts mechanical energy into electrical energy in the form of three phase alternating current and alternating voltage is called as an Alternator.**
- **They are called as synchronous generators, because their speed is fixed by the frequency and the number of poles. They are also called as A.C. Generators.**
  They work on the principle of electromagnetic induction.
- **In an alternator, the armature winding is placed in the stator (stationary part) and the field winding is placed on the rotor (rotating part).**

Alternators may either have

(i) Revolving armature and stationary field

(ii) Revolving field and stationary armature.

(i) ***Revolving armature and stationary field***

- **It has stationary field windings and revolving armature.**
- **It is used for small KVA capacity and low voltage rating alternators.**

(ii) ***Revolving field and stationary armature***

- **It has stationary armature and rotating field poles**
- **Most alternators are of revolving field type**
- **Armature winding is placed on stator and field winding is placed on rotor.**
- **D.C supply is given to the field winding from a D.C source which may be a D.C generator mounted on the same shaft as that of the alternator. But since the field**

windings are rotating, the D.C supply is given to the field windings by means of slip rings and brush assembly.

- **Now, the rotating field windings produce a flux which is being cut by stationary armature windings and hence an emf is being induced in the armature winding.**

Advantages of Revolving Field

- **Output can be directly taken from fixed terminals on stator with brush contacts.**
- **Easy to insulate stationary armature winding for high ac voltage.**
- **Slip rings are transferred to low voltage low power D.C field circuit which can be easily insulated.**
- **The armature windings can be more easily braced to prevent any deformation, which could be produced by mechanical stresses set up as a result of short circuit and high centrifugal forces.**

CONSTRUCTION OF ALTERNATOR

In alternator the armature winding is mounted on the stationary part called STATOR and the field windings is mounted on the rotating part called ROTOR.

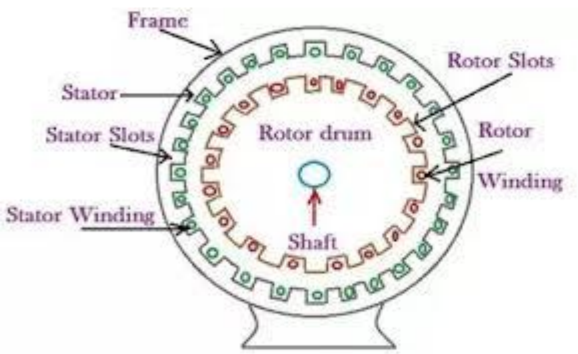


Fig. 1 Construction of Alternator

(1) STATOR FRAME

- **In a D.C machine the outer frame serves to carry magnetic flux. But in alternator it is used for /*olding armature windings and stampings in position.**
- **Frames are made from mild steel plates, welded together to form a frame having a box type section.**
- **Ventilation is maintained with the help of holes cast in the frame.**

(2) STATOR CORE

- **The stator core is supported by stator frame.**
- **It is built up of laminations of magnetic iron (or) steel alloy.**
- **The slots for placing the armature conductors lie along the inner periphery of the core.**
- **The laminations are insulated from each other with varnish (or) paper, and have spaces between them to allow the cooling air to pass through it.**
- **The slots may be wide open, semi closed (or) fully closed.**
- **In these slots, three phase Δ (or) Y connected windings are placed.**

(3) ROTOR

It is fly wheel like structure having a large number of alternate North and South poles fixed to the outer rim. These poles are excited by providing D.C supply. Since the field magnets rotate, D.C supply is provided through slip rings and brushes.

Two types of rotor are used in alternator.

(i) Salient pole (or) projecting pole

(ii) Non salient pole (or) smooth cylindrical pole

(i) ***Salient pole (or) Projecting poles***

- **It has a large number of projecting poles having their cores bolted into a heavy magnetic wheel of cast iron (or) steel.**
- **They are made of thick steel lamination.**
- **It is used for low and medium speed alternators (125.500 rpm)**
- **Such generators are characterized by their large diameters and short axial lengths.**
- **The pole core and pole shoes are laminated to minimize eddy current losses.**

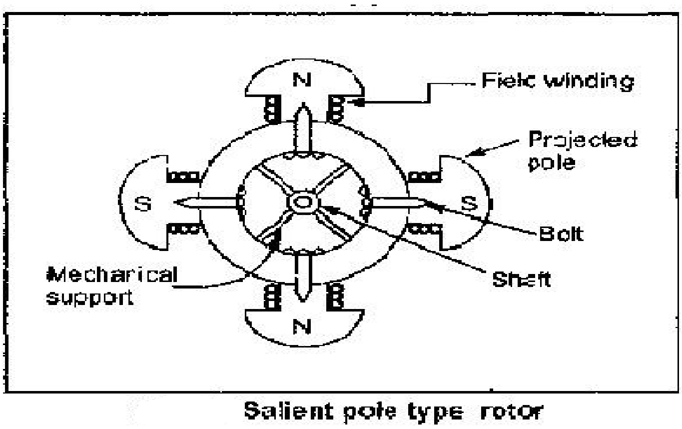


Fig. 2 Salient pole type rotor

(ii) ***Non salient pole (or) Smooth cylindrical pole***

- **It consists of smooth forged steel cylinder having a number of slots milled out at intervals along the outer periphery for accommodating field coils.**
- **It is used for very high speed machines designed for two (or) four poles.**
- **Two (or) four region corresponding to the central polar areas are left unslotted.**
- **The central polar areas are surrounded by field windings placed in slots.**
- **Field coils are so arranged around these polar areas that flux density is maximum on the polar central line and gradually falls on either side.**
- **Here poles are non salient i.e., they do not project outside.**
- **They are characterized by very small diameters and long axial lengths.**
- **They are preferred for high speed (1500-3000 rpm).**

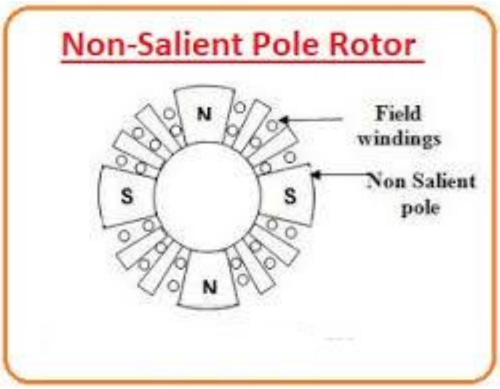


Fig. 3 Non Salient pole type rotor

Difference between salient and non-salient pole

Salient pole	Non-salient pole

1. Poles are projecting out.	**1. No projected poles. Smooth cylindrical poles.**
2. Air gap is non-uniform.	**2. Uniform air gap.**
3. Large diameter and small axial length.	**3. Small diameter and large axial length.**
4. Used for low and medium speed application.	**4. Used for high speed applications.**
5. Mechanically weak.	**5. Mechanically robust.**
6. For some size, rating is smaller than cylindrical type.	**6. For same size rating is higher than salient pole.**
7. Prime movers are water turbines, I.C. Engines.	**7. Prime movers are steam turbines and electric motors.**

Excitation system

An alternator is a separately excited machine. Its field winding require D.C excitation. It is generally supplied by a D.C generator mounted on the same shaft as that of the alternator.

WORKING PRINCIPLE

- **When the field windings in the rotor is given D.C supply, a magnetic field is produced.**
- **When the rotor rotates, the stationary armature conductors cut the rotating magnetic field of the rotor, and so by Faradays law of electromagnetic induction, an emf is induced in the armature conductors and hence a current flows in the conductor.**
- **The direction of the induced emf is given by Flemings right hand rule.**
- **The frequency of the induced emf depends on the number of N and S poles moving past a conductor in one second.**

Expression for frequency of induced emf

Let P = number of poles

N = speed of the rotor in rpm

f = frequency of induced emf.

One cycle of emf is induced when one pair of poles passes over it. The number of cycles of emf produced in one revolution is equal to number of pair of poles.

Number of cycles / revolution = $\frac{P}{2}$

Number of revolutions / second = $\frac{N}{60}$

$$f = \frac{\text{cycles}}{\text{second}} = \frac{\text{cycles}}{\text{revolution}} * \frac{\text{revolution}}{\text{second}}$$

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

$f = \frac{PN}{120}$ **cycles per second or Hz.**

SYNCHRONOUS SPEED [N_s]

It is the speed at which the alternator must run in order to generate an emf at the required frequency.

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

EMF EQUATION OF AN ALTERNATOR

Let

Z = number of conductors / phase

Z = 2T; T = number of turns / phase

P = number of poles

f = frequency of induced emf in Hz

ϕ = flux / pole in wb

N = rotor speed in rpm

K_d = distribution factor

K_c (or) K_p = coil span factor (or) pitch factor

K_f = form factor = 1.11

Time taken to complete one revolution is

$$dt = \frac{60}{N} \text{seconds}$$

In one revolution of rotor, each stator conductor is cut by a flux = $d\phi = P\phi$ webers.

Average emf induced / conductor = $\frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60}$

On substituting the value of $N = \frac{120f}{P}$ **,**

Average emf / conductor = $\frac{P\phi}{60} * \frac{120f}{P} = 2\phi f$ volts

If there are Z conductors in series/phase, then average value of

emf/phase = 2fϕ ∗ Z = 2ϕf ∗ 2T (Z = 2T)

Average emf/phase = 4fϕT volts

RMS value of emf/phase = form factor ∗ average value

= 1.11 ∗ 4fϕT

RMS value of emf/phase = 4.44fϕT volts

This is the actual value of emf if coil is full pitched and concentrated.

But if the windings are distributed and the coils are short pitched then, the emf equation is multiplied by two factors Kc and Kd.

Emf/ph = 4.44 ∗ K_c **∗** K_d *** fϕT volts**

(or)

E = 4.44 $K_f K_c K_d f\phi T$ **volts**

where

$$K_d = \frac{\text{emf in distributed wdg}}{\text{emf in concentrated wdg}};$$

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

$$K_c = \frac{\text{emf in short pitched co}}{\text{emf in full pitched coil}}$$

m = number of slots / pole / phase

β = angular displacement between slots

$$\beta = \frac{180}{n}$$

$$n = \frac{\text{slots}}{\text{pole}}$$

$$Kc = \cos\frac{\alpha}{2}$$

α = 180 – Actual coil span of coils

(or)

$\alpha = \beta *$ number of slots by which the coils are short pitched

PARAMETERS OF ARMATURE WINDING

The parameters of armature winding are

(i) Armature resistance (R_a)

(ii) Armature leakage reactance (X_L)

(iii) Reactance corresponding to armature reaction (X_{ar})

(i) ***Armature Resistance (R_a)***

- **Generally the value of R_a is measured by applying a d.c voltage and measuring the current flowing through it.**

$$R_a(\text{d.c}) = \frac{V}{I}; \qquad R_a(\text{ac}) = 1.6 * R_a(\text{dc})$$

When the armature is Y connected

When voltage is applied across any two terminals for eg. b/w R & Y terminal, then the equivalent resistance is

$$R_{RY} = R_a + R_a = 2R_a$$

$$\mathbf{R_{RY} = 2R_a}$$

$$R_a = \frac{R_{RY}}{2} \quad \Omega/\text{ph.}$$

When armature is Δ connected

In Δ connection when voltage is applied b/w any two terminals then one winding is in parallel with the series combination of two.

$$R_{RY} = R_a \parallel 2R_a = \frac{R_a \times 2R_a}{R_a + 2R_a} = \frac{2R_a{}^2}{3R_a} = \frac{2}{3}R_a$$

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

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

(ii) ***Armature Leakage Reactance (X_L)***

- **When current flows through armature, it produces a flux.**
- **Some amount of flux completes its path through the air around the conductor and is called as leakage flux.**
- **If L is the leakage inductance; $X_L = 2\pi fL$ is the leakage reactance.**
- **X_L makes the armature winding inductive in nature.**

(iii) ***Armature Reaction Reactance X_{ar}***

"The effect of armature flux on the distribution of main field flux is called as armature reaction"

- **The effect of armature flux depends on:**
  - → **Magnitude of current in armature**
  - → **Nature of power factor of load connected**

Let us discuss the effect of p.f of load on the armature reaction.

SYNCHRONOUS REACTANCE (Xs)

It is the sum of the leakage reactance (X_L) and the armature reaction reactance (X_{ar})

$X_S = X_L + X_{ar}$

SYNCHRONOUS IMPEDANCE (Z_S)

The impedance obtained by combining the values of armature resistance (Ra) and synchronous reactance (X_S) is called as synchronous impedance.

$Z_S = R_a + jX_S$

EQUIVALENT CIRCUIT OF ALTERNATOR

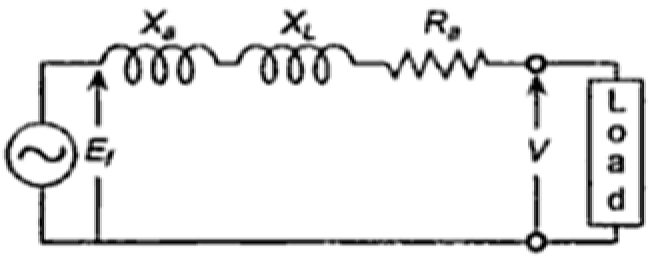


Fig.4 Salient pole type rotor

VOLTAGE EQUATION OF ALTERNATOR

The emf generated in an alternator (Eph) is not available completely at the load due to drops across (i) R_a (ii) X_S

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

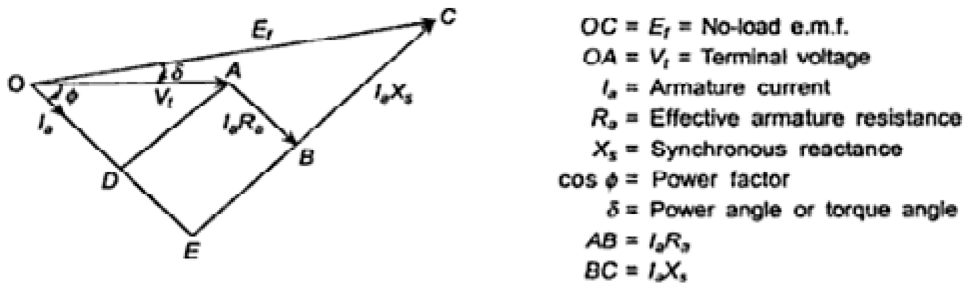
(or)

$$E_{ph} = V_{ph} + I_aZ_S$$

This is the voltage equation of an alternator.

PHASOR DIAGRAM OF A LOADED ALTERNATOR

Lagging power factor load



For lagging power factor load.

- **The phasor diagram is draw by taking V_{ph} as reference. OA = V_{ph}**
- **An inductive load is connected, the current I_a lags the voltage V_{ph} by an angle ϕ.**
- **The I_aR_a drop is in phase with I_a. It is represented by AB = I_aR_a**
- **The I_aX_S drop is at 90° to I_aR_a. BC = I_aX_S**
- **I_aZ_S is the vector sum of I_aR_a and I_aX_S. AC = I_aZ_S**
- **The emf $\overrightarrow{E_{ph}} = \overrightarrow{V_{ph}} + \overrightarrow{I_a Z_S}$. OC = E_{ph}.**
- **Form a right angled triangle ODC by extending B and O. OA = V_{ph};**

OE = $V_{ph}\cos\phi$ AB = ED = IaRa; AE = BD = $V_{ph}\sin\phi$

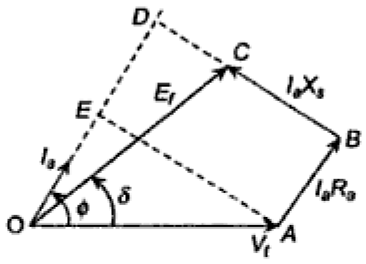
In triangle ODC; $OC^2 = OD^2 + DC^2$

$$OC^2 = (OE + ED)^2 + (DB + BC)^2$$

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

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

Leading power factor load



at leading power factor.

- **OA = Vph is reference vector.**
- **Capacitive load is connected the current I_a leads V_{ph} by an angle ϕ.**
- **I_aR_a is inphase with I_a. AB = I_aR_a**
- **I_aX_S is at 90° to I_aR_a. BC = I_aX_S**
- **I_aZ_S is vector sum of I_aR_a & I_aX_S. AC = I_aZ_S**
- **$E_{ph} = V_{ph} + I_aZ_S$. OC = E_{ph}**
- **Form triangle ODC by extending BC to D and O.**

DE = AB = I_aR_a; AE = BD = $V_{ph}\sin\phi$; OE = $V_{ph}\cos\phi$

From triangle ODC

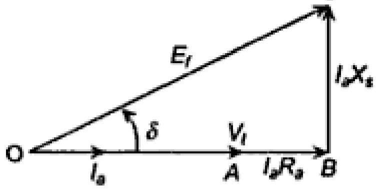
$$OC^2 = OD^2 + CD^2$$

$$OC^2 = (OE + ED)^2 + (BD - BC)^2$$

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

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

Unity power factor load



For unity power factor load.

V_{ph} is reference. OA = V_{ph}

For a pure resistive load, the P.f is unity and I_a and V_{ph} are in phase with each other.

AB = I_aR_a is in phase with I_a.

BC = I_aX_S is at 90° to I_aR_a.

AC = I_aZ_S is the vector sum of I_aR_a and I_aX_S.

OC = E_{ph} is the vector sum of $\overrightarrow{V_{ph}} + \overrightarrow{I_a Z_S}$

From triangle OBC

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

$OC^2 = (OA + AB)^2 + BC^2$

$$E_{ph}^2 = (V_{ph} + I_aR_a)^2 + (I_aX_S)^2$$

$$E_{ph} = \sqrt{(V_{ph} + I_aR_a)^2 + (I_aX_S)^2}$$

VOLTAGE REGULATION OF ALTERNATOR

It is defined as the change in the voltage of an alternator as the load on the alternator is varied from no load to full load and is expressed as a percentage of the rated load value

$$\% \quad Reg = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

Synchronous Impedance Method or E.M.F Method (for finding Voltage Regulation)

The method is also called E.M.F. method of determining the voltage regulation. The method requires following data to calculate the regulation.

1. The armature resistance per phase (R_a).

2. Open circuit characteristics which is the graph of open circuit voltage against the field current. This is possible by conducting open circuit test on the alternator.

3. Short circuit characteristics which is the graph of short circuit current against field current. This is possible by conducting short circuit test on the alternator.

Let us see, the circuit diagram to perform open circuit as well as short circuit test on the alternator. The alternator is coupled to a prime mover capable of driving the alternator at its synchronous speed. The armature is connected to the terminals of a switch. The other terminals of the switch are short circuited through an ammeter. The

voltmeter is connected across the lines to measure the open circuit voltage of the alternator.

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

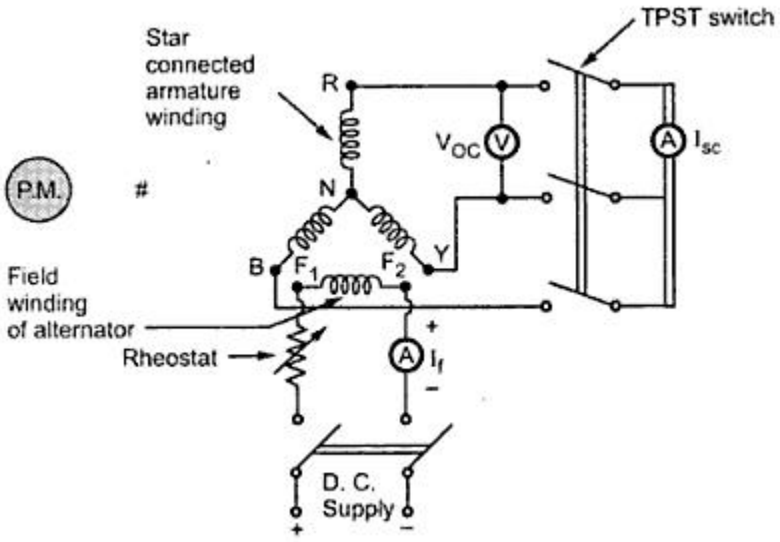


Fig. 5 Circuit diagram for open circuit and short circuit test on alternator

<u>1.O.C. Test:</u>

Procedure:

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

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

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

iv) With the help of rheostat, field current is varied from its minimum value to the rated value. Due to this, flux increasing the induced e.m.f. Hence voltmeter reading, which is measuring line value of open circuit voltage increases. For various values of field current, voltmeter readings are observed.

Observation table for open circuit test :

Sr. No.	I_f A	V_{oc} (line) V	V_{oc} (phase) = V_{oc} (line)/$\sqrt{3}$ V
1			
2			
:			
:			

From the above table, graph of $(V_{oc})_{ph}$ against I_f is plotted.

Note : This is called open circuit characteristics of the alternator, called O.C.C. This is shown in the Fig.

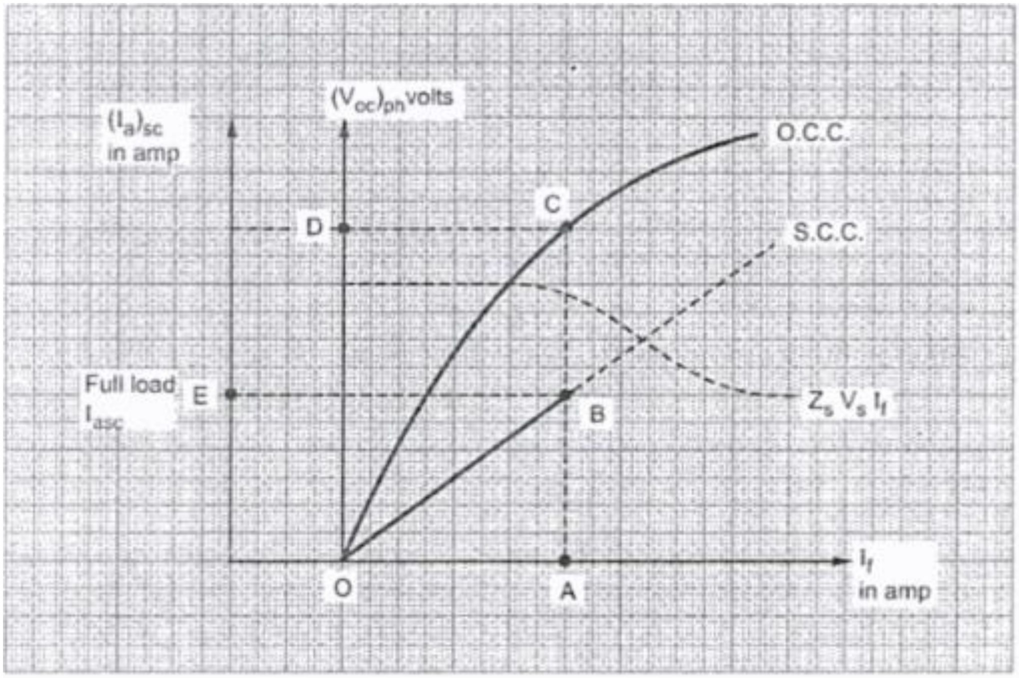


Fig. 6 O.C.C. and S.C.C. of an alternator

<u>2. S.C.Test</u>

After completing the open circuit test observation, the field rheostat is brought to maximum position, reducing field current to a minimum value. The T.P.S.T switch is closed. As ammeter has negligible resistance, the armature gets short circuited. Then the field excitation is gradually increased till full load current is obtained through armature winding. This can be observed on the ammeter connected in the armature circuit. The graph of short circuit armature current against field current is plotted from the observation table of short circuit test. This graph is called short circuit characteristics, S.C.C. This is also shown in the Fig. 2.

Observation table for short circuit test :

Sr. No.	I_f A	Short circuit armature current per phase (I_{asc}) A
1		
2		

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

Note : As S.C.C. is straight line graph, only one reading corresponding to full load armature current along with the origin is sufficient to draw the straight line.

<u>3. Determination of Impedance from O.C.C. and S.C.C.</u>

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

In short circuit test, external load impedance is zero. The short circuit armature current is circulated against the impedance of the armature winding which is Z_s. The voltage responsible for driving this short circuit current is internally induced e.m.f. This can be shown in the equivalent circuit drawn in the Fig.

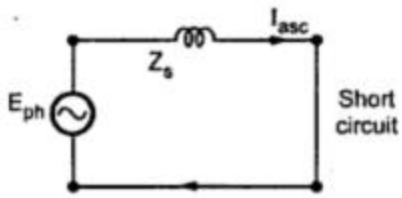


Fig. 7 Equivalent circuit on short circuit

From the equivalent circuit we can write,

$Z_s = E_{ph} / I_{asc}$

This is what we are interested in obtaining to calculate value of Z_s. So expression for Z_s can be modified as

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

Thus in general,

$$\boxed{Z_s = \left.\frac{\text{Phase e.m.f. on open circuit}}{\text{Phase current on short circuit}}\right|_{\text{For same excitation current}}}$$

So O.C.C. and S.C.C. can be effectively to calculate Z_s.

4. Regulation Calculations:

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

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

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

$\therefore$ $$X_s = \sqrt{(Z_s)^2 - (R_a)^2}\ \Omega/ph$$

So synchronous reactance per phase can be determined.

No load induced e.m.f. per phase, E_{ph} can be determined by the mathematical expression derived earlier.

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

where V_{ph} = Phase value of rated voltage
I_a = Phase value of current depending on the load condition
cosΦ = p.f. of load

Positive sign for lagging power factor while negative sign for leading power factor, R_a and X_s values are known from the various tests performed.
The regulation then can be determined by using formula,

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

Advantage:
synchronous impedance Z_s for any load condition can be calculated. Hence regulation of the alternator at any load condition and load power factor can be determined.
Limitation:
The main limitation of this method is that the method gives large values of synchronous reactance. This leads to high values of percentage regulation than the actual results. Hence this method is called pessimistic method.
This is all about synchronous Impedance method for calculation voltage regulation of synchronous machine.

MMF method for determining voltage regulation of Alternator:

MMF method is used for determining the voltage regulation of an alternator or synchronous generator is also called *Ampere turns method* or Rothert's MMF method. This *MMF method* is based on the results of open circuit test and short circuit test on an alternator. For any synchronous generator or alternator, MMF is required, which is a product of field current and turns of the field winding for two separate purposes.

1. It must have an MMF necessary to induce the rated terminal voltage on the open circuit.
2. It must have an MMF equal and opposite to that of armature reaction MMF.

In most of the cases, as the number of turns on the field winding is not known, the MMF is calculated and expressed in terms of the field current itself.

The field mmf which is required for inducing the rated terminal voltage on the open circuit can be obtained from open circuit test results and open circuit characteristics. This is denoted as FO.

Synchronous impedance consists of two components. They are armature resistance and synchronous reactance. Now synchronous reactance also has two components, armature leakage reactance and armature reaction reactance. In the short-circuit test, field MMF is necessary to overcome drop across armature resistance and leakage reactance and also to overcome the effect of armature reaction.
But drop across armature resistance and leakage reactance is very small and can be neglected. Thus in short circuit test, field MMF circulates the full load current balancing the armature reaction effect. The value of ampere-turns required to circulate full load current can be obtained from short circuit characteristics. This is denoted as FAR.
Under short circuit condition as resistance and leakage reactance of armature has no significant role, the armature reactance is dominating and hence the power factor of the purely reactive circuit is zero lagging. Hence FAR gives demagnetising ampere-turns. Thus the field MMF is entirely used to overcome the armature reaction which is wholly demagnetising in nature.

The two components of total field mmf which are FO and F_{AR} are indicated in

OCC(open circuit characteristics) and SCC (short circuit characteristics) as shown in the below figure.

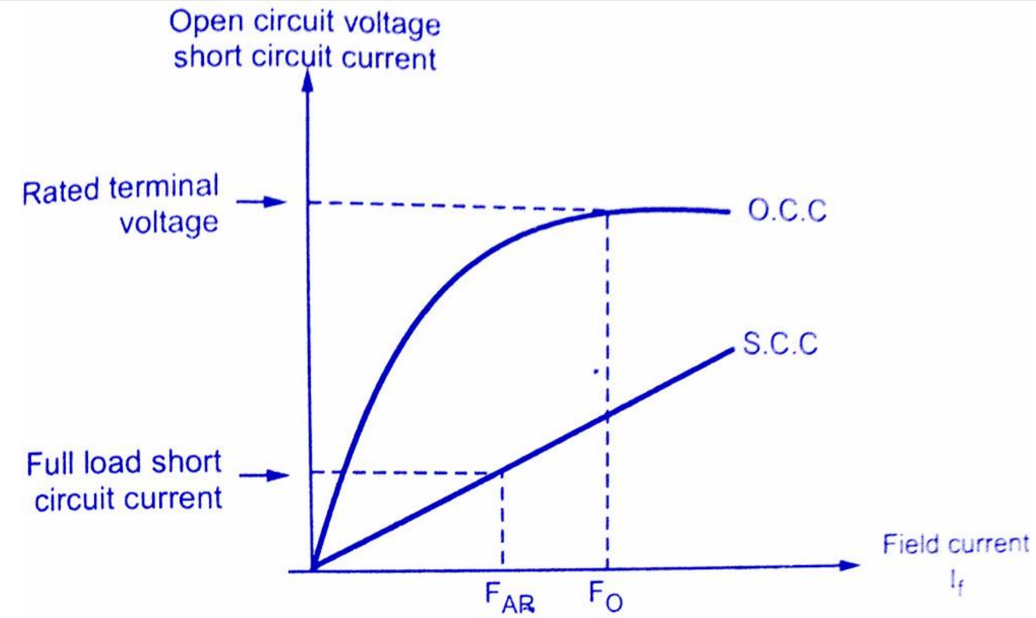


Fig. 8 Salient pole type rotor

If the alternator is supplying full load, then total field MMF is the vector sum of its two components Fo and F_{AR}. This depends on the power factor of the load which alternator is supplying. The resultant field MMF is denoted as F_R. Let us consider the various power factors and the resultant F_R.

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

Fig. 9. Zero lagging p.f

AB = FAR DEMAGNETISING OB = FR = FO + FAR

Total field MMF is greater than Fo

Zero leading p.f : When the power factor is zero leading then the armature reaction is totally magnetising and helps main flux to induce rated terminal voltage. Hence net field required is less than that required to induce rated voltage normally, as part of its function is done by magnetising armature reaction component. The net field mmf in this MMF method is the algebraic difference between the two components FO and FAR.

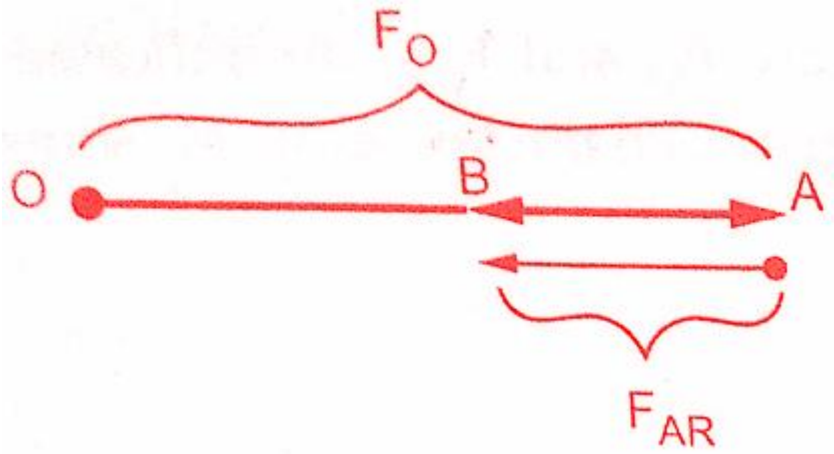


Fig. 10. Zero leading p.f

AB = F_{AR} MAGNETISING

OB = FO - F_{AR} = F_R

Total MMF is less than FO.

Unity p.f : Under unity power factor condition, the armature reaction is cross magnetising and its effect is to distort the main flux. Thus FO and FAR are at right angles to each other and hence resultant MMF is the vector sum of FO and FAR in this MMF method.This is shown in the below figure.

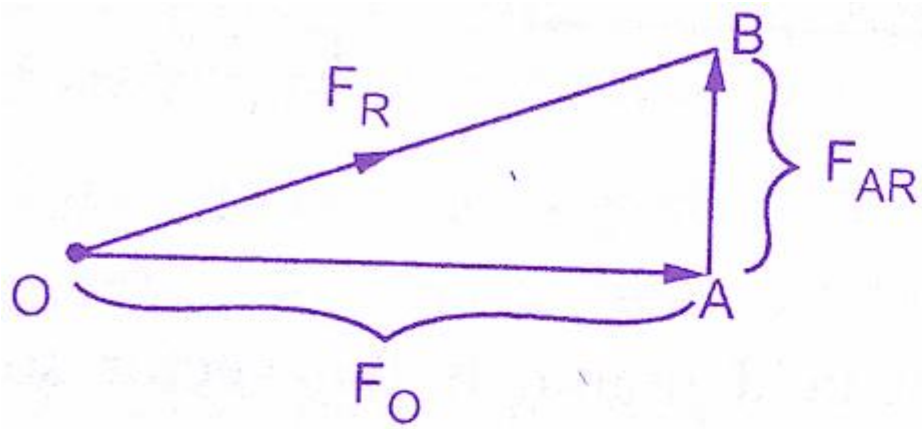


Fig. 11. Unity p.f

OA=F_O: AB = F_{AR} CROSS MAGNETISING

OB = F_R = F_O + F_{AR}

Here below is the following considerations for MMF or Ampere turn method for determining voltage regulation of Alternator.

General Case: Now consider that the load power factor is cos Φ. In such case, the resultant MMF is to be determined by vector addition of F_O and F_{AR}.

cos Φ, lagging p.f : When the load p.f. is cos Φ lagging, the phase current Iaph lags Vph by angle Φ.The component FO is at right angles to Vph while FAR is in phase with the current Iaph. This is because the armature current Iaph decides the armature reaction. The armature reaction FAR due to current Iaph is to be overcome by field MMF.

Hence while finding resultant field MMF, - F_{AR} should be added to F_O vectorially. This is because the resultant field MMF tries to counterbalance armature reaction to produce rated terminal voltage. The phasor diagram of Ampere turn method or MMF method is shown below.

From the phasor diagram the various magnitudes are,

OA = Fo , AB = FAR, OB = FR

Consider triangle OCB which is right angle triangle. The FAR is split into two parts as, AC = FAR sin Φ and BC= FAR cos Φ .

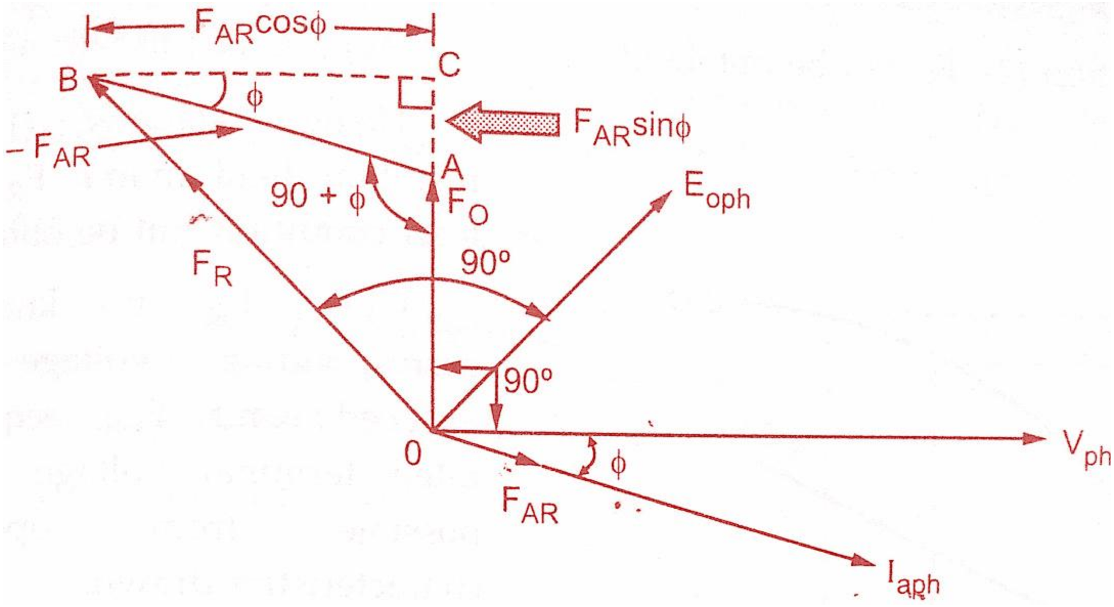


Fig. 12. Unity p.f

FR = (FO + FAR sin Φ)² + (FAR cos Φ)²

FR can be obtained from the above relation.

Cos Φ, leading p.f : When the load p.f. is cos Φ leading, the phase current Iaph leads Vph by Φ. The component Fo is at right angles to Vph, and FAR is in phase with Iaph. The resultant F_R can be obtained by adding F_{AR} to F_o. The phasor diagram is shown in the below figure.

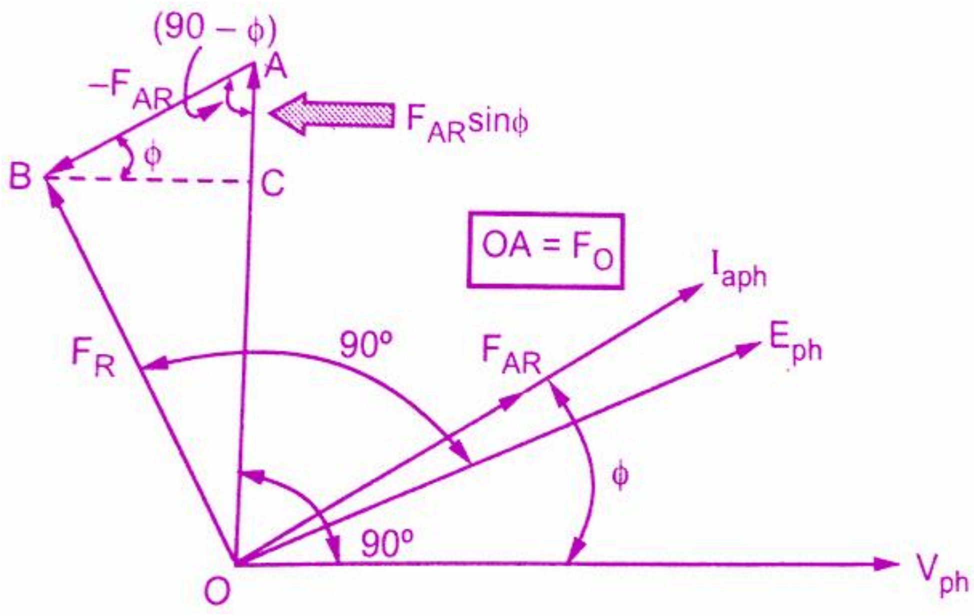


Fig. 13. Phasor diagram

From the phasor diagram , various magnitudes are,
AC = F_{AR} sin Φ and BC = F_{AR} cos Φ
OA = F_O , AB = F_{AR} and OB = F_R .
Consider triangle OCB which is right angle triangle.
$OB)^2 = (OC)^2 + (BC)^2$ $(F_R)^2 = (FO - FAR \sin \Phi)^2 + (FAR \cos \Phi)^2$, Thus F_R can be obtained,

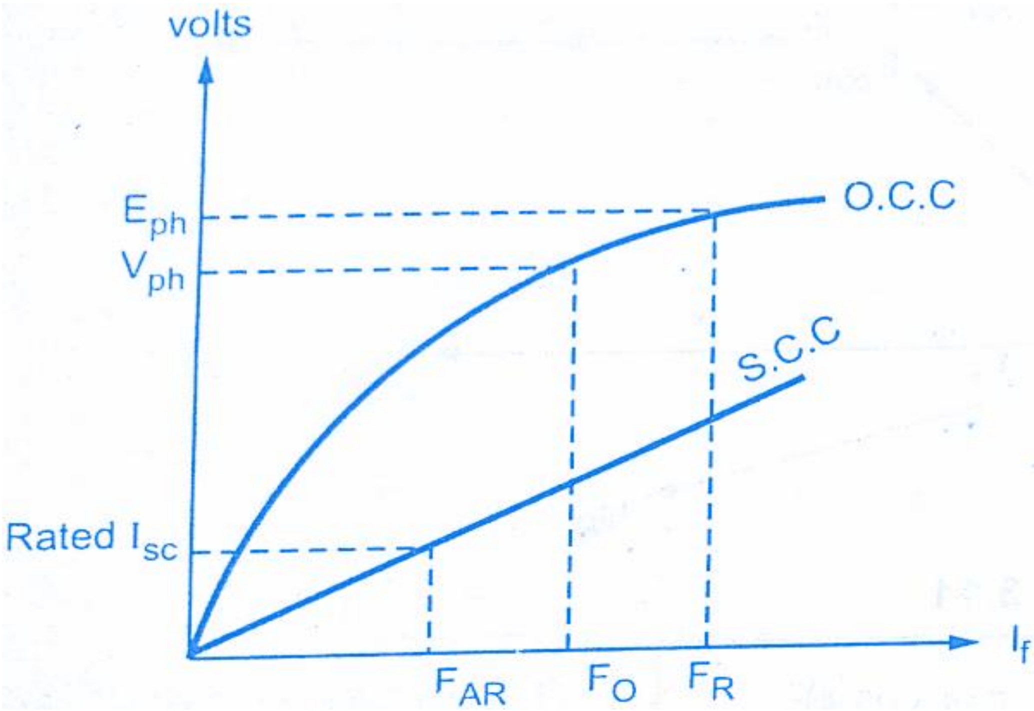


Fig. 14. Phasor diagram

Using relations (1) and (2) resultant field MMF FR for any p.f load condition can be obtained from the above MMF method characteristics diagram. Once F_R is known, obtain a corresponding voltage which induced EMF Eph, required to get rated terminal voltage Vph. This is possible from open circuit characteristics drawn.

Once Eph is known then the voltage regulation can be obtained as,

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

Note : To obtain Eph corresponding to FR O.C.C. must be drawn to the scale, from the open circuit test readings.

This ampere turn method gives the voltage regulation of an <u>alternator</u> which is lower than that actually observed. Hence this MMF method *is called optimistic method.*

Important note: When the armature resistance is neglected then Fo is field mmf required to produce rated Vph at the output terminals. But if the effective armature resistance Raph, is given then Fo is to be calculated from O.C.C. such that Fo represents the excitation (field current) required to produce a voltage of Vph + Iaph Ra cos Φ where

Vph = rated voltage per phase

Iaph = full load current per phase

Ra = armature resistance per phase

cos Φ = power factor of the load

It can also be noted that FR can be obtained using the cosine rule to the triangle formed by Fo, FAR and Fo as shown in the below.

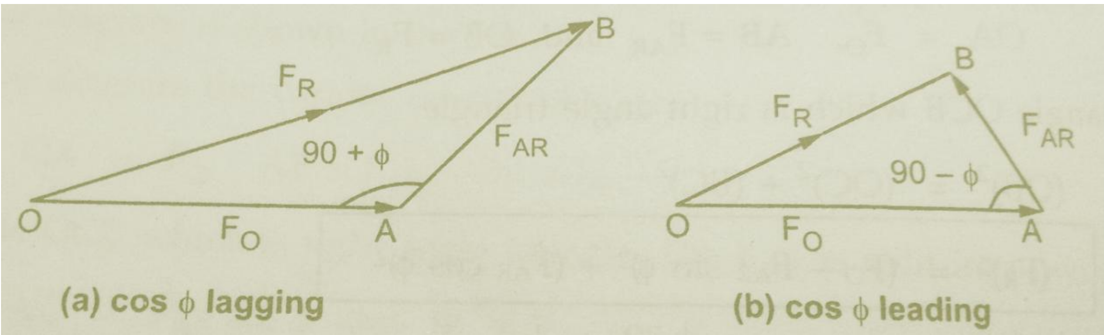


Fig. 15. Phasor diagram

Using cosine rule to triangle OAB,

$(F_R)^2 = (F_O)^2 + (F_{AR})^2 - 2\, F_O\, F_{AR}\, \text{Cos}\,(F_O,F_{AR})$, $(F_O,F_{AR}))=90 + \Phi$. if Φ is lagging

$= 90 - \Phi$ if Φ is leading.

Once FR is known, obtain a corresponding voltage which induced EMF Eph, required to get rated terminal voltage Vph. This is possible from open circuit characteristics drawn.

Once Eph is known then the voltage regulation can be obtained as,

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

Zero Power Factor (ZPF) for regulation of alternator:

This Zero power factor (ZPF) method is used to determine the voltage regulation of synchronous generator or alternator. This method is also called Potier method. In the operation of an alternator, the armature resistance drop IRa and armature leakage reactance drop IXL are actually emf quantities while the armature reaction is basically MMF quantity. In the synchronous Impedance, all the quantities are treated as EMF quantities as against this in MMF method all are treated as MMF quantities.

Key Point: This ZPF method is based on the separation of armature leakage reactance and armature reaction effects. The armature leakage reactance XL is called Potier reactance in this method, hence ZPF method is also called Potier reactance method.

To determine armature leakage reactance and armature reaction MMF separately two tests are performed on the alternator. The two tests are

1. **Open circuit test**
2. **Zero power factor test**

1.Open circuit test:

The below is the block diagram to perform open circuit test on the alternator.

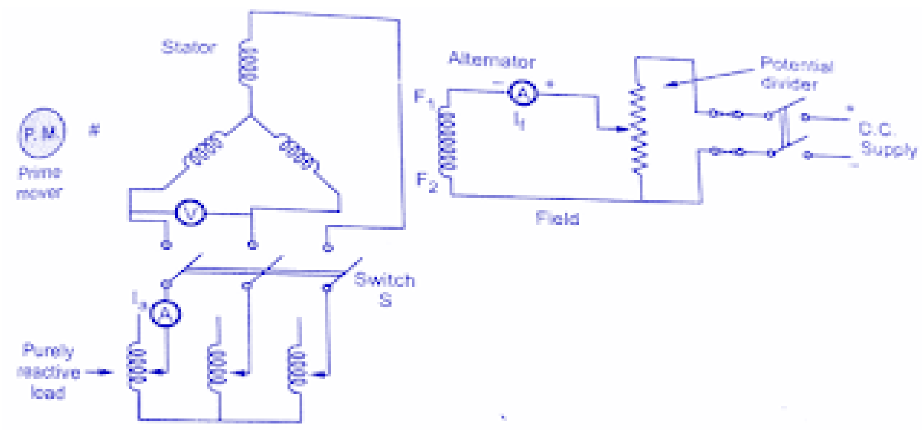


Fig. 16. Open circuit test

Open circuit test is done step by step from the following points,

1. The switch S is opened.

2. The alternator is made to rotate using prime mover at synchronous speed and same speed is maintained constant throughout the test.

3. The excitation value is changed using a potential divider, from zero up to the rated value in a definite number of steps. The open circuit EMF is measured with the help of voltmeter. The readings are tabulated.

4. A graph of If and (Voc)ph i.e. field current and open circuit voltage per phase is plotted to some scale. This is open circuit characteristics.

2.Zero power factor test:

To conduct ***zero power factor test,*** **the switch S is kept closed. Due to this, a purely inductive load gets connected to an alternator through an ammeter. A purely inductive load has a power factor of cos 90° i.e. zero lagging hence the test is called zero power factor test.**

The machine speed is maintained constant at its synchronous value. The load current delivered by an alternator to purely inductive load is maintained constant at its rated full load value by varying excitation and by adjusting variable inductance of the inductive bad. Note that, due to purely inductive load, an alternator will always operate at zero power factor lagging.

Key Point: ***In this test, there is no need to obtain a number of points to obtain the curve. Only two points are enough to construct a curve called zero power factor saturation curve.***

The below is the graph of terminal voltage against excitation when delivering full load zero power factor current. One point for this curve is zero terminal voltage (short circuit condition) and the field current required to deliver full load short circuit armature current. While other point field current required to obtain rated terminal voltage while delivering rated full load armature current. With the help of these two points, the zero power factor saturation curve can be obtained as

1. Plot open circuit characteristics on a graph paper as shown in the below figure.

2. Plot the excitation corresponding to zero terminal voltage i.e. short circuit full zero power factor armature current. This point is shown as A in the below figure which the

x-axis. Another point is the rated voltage when the alternator is delivering full current at zero p.f. lagging. This point is P as shown in the below figure

-

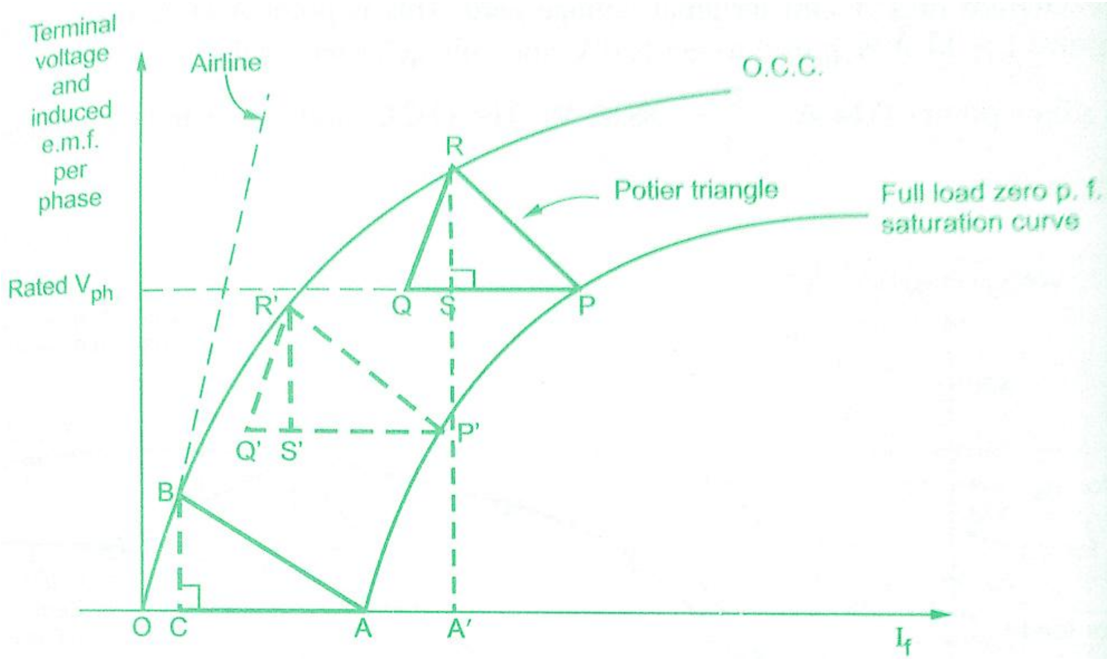


Fig. 17. ZPF method

3. Draw the tangent to O.C.C. through origin which is line OB as shown dotted in below figure. This is called the airline.

4. Draw the horizontal line PQ parallel and equal to OA.

5. From the point, Q draw the line parallel to the airline which intersects O.C.C. at point R. Join RQ and join PR. The triangle PQR is called Potier triangle.

6. From point R, drop a perpendicular on PQ to meet at point S.

7. The zero power factor full load saturation curve is now be constructed by moving triangle PQR so that R remains always on OCC and line PQ always remains horizontal. The dotted triangle is shown in the above figure. It must be noted that the Potier triangle once obtained is constant for a given armature current and hence can be transferred as it is.

8.Though point A, draw a line parallel to PR meeting OCC at point B. From B, draw a perpendicular on OA to meet it at point C. Triangles OAB and PQR are similar triangles.

9. The perpendicular RS gives the voltage drop due to the armature leakage reactance i.e. IXL

10. The length PS gives field current necessary to overcome the demagnetising effect of armature reaction at full load.

11. The length SQ represents field current required to induce an EMF for balancing leakage reactance drop RS. These values can be obtained from any Potier triangle such as OAB, PQR and so on.

So armature leakage reactance can be obtained as,

$$l\,(RS) = l\,(BC) = (I_{aph})_{F.L.} \times X_{L\,ph}$$

$$X_{L\,ph} = \frac{l\,(RS) \text{ or } l(BC)}{(I_{aph})\ F.L.}\quad \Omega$$

This is nothing but the Potier reactance.

Use of Potier reactance to determine regulation of alternator:

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

1. Draw the rated terminal voltage Vph as a reference phasor. Depending upon at which power factor (cos Φ) the regulation is to be predicted, draw the Current phasor Iph lagging or leading Vph by angle Φ.

2. Draw Iph Raph voltage drop to Vph which is in phase with Iph. While the voltage drop Iph XLph is to be drawn perpendicular to Iph Raph, vector but leading Iph Raph at the extremity of Vph.

3. The Rph is to be measured separately by passing a d.c current and measuring the voltage across armature winding. While XLph is *Potier reactance* obtained by Potier method

Phasor sum of V_{ph} rated, I_{ph} Ra_{ph} and I_{ph} XL_{ph} gives the e.m.f. which is say E1ph.

$$E1_{ph} = V_{ph} + I_{ph} Ra_{ph} + Iph\ XL_{ph}$$

4. Obtain the excitation corresponding to E1ph from OCC which is drawn. Let this excitation be Ff1. This is excitation required for inducing EMF which does not consider the effect of armature reaction.

5. The field current required to balance armature reaction can be obtained from Potier triangle method, which is say FAR.

$$F_{AR} = I\ (PS) = I\ (AC)\ ....$$

6. The total excitation required is the vector sum of the F_{f1} and F_{AR}. This can be obtained exactly similar to the procedure used in <u>MMF method</u>.

7. Draw vector F_{f1} to some scale, leading E1ph by 90°. Add F_{AR} to F_{f1} by drawing vector F_{AR} in phase opposition to Iph. The total excitation to be supplied by field is given by F_R.

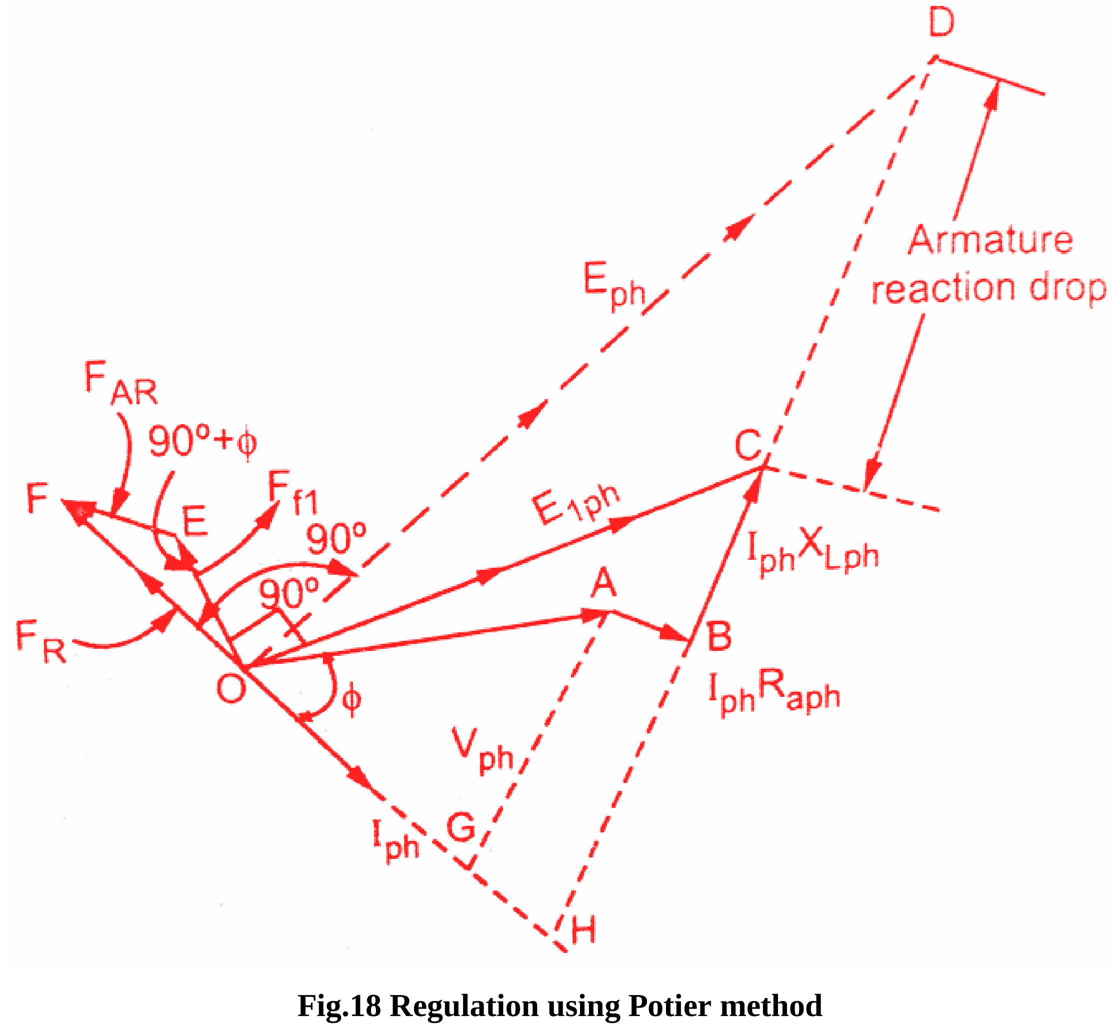


Fig.18 Regulation using Potier method

Once the total excitation is known which is F_R, the corresponding induced emf Eph can be obtained from OCC. This Eph lags F_R by 90°. The length CD drops due to the armature reaction. Drawing perpendicular from A and B on current phasor meeting at points G and H respectively, we get triangle OHC as right-angle triangle. Hence E1ph can be determined, analytically also. Once Eph is known, the regulation of an alternator can be predicted as,

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

ZPF method takes into consideration the armature resistance and leakage reactance voltage drops as EMF quantities and the effect of armature reaction as MMF quantity. This is the reality hence the results obtained by this method are nearer to the reality the those obtained by synchronous impedance method and ampere-turns method. The only drawback of the ZPF method is that the separate curve for every load condition is necessary to plot if Potier triangles for various load conditions are required

BLONDEL'S TWO REACTION THEORY OF SALIENT POLE MACHINE

- In a smooth cylindrical pole (Non-salient pole) the length of air gap of machine is constant. So the reluctance of air gap is constant. So the mmf of armature and field act throughout the entire air gap and so can be added vectorially.
- But in the case of a salient pole (Projected pole) machine, the length of the air gap is not uniform. So the reluctance of air gap is not constant. So the distribution of armature and field mmf in the airgap is not constant. So they cannot be added vectorially.

∴ to find the resultant mmf the blondels theory is used. According to this theory the armature current is divided into two component.

- Component of armature current along direct axis "I_d"
- Component of armature current along quadrature axis "I_q"

and the armature mmf is also divided into two components.

- Component of armature mmf along direct axis "F_d"
- Component of armature current along quadrature axis "F_q"
- The axis along the field poles is called the direct axis (or) d-axis (or) pole axis

- **The axis between the interpolar regions (or) at 90° to the d-axis is called as quadrature axis (or) q-axis.**
- **The d-axis is the axis of low reluctance.**
- **The q-axis is the axis of high reluctance.**
- **The field mmf F_f acts only along the direct axis.**

F_f produces a voltage of E_0 (or) E_{ph}.

- **But the armature mmf acts along d-axis and q-axis.**

F_d = mmf along direct axis.

F_q = mmf along quadrature axis.

I_d = armature current along direct axis.

I_q = armature current along quadrature axis.

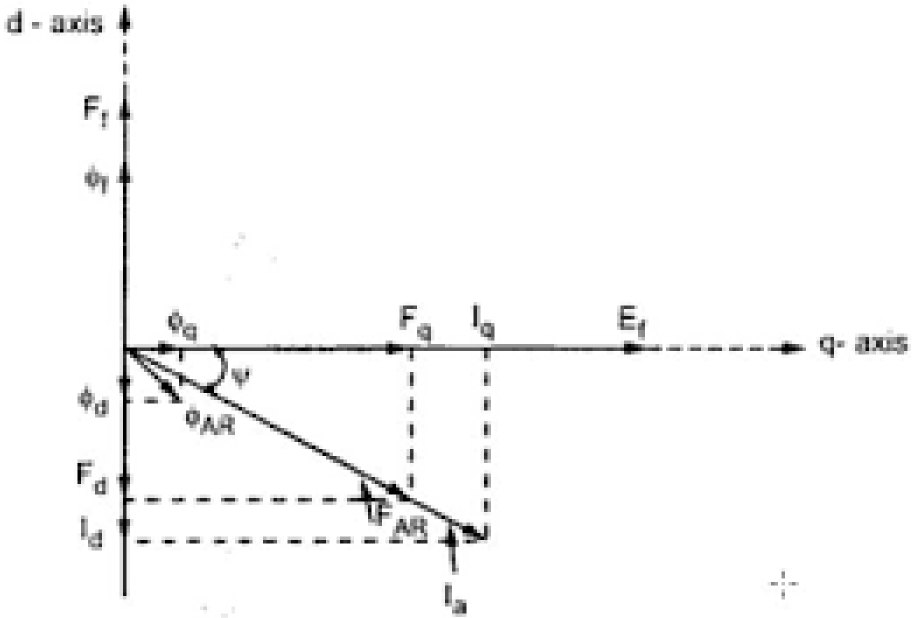


Fig.19 Two reaction Theory

- **Field mmf F_f acts along d-axis and produces a flux ϕ_f.**
- **Flux ϕ_f produces an emf E_{ph}. E_{ph} logs ϕ_f by an angle 90°.**
- **Current I_a lags E_{ph} by an angle ψ.**
- **I_a has two components**
  - → **I_d along d-axis,**
  - → **I_q along q-axis,**
- **I_d produced mmf F_d, and I_q produces mmf F_q.**
- **F_d produces flux ϕ_d; F_q gives flux ϕ_q.**

- **Resultant armature flux ϕ_{AR} is not in phase with I_a because along d-axis, reluctance is less so F_d is more, and in q axis reluctance is high so F_q is less.**

DIRECT AND QUADRATURE AXIS SYNCHRONOUS REACTANCE

Flux ϕ_{ar} has two components ϕ_d and ϕ_q

$$\text{Flux} = \frac{\text{mmf}}{\text{reluctance}} = \frac{1}{\text{reluctance}} \times \text{mmf}$$

$$\frac{1}{\text{reluctance}} = \text{Permeance} = \text{P}$$

Flux = Permeance × mmf

$\phi = P * F$

$\phi_d = P_d * F_d$

$\phi_q = P_q * F_q$

Mmf F = number of turns × current = NI (or)

armature reaction coefficient ∗ current

$F_d = K_{ar} * I_d$

$F_q = K_{ar} * I_q$

$\phi_d = P_d * K_{ar} * I_d$

$\phi_q = P_q * K_{ar} * I_q$

ϕ_d produces emf E_d which lag ϕ_d by 90°

$E_d = K_e \phi_d$ **K_e = emf constant.**

ϕ_q produces emf E_q which lags ϕ_q by 90°

$E_q = K_e \phi_q$

F_f produces a flux ϕ_f which gives an emf E_{ph}.

∴ the resultant emf is given by

$$\overrightarrow{E_R} = \overrightarrow{E_{ph}} + \overrightarrow{E_d} + \overrightarrow{E_q}$$

$$\overrightarrow{E_R} = \overrightarrow{E_{ph}} - jK_e\phi_d - jK_e\phi_q$$

$$\overrightarrow{E_R} = \overrightarrow{E_{ph}} - jK_eP_dK_{ar}I_d - jK_eP_qK_{ar}I_q$$

Let $K_eP_dK_{ar} = X_{ard}$ = component of armature reaction rectance along d-axis.

$K_eP_qK_{ar} = X_{arq}$ = component of armature reaction reactance (X_{ar}) along q-axis.

$$\overrightarrow{E_R} = \overrightarrow{E_{ph}} - jX_{ard}I_d - jX_{arq}I_q \qquad \textbf{(1)}$$

For an alternator the emf equation is

$$\overrightarrow{E_R} = \overrightarrow{V_{ph}} + \overrightarrow{I_a R_a} + j\overrightarrow{I_a X_L}$$

$$\overrightarrow{I_a} = \overrightarrow{I_d} + \overrightarrow{I_q}$$

$$\overrightarrow{E_R} = \overrightarrow{V_{ph}} + \overrightarrow{I_a R_a} + j(I_d + I_q)X_L$$

$$\overrightarrow{E_R} = \overrightarrow{V_{ph}} + \overrightarrow{I_a R_a} + j\overrightarrow{I_d}X_L + j\overrightarrow{I_q}X_L \qquad \textbf{(2)}$$

On equating (1) = (2)

$$E_{ph} - jX_{ard}\overrightarrow{I_d} - jX_{arq}\overrightarrow{I_q} = V_{ph} + \overrightarrow{I_a}R_a + j\overrightarrow{I_d}X_L + j\overrightarrow{I_q}X_L$$

$$\mathbf{E_{ph} = V_{ph} + I_aR_a + jI_dX_L + jI_qX_L + jX_{ard}I_d + jX_{arq}I_q}$$

$$\mathbf{= V_{ph} + I_aR_a + jI_d(X_L + X_{ard}) + jI_q(X_L + X_{arq})}$$

$$\mathbf{X_L + X_{ard} = X_d; \quad X_L + X_{arq} = X_q}$$

X_d = d-axis synchronous reactance.

X_q = q-axis synchronous reactance.

$$\mathbf{E_{ph} = V_{ph} + I_aR_a + jI_dX_d + jI_qX_q}$$

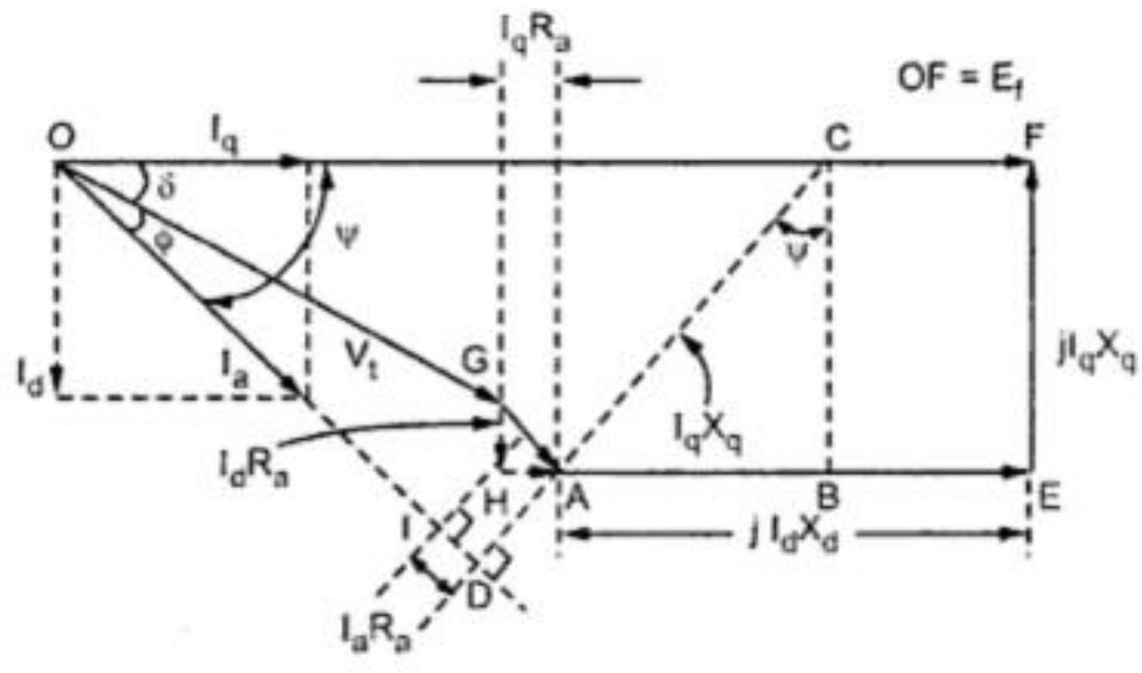


Fig.20 Direct And Quadrature Axis Synchronous Reactance

❖ **Draw the V_{ph} vector OA.**

- **For logging load I_a lags V_{ph} by an angle ϕ.**
- **I_a has two components I_d and I_q.**
- **I_aR_a drop is in phase with I_a; AB = I_aR_a.**
- **I_dX_d is at 90° to I_d. BC = I_dX_d**
- **I_qX_q is at 90° to I_q. CD = I_qX_q**
- **$E_{ph} = V_{ph} + I_aR_a + I_dX_d + I_qX_q$**
- **Join OD to get E_{ph}; OD = E_{ph}**
- **Angle b/w E_{ph} & V_{ph} is δ; Angle b/w E_{ph} and I_a is θ**
- **From phasor diagram I_a has two components I_d & I_q**

  $I_d = I_a \sin\theta$

  $I_q = I_a \cos\theta$

  $$\cos\theta = \frac{I_q}{I_a} \qquad (1)$$

- **The I_aR_a drop represented by AB can be resolved into two components I_dR_a and I_qR_a; AE = I_dR_a; EB = I_qR_a.**
- **From A drop a perpendicular to OD to meet at point F**
- **From B drop a perpendicular to OD to meet at point G**

  $$FG = EB = I_qR_a \qquad (2)$$

- **Extend the current vector I_a**
- **Draw a perpendicular HBI to the vector I_a**
- **From I drop a perpendicular to BC to meet at K**
- **In triangle BIK;**

  $$\cos\theta = \frac{IK}{BI} = \frac{I_qX_q}{BI}$$

  $IK = CD = I_qX_q$

  $$BI = \frac{I_qX_q}{\cos\theta} \qquad \cos\theta = \frac{I_q}{I_a}$$

  $$BI = \frac{I_qX_q}{\frac{I_q}{I_a}} = \frac{I_qX_q}{I_q} \times I_a = I_aX_q$$

  $$BI = I_aX_q \qquad (3)$$

In right angled triangle OHI

$$\tan\theta = \frac{HI}{OH}$$

HI = HB + BI

HB = AJ; In triangle OAJ AJ = V_{ph} sin ϕ, OJ = V_{ph} cos ϕ

HB = AJ = V_{ph} sin ϕ

BI = OJ + JH

JH = AB = I_aR_a

$$\tan\theta = \frac{HI}{OH} = \frac{HB+BI}{OJ+JH} = \frac{V_{ph}\sin\phi + I_aX_q}{V_{ph}\cos\phi + I_aR_a}$$

$$\theta = \tan^{-1}\left(\frac{V_{ph}\sin\phi + I_aX_q}{V_{ph}\cos\phi + I_aR_a}\right)$$

General formula $\theta = \tan^{-1}\left(\frac{V_{ph}\sin\phi \pm I_aX_q}{V_{ph}\cos\phi \pm I_aR_a}\right)$ **+ lag, – lead**

$\theta = \phi \pm \delta$ **+ for lag** $\Rightarrow \theta = \phi + \delta$

– for lead $\Rightarrow \theta = \phi - \delta$

For lag $\theta = \phi + \delta$

$\delta = \theta - \phi$

For lead $\theta = \phi - \delta$

$\delta = \phi - \theta$

From phasor E_{ph} = OD = OF + FG + GD

In triangle OAF; OF = V_{ph} cos δ

FG = I_qR_a; GD = BC = I_dX_d

E_{ph} = V_{ph} cos δ + I_qR_a + I_dX_d

General formula E_{ph} = V_{ph} cos $\delta \pm I_qR_a \pm I_dX_d$

$$Reg = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

SYNCHRONISATION OF ALTERNATOR

- **Synchronization is the process of connecting two alternators in parallel without any interruption.**

  (or)

- **It can also be defined as the process of connecting an alternator with a common bus bar.**
- **The bus bar to which the alternators are connected for parallel operation is called as an Infinite bus bar.**
- **An infinite bus bar is one which has constant frequency and constant voltage, and remains unaffected by changes in condition of any one of the machine connected to it.**

Need for synchronization

- **Local (or) regional power use may exceed the power of a single available alternator**
- **When alternators are in parallel, one or more alternators can be shut down for emergency maintenance without interruption of power to load**
- **Increased load can be supplied by adding machines without disturbing the original installation.**

Conditions for synchronization

- **The terminal voltage of the m/e's to be synchronized must be equal**
- **Frequency of both m/c must be same**
- **Phase sequence of the voltages must be same**

Synchronisation of single phase alternator

(a) Lamps dark method

(b) Lamps bright method

(a) ***Lamps dark method***

- **The voltage of both the machine is measured by the voltmeter. If the voltage of m/c 2 is not equal to m/c 1 then the field of alternator 2 in varied to make the two voltages equal.**
- **The lamps L1, L2 are connected in such a way so as to check the polarity and frequency of m/c.**
- **If the frequency of both the alternators are same and if the voltages are in phase opposition, the resultant voltage across the switch terminals is zero. So the lamps will not glow. It is shown by the waveform given below.**

- If the frequency of both m/c's are not equal, then a resultant voltage will appear across the switch terminals, which will be the difference b/w vges V_1 and V_2.
- Now the lamps will become alternately bright and dark.
- It can be seen that with unequal frequencies of two alternators a light beat is produced whose number is equal to difference in frequencies of the two m/c. So by adjusting speed the frequencies are made equal.
- So now when the vges are in phase opposition and with equal frequency and voltage the lamps willl glow dark. At this instant the alt_2 should be connected to alt_1 by closing the switch.

(b) ***Lamps bright method***

- In this method the lamps are cross connected.
- So when the vges are equal and in phase opposition and when frequency is equal the lamps will glow bright.
- And the alternator is synchronized in the instant when both the lamps are bright.

Synchronization of 30 Alternator

(a) Lamps dark and bright method

(b) Synchroscope method

(a) ***Lamps dark and bright method***

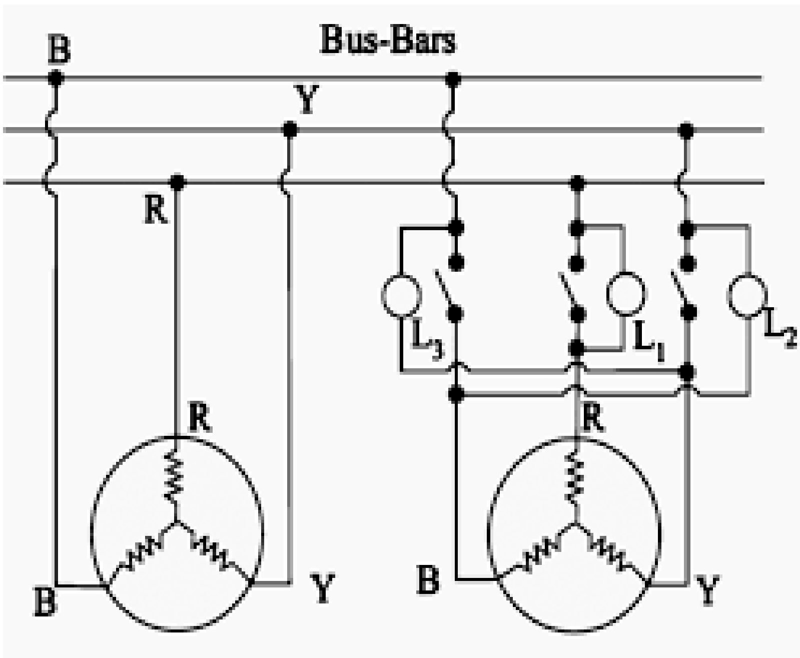


Fig.21 Lamps dark and bright method

- **Here alternator 2 is to be synchronized with alternator 1**
- **The circuit connection is shown in figure. Alt 1 and 2 are run by two separate prime movers.**
- **In alt 2, lamp L_1 is direct connected, whereas lamp L_2, L_3 are cross connected.**
- **Turn on alt 2. By means of the prime mover connected to alt 2, run the alternator close to synchronous speed.**
- **Now measure the Vge across both alternators.**
- **If the voltages are not equal then adjust the field excitation of alternator 2 and make $V_1 = V_2$.**
- **If the frequency of the alternators are not equal then the lamps will glow alternately dark and bright in a sequence. This sequence will tell if the speed (frequency) N & f of the m/c has to be increased or decreased.**
- **If the sequence is L_1, L_2, L_3 it means the speed of all 2 in higher than alternator 1 [(or) freq. of alternator 2 in higher than freq. of alt 1] so the speed of alt 2 has to be reduced till lamp L_1 in dark and L_2 and L_3 are bright. Speed in varied by adjusting the speed of prime mover connected to alt 2.**
- **If the sequences is L_1, L_3, L_2 it means alt 2 in running at speed lesser than alt 1 (freq. of alternator 2 in < freq. of alternator 1). So the speed of alt 1 has to be increased. This is done by adjusting speed of the prime mover connected to alt 1.**

Now when lamp L_1 is dark and lamp L_1, L_3 is bright then the voltage, frequency and phase sequence are same and then the switch S is closed and alt 2 in synchronized with alt 1.

(b) Synchroscope method

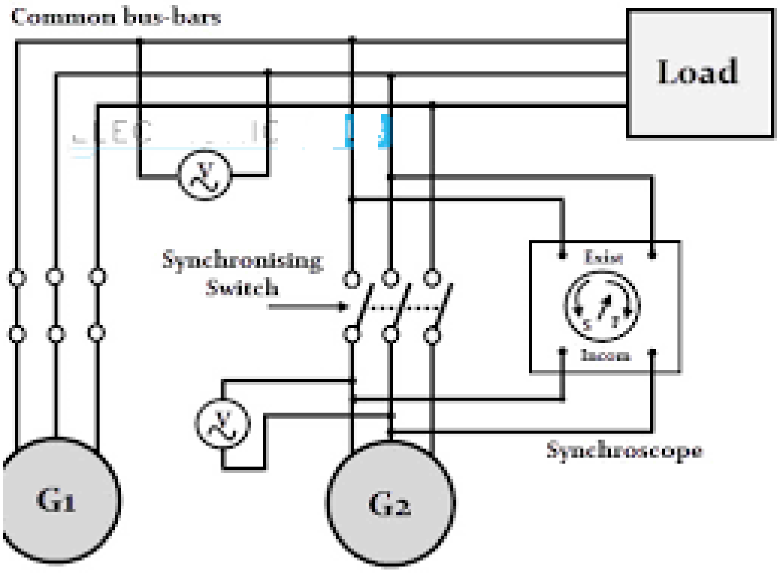


Fig.22 Synchroscope method

- ❖ **In the previous method it is very difficult to judge the speed by the darkness and brightness of lamps**
- ❖ **So a device called a synchroscope is used. It has a row marked slow and fast.**
- ❖ **If the arrow moves anti clockwise it means speed of alt 2 in higher than alt 1. So reduce speed of alt 2.**
- ❖ **If the arrow moves clockwise it means speed of alt 2 in slow that alt 1. So speed of alternator 2 has to be increased.**
- ❖ **Voltage is checked by voltmeter.**
- ❖ **Phase sequence is checked by phase sequence meter.**

When all values are equal the alternator 2 is connected to alternator 1.

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SCHOOL OF ELECTRICAL & ELECTRONICS ENGINEERING
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT - II
AC Machines – SEEA1303

II SYNCHRONOUS MOTORS

Principle of Operation - Starting Methods - Effect of Increased Load with Constant Excitation - Effect of Changing Excitation on Constant Load - Different Torque - Power flow equation - Phasor diagram - V and inverted V curves - Hunting and suppression methods.

- **Synchronous motor is a device which converts electrical energy to mechanical energy by running at synchronous speed.**
- **It is similar in construction to that of an alternator, but in synchronous motor 30 ac supply is given to the stator coinding.**

Characteristics of synchronous motor

- **Synchronous motor runs either at synchronous speed or not at all. The speed can be changed only by changing frequency.**
- **It is not inherently self starting. It has to be run upto synchronous (or) near synchronous speed by some means.**
- **It can operate under a wide range of power factors both lagging and leading.**
- **When the motor is overloaded it will stop.**

Advantages of synchronous motor

- **These motors can be used for power factor correction in addition to supplying torque to drives.**
- **They are more efficient than induction motor.**
- **They give constant speed from no load to full load.**
- **Electromagnetic power varies linearly with voltage.**

Disadvantages of synchronous motor

- **They require dc excitation.**
- **They have tendency to hunt.**
- **They cannot be used for variable speed jobs as speed adjustments cannot be done.**
- **They require collector rings and brushes.**
- **They cannot be started under load. Their starting torque is zero.**
- **They may fall out of synchronism and stop when overloaded.**

ROTATING MAGNETIC FIELD (RMF)

- **In order to know the working of synchronous motor it is necessary that we know how a rotating magnetic field is produced in a stationary winding.**
- **The rotating magnetic field is defined as a field or flux having constant magnitude, but whose axis rotates in plane at a certain speed called synchronous speed.**
- **RMF can be produced in two ways**
  - → **By physically rotating the field winding**
  - → **By giving a 30 AC supply to a stationary 30 wdg**

Let us see how a RMF is produced in a stationary 30 armature winding when 30 ac supply is given to it.

Production of RMF

- **The three phase stationary armature windings are R, Y, B. The three phase windings are displaced from each other by an angle of 120°.**
- **When 30 supply is given to the 30 winding current flows through all the 3 phases which also be displaced in space by 120°. The 30 currents will be I_R; I_Y; I_B. If phase sequence is RYB, then**

  $I_R = I_m \sin\theta$ **(I_m = max value of current)**

  $I_Y = I_m \sin(\theta - 120)$

  $I_B = I_m \sin(\theta - 240)$

- **These currents produces flux in all these windings which will be in phase with currents. They will also be displaced from each other by an angle of 120°.**

  $\phi_R = \phi_m \sin\theta$

  $\phi_Y = \phi_m \sin(\theta - 120)$

  $\phi_B = \phi_m \sin(\theta - 240)$

  ϕ_m **= max value of flux**

  Total flux $\overrightarrow{\phi_T} = \overrightarrow{\phi_R} + \overrightarrow{\phi_Y} + \overrightarrow{\phi_B}$.

- **The waveforms for the 3 fluxes can be drawn as follows. In sequence RYB; ϕ_R starts first; ϕ_Y starts 120° after ϕ_R; ϕ_B starts 240° after ϕ_R.**
- **We know that the resultant flux** $\overrightarrow{\phi_T} = \overrightarrow{\phi_R} + \overrightarrow{\phi_Y} + \overrightarrow{\phi_B}$.

  Let us find the value of flux at position 1, 2, 3, 4 is at θ = 0°, 60°, 120° and 180°.

At position 1; when $\theta = 0$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 0 = 0$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(0 - 120) = -0.866\ \phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(0 - 240) = 0.866\ \phi_m$

Now representing them in vector.

- **Resultant ϕ_T = OC.**
- **From A drop a perpendicular bisector "AD" to OC.**

$$OD = DC = \frac{\phi_T}{2}.$$

In triangle OAD; $\cos 30^\circ = \frac{OD}{OA} = \frac{\frac{\phi_T}{2}}{0.866\ \phi_m}$

$$0.866 = \frac{\phi_T}{2 \times 0.866\ \phi_m}$$

$\phi_T = 1.5\ \phi_m$

Magnitude is 1.5 ϕ_m and is pointed vertically upwards.

At position 2; when $\theta = 60^o$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 60 = 0.866\ \phi_m$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(60 - 120) = -0.866\ \phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(60 - 240) = 0$

On representing in vector.

- **Resultant ϕ_T = OC.**
- **From A drop a perpendicular bisector "AD" to OC.**

$$OD = DC = \frac{\phi_T}{2}.$$

In triangle OAD; $\cos 30^\circ = \frac{OD}{OA} = \frac{\frac{\phi_T}{2}}{0.866\ \phi_m}$

$$0.866 = \frac{\phi_T}{2 \times 0.866\ \phi_m}$$

$\phi_T = 1.5\ \phi_m$

So magnitude is 1.5 ϕ_m, but the vector is rotated in space from the initial position by an angle of 60°.

At position 3; when $\theta = 120°$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 120 = 0.866\ \phi_m$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(120 - 120) = 0$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(120 - 240) = -0.866\ \phi_m$

- **Resultant ϕ_T = OC.**
- **From A drop a perpendicular bisector "AD" to OC.**

$$OD = DC = \frac{\phi_T}{2}.$$

In triangle OAD; $\cos 30^\circ = \frac{OD}{OA} = \frac{\frac{\phi_T}{2}}{0.866\ \phi_m}$

$\phi_T = 1.5\ \phi_m$

Magnitude is 1.5 ϕ_m, but the vector is rotated again in space by 60°.

At position 4; when $\theta = 180°$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 180 = 0$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(180 - 120) = 0.866\ \phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(180 - 240) = -0.866\ \phi_m$

- **Resultant ϕ_T = OC.**
- **From A drop a perpendicular bisector "AD" to OC.**

$$OD = DC = \frac{\phi_T}{2}.$$

In triangle OAD; $\cos 30^\circ = \frac{OD}{OA} = \frac{\frac{\phi_T}{2}}{0.866\ \phi_m}$

$\phi_T = 1.5\ \phi_m$

Magnitude is 1.5 ϕ_m, but the vector is rotated again in space by 60°.

It is seen from all the four states that the magnitude of resultant flux is constant, but it keeps rotating in space. The speed at which this flux is rotating is synchronous speed = $N_s = \frac{120f}{P}$.

CONSTRUCTION OF SYNCHRONOUS MOTOR

- **The essential parts of a 30 synchronous motor are**
  - **(i) Laminated stator core with 30 armature winding.**
  - **(ii) Rotating field structure complete with damper windings and slip rings.**
  - **(iii) Brushes and brush holders.**
  - **(iv) Two end shields to house the bearings that support the shaft.**
- **The stator core and wdgs of a synchronous motor are similar to that of a 30 squirrel cage induction motor.**
- **Stator windings terminate in a terminal box mounted on the motor frame.**
- **Rotor is salient pole type.**
- **Number of rotor field poles must be equal to number of states field poles.**
- **Field circuit leads are connected to two slip rings.**
- **To eliminate hunting and to develop necessary starting torque, rotor poles contain pole face conductors which are short circuited at their ends and are called as "squirrel cage windings" (or) "damper windings" (or) "amortisseur windings", which consist of solid copper bars that are short circuited at each end by means of a shorting trip.**

Principle of Operation

- **Let us consider a synchronous motor, whose rotor has two poles and stator has two poles per phase.**
- **The rotor has salient poles and armature conductors are placed in slots.**
- **Rotor is connected to dc supply. So rotor poles retain same polarity.**
- **Stator is connected to ac supply and so its polarity keep changing.**
- **Let us consider that initially the rotor is stationary in the position shown in fig.**
- **In this position, the rotor S-pole is attracted to stator N-pole and so rotor rotates in clockwise direction.**
- **After half a period, polarity of stator pole is reversed, but polarity of rotor pole remains the same as shown in fig.**

- **In this position the rotor S-pose is repelled by the stator S-pole and rotor rotates in anti clockwise direction.**
- **So torque acting on the rotor of a synchronous moto is not unidirectional but pulsating and due to inertia of rotor it will not move in any direction.**
- **So the synchronous motor has no self starting torque. This is the reason why the synchronous motor is not self starting.**
- **Now let us consider the rotor to be rotating in clockwise direction, which is done by external means and is in position shown in fig.**
- **At this instant torque acting on the rotor is in clockwise direction.**
- **After half a period the stator polarity is reversed. But if the rotor is rotated at such a speed by some external means at the starting moment, so that the rotor S-pole advances a pole pitch so that it is again under the influence of stator N-pole as shown in fig. The torque acting on the rotor will be again clockwise.**
- **Hence a continuous (unidirectional) torque will be obtained. Now if the external means is removed, the rotor will continue to rotate in clockwise direction under the influence of clockwise continuous torque acting on the rotor. Hence a magnitude locking is produces between the rotor and staro poles. So the rotor will also rotate at the speed as that of the RMF of stator.**

  $\therefore$ **rotor rotates at synchronous speed** $N_s = \frac{120 * f}{P}$.

METHODS OF STARTING A SYNCHRONOUS MOTOR

Synchronous motor has no self starting torque. The following methods of starting are employed.

(i) Using small dc motors.
(ii) Using AC motors (or) pony motors.
(iii) Using damper winding in the pole faces.
(iv) Running as a slip ring induction motor.

(i) ***Using small dc motors***

The synchronous motors are coupled to dc motors. With the help of dc motor the synchronous motor is run at synchronous speed. The synchronous motor is excited by a dc source. Once the synchronous motor runs at synchronous speed the dc machine

acts as a dc generator and is called as an exciter. The exciter provides dc supply to the field of synchronous motor.

(ii) ***Using ac motors (or) pony motors***

- **A small direct coupled induction motor AC motor called the pony motor is used for starting the synchronous motor. The induction motor is capable of raising the speed of synchronous motor to synchronous speed.**
- **Once the motor attains synchronous speed the dc excitation is given to the rotor. After normal operation is established the pony motor is sometimes uncoupled from the synchronous motor.**

(iii) ***Using damper windings in the pole faces***

- **The synchronous motor is made self starting by providing a special winding on the rotor poles known as "damper winding" (or) "squirrel cage winding" (or) "amortissuer winding".**
- **The damper windings consist of short circuited copper bars embedded in the face of the field poles. When ac supply is given to the stator winding a rotating magnetic field is produced, which is cut by the stationary rotor poles. So an emf is induced in the rotor, due to which a current flows in the damper windings.**
- **Now we have a current carrying damper coinciding (placed in the poles) in a rotating (RMF) magnetic filed. $\therefore$ the rotor experiences a force and starts to rotate.**
- **Synchronous motor is started as induction motor and when it attains 95% of synchronous speed, the rotor winding is exciting and rotor is magnetically locked with RMF of stator and so it runs at synchronous speed.**
- **Damper windings are short circuited, they draw high current at instant of starting. So star-delta starter or auto transformer is used to start synchronous motor as an induction motor.**

(iv) ***As a slip ring induction motor***

- **Starting a synchronous motor as squirrel cage induction motor does not provide high starting torque.**
- **So, for achieving high starting torque, the synchronous motor is started as a slip ring induction motor.**

- **Here the damper winding is constructed as a 30, star (or) delta winding. They are connected in serves to external rheostats by means of slip rings. The rheostats are maintained at maximum position at the instant of starting. Now, the synchronous motor is started as a slip ring induction motor and hence provides high starting torque.**
- **The resistance is gradually cut off as the motor gains speed. When motor attains 95% of synchronous speed, the dc excitation is given to the rotor windings. Now a magnetic locking is established between the stator & rotor and so the rotor runs at synchronous speed. Now the damper windings are shorted by short circuiting the slip rings.**

EFFECT OF LOAD ON A SYNCHRONOUS MOTOR

- **When the motor is on no load the positions of stator and rotor pole is as shown in fig.**
- **At this condition the induced emf is equal to applied voltage.**

Generally $V_{ph} = E_b + I_aZ_S$

- **At no load the motor in take is zero, so the loss I_aZ_S is zero. $\therefore$ $V_{ph} = E_b$.**

[E_b is opposite to V according to lenzs law]

- **Now when the motor is loaded, it shows down momentarily to adjust itself to the change in load conditions. So the rotor poles fall back from the stator poles by an angle "δ" as shown in fig.**
- **δ is called as torque angle, load angle, coupling angle (or) angle of retardation.**
- **The magnetic locking will be still existing between stator and rotor poles, but the magnetic flux lines will be stretched due to the load angle δ.**
- **Now through $E_b = V_{ph}$; E_b will not be in exact phase opposition to each other. But the emf E_b will be displaced by an angle "δ" from its initial position.**

The vector difference between $\overrightarrow{V_{ph}}$ and $\overrightarrow{E_b}$ is resultant $\overrightarrow{E_R}$

$$\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b} = \overrightarrow{I_a Z_S}$$

The load angle δ increases with increase in load.

SYNCHRONOUS MOTOR ON LOAD

(i) ***Operation of synchronous motor at variable load and constant E_b***

- **As the load on the motor increases, the load angle "δ" increases. As "δ" increases, though magnitude of E_b and V are constant, the displacement of E_b from initial position increases.**
- **Resultant vector** $\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b} = \overrightarrow{I_a Z_S}$ $\quad (\because \overrightarrow{V_{ph}} = \overrightarrow{E_b} + \overrightarrow{I_a Z_S})$

  the vector difference between $\overrightarrow{V_{ph}}$ **and** $\overrightarrow{E_b}$ **increases. E_R increases, which means $I_a Z_S$ increases. Since Z_S is constant I_a increases as a result of increase in E_R.**

Let us see the vector representation at light load and a heavy load.

At light load

- **V = E_b**
- **when load is light δ is small**
- **E_b is displaced by δ**
- $\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b}$
- **Resultant current is I_a at an angle of θ from E_R.**
- **Angle between V & I_a = ϕ**

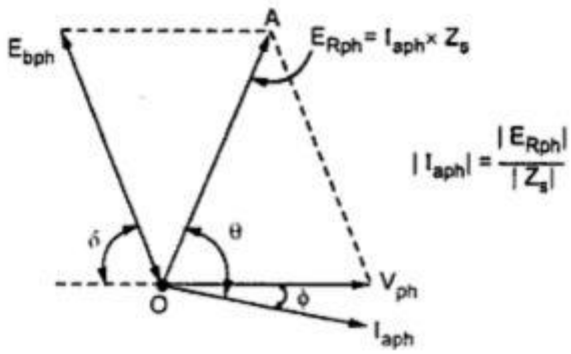

Fig. 1 Synchronous Motor On Load

At heavy load

- **At heavy load the angle δ is also large.**
- **E_b is again displaced by the angle δ.**
- **Now** $\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b}$ **.** $\overrightarrow{E_R}$ **now moves towards V.** $\overrightarrow{E_R}$ **increases.**
- **So the current I_a also increases and angle between V and I_a also increases.**

Constant excitation circle

For constant excitation, when the load is varied then δ keeps changing, due to which $\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b} = \overrightarrow{I_a Z_S}$ keeps changing. The locus (path) of $\overrightarrow{E_R} = \overrightarrow{I_a Z_S}$ is a circle. As δ increases I_a increases and as δ decreases I_a decreases.

(ii) ***Operation of synchronous motor at constant load variable excitation***

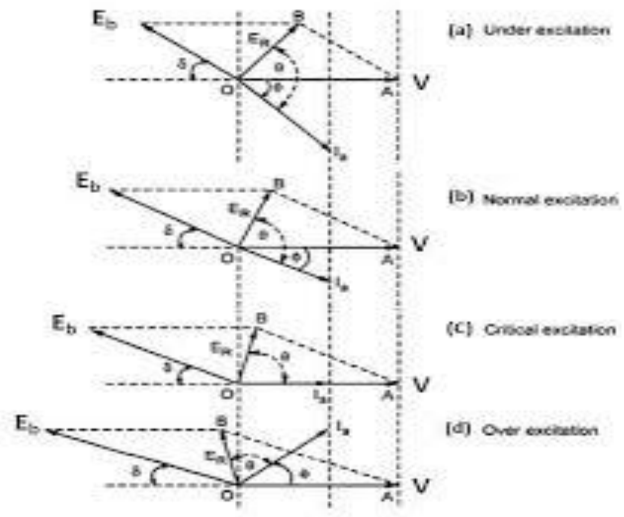

Fig. 2 C*onstant load variable excitation*

- When the load changes for constant excitation, the current drawn by motor increases.
- But when the field is varied by keeping the load constant, the current is constant. So the motor reacts by changing its power factor.
- The change in field excitation, changes only the value of E_b. Since the load is constant, the power remains constant for the same load.

$P_{in} = \sqrt{3} V_L I_L \cos \phi = 3\, V_{ph}\, I_a \cos \phi$

for constant load Pin is constant. Voltage V_{ph} is constant, $I_a \cos \phi$ remains constant for constant power.

- The operation of synchronous motor can be studied under different values of excitation.

(i) ***Normal excitation ($E_b = V_{ph}$)***

- An excitation in which the applied voltage is equal to back emf is called as normal excitation.
- At normal excitation $E_b = V_{ph}$

❖ **The phases diagram is as shown in fig.** $\overrightarrow{E_R} = \overrightarrow{V_{ph}} - \overrightarrow{E_b} = \overrightarrow{I_a Z_S}$ **.** $\overrightarrow{I_a}$ **lags** $\overrightarrow{E_R}$ **by an angle θ angle between V_{ph} & I_a is ϕ.**

(ii) ***Under excitation ($E_b < V_{ph}$)***

❖ **When the excitation is adjusted in such a way that the magnitude of induced emf (E_b) is less than applied Voltage (V) (i.e., $E_b < V_{ph}$), it is called as under excitation.**

E_R increases ($E_R = V_{ph} – E_b$). $E_R = I_a Z_S$. I_a also increases since Z_S is constant. I_a cos ϕ is constant for constant power, the increase in I_a causes cos ϕ to decrease to maintain I_a cos ϕ constant. cos ϕ decreases, ϕ increases. [E_R shifts, so I_a also shifts].

at under exciation the current drawn by the motor increases for the same load and the power factor is lagging.

(iii) ***Over excitation ($E_b > V_{ph}$)***

❖ **The excitation at which E_b is greater than V is called as over excitation.**

❖ **$E_b > V_{ph}$; E_R increases but in the opposite phase.**

I_a also changes its phase. Now the current I_a leads V by an angle ϕ as shown in fig. ϕ changes and so I_a changes to keep I_a cos ϕ constant.

(iv) ***Critical excitation***

❖ **The excitation at which the power factor of the motor is unity is called as critical excitation. At UPF angle b/w V_{ph} & I_a. i.e., ϕ = 0 (or) V and I_a are in phase. cos ϕ = 1. I_a decreases to maintain I_a cos ϕ as constant. At UPF the current drawn is minimum.**

V Curve of a Synchronous Motor

V curve is a plot of the stator current versus field current for different constant loads. The Graph plotted between the armature current I_a and field current I_f at no load the curve is obtained known as V Curve. Since the shape of these curves is similar to the letter "V", thus they are called V curve of synchronous motor.

The power factor of the synchronous motor can be controlled by varying the field current I_f. As we know that the armature current I_a changes with the change in the field current I_f. Let us assume that the motor is running at NO load. If the field current is

increased from this small value, the armature current Ia decreases until the armature current becomes minimum. At this minimum point, the motor is operating at unity power factor. The motor operates at lagging power factor until it reaches up to this point of operation.

If now, the field current is increased further, the armature current increases and the motor start operating as a leading power factor. The graph drawn between armature current and field current is known as V curve. If this procedure is repeated for various increased loads, a family of curves is obtained.

In V curves of a synchronous motor, the point at which the unity power factor occurs is at the point where the armature current is minimum. The curve connecting the lowest points of all the V curves for various power levels is called the Unity Power Factor Compounding Curve. The compounding curves for 0.8 power factor lagging and 0.8 power factor leading are shown in the figure above by a red dotted line.

The loci of constant power factor points on the V curves are called Compounding Curves. It shows the manner in which the field current should be varied in order to maintain constant power factor under changing load. Points on the right and left of the unity power factor corresponds to the over excitation and leading current and under excitation and lagging current respectively.

The V curves are useful in adjusting the field current. Increasing the field current If beyond the level for minimum armature current results in leading power factor. Similarly decreasing the field current below the minimum armature current result results in lagging power factor. It is seen that the field current for unity power factor at full load is more than the field current for unity power factor at no load.

In the graph between power factor and field current at the different loads.it is clear that, if the synchronous motor at full load is operating at unity power factor, then removal of the shaft load causes the motor to operate at a leading power factor. Since the shape of the curves form inverted V shape,they are called inverted V curves.

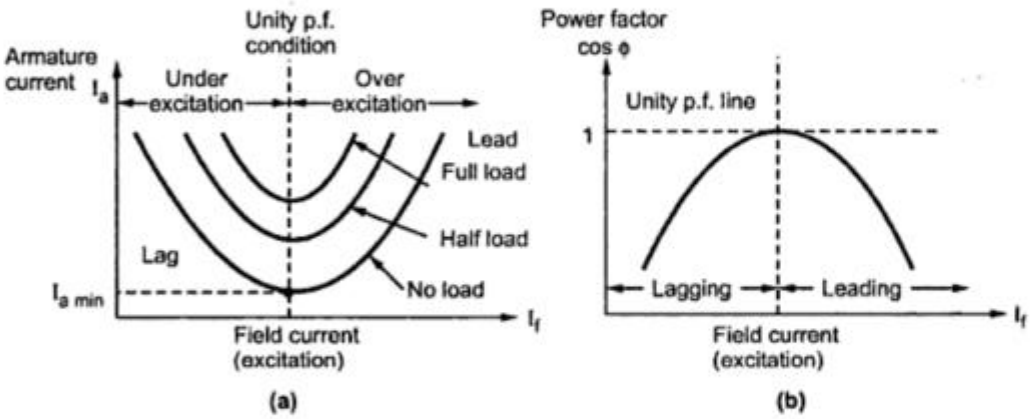

Fig.3 V and inverted V curves

Experimental set up to obtain V and inverted V curves

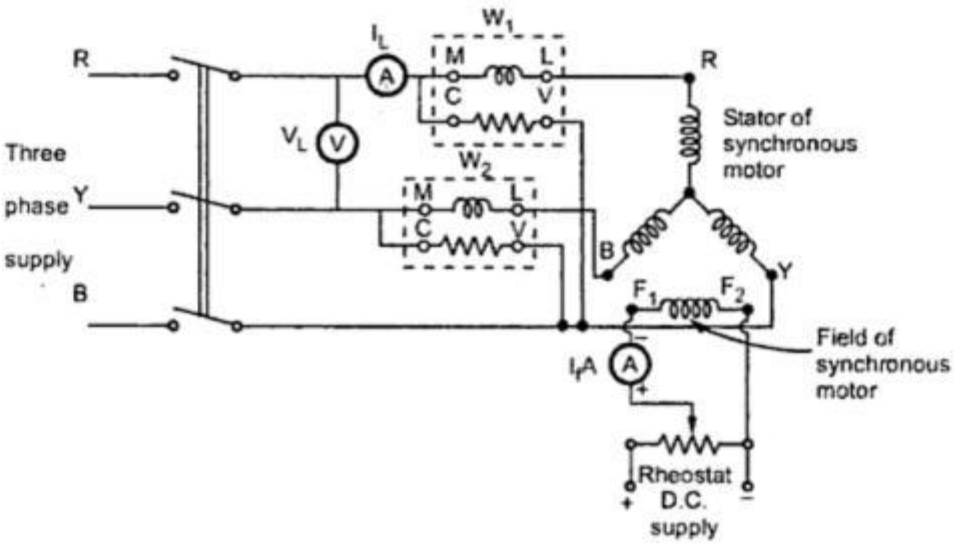

Fig.4 Experimental set up V and inverted V curves

From the previous article, it is clear that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the figure.

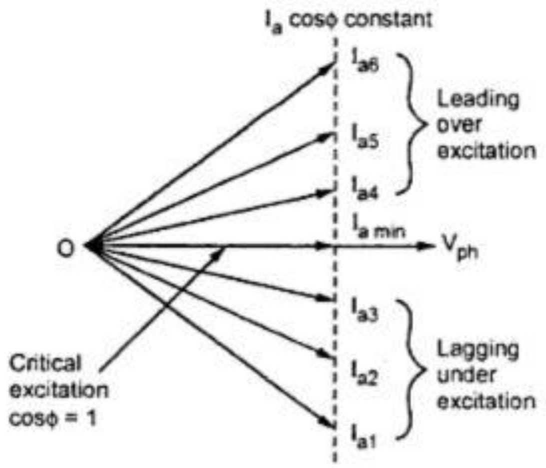

Fig.5 Various excitation conditions

Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (Ia) against field current (If) is plotted, then its shape looks like an english alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V-curves of synchronous motor..

As against this, if the power factor is plotted against field current (If), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor.

Stator is connected to three phase supply through wattmeters and ammeter. The two wattmeter method is used to measure input power of motor. The ammeter is reading line current which is same as armature (stator) current. Voltmeter is reading line voltage.

A rheostat in a potential divider arrangement is used in the field circuit. By controlling the voltage by rheostat, the field current can be changed. Hence motor can be subjected to variable excitation condition to note down the readings. The entire procedure can be repeated for various load conditions to obtain family of V-curves and Inverted V-curves.

Hunting in a Synchronous Motor

The phenomenon of oscillation of the rotor about its final equilibrium position is called Hunting. On the sudden application of load, the rotor search for its new equilibrium position and this process is known as Hunting. The Hunting process occurs in a synchronous motor as well as in synchronous generators if an abrupt change in load occurs.

The speed of the motor slows down temporarily, and the torque angle δ is sufficiently increased. This is done to restore the torque equilibrium and the synchronous speed when there is a sudden increase if the load torque.

The electromagnetic torque is given by the equation shown below.

$$T_e = \frac{3\,VE_f}{\omega_s\,X}\sin\delta \quad \dots\dots\dots(2)$$

If the value of δ is increased, the electromagnetic torque is also increased. As a result, the motor is accelerated. As the rotor reaches the synchronous speed, the torque angle δ is larger than the required value. Here the rotor speed continues to increase beyond the synchronous speed.

As the rotor accelerates above synchronous speed, the torque angle δ decreases. The point where the motor torque becomes equal to the load torque, the equilibrium is not restored because now the rotor speed is greater than the synchronous speed. Therefore, the rotor continues to swing backwards and as a result, the torque angle goes on decreasing.

When the load angle δ becomes less than the required value, the mechanical load becomes greater than the developed power. Therefore, the motor starts to slow down. The load angle starts increasing again. Thus, the rotor starts to swing or oscillates around the synchronous speed.

The motor responds to a decreasing load torque by a temporary increase in speed and a reduction of the torque angle δ. Thus, the rotor swings and rotate around the synchronous speed. Thus, this process of rotation of the rotor speed equal or around the synchronous speed is known as Hunting. Since, during the rotor oscillation, the phase of the phasor Ef changes about phasor V. Thus, hunting is known as Phase Swinging.

The various causes of hunting are as follows:-

- **Sudden changes of load.**
- **Faults were occurring in the system which the generator supplies.**
- **Sudden change in the field current.**
- **Cyclic variations of the load torque.**

Effect of Hunting

The various effects of hunting are as follows:-

- **It can lead to loss of synchronism.**
- **It can cause variations of the supply voltage producing undesirable lamp flicker.**
- **The possibility of Resonance condition increases. If the frequency of the torque component becomes equal to that of the transient oscillations of the synchronous machine, resonance may take place.**
- **Large mechanical stresses may develop in the rotor shaft.**
- **The machine losses increases and the temperature of the machine rises.**

Function of Damper winding

- **The rotor oscillation may dampen out by employing damper winding in the faces of field poles of the motor.**
- **The damper winding is nothing but copper bar embedded in the rotor faces. The copper bars are short circuited at both ends.**
- **The motion of rotor sets up eddy current in the damper winding.**
- **The direction of this eddy current is such that it suppresses the rotor oscillations.**
- **The damper winding does not prevent completely oscillation but reduce to some extent.**

- **The function of the damper winding in the synchronous generator is to suppress the negative sequence field and to dampen oscillation whereas it is used to provide starting torque and reduce effect of hunting to some extent in the synchronous motor.**

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SCHOOL OF ELECTRICAL & ELECTRONICS ENGINEERING
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

UNIT - III
AC Machines – SEEA1303

III THREE PHASE INDUCTION MOTOR

Construction - Types of 3- Phase Induction Motors - Rotating Magnetic Fields - Torque Equation – Condition for Maximum Torque - Slip, Torque Slip Characteristics - Power Stages in Induction Motors - Losses and Efficiency - Plugging - Cogging and Crawling - Concept of Induction Generator.

Introduction

The induction motors are more commonly used. The conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In dc motor the electric power is given directly to the rotor of the motor through brush and commutator. Hence a dc motor is called as a conduction motor.

But in an ac motor, rotor does not receive electric power by conduction, but by induction in exactly the same way as the secondary of a transformer receives its power from the primary. That is why such motors are known as induction motors.

An induction motor can be treated as a rotating transformer (i.e.,) one in which primary winding is stationary but the secondary is free to rotate.

Construction of a 3ϕ induction motor

An induction motor consists of two parts.

(i) A stationary part called stator in which the 3ϕ winding is placed.

(ii) A rotating part called rotor which is connected to the mechanical load through shaft.

Stator

- **It has laminated construction made up of stamping which are 0.4 to 0.5mm thick.**
- **The stampings have slots on the inner periphery to carry the stator windings.**
- **Stampings are made of silicon steel.**
- **The stampings are stamped together to form the stator core.**
- **Laminated silicon steel stampings minimizes the iron lors.**
- **Stator core consists of 3ϕ winding connected in Y or Δ and are called stator winding.**
- **The stator winding is excited by a 3ϕ supply to produce a rotating magnetic field.**

Rotor

- **Rotor is placed inside the stator.**

- It is laminated and has slots on the outer periphery to carry the rotor windings (or) rotor conductors.
- It is made of cast iron.

There are two types of rotor construction.

(i) squirrel cage rotor (ii) slip ring induction motor (or) phase wound rotor.

(i) *Squirrel cage rotor*

- **It consists of cylindrical laminated core with slots to place the rotor conductors which are nearly parallel to the shaft axis (or) skewed.**
- **The rotor conductors are not wires, but then bars of Cu, Al or Alloy.**
- **One bar is placed in each slot.**
- **At each end of the rotor, the rotor bar conductors are short circuited by heavy end rings.**
- **Since the rotor bars are permanently short circuited it is not possible to add any external resistance in series with rotor for starting purposes.**

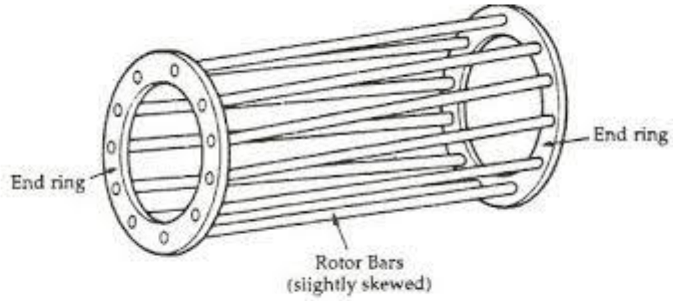


Fig.1 Squirrel cage Induction Motor

The rotor is skewed because

(a) It helps the motor to run quietly with reduced noise.

(b) Reduces locking tendency of rotor (i.e.,) Rotor teeth remain under stator teeth due to magnetic attraction between the two.

(ii) *Slip ring motor (or) Phase wound rotor*

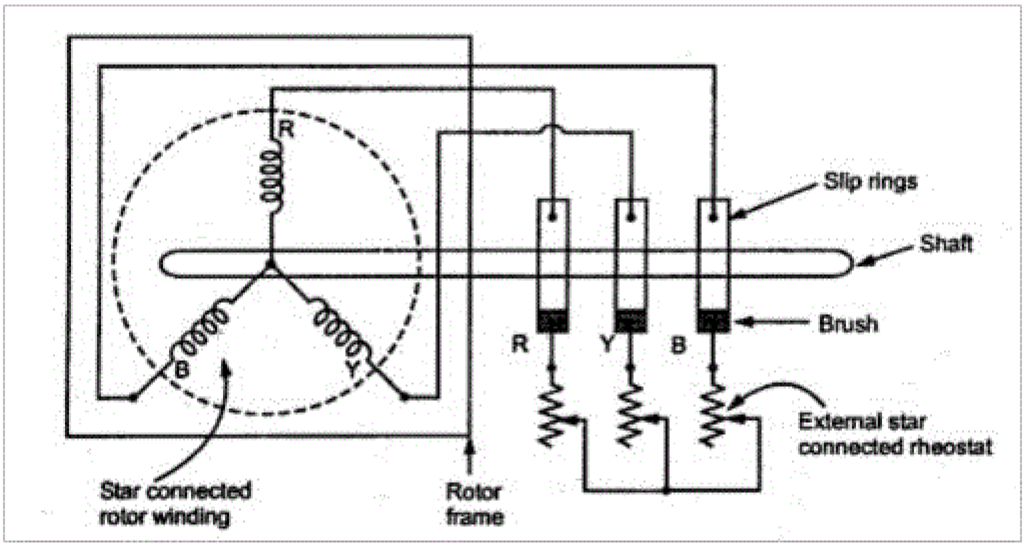


Fig.2 Squirrel cage Induction Motor

- **In this rotor winding is similar to stator.**
- **Rotor carries 3ϕ Y or Δ connected windings.**
- **These windings are placed in slots in rotor.**
- **One end of all the windings are connected to a common point.**
- **The other 3 ends of 3ϕ winding are brought out and connected to slip rings mounted on shaft with brushes on them.**
- **These brushes are then externally connected to a 3ϕ star connected rheostat.**
- **The use of brush, slip ring and external resistors is**
  (a) to increase the starting torque and decrease the starting current.
  (b) to control the speed of the motor.

Principle of Operation

- **It works on the principle of electromagnetic induction.**
- **When a 3ϕ supply is given to a 3ϕ stator winding a rotating magnetic field is produced.**
- **The speed of the rotating magnetic field is synchronous speed denoted by N_s in rpm.**

$$N_s = \frac{120f}{p}$$ **where f = supply frequency, P = no. of poles.**

- **Let the direction of rotation of magnetic field is in clockwise direction.**
- **Now rotor is stationary. Stator magnetic field is revolving at a speed of N_s. This revolving field is cut by the stationary rotor conductors.**

- **When conductor cuts the magnetic flux an emf is induced in the conductors. When there is a closed path a currents starts flowing due to the emf.**
- **Now we have a current carrying conductor placed in a magnetic field. Therefore by the law of interaction, when a current carrying conductor is placed in a magnetic field, the conductor experiences a force.**
- **Hence all the conductors experience a force which together gives a torque which tends to rotate the rotor.**
- **The direction of force is same as that of the rotating magnetic field. Hence the rotor starts rotating in the same direction as the rotating magnetic field.**

  N_s = speed the rotating magnetic field in rpm.

  N = speed of rotor (i.e.,) actual speed of motor.

  [N_s – N] = relative speed b/w the two.
- **The rotor always rotates in the same direction as that of the rotating magnetic field.**
- **When the rotor rotates, it tries to catch the speed of the RMF. If it catches the speed of RMF, then the relative motion is = 0 (i.e., N_s – N = 0). Because relative motion is the main cause for emf, Therefore emf = 0. So, the rotor flux required to produce torque = 0 and therefore the rotor will not rotate.**
- **Induction motor never runs at synchronous speed. The speed at which the motor rotates is called as the subsynchronous speed and the motor is called as Asynchronous motor.**

Slip of Induction Motor

Speed of stator = Speed of rotating magnetic field = synchronous speed = N_s.

Speed of rotor = Actual speed of motor = N

Slip speed

[N_s – N] = slip speed.

i.e., the difference between the speed of the RMF and that of the rotor is called as slip speed.

Slip [or] Absolute Slip [or] Fractional Slip: [S]

- **Difference between the synchronous speed (N_s) and actual speed of rotor (N), expressed as a fraction of synchronous speed is called as slip of motor.**

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

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

Speed of motor in terms of slip

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

S . N_s **=** N_s **– N**

N = N_s **–** SN_s **=** N_s **(1–S)**

$\therefore$ **N =** N_s**(1–S)**

Slip at starting condition

At the time of start, the speed of motor = 0

$\therefore$ **N = 0**

$\because$ **S =** $\frac{N_s - N}{N_s} = \frac{N_s}{N_s}$ **= 1**

$\therefore$ **S = 1**

This is the maximum value of slip and it occurs at starting condition.

when slip S = 0; N_s **= N; N =** N_s**(1–S) =** N_s**.** $\therefore$ **N =** N_s

But N_s **= N is not possible for an induction motor.** $\therefore$ **Slip of motor cannot be zero at any case.**

Effect of slip on rotor parameters

Let us study the effect of slip on the following rotor parameters.

1. Rotor frequency **2. Magnitude of rotor induced emf**

3. Rotor reactance **4. Rotor power factor** **5. Rotor current.**

1. ***Effect of slip on frequency of rotor current:***

- **when rotor is stationary the frequency of the rotor current = supply frequency = f**
- **when rotor is rotating the frequency of the rotor current will be dependent on the slip speed.**
- **Let fr = frequency of rotor current at running condition**

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

$$(N_s - N) = \frac{120fr}{P}$$

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

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

fr = Sf [frequency of rotor fr = Sf]

2. ***Effect of slip on rotor induced emf***

When rotor is stationary S = 1

- **At stationary condition:**
  - **Relative speed is maximum**
  - **Emf induced in rotor is maximum and is propotional to synchronous speed N_s. i.e., $E_2 \propto N_s$.**

  where E_2 = Emf induced in rotor when it is stationary.
- **At running condition**
  - **As rotor starts rotating, relative speed b/w the rotating magnetic field and rotor decreases and hence the emf also decreases and is proportional to the relative speed $(N_s - N)$**

  i.e., $E_{2r} \propto (N_s - N)$

where E_{2r} = rotor induced emf at running condition.

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

$E_{2r} = S\,E_2$

3. ***Effect of slip on rotor resistance and reactance***

- **Rotor winding has its own value of resistance and inductance.**

At standstill condition (i.e., at N = 0)

Let

R_2 = rotor resistance / phase

X_2 = rotor reactance / phase

At standstill fr = f

If L_2 is the inductance of rotor

$X_2 = 2\pi f L_2\ \Omega/ph$

At running condition

fr = Sf

$X_{2r} = 2\pi frL_2 = 2\pi S_f L_2 = S \cdot [2\pi fL_2] = SX_2$

$\therefore\ X_2fr = SX_2$

where X_{2r} = rotor reactance at running condition.

Rotor resistance is same at standstill and at running condition.

Rotor impedance at standstill = Z_2

$$Z_2 = R_2 + jX_2 = \sqrt{R_2^2 + X_2^2}$$

At running condition impedance = Z_{2r} $X_{2r} = SX_2$

$$Z_{2r} = R_{2r} + jX_{2r} = \sqrt{R_2^2 + X_{2r}^2} = \sqrt{R_2^2 + (SX)^2}$$

$$Z_{2r} = \sqrt{R_2^2 + (SX)^2}$$

4. *Effect of slip on rotor current:*

Let I_2 = rotor current / ph at standstill

E_2 = Emf/ph at standstill

Z_2 = Impedance / ph at standstill

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

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

$E_{2r} = SE_2$ = Emf / ph at running condition.

$$Z_{2r} = \sqrt{R_2^2 + (SX)^2}$$

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

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

5. *Effect of slip on power factor:*

$$\cos\phi_2 = \frac{R_2}{Z_2}$$ **at standstill condition.**

$$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$ **at running condition.**

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

$$\cos\phi_{2r} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$ **= power factor at running condition.**

Torque Equation of Induction Motor

- **Torque produced in induction motor is dependent on**

(i) **flux required to produce emf [ϕ]**

(ii) **rotor current [I_{2r}]**

(iii) **power factor of rotor ckt at running condition [cos ϕ_{2r}]**

i.e., $T \propto \phi\, I_{2r} \cos\phi_{2r}$ **(1)**

- **Flux produced in stator is dependent on stator applied voltage is $\phi \propto E_1$**
- **We know that at stand still** $\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$

$$\frac{E_2}{E_1} = K$$ **$E_1 \propto \phi$**

$$\frac{E_2}{\phi} = K$$

$E_2 = K\phi$

[or]

$E_2 \propto \phi$ **(2)**

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \quad \text{(3)}$$

$$\cos\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}} \quad \text{(4)}$$

Substituting eqn. (2), (3), (4) in (1) we get

$$T \propto E_2 \cdot \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} * \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$T \propto \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

$$T = K \cdot \frac{SE_2^2 R_2}{R_2^2 + [SX_2]^2}$$

where K = constant of proportionality

For 3ϕ induction motor $K = \frac{3}{2\pi ns}$

where ns = synchronous speed in rps = $\frac{N_s}{60}$

$$\text{Torque} = T = \frac{3}{2\pi ns} \cdot \frac{SE_2^2 R_2}{R_2^2 + [SX_2]^2} \textbf{ N-m}$$

This is the equation for torque developed at running condition.

Equation for Starting Torque [T_{st}]:

At the instant of starting N = 0. $\therefore S = \frac{N_s - N}{N_s} = \frac{N_s}{N_s} = 1$

$\therefore$ **S = 1**

On substituting S = 1 in equation for torque.

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

$$\therefore T_{st} \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition for Maximum Torque under Running Condition:

For maximum torque $\frac{dT}{ds} = 0$ **($\because$ slip is variable in torque equation)**

$$T = K \cdot \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2} = K \cdot \frac{SE_2^2 R_2}{R_2^2 + S^2 X_2^2}$$

$$\frac{dT}{ds} = \frac{d}{ds}\left[K \cdot \frac{SE_2^2R_2}{R_2^2 + S^2X_2^2}\right]$$

$$= \frac{[R_2^2 + S^2X_2^2] * KE_2^2R_2 - [K \cdot SE_2^2R_2] * 2SX_2^2}{[R_2^2 + S^2X_2^2]^2} = 0$$

$$\Rightarrow K \cdot E_2^2R_2^3 + K \cdot E_2^2R_2S^2X_2^2 - 2KS^2E_2^2R_2X_2^2 = 0$$

$$K \cdot E_2^2R_2^3 + KS^2E_2^2R_2X_2^2 = 0$$

$$K \cdot E_2^2R_2[R_2^2 - S^2X_2^2] = 0$$

$$R_2^2 - S^2X_2^2 = 0$$

$$S^2X_2^2 = R_2^2$$

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

$$S = \sqrt{\frac{R_2^2}{X_2^2}} = \sqrt{\left(\frac{R_2}{X_2}\right)^2}$$

$$\therefore S = \pm\frac{R_2}{X_2}$$

neglecting negative values of slip

$S = \frac{R_2}{X_2}$ **[This is the value of slip at maximum torque]**

$\therefore S_m = \frac{R_2}{X_2}$ **is the condition for maximum torque.**

Magnitude of Maximum Torque: (T_{max})

1. Maximum torque is obtained at slip $S_m = \frac{R_2}{X_2}$.

So to obtain T_{max} put $S = S_m = \frac{R_2}{X_2}$ **in torque eqn.**

$$\therefore T_{max} = \frac{K \cdot S_m \cdot E_2^2R_2}{R_2^2 + S_m^2X_2^2}$$

$$T_{max} = \frac{K \cdot \frac{R_2}{X_2} \cdot E_2^2 R_2}{R_2^2 + \frac{R_2^2}{X_2^2} * X_2^2} = K \cdot \frac{E_2^2 R_2^2}{X_2[R_2^2 + R_2^2]}$$

$$T_{max} = \frac{K \cdot E_2^2 R_2^2}{X_2 * 2R_2^2} = \frac{K \cdot E_2^2}{2X_2}$$

$$\therefore T_{max} = \frac{K \cdot E_2^2}{2X_2} = \frac{3}{2\pi n_s} * \frac{E_2^2}{2X_2} \quad \textbf{N – m}$$

Condition for Maximum Starting Torque:

At starting S = 1, $\therefore$ Put S_m = 1 in $S_m = \frac{R_2}{X_2}$.

$$\therefore \frac{R_2}{X_2} = 1$$

$R_2 = X_2$ is the condition for maximum starting torque.

Starting Torque of Squirrel Cage Rotor:

- ❖ **Resistance of squirrel cage rotor is small than reactance and is constant. Starting current I_2 is of very high magnitude and lags behind E_2 by a very large angle, so starting torque is very poor. So it is not used for motor which is used to start against heavy loads.**

Starting Torque of Slip Ring Rotor:

- ❖ **Starting torque of this motor is increased by improving its power factor by adding external resistance which is cut out as the motor achieves speed.**

Torque Slip Characteristics:

- ❖ **The curve obtained by plotting torque against slip is called as torque-slip chs of induction motor.**
- ❖ **When the induction motor is loaded the speed decreases, $\therefore$ the slip increases. One to the increased load, the motor must produce more torque to meet the load demand. $\therefore$ the torque depends on slip.**

w.k.t

$$T = k \cdot \frac{S \cdot E_2^2 R_2}{R_2^2 + S^2 X_2^2}$$

For a constant supply voltage, E_2 will be constant.

$\therefore$ **we can write the torque equation as follows.**

$$T \propto \frac{S \cdot R_2}{R_2^2 + (SX_2)^2}$$

$\therefore$ **When S = 0, the torque T is also = 0 [T = 0]. So the curve starts from zero.**

Low slip region:

- **When the speed of the rotor is close to the synchronous speed then slip is very small.**
- $\therefore$ **the value $(SX_2)^2$ is very small compared to R_2^2. So $(SX_2)^2$ can be neglected.**

$$\therefore T \propto \frac{SR_2}{R_2^2}$$

$\because$ **R_2 is constant; $T \propto S$**

$\therefore$ **For low values of slip, torque is directly proportional to slip and so the graph is a straight line.**

High Slip Region:

- **As the load increases, the speed decreases. $\therefore$ the slip S increases and torque increases and reaches a maximum values. T_{max}, at $S = S_m = \frac{R_2}{X_2}$.**
- **This torque is also called as pull our torque [or] breakdown torque [or] stalling torque.**
- **With further increase in motor load the speed decreases and hence slip increases and its value approaches unity [1].**
- **Here $R_2^2 << (SX_2)^2$ and so R_2^2 can be neglected.**

$$\therefore T \propto \frac{SR_2}{(SX_2)^2}$$

when R_2 and X_2 are constant, $T \propto = \frac{S}{S^2}, \quad \therefore T \propto \frac{1}{S}$

- **Now as load increases, speed decreases, so slip increases. But then $\therefore T \propto \frac{1}{S}$, torque decreases. Thus the curve is a rectangular hyperbola.**

- **So beyond the point of max torque, any further increase in motor load, results in decrease of torque developed. So the motor slows down and stops.**

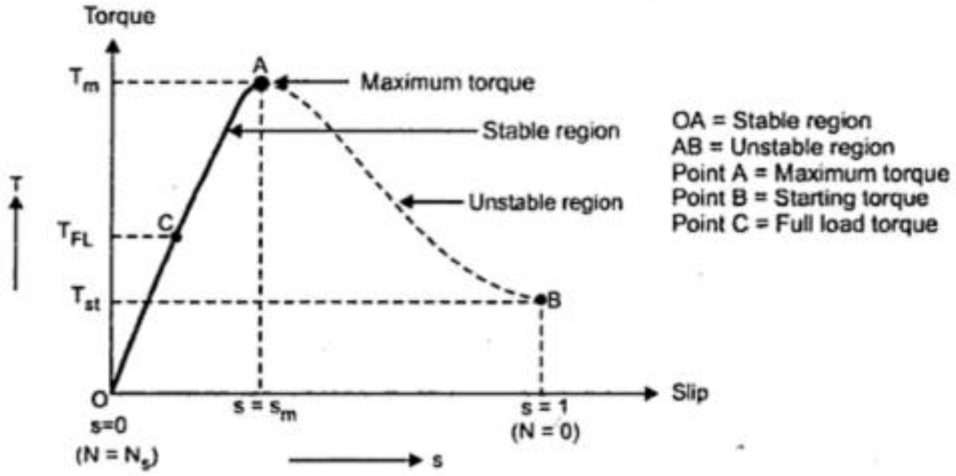


Fig.3 Torque – Slip Cahracteristics

Effect of Change in Rotor Resistance on Torque-slip characteristics

$$T \propto \frac{SE_2^2R_2}{R_2^2+(SX_2)^2}$$

where

R_2 = Rotor resistance / ph

R_2eq = new rotor resistance / ph then when

corresponding $P' \propto \frac{SE_2^2R_2eq}{R_2^2eq+(SX_2)^2}$

At S = 1 for R_2 and R_2eq P_{st} will be

$$P_{st} \propto \frac{E_2^2R_2}{R_2^2+X_2^2}$$

$$P'_{st} \propto \frac{E_2^2R_2eq}{R_2^2eq+X_2^2}$$

$$T_m \propto \frac{E_2^2}{2X_2}$$

- **T_m is independent of R_2. $\therefore$ whatever may be the rotor resistance, the maximum torque never changes. But the slip and speed at which it occurs depends on R_2.**

$$S_m = \frac{R_2}{X_2}$$

$$S'_m = \frac{R_2 eq}{X_2}$$

$R_2eq > R_2$; $\therefore \; S'_m > S_m$.

$T'_{st} > T_{st}$ **(if R_2 is increased)**

- **If high R_2 is kept permanently in the circuit, there will be large I^2R losses e hence η will be poor. $\therefore$ External resistance is gradually cut off & removed in the normal running condition of the motor.**

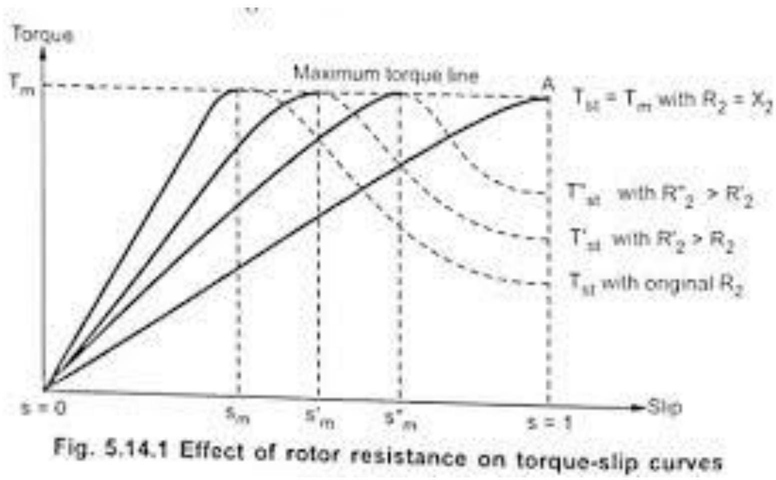


Fig.4 Effect of rotor resistance on Torque – slip characteristics

Full Load Torque:

The load which the motor can drive safely while operating continuously and due to which the current drawn is within safe limits is called as full load condition of motor.

Equivalent Circuit of Induction Motor:

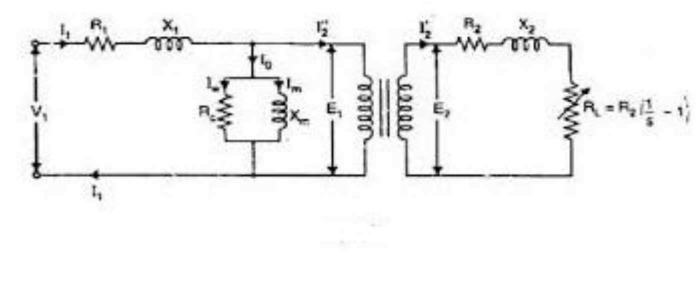


Fig.5 Electrical Equivalent Circuit of Induction Motor

- **Induction motor works on the principle of electromagnetic induction.**
- **It is also called as a rotating transformer.**

- **Stator acts as primary wdg and rotor acts as secondary wdg.**

As standstill condition; let

E_1 = Induced voltage in stator per phase.

E_2 = Rotor induced emf per phase on standstill.

$$K = \frac{N_2}{N_1} = \frac{\text{rotor turns}}{\text{stator turns}}$$

- **when voltage V_1 is applied to stator, it produces flux. Due to self induction emf E_1 is induced in stator while E_2 is the emf induced in rotor due to mutual induction at standstill.**
- **In running condition the emf induced in rotor = E_{2r} = SE_2**

E_{2r} = rotor induced emf in running condition.

R_2 = rotor resistance / ph.

X_2 = rotor reactance / ph at standstill.

X_{2r} = SX_2 = rotor reactance / ph at running condition.

R_1 = Rotor resistance / ph.

X_1 = Stator reactance / ph.

when induction motor is on no load, it draws a current from supply to produce flux in air gap and to supply iron losses.

$\therefore$ I_0 has two components

(i) I_w = supply iron loss

(ii) I_μ = produces flux.

R_0 = represent loss at no load = $\dfrac{V_1}{I_w}$.

X_0 = represent flux set up = $\dfrac{V_1}{I_\mu}$

I_0 is the sum of I_μ and I_w

$$\therefore \overrightarrow{I_0} = \overrightarrow{I_w} + \overrightarrow{I_\mu}$$

Equivalent circuit of induction motor can be represented as follows:

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

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

As load varies, speed decreases and hence slip varies, with variation in slip X_{2r} changes $\because$ $X_{2r} = SX_2$. So it is shown as variable in equivalent circuit.

$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$ **divide numerator and denominator by S**

$$\therefore I_{2r} = \frac{\frac{SE_2}{S}}{\sqrt{\left(\frac{R_2}{S}\right)^2 + \left(\frac{SX_2}{S}\right)^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{S}\right)^2 + X_2^2}}$$

$\therefore$ **Now in the rotor ckt at running condition we can replace the fixed resistance and variable reactance by a variable resistance and fixed reactance.**

Now $\frac{R_2}{S}$ **can be written as**

$$\frac{R_2}{S} = \frac{R_2}{S} + R_2 - R_2 = R_2 + \left[\frac{R_2}{S} - R_2\right]$$

$$= R_2 + R_2\left(\frac{1}{S} - 1\right)$$

$$\therefore \frac{R_2}{S} = R_2 + R_2\left(\frac{1-S}{S}\right)$$

So variable resistance $\frac{R_2}{S}$ **has two parts:**

(i) Rotor resistance R_2 represent copper loss is rotor

(ii) $R_2\left(\frac{1-S}{S}\right)$ **represents the load resistance R_L = electrical equivalent of mechanical load on motor**

Now let us obtain the equivalent ckt referred to stator side.

$$K = \frac{E_2}{E_1}$$

$E_2' = \frac{E_2}{K}$ **(after transferring to stator) = E_1**

when I_2 is transferred to stator = $I_{2r}' = KI_{2r} = \frac{KSE_2}{\sqrt{R_2^2 + (SX_2)^2}}$

when X_2 is transferred to stator = $X'_2 = \frac{X_2}{K^2}$

when R_2 is transferred to stator = $R'_2 = \frac{R_2}{K^2}$

when R_L is transferred to stator = $R'_L = \frac{R_L}{K^2} = \frac{R_2}{K^2}\left(\frac{1-S}{S}\right)$

$$R'_L = R'_2\left(\frac{1-S}{S}\right)$$

∴ **Equivalent ckt referred to stator can be as follows.**

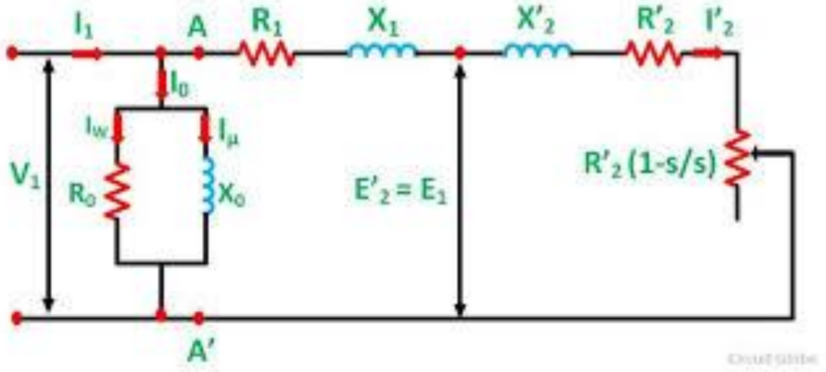


Fig.6 Equivalent Circuit of Induction Motor referred to stator

The no load component of current I_0 is very less compared to the load current I_1, so the drop across R_1 and X_1 due to I_0 can be neglected and I_0 component can be shifted before R_1 and X_1.

$R_1 + R'_2 = R_{1e} =$ **equivalent resistance referred to stator.**

$X_1 + X'_2 = X_{1e} =$ **equivalent reactance referred to stator.**

$$\therefore I'_{2r} = \frac{V_1}{Z_{1e}} = \frac{V_1}{(R_{1e} + R'_L) + jX_{1e}}$$

$$I'_{2r} = \frac{V_1}{\sqrt{(R_{1e} + R'_L)^2 + X_{1e}^2}}$$

Power Stages in an Induction Motor:

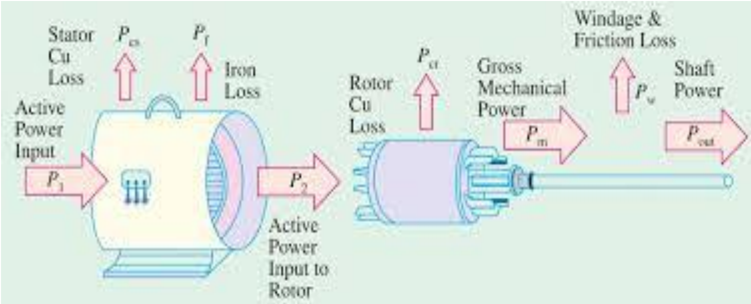


Fig.7 Power Stages in an Induction Motor

- **Power input to the stator = P_{in} = P_1 = $\sqrt{3}\, V_L I_L \cos\phi$**
- **Rotor input [P_2] = stator input – stator loss**

  $\therefore$ $P_2 = P_{in}$ – stator loss
- **Rotor cu loss [P_c] = $3\, I_{2r}^2 R_2$**
- **Mechanical power developed in rotor = $P_m = P_2 - P_c$.**
- **Power output at rotor = $P_{out} = P_m$ – mechanical loss**
- **Net motor efficiency =** $\frac{P_{out}}{P_{in}} \times 100$
- **Rotor efficiency =** $\frac{\text{Rotor o/p}}{\text{Rotor i/p}} = \frac{P_m}{P_2} \times 100$

Relationship Between P_2, P_c and P_m:

Power input to rotor = $P_2 = T_g * w_s = \frac{2\pi N_s}{60} T_g$

where

T_g = gross torque developed in N – m.

$w_s = \frac{2\pi N_s}{60}$ **= angular speed at which power is given as input.**

[N_s is used, since P_2 in power to rotor receives from stator whose magnetic field revolves at N_s rpm].

Gross mechanical power developed in the rotor = $P_m = T_g * w = \frac{2\pi N}{60} T_g$

[N is used since P_m is power developed by rotor which runs at a speed of N rpm].

w.k.t

$P_m = P_2 - P_c$

$P_c = P_2 - P_m$

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

$$P_c = \frac{2\pi T_g}{60} [N_s - N]$$

$$\frac{P_c}{P_2} = \frac{\frac{2\pi T_g}{60}[N_s - N]}{\frac{2\pi N_s}{60} T_g} = \frac{N_s - N}{N_s} = S$$

$$\frac{P_c}{P_2} = S$$

$P_c = SP_2$

$P_m = P_2 - P_c = P_2 - SP_2$

$P_m = P_2(1-S)$

$$\frac{P_2}{P_m} = \frac{1}{1-S}$$

$P_2 : P_c : P_m = 1 : S : (1-S)$

$$\frac{P_2}{P_c} = \frac{1}{S}; \quad \frac{P_2}{P_m} = \frac{1}{1-S}; \quad \frac{P_c}{P_m} = \frac{S}{1-S}$$

Derivation of K in Torque Equation:

$$T = \frac{KSE_2^2 R_2}{R_2^2 + (SX_2)^2} \qquad \textbf{(1)}$$

$$P_c = 3I_{2r}^2 R_2$$

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

Substituting the value of I_{2r} in P_c we get

$$P_c = 3 * \left[\frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}\right]^2 * R_2 = \frac{3S^2E_2^2R_2}{R_2^2 + S^2X_2^2}$$

$$\frac{P_c}{P_m} = \frac{S}{1-S}$$

$$P_m = \frac{(1-S)*P_c}{S}$$

$$P_m = \frac{(1-S)}{S} * \frac{3S^2E_2^2R_2}{R_2^2 + S^2X_2^2}$$

$$P_m = 3(1-S) * \frac{E_2^2R_2}{R_2^2 + S^2X_2^2}$$

w.k.t $\mathbf{P_m = T_g * \omega}$

$$\therefore T_g = \frac{P_m}{\omega} = \frac{P_m}{\left(\frac{2\pi N}{60}\right)} \qquad \omega = \frac{2\pi N}{60}$$

$$\therefore T_g = \frac{3(1-S)\frac{E_2^2R_2}{R_2^2 + (SX_2)^2}}{\left(\frac{2\pi N}{60}\right)} \qquad \mathbf{N = N_s(1-S)}$$

$$T_g = \frac{3(1-S)*E_2^2R_2}{\frac{2\pi N_s(1-S)}{60}[R_2^2 + (SX_2)^2]} \qquad \frac{N_s}{60} = n_s$$

$$T_g = \frac{3}{2\pi n_s}\frac{E_2^2R_2}{R_2^2 + (SX_2)^2} \qquad \textbf{(2)}$$

On comparing (1) and (2) we get

$$K = \frac{3}{2\pi n_s}$$

Power Equations from Equivalent Circuit:

$\mathbf{P_{in}} =$ $\sqrt{3}$ $\mathbf{V_L I_L \cos\phi = 3\, V_{ph}\, I_{ph} \cos\phi}$

Stator core loss = $3I_w^2R_0$

Stator copper loss = $3I_1^2R_1$

$P_c = 3I_{2r}'^2R_2'$ **= Rotor copper loss**

$$\because P_c = SP_2; \quad P_2 = \frac{P_c}{S} = \frac{3I_{2r}'^2R_2'}{S}$$

$$P_2 = \frac{3I_{2r}'^2R_2'}{S}$$

$$P_m = P_2 - P_c = \frac{3I_{2r}'^2 R_2'}{S} - 3I_{2r}'^2 R_2'$$

$$P_m = 3I_{2r}'^2 R_2' \left[\frac{1}{S} - 1\right]$$

$$P_m = 3I_{2r}'^2 R_2' \left[\frac{1-S}{S}\right]$$

$$P_m = \frac{2\pi N}{60} T_g$$ **N = N_s(1–S)**

$$T_g = \frac{P_m}{\left(\frac{2\pi N}{60}\right)} = \frac{3I_{2r}'^2 R_2' \left[\frac{1-S}{S}\right]}{\frac{2\pi N}{60}} = \frac{3I_{2r}'^2 R_2' \left[\frac{1-S}{S}\right]}{\frac{2\pi N_s}{60}(1-S)}$$

$$T_g = \frac{\left[\frac{3I_{2r}'^2 R_2'}{S}\right]}{\left[\frac{2\pi N_s}{60}\right]} = \frac{9.55\left[\frac{3I_{2r}'^2 R_2'}{S}\right]}{N_s}$$ **N–m**

$$T_g = \frac{9.55\left[\frac{3I_{2r}'^2 R_2'}{S}\right]}{N_s}$$ **N–m**

Maximum power output:

In the equivalent ckt, when I_0 is neglected the ckt is as follows:

w.k.t $\overrightarrow{I_1} = \overrightarrow{I_0} + \overrightarrow{I_{2r}'}$

when I_0 is neglected $I_1 = I_{2r}'$

$$Z_T = (R_{1e} + R_L') + jX_{1e}$$

$$I_1 = \frac{V_1}{\sqrt{(R_{1e} + R_L') + X_{1e}^2}}$$

P_{out} per phase = $I_1^2 R_L'$

Total P_{out} = $3\, I_1^2 R_L'$

$$P_{out} = 3\left[\frac{V_1}{\sqrt{[R_{1e} + R_L']^2 + X_{1e}^2}}\right]^2 R_L'$$

To obtain P_{out} (max) differentiate P_{out} w.r.t. R'_L and equal to zero.

$$\frac{d}{dR'_L}\left[\frac{3V_1^2R'_L}{(R_{1e}+R'_L)^2+X_{1e}^2}\right]=\frac{\left([R_{1e}+R'_L]^2+X_{1e}^2\right)*3V_1^2-V_1^2R'_L\left[2[R_{1e}+R'_L]^2\right]}{\left[(R_{1e}+R'_L)^2+(X_{1e})^2\right]}$$

On equating to zero

$$\frac{3V_1^2\left[(R_{1e}+R'_L)^2+X_{1e}^2-2R_{1e}R'_L-2R'^2_L\right]}{[(R_{1e}+R'_L)^2+X_{1e}^2]^2}=0$$

$$\therefore (R_{1e}+R'_L)^2-X_{1e}^2-2R_{1e}R'_L-2R'^2_L=0$$

$$R_{1e}^2+R'^2_L+2R_{1e}R'_L+X_{1e}^2-2R_{1e}R'_L-2R'^2_L=0$$

$$Z_{1e}^2-R'^2_L=0 \qquad\qquad R_{1e}^2+X_{1e}^2=Z_{1e}^2$$

$$\therefore R'^2_L=Z_{1e}^2$$

$R'_L=Z_{1e}$ **is the condition for maximum P_{out}.**

Slip at P_{out} (MAX):

$$R'_L=Z_{1e}$$

$$R'_2\frac{(1-S)}{S}=Z_{1e}$$

$$R'_2-SR'_2=SZ_{1e}$$

$$R'_2=SZ_{1e}+SR'_2$$

$$R'_2=S[Z_{1e}+R'_2]$$

$$\therefore S=\frac{R'_2}{R'_2+Z_{1e}}$$

Phasor Diagram of Induction Motor:

Stator vge $\overrightarrow{V_1}=\overrightarrow{E_1}+\overrightarrow{I_1R_1}+j\overrightarrow{I_1X_1}$

- **Phasor diagram is drawn by taking ϕ as reference.**
- **Emf E_1 lag ϕ by an angle of 90° .**
- **Emf E_{2r} is produced in rotor and is in phase with E_1.**

  E_{2r} = I_{2r} Z_2
- **Current I_{2r} lags E_{2r} by an angle of ϕ_{2r}.**
- **I_2R_2 is in phase with I_2 and I_2X_2 is at 90° to ϕ.**

- I'_{2r} **is anti phase with I_{2r}**
- **I_μ is in phase with ϕ; I_w is at 90° to ϕ.**

$$\overrightarrow{I_0} = \overrightarrow{I_\mu} + \overrightarrow{I_w}$$

- $\overrightarrow{I_1} = \overrightarrow{I_0} + \overrightarrow{I'_{2r}}$
- **To get V_1, draw $-E_1$ anti phase with E_1.**
- **To the tip of $-E_1$, draw I_1R_1 in phase with I_1 and I_1X_1 at 90° to I_1.**

$$\overrightarrow{V_1} = \overrightarrow{E_1} + \overrightarrow{I_1R_1} + \overrightarrow{I_1X_1}.$$

- **Angle between V_1 and I_1 is ϕ.**

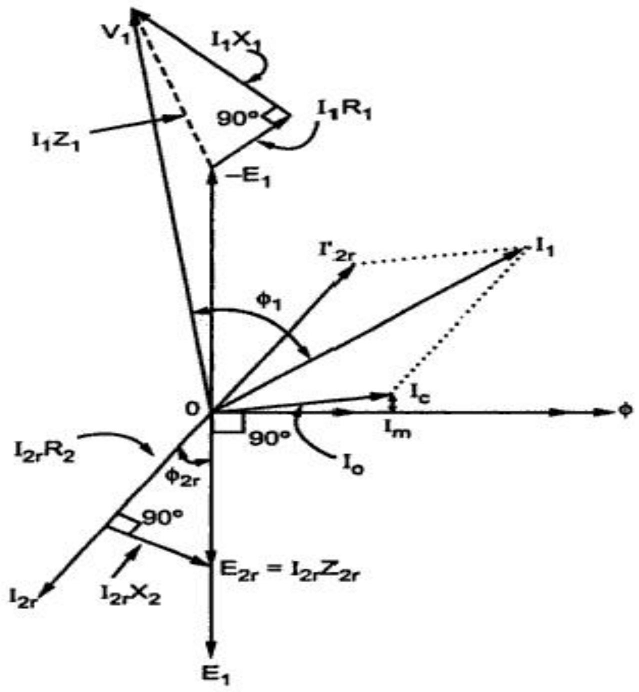


Fig.8 Phasor Diagram of Induction Motor

Concept of Induction Generator

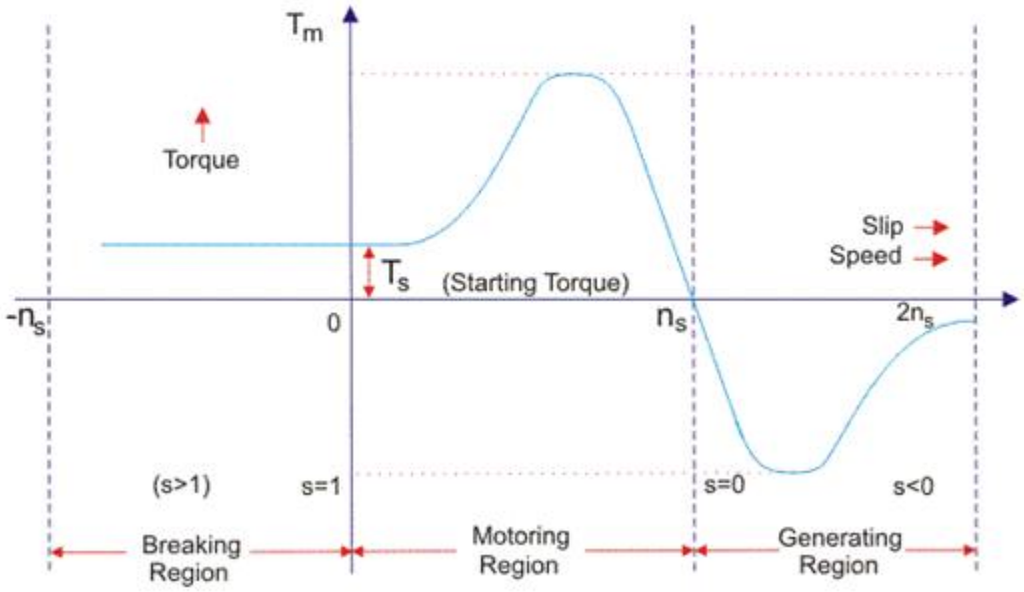


Fig.9 Operating regions of Induction Motor

Induction machines are sometimes used as a generator. These are known as induction generators or asynchronous generators.

An induction machine will behave as an induction generator when:

- **Slip becomes negative due to this the rotor current and rotor emf attains negative value.**
- **The prime mover torque becomes opposite to electric torque.**

Suppose that an induction machine is coupled with the prime mover whose speed can be controlled. If the speed of the prime mover is increased such that the slip becomes negative (i.e. speed of the prime mover becomes greater than the synchronous speed).

Due to this, all the conditions that we have mentioned above will become fulfilled and the machine will behave like an induction generator. Now if the speed of the prime mover is further increased such that it exceeds the negative maximum value of the torque produced then the generating efficiency of the generator vanishes. Clearly, the speed of the induction generator during the whole operation is not synchronous, therefore the induction generator is also called a synchronous generator.

- **An induction generator is not a self-excited machine. Therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The**

induction generator obtains its magnetizing current and reactive power from the various sources like the supply mains or it may be another synchronous generator.

- **An induction generator can't work in isolation because it continuously requires reactive power from the supply system. However, we can have a self-excited or isolated induction generation if we use a capacitor bank for reactive power supply instead of an AC supply system. We'll now discuss isolated induction generators in detail.**
- ***Isolated Induction Generator***
- **This type of generator is also known as a self excited generator. Now why it is called self-excited? It is because it uses a capacitor bank which is connected across its stator terminals as shown in the diagram given below.**

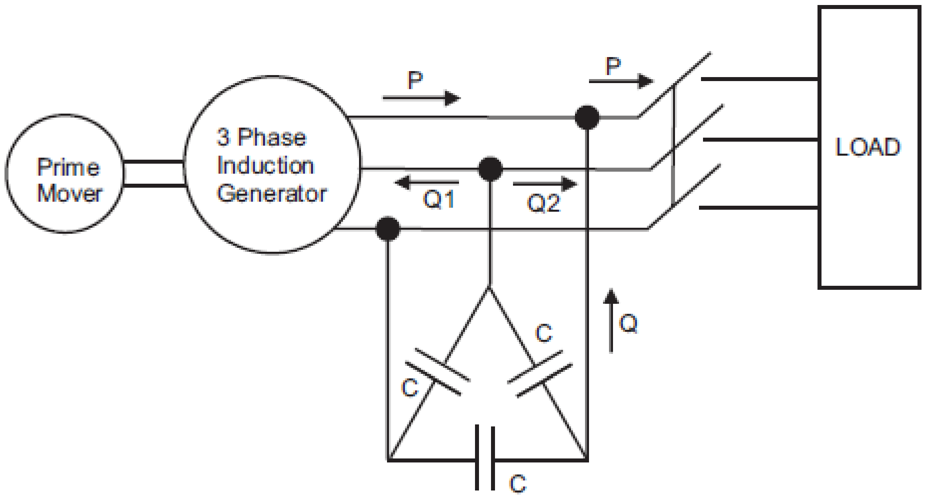


Fig.10 Three phase Induction Generator

The function of the capacitor bank is to provide the lagging reactive power to the induction generator as well as load. So mathematically we can write total reactive power provided by the capacitor bank is equals to the summation of the reactive power consumed by the induction generator as well as the load.

Application of Induction Generator

Let us discuss application of induction generator: We have two types of induction generator let us discuss the application of each type of generator separately: Externally excited generators are widely used for regenerative breaking of hoists driven by the three phase induction motors.

Self-excited generators are used in the wind mills. Thus this type of generator helps in converting the unconventional sources of energy into electrical energy.
Now let us discuss some disadvantages of externally excited generator:

- **The efficiency of the externally excited generator is not so good.**
- **We cannot use externally excited generator at lagging power factor which major drawback of this type of generator.**
- **The amount of reactive power used to run these types of generator required is quite large.**

Advantages of Induction Generators

- **It has robust construction requiring less maintenance**
- **Relatively cheaper**
- **Small size per kW output power (i.e. high energy density)**
- **It runs in parallel without hunting**
- **No synchronization to the supply line is required like a synchronous generator**

Disadvantages of Induction Generators

- **It cannot generate reactive voltamperes. It requires reactive voltamperes from the supply line to furnish its excitation.**

The important characteristics normally shown by a squirrel cage induction motors are crawling and cogging. These characteristics are the result of improper functioning of the motor that means either motor is running at very slow speed or it is not taking the load.

Crawling of Induction Motor

It has been observed that squirrel cage type induction motor has a tendency to run at very low speed compared to its synchronous speed, this phenomenon is known as crawling. The resultant speed is nearly 1/7th of its synchronous speed. This action is due to the fact that harmonics fluxes produced in the gap of the stator winding of odd harmonics like 3rd, 5th, 7th etc. These harmonics create additional torque fields in addition to the synchronous torque. The torque produced by these harmonics rotates in the forward or backward direction at $N_s/3$, $N_s/5$, $N_s/7$ speed respectively. Here
only 5th and 7th harmonics are considered and rest are neglected. The torque produced by the 5th harmonic rotates in the backward direction.
This torque produced by fifth harmonic which works as a braking action is small in quantity, so it can be neglected. Now the seventh harmonic produces a forward rotating

torque at synchronous speed $N_s/7$. Hence, the net forward torque is equal to the sum of the torque produced by 7^{th}harmonic and fundamental torque. The torque produced by 7^{th} harmonic reaches its maximum positive value just below 1/7 of N_s and at this point slip is high. At this stage motor does not reach up to its normal speed and continue to rotate at a speed which is much lower than its normal speed. This causes crawling of the motor at just below 1/7 synchronous speed and creates the racket. The other speed at which motor crawls is 1/13 of synchronous speed.

Cogging of Induction Motor

This characteristic of **induction motor comes into picture when motor refuses to start at all. Sometimes it happens because of low supply voltage**. But the main reason for starting problem in the motor is because of cogging in which the slots of the stator get locked up with the rotor slots. There is series of slots in the stator and rotor of the induction motor. When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this stage the reluctance of the magnetic path is minimum and motor refuse to start. This characteristic of the induction motor is called cogging. Apart from this, there is one more reason for cogging. If the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage then it causes torque modulation. As a result, of it cogging occurs. This characteristic is also known as magnetic teeth locking of the induction motor.

Methods to overcome cogging

This problem can be easily solved by adopting several measures. These solutions are as follows:

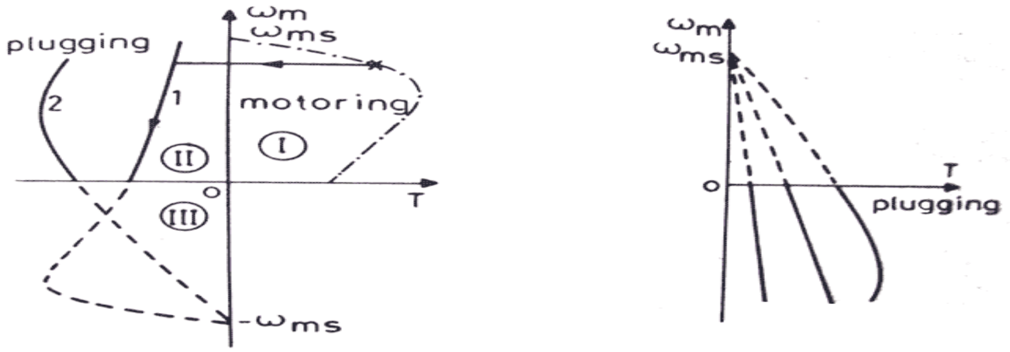
- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

- Plugging Braking of Induction Motor

- Plugging induction motor braking is done by reversing the phase sequence of the motor. Plugging braking of induction motor is done by interchanging connections of any two phases of stator with respect of supply terminals. And with that the operation of motoring shifts to plugging braking. During plugging the slip is (2 - s), if the original slip of the running motor is s,

$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$

then it can be shown in the following way.



(a) 1: natural characteristic
2: with external resistance in rotor

(b) Plugging in IV quadrant with large external resistance in rotor

Fig.11 Plugging braking of an Induction Motor

From the figure beside we can see that the torque is not zero at zero speed. That's why when the motor is needed to be stopped, it should be disconnected from the supply at near zero speed. The motor is connected to rotate in the reverse direction and the torque is not zero at zero or any other speed, and as a result the motor first decelerates to zero and then smoothly accelerates in the opposite direction.

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UNIT - IV
AC Machines – SEEA1303

IV CIRCLE DIAGRAM AND CONTROL METHODS OF 3-PHASE INDUCTION MOTOR

No load and Blocked rotor tests - Equivalent circuit - Construction of Circle diagram - Starting methods - Speed control - Double cage Induction motor.

What is a Circle Diagram

A circle diagram is a graphical representation of the performance of an electrical machine. It is commonly used to illustrate the performance of transformers, alternators, synchronous motors, and induction motors. It is very useful to study the performance of an electric machine under a large variety of operating conditions. The diagrammatic representation of a circle diagram makes it much easier to understand and remember compared to theoretical and mathematical descriptions.

Importance of Circle Diagram

The diagram provides information which is not provided by an ordinary phasor diagram. A phasor diagram gives relation between current and voltage only at a single circuit condition. If the condition changes, we need to draw the phasor diagram again. But a circle diagram may be referred to as a phasor diagram drawn in one plane for more than one circuit conditions. On the context of induction motor, which is our main interest, we can get information about its power output, power factor, torque, slip, speed, copper loss, efficiency etc. in a graphical or in a diagrammatic representation.

Circle Diagram:

The following tests have to be done on the induction motor to draw the circle diagram.

(i) No load test (or) open circuit test.

(ii) Blocked rotor test (or) short circuit test.

No load test:

- **In this test the motor is run on no load.**
- **The 3ϕ supply is turned on. Rated voltage is being applied to the stator.**

❖ **The readings of voltmeter, ammeter and waltmeter are being noted down.**

The readings are as follows:

V_0 = rated voltage on no load

I_0 = current on no load

W_0 = no load input power = iron loss

[$\because$ on no load the I is decrease so cu loss is less and can be neglected $\therefore$ input = iron loss]

$I_w = I_0 \cos \phi_0$

$I_\mu = I_0 \sin \phi_0$

$$R_0 = \frac{V_0}{I_w}; \qquad X_0 = \frac{V_0}{I_\mu}$$

Blocked rotor test:

❖ **The rotor is blocked by tightening the spring balance.**

❖ **By adjusting the variac, the rated current is applied to the stator.**

❖ **The readings of voltmeter, Ammeter and Waltmeter is noted odwn on short circuit.**

V_{sc} = short circuit reduced voltage.

I_{sc} = rated current on short circuit.

W_{sc} = input power on short circuit.

$W_{sc} = \sqrt{3}\ V_{sc}\ I_{sc}\ ws\phi_{sc}$

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

when rotor is blocked N = 0

$$\therefore \textbf{ S = 1} \qquad \left(\because S = \frac{N_s - N}{N_s} = \frac{N_s - 0}{N_s} = 1\right)$$

$\because R'_L = 0$ **the equivalent ckt is**

$$W_{sc} = 3I_{sc}^2 R_{1e}$$

$$R_{1e} = \frac{W_{sc}}{3I_{sc}^2}$$

$$Z_{1e} = \frac{V_{sc}}{I_{sc}}$$

$$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}$$

W_{sc} = stator copper loss + rotor copper loss

[∵ at s.c V_{sc} is decrease iron loss is negligible]

V_{sc} = reduced short circuit voltage.

V_L = normal rated voltage = V_{rated}

To draw circle diagram we need to find the current (I_{SN}) and power (W_{SN}) on short circuit when normal voltage (V_L) is applied.

$$I_{SN} = \left[\frac{V_{rated}}{V_{sc}}\right] * I_{SC}$$

I_{sc} = short circuit current at reduced voltage V_{sc}.

I_{SN} = short circuit current at normal voltage or rated voltage.

$$W_{SN} = \left[\frac{I_{SN}}{I_{sc}}\right]^2 * W_{SC} \quad \textbf{or} \quad W_{SN} = \sqrt{3}\, V_L I_{SN} \cos \phi_{sc}$$

W_{SN} = short circuit power at rated normal v_{ge} (V_{rated})

W_{SN} = core loss + stator cu loss + rotor cu loss

Procedure to draw circle diagram:

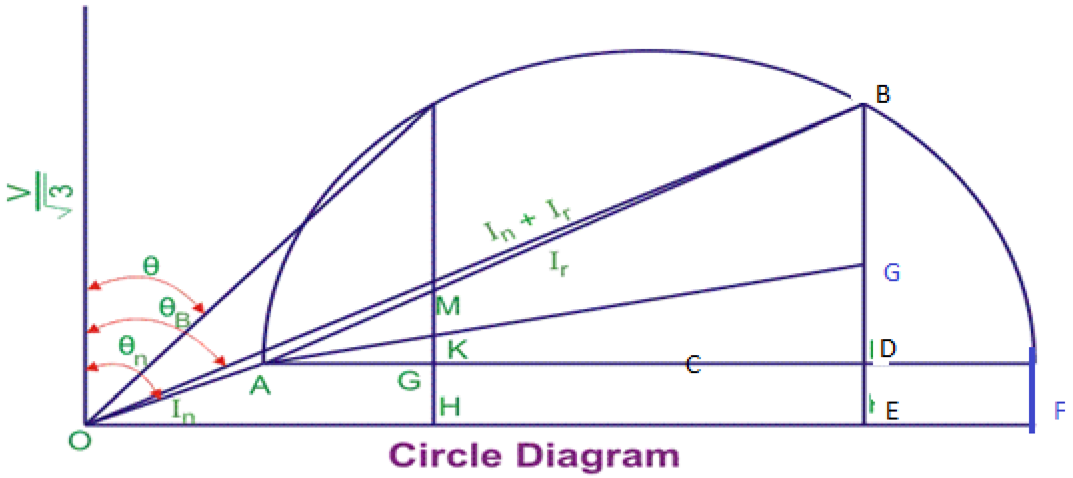

Fig.1 Circle Diagram

1. **Voltage is taken along Y axis and current along X axis.**
2. **From no load test find I_0 and ϕ_0.**

$\phi_0 = \cos^{-1}\left[\frac{W_0}{\sqrt{3}\, V_0 I_0}\right]$

- **Select a suitable current scale.**
- **Draw I_0 lagging behind voltage by an angle ϕ_0.**

OA = I_0

3. **From point 'A' draw a line parallel to X axis called as base line.**
4. **Find I_{SN} and ϕ_{sc}.**

$I_{SN} = \frac{V_{rated}}{V_{sc}} * I_{sc}$

$\phi_{sc} = \cos^{-1}\left[\frac{W_{sc}}{\sqrt{3}\, V_{sc} I_{sc}}\right]$

- **Draw ISN lags V by an angle ϕsc**

OB = I_{SN}

5. **Join AB. AB is called output line.**
6. **Draw a perpendicular bisector to o/p line AB and extend it to meet base line at point C.**
7. **Draw a line parallel to Y axis from point B. It meets base line at point D and X axis at point E.**
8. **With 'C' as centre, AC as radius draw a circle to meet base line at point F.**
9. **BE = Power input at s.c at normal voltage = W_{SN}.**

   W_{SN} = fixed loss + stator cu loss + rotor cu loss.
10. **DE = fixed loss = core loss.**

    BD = rotor cu loss + stator cu loss.

    $\frac{BG}{GD} = \frac{\text{Rotor cu loss}}{\text{Stator cu loss}}.$
11. **Join AG. AG = torque line**
12. **Location of point G**

For slip ring motor:

$$\frac{BG}{GD} = \frac{\text{Rotor cu loss}}{\text{Stator cu loss}} = \frac{I_2^2 R_2}{I_1^2 R_1} = \left[\frac{I_2}{I_1}\right]^2 * \frac{R_2}{R_1} = \frac{1}{K^2} * \frac{R_2}{R_1}$$

$$= \frac{R_2}{K^2} * \frac{1}{R_1} * \frac{R_2'}{R_1} \qquad \left(\because \frac{R_2}{K^2} = R_2' \right)$$

$$\therefore \frac{BG}{GD} = \frac{R_2'}{R_1}$$

For squirrel cage motor:

$$\frac{BG}{GD} = \frac{\text{Rotor cu loss}}{\text{Stator cu loss}}.$$

Stator cu loss = $3I_{SN}^2 R_1$

W_{SN} = stator cu loss + rotor cu loss

Rotor cu loss = W_{SN} – stator cu loss = W_{SN} – $3I_{SN}^2 R_1$

$$\therefore \frac{BG}{GD} = \frac{W_{SN} - 3I_{SN}^2 R_1}{3I_{SN}^2 R_1}.$$

(13) Power scale factor (PSF)

From Graph W_{SN} = BE

Power Scale Factor = PSF = $\frac{W_{SN}}{\ell(BE)}$

To find maximum quantities:

Maximum Output:

- ❖ **Draw a line parallel to output line (AB) and also tangent to the circle at point H.**

  [or]

- ❖ **It can also be determined by extending the perpendicular bisector drawn from point 0 to meet at point H.**
- ❖ **From 'H' drop a perpendicular to meet the output line (AB) at H′.**

  length of HH′ ∗ PSF = maximum output

Maximum Torque:

- ❖ **Draw a line parallel to torque line AG and also is tangent to circle at point I.**
- ❖ **Drop a perpendicular from I to meet the torque line at I′**

length of II′ ∗ PSF = maximum torque in synchronous watts.

Maximum Input:

- **Draw a line parallel to X axis and also tangent to the circle at point J.**
- **Drop a perpendicular from J to meet X axis at J′**

  length of JJ′ ∗ PSF = maximum input

Maximum Power Factor:

- **Draw a tangent to the circle from origin to meet at point K. Drop a perpendicular to meet X axis at point K′.**

  Maximum power factor = cos(KK′)

  [or]

  Maximum power factor = $\frac{KK'}{OK}$

Starting Torque:

At start slip S = 1

$$\frac{P_2}{P_C} = \frac{1}{S} = \frac{1}{1}$$

∴ $P_2 = P_c$ = rotor cu loss = length (BG) ∗ PSF

∴ Starting torque = T_{st} = length of BG ∗ PSF in synchronous watts

Full Load Condition:

Rated motor o/p is given in HP

Convert to KW.

Represent the power in cm as BB′

o/p power in cm = BB′ = $\frac{\text{power in KW}}{\text{PSF}}$

Extend B to B′

- **Draw from point B′ a line parallel to o/p line AB to meet the circle at point P.**
- **Join OP. OP is the current at full load.**
- **Drop a perpendicular from point P, to meet the X axis at point T, output line at Q, torque line at R and base line at S.**

Overall Formula of Circle Diagram:

1) **Fixed loss = $\ell(DE) * PSF$**

2) **Stator cu loss = $\ell(DG) * PSF$**

3) **Rotor cu loss = $\ell(BG) * PSF$**

4) **Maximum torque = $\ell(II') * PSF$**

5) **Maximum output = $\ell(HH') * PSF$**

6) **Maximum input = $\ell(JJ') * PSF$**

7) **Maximum efficiency =** $\frac{\text{Max o/p}}{\text{Max i/p}}$

8) **Max power factor =** $\frac{KK'}{OK}$. **(or) cos(OKK′)**

9) **Full load current = ℓ (OP) ∗ current scale factor**

10) **Full load power factor =** $\frac{PT}{OP}$ **(or) cos(OPT)**

11) **Full load torque = $\ell(PR) * PSF$ in synchronous watts**

12) **Full load output power = $\ell(PQ) * PSF$**

13) **Full load input power = $\ell(PT) * PSF$**

14) **Full load efficiency =** $\frac{\text{Full load o/p}}{\text{Full load i/p}}$

15) **Full load fixed loss = $\ell(ST) * PSF$**

16) **Full load stator cu loss = $\ell(RS) * PSF$**

17) **Full load rotor cu loss = $\ell(QR) * PSF$**

18) **Full load rotor input = $\ell(TR) * PSF$**

19) **Total loss = $\ell(QT) * PSF$**

20) **Full load slip =** $\frac{\text{Full load rotor cu loss}}{\text{Full load rotor i/p}} = \frac{P_c}{P_2}$

$$S = \frac{QR}{PR}$$

21) **Full load speed = $N_s(1-S)$**

22) **Starting torque = $T_{st} = \ell(BG) * PSF$**

23) Rotor efficiency = $\frac{\text{Rotor o/p}}{\text{Rotor i/p}} = \frac{PQ}{PR}$

Starters:

Need for starter in induction motor:

The rotor current at running condition is given by $I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$.

- **Induced emf decides the magnitude of rotor current.**
- **But induced emf depends on slip.**
- **At instant of starting speed of motor N = 0. $\therefore$ slip is maximum (i.e.) S = 1.**
- **$\therefore$ magnitude of emf is maximum at time of start.**
- **$\because$ rotor conductors are short circuited, large emf circulates large current in rotor at time of start.**
- **In induction motor, when rotor current is high, stator draws a very high current. This in 5–8 times the full load current.**

  Heavy in rush of current causes

  - **damage to motor wdg**
  - **large line vge drop**

$\therefore$ to limit the high starting current a starter is used.

A starter is a device which is used to limit high starting current by supplying reduced voltage to motor at time of starting.

Starter provides protection to induction motor against over loading or low vge.

Types of starter:

1) Stator resistance starter

2) Auto transformer starter

3) Star-delta starter

4) Rotor resistance starter

5) Direct on line starter

1) ***Stator resistance starter:***

- Three resistances are added in series with each phase of the stator wdg.
- Initially the resistance are kept at maximum position.
- Large vge gets dropped across resistances.
- So reduced vge is applied to stator, and so the starting current is reduced.
- When motor starts running the resistances are gradually cut off.
- When the resistances are entirely removed the motor runs at normal speed.

Advantage:

- Simple construction.
- Cheap.
- Can be used for both star and delta connected stator.

Disadvantage:

Large power losses due to resistance.

Starting torque is reduced due to reduced.

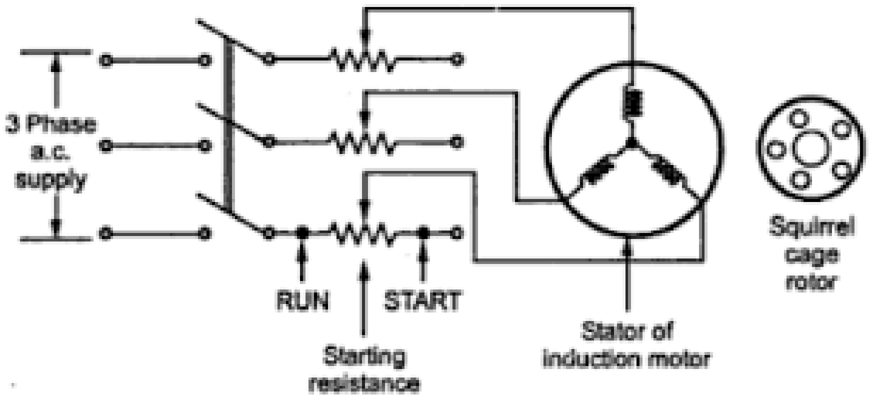

Fig.2 Stator resistance starter

2) ***Auto transformer starter:***

- A 3ϕ star connected auto transformer can be used to reduce the vge applied to stator.
- It has a change over switch.
- When switch is in start position, the stator wdg is supplied with reduced vge, which is controlled by tappings provided with auto transformer.
- When motor gathers 80% of normal speed, the change over switch is thrown into run position.
- Now rated voltage is applied to stator wdg.

- Motor starts rotating with normal speed.
- Change of switch is done by relays.

Advantage:

- Power loss is less.

Disadvantage:

- Expensive than stator resistance starter.

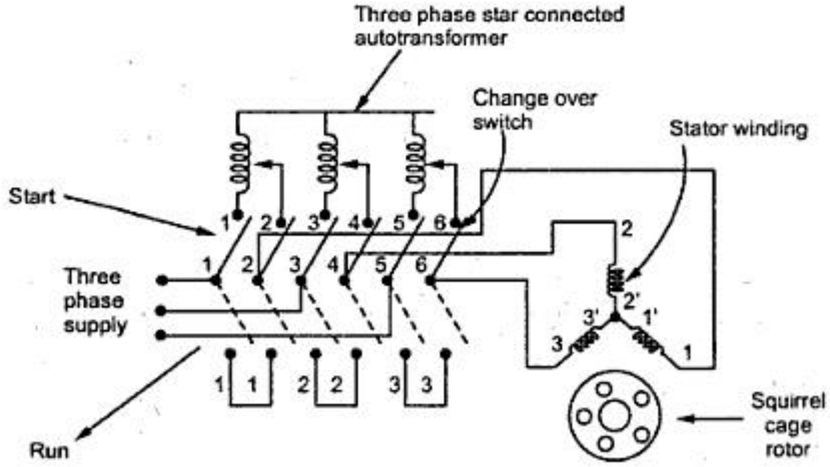

Fig.3 Auto transformer starter

3) ***Star delta starter:***

- **It is the most commonly used starter for induction motor.**
- **It has a triple pole double throw switch (TPDT).**
- **The TPDT connects the stator winding in star at the time of start.**
- **the phase vge gets reduced by the factor** $\frac{1}{\sqrt{3}}$.
- **Due to this reduced vge is given to stator and starting current is limited.**
- **After motor gains normal speed, the switch is thrown to the other side and so it gets rated vge (i.e., when the wdgs are connected in delta at running condition).**
- **Relays can be used for operation of switch.**

Advantage:

- **Cheapest of all.**
- **Maintenance free operation.**

Disadvantage:

- **Used only for normal delta connected motor.**

❖ Factor by which vge changes is $\frac{1}{\sqrt{3}}$ and cannot be varied.

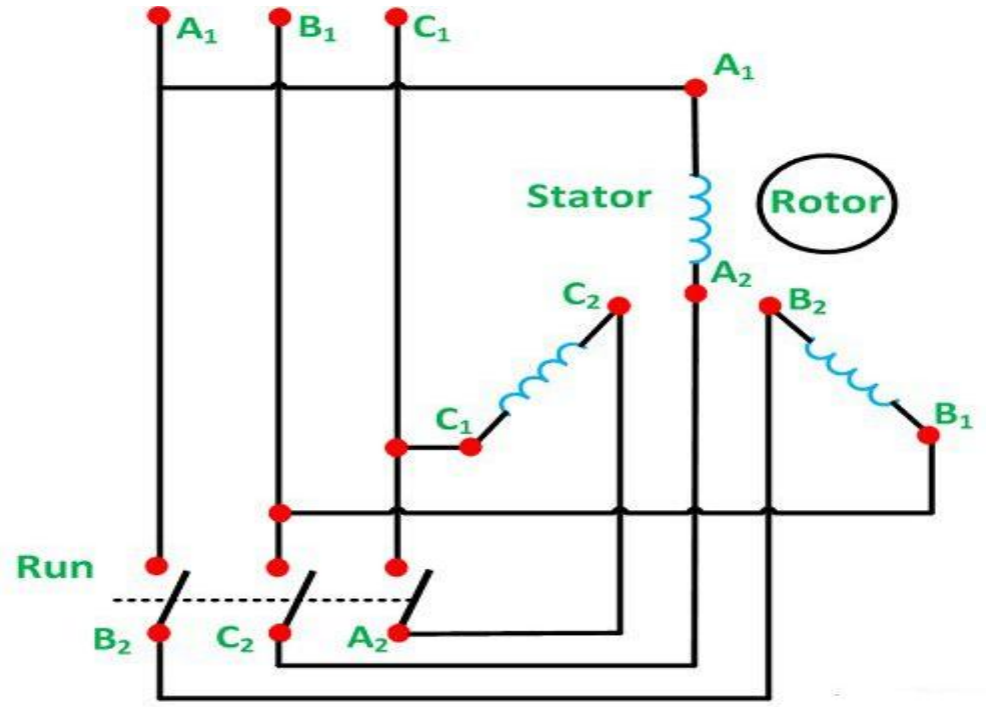

Fig.4 Star Delta starter

4) ***Rotor resistance starter:***

- ❖ **Here a resistance is inserted in each wdg of rotor. This reduces the current drawn by motor.**
- ❖ **The resistance are connected in star.**
- ❖ **The external resistance is inserted in each phase through a slip ring and brush assembly. Initially they are at max position.**
- ❖ **As the motor gathers speed the resistance is gradually cut off.**

Advantage:

∵ $T \propto R_2$; R_2 is high at starting so torque is high.

Disadvantage:

Can be used only for squirrel cage rotor.

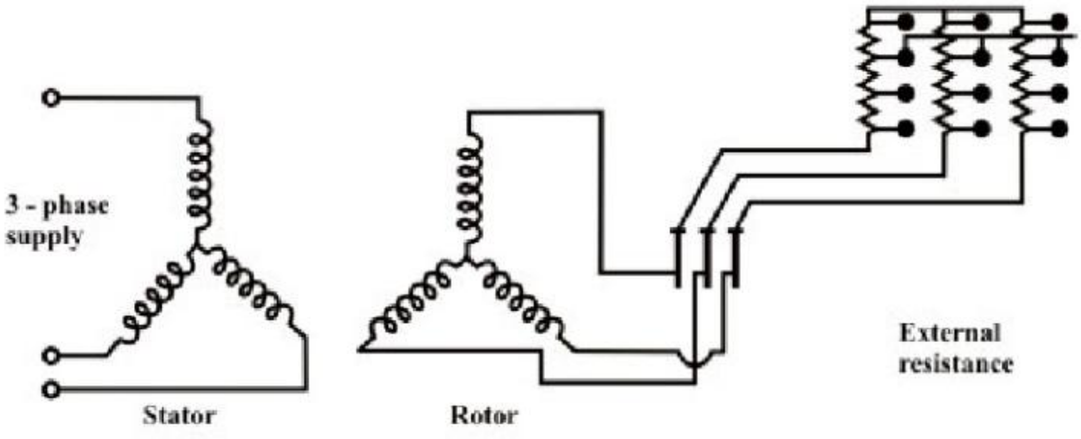

Fig.5 Rotor Resistance starter

5) ***Direct on line starter: [D.O.L] starter.***

- **In low capacity motors < 5HP, the starting current is not high.**
- **They can withstand the starting current without any starter and so there is no need to reduce the vge to control the starting current.**
- **They use a starter, which connects the stator directly to supply without reducing voltage and hence is known as direct on line starter.**
- **Though it does not reduce vge it protects the motor from overloading, low voltage etc.**
- **"NO" contact is normally open , "Nc" is normally closed.**
- **At start NO is closed for fraction of second, due to which coil is energized and attracts contactor and so at stator directly gets supply.**
- **The additional contact ensures that as long as supply is ON, the coil gets supply and keeps contactor in ON position.**
- **When Nc is pressed, the coil circuit gets opened due to which coil gets de-energised and motor gets switched off from supply.**
- **On overload, current drawn by motor increases ad so heat is produced, which increases tempt beyond limit. Thermal relays get opened due to high tempt, protecting the motor from overload condition.**

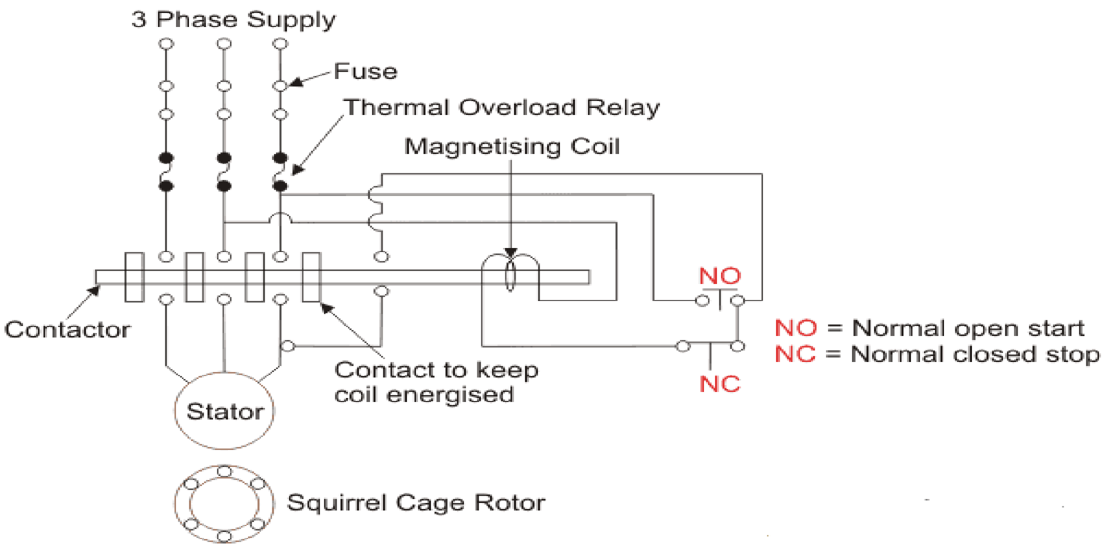

Fig.6 Direct on line starter

Speed control of induction motor:

For induction motor w.k.t

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

From this equation it can be seen that speed of induction motor can be changed by changing its synchronous speed (or) by changing the slip S.

$$\text{w.k.t} \quad T \propto \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

when R_2, E_2 are changed, then to keep the torque constant for constant load condition, motor reacts by change in its slip and hence speed changes.

Speed of induction motor can be controlled by two methods

(i) From stator side.

(ii) From rotor side.

Stator side includes the following methods:

(a) Supply frequency control (or) V/f control.

(b) Supply voltage control.

(c) Controlling number of stator poles.

(d) Adding rheostats in stator circuit.

Rotor side includes following methods:

(a) Adding external resistance in rotor circuit.

(b) Cascade control.

(c) By injection of emf in rotor circuit.

a) ***Supply frequency control (or) V/f control:***

w.k.t $N_s = \frac{120f}{P}$

by varying f, N_s can be varied.

R = 4.44 f ϕ N volts.

$$\phi = \frac{E}{4.44fN}$$

E $\propto$ V

$$\therefore \phi = \frac{1}{4.44N} * \frac{V}{f}$$

If f varies; ϕ varies.

This results in saturation of stator and rotor core, which leads to increase in no load current of motor.

$\therefore$ ϕ should be maintained constant.

$\therefore$ to maintain ϕ as constant, along with 'f', V also must be changed, to keep $\left(\frac{V}{f}\right)$ constant.

$\therefore$ this is called V/f control method.

This method requires a variable vge, variable frequency supply, which is achieved by converter-inverter circuitry.

Constant 'V' and constant 'f' ac supply is converted to dc by means of a converter.

The inverter converts d.c. supply to variable 'V', variable 'f' a.c. supply.

By selecting the proper frequency and maintaining V/f constant, smooth speed control of induction motor is possible.

Disadvantage:

Supply obtained by this method cannot be used to supply other devices which require constant vge. Hence an individual scheme for a separate motor is required which makes it costly.

b) ***Supply voltage control:***

w.k.t $T \propto \frac{S E_2^2 R_2}{R_2^2 + (SX_2)^2}$

$\frac{E_2}{E_1} = K;$ **$E_2 = KE_1$; $E_2 \propto E_1$; $E_1 \propto V \therefore E_2 \propto V$**

Also for low slip region, $(SX_2)^2 << R_2$ and hence can be neglected.

$$\therefore T \propto \frac{SV^2 R_2}{R_2^2} \propto SV^2 \quad \textbf{for constant } R_2.$$

$\therefore$ If V decrease; T increase. But to supply the same load, it is necessary to develop same torque. Hence slip increases which means motor speed N decreases. $\therefore$ Required torque is developed at a lower speed.

Disadvantage:

- **Due to decrease in vge, I increase, and hence motor may get overheated.**
- **Large change in voltage for small change in speed is a big disadvantage. So additional vge changing equipment is needed.**

c) ***Controlling number of poles:***

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

- **By changing P, Ns can be changed**
- **Change in number of poles is obtained by having two or more entirely independent stator windings in the same slots.**
- **Each wdg gives a different number of poles and so different values of synchronous speed.**
- **For eg. A 36-slot stator may have two 3ϕ wdgs, one with 4 poles and other with 6 poles.**
- **for 50Hz;** $N_s = \frac{120 \times 50}{4} = 1500$ **rpm for 4 pole wdg.**

$$N_s = \frac{120 \times 60}{6} = 1000$$ **rpm for 6 pole wdg.**

- **Motors with four independent stator wdg are also possible $\therefore$ four different speed can be obtained.**
- **One winding is used at a time, others are disconnected.**
- **This method is used in elevators, motors, traction motors etc.**

d) ***Adding rheostats in stator circuit:***

- **Reduced vge is applied to stator wdg by adding rheostats in stator circuit. As V decreases; N decreases.**

Disadvantage:

- **Large power loss because entire line current flows through the rheostats.**
- **Less efficient method of speed control.**

Speed Control on Rotor Side

1) ***Adding external resistance in rotor circuit:***

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (SX_2)^2}$$

- **For low slip region $(SX_2)^2$ << R_2 and can be neglected.**
- **For constant supply, E_2 is also constant.**

$$T \propto \frac{SR_2}{R_2^2} \propto \frac{S}{R_2}$$

- **If R_2 is increase; T decrease.**
- **But when load on motor is same, motor has to supply same torque. $\therefore$ motor slip increase; N decrease and maintains load torque constant. [$\therefore$ by increase R_2 N decrease]**

Disadvantage:

- **Large speed control is not possible.**
- **Cannot be used for squirrel cage induction motor.**
- **Speed above normal values cannot be obtained.**
- **Large power loss due to large I^2R loss.**
- **Efficiency is low.**

Cooling arrangement makes it bulky and expensive.

2) ***Cascade control:***

- **It is also called as concatenation or random operation.**
- **Two induction motors are mounted on same shaft.**
- **One motor is a slip ring motor and is called as the main motor.**
- **Second motor may be slip ring (or) squirrel cage type and is called as auxiliary motor.**
- **Stator winding of main motor is connected to 3ϕ supply.**
- **Supply of auxiliary motor is obtained at a slip frequency from the slip rings of the main motor.**
- **This is called as cascading of the motors.**
- **If the torque produced by both the motors are in the same direction, it is called as cumulative cascading.**
- **If torque produced are in opposite direction, it is called as differential cascading.**

Let

P_A = number of poles of main motor

P_B = number of poles of auxiliary motor.

$$N_{SA} = \frac{120f}{P_A}$$

where f = supply frequency

N = speed of the set [N is same for both the motors since they are mounted on same shaft]

$$\therefore S_A = \frac{N_{SA} - N}{N_{SA}}$$

f_A = frequency of emf induced in rotor of motor A

$f_A = S_A * f$ [Similarly as fr = Sf]

$\because$ supply to motor B is at frequency f_A.

$\therefore f_B = f_A$

$$\therefore N_{SB} = \frac{120f_B}{P_B} = \frac{120f_A}{P_A} = \frac{120 * S_A f}{P_B} = \frac{120 * (N_{SA} - N)f}{P_B * N_{SA}}$$

On No load, speed of motor (rotor) B is almost equal to its synchronous speed

i.e., $N_{SB} \simeq N$

$$\therefore N = N_{SB} = 120 * \left(\frac{N_{SA} - N}{N_{SA}}\right) * \frac{f}{P_B}$$

$$\therefore N = \frac{120f}{P_B} * \left[1 - \frac{N}{N_{SA}}\right]$$

$$\therefore N = \frac{120f}{P_B} * \left[1 - \frac{N}{\left(\frac{120f}{P_A}\right)}\right]$$

$$\therefore N = \frac{120f}{P_B} * \left[1 - \frac{NP_A}{120f}\right]$$

$$N_{SB} = \frac{120f}{P_B} - \frac{120f_A}{P_B} * \frac{NP_A}{120f} = \frac{120f}{P_B} - \frac{NP_A}{P_B}$$

$$\therefore N + N\frac{P_A}{P_B} = \frac{120f}{P_B}$$

$$N\left[1 + \frac{P_A}{P_B}\right] = \frac{120f}{P_B}$$

$$\frac{N(P_B + P_A)}{P_B} = \frac{120f}{P_B}$$

$$\therefore N = \frac{120f}{P_A + P_B}$$ **= speed of the set.**

If by interchanging any two terminals of motor B, the reversal of direction of rotating magnetic field of B is achieved, then the set runs as differentially cascaded set. So the effective number of poles = $P_A – P_B$.

∴ In cascade control four different speeds are possible.

(i) with respect to synchronous speed of motor A

$$N_s = \frac{120f}{P_A}$$

(ii) with respect to synchronous speed of motor B

$$N = \frac{120f}{P_A + P_B}$$

(iii) Running set as cumulatively cascaded with

$$N = \frac{120f}{P_A + P_B}$$

(iv) Running set as differentially cascaded with

$$N = \frac{120f}{P_A - P_B}$$

f_A = f_B = supply frequency of motor B.

$f_{B'}$ **= rotor frequency of motor B.**

$f_{B'}$ **= Sf**

$f_A = S_A f$

$f_B = f_A$

$f_{B'}$ **= $S_B f_B = S_B f_A$**

Disadvantages:

Expensive due to use of two motors.

Smooth speed control is not possible.

Complicated operation.

Starting torque is not sufficient to start the set.

Set cannot be operated if $P_A = P_B$.

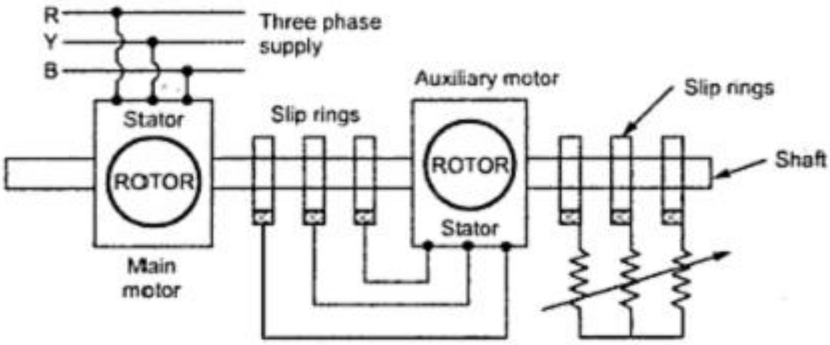

Fig.7 Cascade control

3) ***Injecting slip-frequency emf into rotor circuit:***

- **In this method a voltage is injected in the rotor ckt.**
- **Frequency of rotor is at slip frequency [fr = Sf].**
- $\therefore$ **vge injected must be at slip frequency.**

- **If injected vge opposes the rotor induced emf (Phase opposition) effective rotor resistance increases.**
- **If injected vge is in phase with rotor induced emf then effective rotor resistance decreases.**
- **$\therefore$ by changing the magnitude of injected emf; R_2 can be varied and hence speed N can be varied.**

There are two methods of speed control:

a) Kramer system b) Scherbius system

a) ***Kramer system:***

- **M is the main induction motor whose speed is to be controlled.**
- **A dc motor and a rotory conveter is used.**
- **Slip rings of main motor is connected to ac side of rotary converter.**
- **dc side of rotary converter feeds a dc shunt motor, which is directly connected to shaft of the main motor.**
- **Separate dc supply is required to excite the field wdg of dc motor and exciting wdg of rotary converter.**
- **A variable resistance is connected in field of dc motor.**
- **Speed of set is varied by varying the rheostat of the dc motor, which changes the value of E_b.**
- **$\therefore$ vge across commutator changes and so dc vge on dc side of rotary converter changes. $\therefore$ vge across ac side also changes.**
- **$\therefore$ this ac vge is give to slip rings of main motor, the vge injected in the rotor of motor M changes which produces the required speed control.**
- **This method is used in very large motors above 4000 KW in steel rolling mills.**

Advantages:

- **Smooth speed control.**
- **Wide range of speed control.**
- **Design of rotary converter is independent of speed control required.**
- **When rotary converter is over excited, it draws leading current, $\therefore$ power factor improvement is possible.**

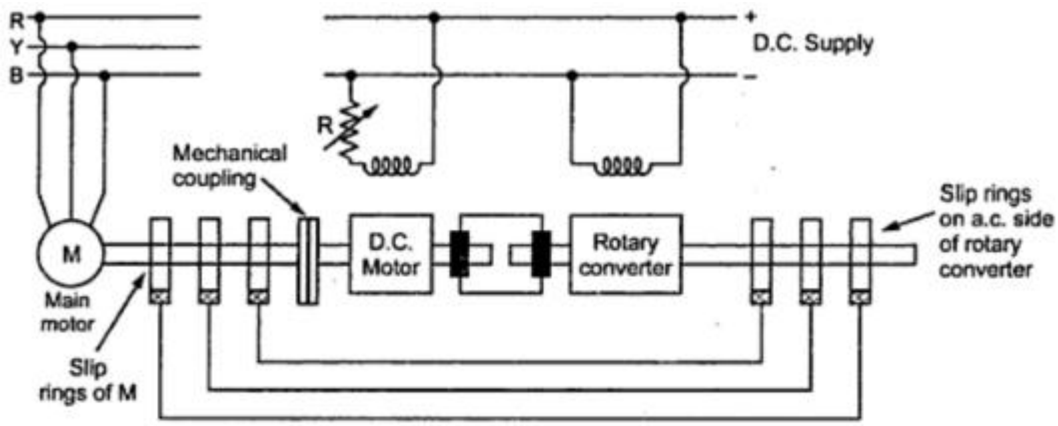

Fig.9 Kramer system

b) ***Scherbius system:***

- **This method needs an auxiliary 3ϕ or 6ϕ ac commutator m/c called as Scherbius machine.**
- **Scherbius m/c is not directly connected to the main motor whose speed is to be controlled.**
- **Scherbius m/c is excited at slip frequency from the rotor of a main motor through a regulating transform.**
- **By varying the taps on the regulating transform the vge developed in rotor of Scherbius m/c, which is injected in rotor of main motor can be changed. This changes the speed of main motor.**
- **Scherbius m/c is connected directly to the induction motor supplied from main line so that its speed deviates only to the extent of slip of auxiliary IM.**
- **Used to control speed of large motors.**

Disadvantages:

It can be used only for slip ring induction motors.

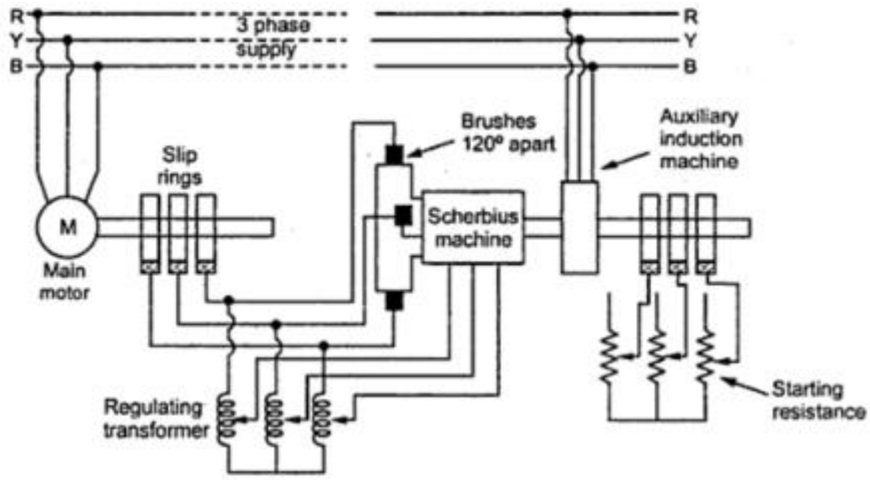

Fig. 10 Scherbius system

Double Cage Induction Motor

One of the advantages of the slip-ring motor is that resistance may be inserted in the rotor circuit to obtain high starting torque (at low starting current) and then cut out to obtain optimum running conditions. However, such a procedure cannot be adopted for a squirrel cage motor because its cage is permanently short-circuited. In order to provide high starting torque at low starting current, double-cage construction is used.

Construction

As the name suggests, the rotor of this motor has two squirrel-cage windings located one above the other. *The outer winding* consists of bars of smaller cross-section short-circuited by end rings. Therefore, the resistance of this winding is high. Since the outer winding has relatively open slots and a poorer flux path around its bars it has a low inductance. Thus the resistance of the outer squirrel-cage winding is high and its inductance is low. *The inner winding* consists of bars of greater cross-section short-circuited by end rings. Therefore, the resistance of this winding is low. Since the bars of the inner winding are thoroughly buried in iron, it has a high inductance Thus the resistance of the inner squirrel cage winding is low and its inductance is high.

Working

When a rotating magnetic field sweeps across the two windings, equal e.m.f.s are induced in each.

(i) At starting, the rotor frequency is the same as that of the line (i.e., 50 Hz), making the reactance of the lower winding much higher than that of the upper winding. Because of the high reactance of the lower winding, nearly all the rotor current flows in the high-resistance outer cage winding. This provides the good starting characteristics of a high-resistance cage winding. Thus the outer winding gives high starting torque at low starting current.

(ii) As the motor accelerates, the rotor frequency decreases, thereby lowering the reactance of the inner winding, allowing it to carry a larger proportion of the total rotor current At the normal operating speed of the motor, the rotor frequency is so low (2 to 3 Hz) that nearly all the rotor current flows in the low-resistance inner cage winding. This results in good operating efficiency and speed regulation.

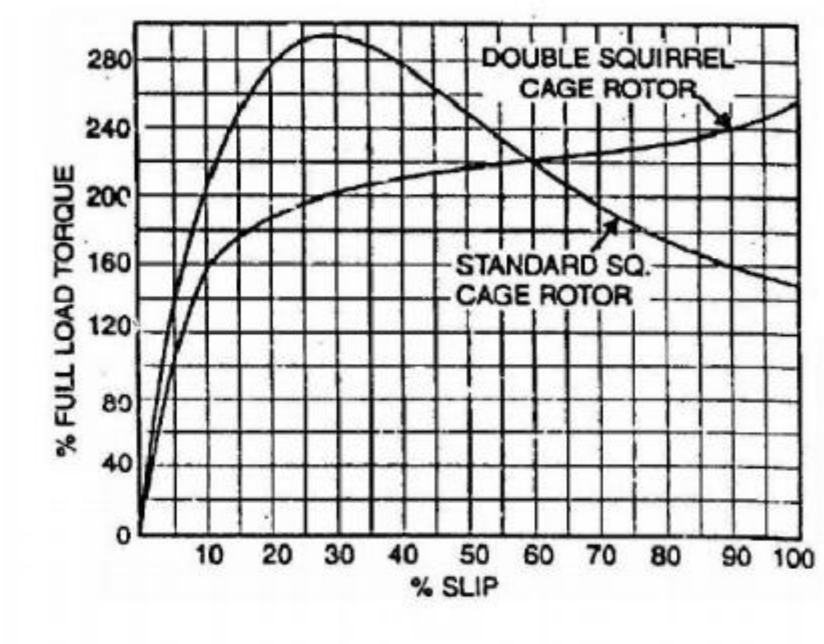

Fig. 11 Double Cage Motor Vs standard squirrel cage motor

Figure shows the operating characteristics of double squirrel-cage motor. The starting torque of this motor ranges from 200 to 250 percent of full-load torque

with a starting current of 4 to 6 times the full-load value. It is classed as a high-torque, low starting current motor.

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V SINGLE PHASE AC MOTORS

Double Field Revolving Theory - Types of Single Phase Induction Motor - Equivalent Circuit (Qualitative) -Repulsion Motor - Series Motor - Universal motor, AC Servomotor, Linear Induction Motor, Hysteresis motor.

Double Field Revolving Theory in single-phase induction motors:

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating quantity. In case of *single-phase induction motors*, the stator winding produces an alternating magnetic field having the maximum magnitude of Φ1m.

According to double-revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e (Φ1m/2). Both these components are rotating in opposite directions at the synchronous speed Ns which is dependent on frequency and stator poles.

Let Φf is forward component rotating in anticlockwise direction while Φb is the backward component rotating in a clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at that instant. So resultant of these two is the original stator flux. The below figure shows the stator flux and its two components Φf and Φb
At the start, both the components are shown the opposite to each other in figure(a). Thus the resultant Φ_R = 0. This is nothing but the instantaneous value of stator flux at the start. After 90°, as shown in figure(b), the two components are rotated in such a way that both are pointing in the same direction.

Hence the resultant ΦR is the algebraic sum of the magnitudes of the two components. So Φ_R = (Φ1m/2) + (Φ1m/2) =Φ1m.This is nothing but the instantaneous

value of the stator flux at 0 = 90° as shown in figure(c). Thus continuous rotation of two components gives the original alternating stator flux.

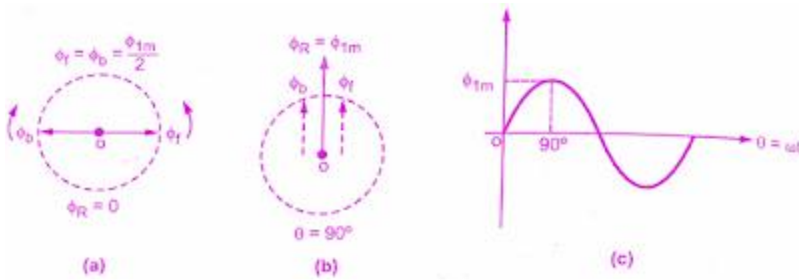

Fig.1 Double Revolving Field Theory

Both the components are rotating and hence get cut by the rotor conductors. Due to the cutting of flux, e.m.f gets induced in the rotor which circulates the rotor current. The rotor current produces rotor flux. This flux interacts with forwarding component Φf to produce a torque in one particular direction say anticlockwise direction. While the rotor flux interacts with the backward component Φb to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative.

At the start, these two torques are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at the start. And hence the single-phase induction motors are not self-starting.

Torque-Speed Characteristics in Single-phase Induction Motors:

The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics.

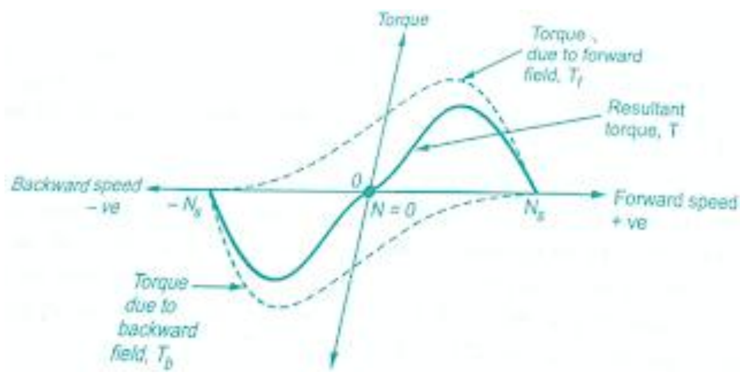

Fig. 2 Torque-Speed Characteristics

It can be seen that at start N = 0 and at that point resultant torque is zero. So single phase induction motors are not self starting.However if the rotor is given an initial rotation in any direction, the resultant average torque increases in the direction in which rotor is initially rotated and the motor starts rotating in that direction.

But in practice, it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.

Single phase Induction motors

As the power requirements of single load systems are usually small, all our homes, offices are supplied with a single–phase A.C. supply only. To get proper working conditions using this single-phase supply, compatible motors have to be used. Besides being compatible, the motors have to be economical, reliable and easy to repair. One can find all of these characteristics in a single phase induction motor readily. Similar to three-phase motors but with some modifications, single-phase induction motors are a great choice for domestic appliances. Their simple design and low cost have attracted many applications.

Single-phase induction motors are the simple motors which operate on single -phase A.C. and in which torque is produced due to induction of electricity caused by the

alternating magnetic fields. Single phase induction motors are of different types based on their starting conditions and various factors. They are-

Single Phase Induction Motor Construction

The main parts of a single -phase induction motor are the Stator, Rotor, Windings. The stator is the fixed part of the motor to which A.C. is supplied. The stator contains two types of windings. One is the main winding and the other is the Auxiliary winding. These windings are placed perpendicular to each other. A capacitor is attached to Auxiliary winding in parallel.

As A.C. supply is used for working of single -phase induction motor, certain losses should be looked out for such as- Eddy current loss, Hysteresis loss. To remove the eddy current loss the stator is provided with laminated stamping. To reduce the hysteresis losses, these stampings are usually built with silicon steel.

The rotor is the rotating part of the motor. Here the rotor is similar to the squirrel cage rotor. Besides being cylindrical the rotor has slots all over its surface. To get smooth, quite working of the motor, by preventing magnetic locking of the stator and rotor, slots are skewed rather than being parallel.

Rotor conductors are the aluminium or coppers bars, are placed in the slots of the rotor. End rings made up of either aluminium or copper electrically shorts the rotor conductors. In this single-phase induction motor slip rings and commutators are not used, so their construction becomes very simple and easy.

Working Principle of Single Phase Induction Motor

Single-phase induction motors main winding is supplied with a single -phase A.C. current. This produces fluctuating magnetic flux around the rotor. This means as the direction of the A.C. current changes, the direction of the generated magnetic field changes. This is not enough condition to cause rotation of the rotor. Here the principle of double revolving field theory is applied.

According to the double revolving field theory, a single alternating filed is due to the combination of two fields of equal magnitude but revolving in the opposite direction. The magnitude of these two fields is equal to the half the magnitude of the alternating

field. This means that when A.C. is applied, two half magnitude fields are produced with equal magnitudes but revolving in opposite directions.

So, now there is a current flowing in the stator and magnetic field revolving on the rotor, thus Faraday's law of electromagnetic induction acts on the rotor. According to this law, the revolving magnetic fields produce electricity in the rotor which generates force 'F' that can rotate the rotor.

Why Single Phase Induction Motor is Not Self Starting?

When faradays electromagnetic induction law is applied to the rotor, electricity is induced and force is generated on the rotor bars. But according to Double Revolving Field theory, there are two magnetic fields with the same magnitude but revolving in the opposite direction. Thus, two force vectors are produced with equal magnitude but opposite in direction.

Thus, these force vectors, as they are of the same magnitude but opposite in direction, doesn't cause the rotor to rotate. So, single-phase induction motors are not self-starting. The motor simply buzzes in this condition. To prevent this situation and rotate the rotor, the starting force has to be applied for a single -phase motor. As the force in one direction, becomes greater than the force the other direction, the rotor starts rotating. In single -phase induction motors, Auxiliary windings are used for this purpose.

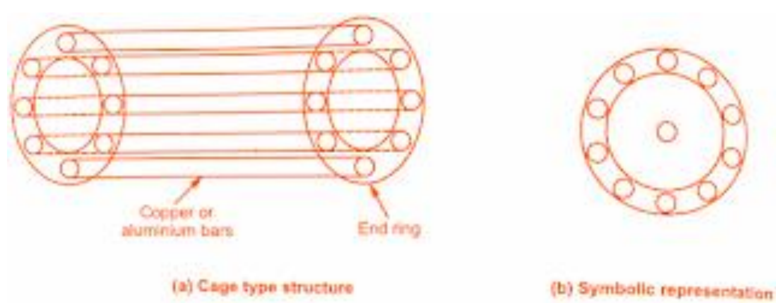

Fig. 3 Cage type structure

As the bars are permanently shorted to each other, the resistance of the entire rotor is very very small. The air gap between stator and rotor is kept uniform and as small as possible. The main feature of this rotor is that it automatically adjusts itself for the same the number of poles as that of the stator winding. The schematic diagram of two-pole single phase induction motor is shown in the below figure:

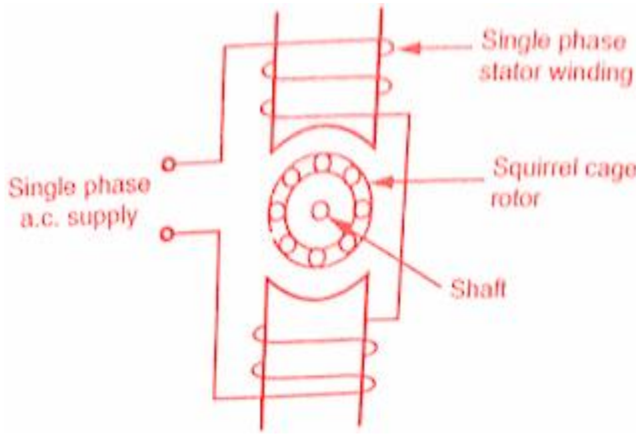

Fig. 4 Two-pole single phase induction motor

Types of Single-Phase Induction Motor

These are classified into different types depending upon the different starting methods. They are

- **Split Phase Induction motor**
- **Capacitor Start Induction motor**
- **Capacitor Start capacitor-run Induction motor**
- **Permanent Capacitor**
- **Shaded Pole type**

The required motors are selected depending upon required staring and running torque, starting and running currents drawn from the supply and duty cycle.

1) Split-Phase

In Split-phase IM, a resistance is connected in series with the starting winding. So, it is also called as resistance-start IM. A switch (SW) is also connected in series with the

winding to switch off after the rotor has attained running speed. The main winding and the starting winding or auxiliary winding are displaced at an angle 90 degrees to each other. The split-phase IM is shown in the figure below.

The main winding has low resistance and high reactance whereas the auxiliary winding has high resistance and low reactance value. The winding diagram of the Split Phase IM is shown in the figure below.

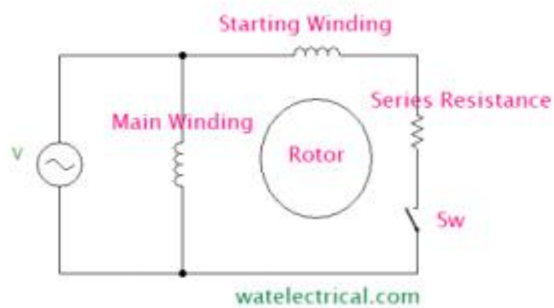

Fig. 5 single phase induction motor

The phasor diagram of split-phase IM is shown in the figure.

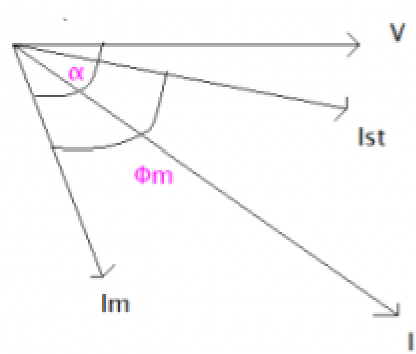

Fig. 6 Phasor Diagram

From the phasor diagram, we can understand that the main field current lags the voltage by an angle. But due to the starting winding, the starting current phasor angle decreases. It is almost in the phasor with the voltage. So, an initially high starting torque can be developed.

2) Capacitor Start Induction Motor

A capacitor is connected in series with the starting winding associated with a centrifugal switch. This capacitor is used to start the motor initially until it attains sufficient speed, after that the capacitor is disconnected by opening the switch. The capacitor start IM is shown in the figure below.

The winding diagram of the capacitor start IM is shown in the figure below.

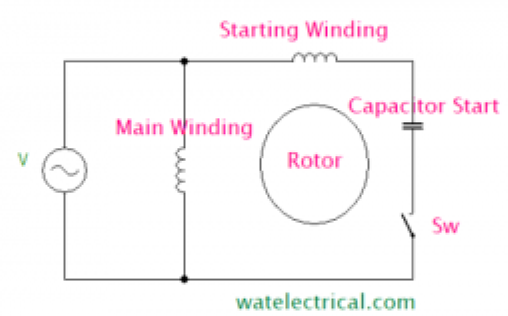

Fig. 7 Capacitor Start Induction Motor

The phasor diagram corresponding to the capacitor start motor is shown in the figure below.

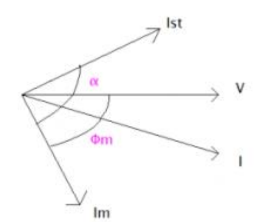

Fig. 8 Capacitor Start Phasor Diagram

From the phasor diagram, we can understand that the main field winding will be leading the voltage as it is capacitive nature due to the introduction of a capacitor. The starting torque would be high and with improved power factor. But poor running torque due to the removal of a capacitor using a switch after the rotor initiation.

Capacitor Start Capacitor-Run Induction Motor

A capacitor is connected in series with the starting winding associated with a centrifugal switch and also a capacitor is connected in parallel to the starting capacitor. This capacitor is used to start the motor initially until it attains sufficient speed, after that the capacitor is disconnected by opening the switch. But the capacitor connected in parallel remains as it is to improve the running conditions. The capacitor start capacitor run IM is shown in the figure below.

The winding diagram of the capacitor start capacitor run IM is shown in the figure below.

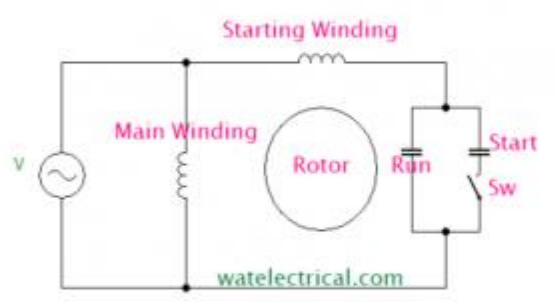

Fig. 9 **Capacitor Start Capacitor-Run Induction Motor**

Capacitor Start Capacitor Run

The phasor diagram corresponding to the capacitor start capacitor run motor is shown in the figure below.

From the phasor diagram, we can understand that the main field winding will be leading the voltage as it is capacitive nature due to the introduction of a capacitor. The starting torque would be high and with improved power factor and the running torque is also good. The running torque is good because though the starting capacitor is switched off, the running capacitor remains operating to maintain good torque.

Shaded Pole

The shaded pole IM consists of a squirrel cage rotor which is rotated under the salient pole magnetic field. ON end of the salient pole is attached by a copper coil which is also considered as a shaded ring which is short-circuited. Shaded pole type IM is shown in the figure below.

Fig. 10 Shaded pole type Induction Motor

The magnetic field induced in the main poles is induced into the shaded coil by means of an Induction Principle. The magnetic flux produced is an alternating field. The flux induced in the shaded coil opposes the flux of the main pole. During the positive cycle, the flux opposition is more towards the main field and vice-versa during the negative cycle. Thus, a rotating magnetic field is developed due to the field oppositions during the entire cycle. Therefore, a unique torque is developed which is able to rotate the rotor. This is the working of how it is a self-starting motor. The winding diagram of the shaded pole IM is shown in the figure below.

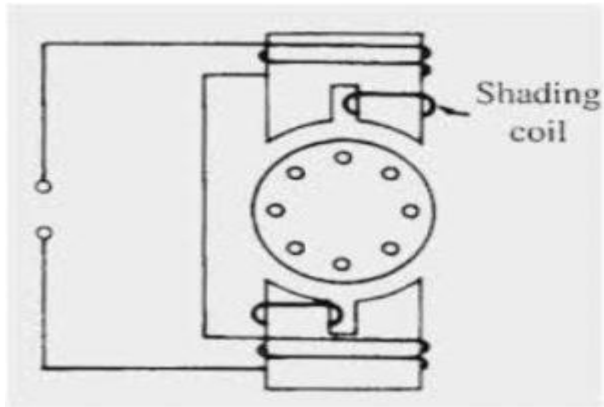

Fig. 11 Shaded pole type Induction Motor

Shaded Pole Type Diagram

Applications of Different Types of Single-Phase Induction Motor

Split-Phase

- **These are used for starting loads such as fans, blower-fans, mixer-grinders, and washing machines.**

Capacitor Start

- **These are used at heavy load applications such that where frequent starting is required.**
- **Used in air conditioners, compressors of Refrigerators, conveyor belts, and other machine applications.**

Capacitor Start Capacitor Run

- **These are used in heavy load applications and also where frequent starting and high inertia is required.**
- **Used in air conditioners, refrigerators, and pumps.**

Permanent Capacitor

- **This Motor has high efficiency and improved power factor. These are used in fans, blowers, air conditioners, and compressors in refrigerators.**

Shaded Pole Type

- **These are used for low starting applications such as in cooling fans, exhaust fans, blowers, fans of different types, relays, and in table fans.**
- **Cheap**
- **No need for an external source**
- **Self-starting**

Disadvantages of Single-Phase Induction Motor

- **Low starting torque**
- **More Looses**
- **Poor efficiency**
- **We cannot reverse the direction**
- **Low Power Factor.**

Hence, we had an overview of a one-phase IM, it is a machine that works on the principle of electromagnetic induction. This RMF is developed by certain starting methods which enables the motor to self-start by itself. We had also studied what are the types of single-phase induction motor, Working, types of starting methods, advantages, disadvantages, and applications of different types of single-phase induction motor. Here is a question for the readers, what are the advantages of different types of one Phase IM?

Equivalent Circuit of a Single Phase Induction Motor

There is a difference between single phase and three phase equivalent circuits. The single phase induction motor circuit is given by double revolving field theory which states that-

A stationary pulsating magnetic field might be resolved into two rotating fields, both having equal magnitude but opposite in direction. So the net torque induced is zero at standstill. Here, the forward rotation is called the rotation with slip s and the backward rotation is given with a slip of (2 – s). The equivalent circuit is-

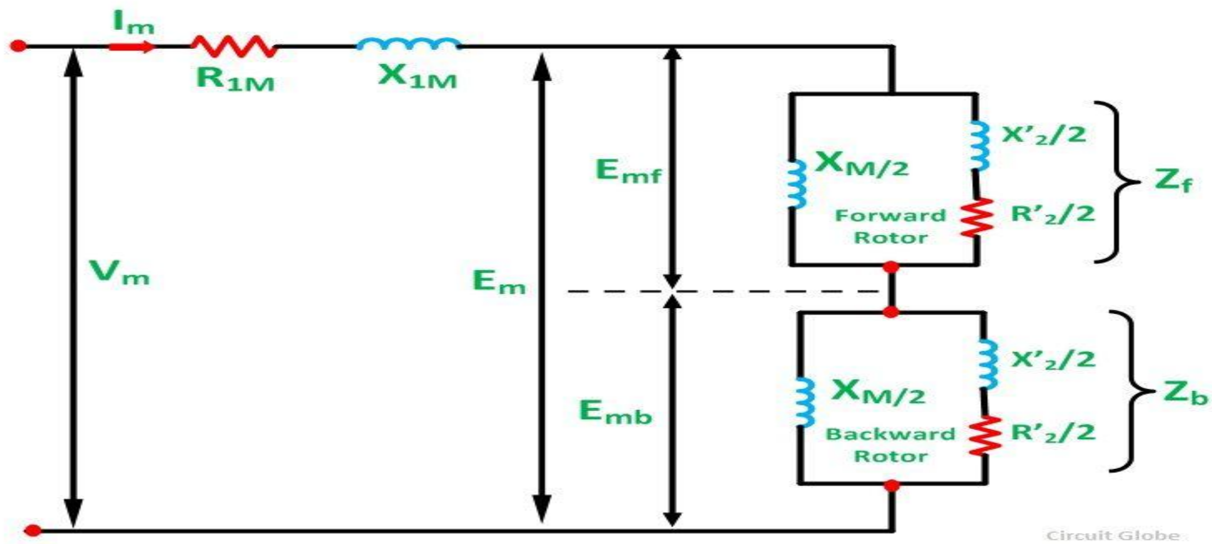

Fig. 12 **Equivalent Circuit of a Single Phase Induction Motor**

In most of the cases the core loss component r_0 is neglected as this value is quite large and does not affect much in the calculation. Here, Z_f shows the forward impedance and Z_b shows the backward impedance. Also, the sum of forward and backward slip is 2 so in case of backward slip, it is replaced by (2 – s).
R_1m = Resistance of stator winding.
X_{1m} = Inductive reactance of the stator winding.
X_m = Magnetising reactance.
R_2' = Rotor Reactance with referred to stator.
X_2' = Rotor inductive reactance with referred to stator.

Calculation of Power of Equivalent Circuit

1. **Find Z_f and Z_b.**
2. **Find stator current which is given by Stator voltage/Total circuit impedance.**

3. Then find the input power which is given by Stator voltage × Stator current × Cos(ϴ) Where, ϴ is the angle between the stator current and voltage.
4. Power Developed (P_g) is the difference between forward field power and backward power. The forward and backward power is given by the power dissipated in the respective resistors.
5. The rotor copper loss is given by- slip × P_g.
6. Output Power is given by- P_g – s × P_g – Rotational loss. The rotational losses include friction loss, windage loss, Core loss.
7. Efficiency can also be calculated by diving output power by input power.

Linear Induction Motor

A Linear Induction Motor (LIM) is an advanced version of rotary induction motor which gives a linear translational motion instead of the rotational motion. The stator is cut axially and spread out flat. In this type of motor, the stator and rotor are called primary and secondary respectively. The secondary of the linear induction motor consists of a flat aluminium conductor with a ferromagnetic core.

The poly phase rotator induction motor is shown below.

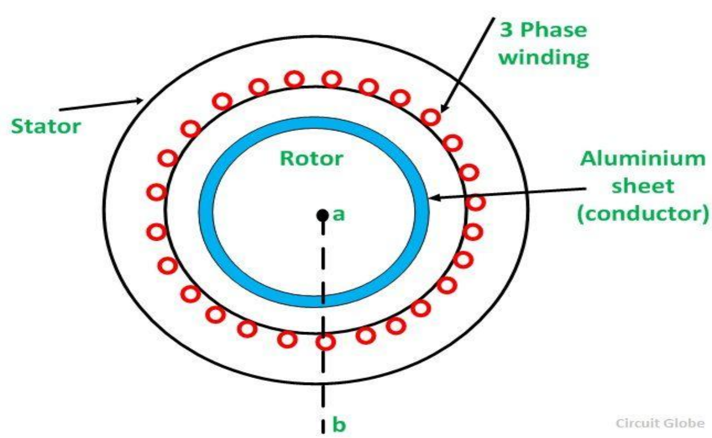

Fig.13 Poly phase rotor

If the stator is cut along the line ab and spread out flat the figure formed is shown below. This portion forms primary of the LIM.

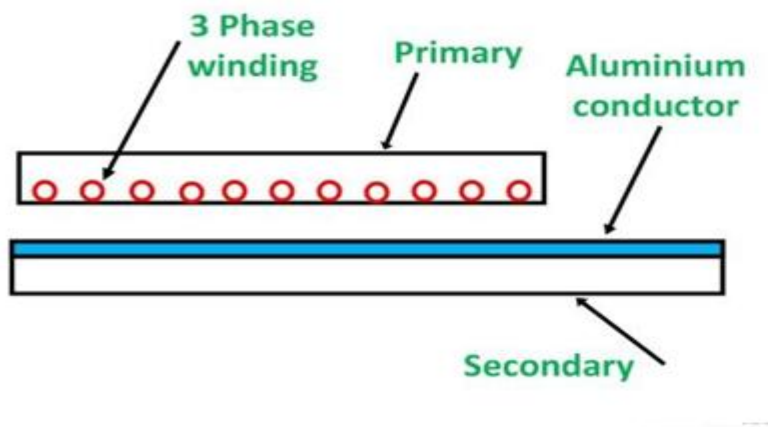

Fig.14 Linear Induction Motor

If a three phase supply is connected to the stator of an induction motor, a rotating flux is produced. This flux rotates at a synchronous speed in the air gap. Similarly, if the primary of the linear induction motor is connected to the three phase supply, a flux is produced which travel across the length of the primary. A current is generated in the conductor which is made of the aluminium material.

The current, which is induced in the linear induction motor interacts with the travelling flux produces a linear force. If secondary of the linear induction motor is fixed and the primary is free to move, the force will move the primary in the direction of the travelling wave.The double sided linear induction motor (DLIM) is shown in the figure below.

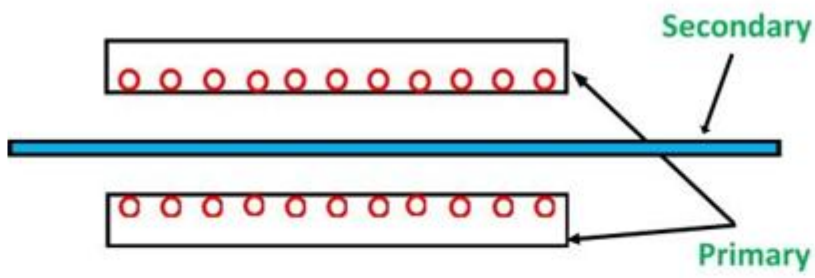

Fig.15 Double sided linear induction motor

The Double sided linear induction motor has primary on both the sides of the secondary.

Performance of the Linear Induction Motor

The linear synchronous speed of the travelling wave is given by the equation shown below.

$$v_s = 2f\,(\text{pole pitch})\,\frac{\text{m}}{\text{s}} \ldots\ldots..(1)$$

Where f is the supply frequency in hertz.

In the rotary induction motor, the speed of the secondary in the linear induction motor is less than the synchronous speed v_s and is given as

$$v_r = v_s\,(1 - s) \ldots\ldots..(2)$$

Where s is the slip of the linear induction motor and is given as

$$s = \frac{v_s - v_r}{v_s} \text{ pu} \quad \dots\dots\dots (3)$$

The linear force is given by the equation shown below.

$$F = \frac{\text{air gap power}}{\text{linear synchronous velocity } (v_s)}$$

The thrust velocity curve of the linear induction motor is similar to that of the speed torque curve of the rotary induction motor. It is shown in the figure below.

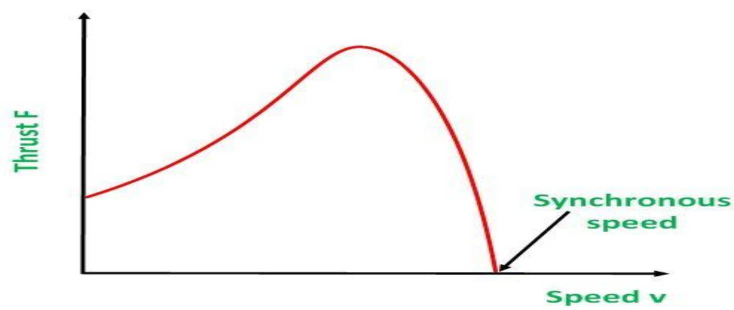

Fig.16 Speed – torque curve

If a rotary induction motor is compared with the linear induction motor, the LIM requires a larger air gap and hence, the magnetising current is greater and the power factor and efficiency of the motor are lower. In the rotary induction motor the stator and the rotor area are same whereas in the LIM the one of the two is shorter than the other. At the steady speed, the shorter part will be passing continuously over a new part of the other member.

Applications of the Linear Induction Motor

The various applications of the LIM are as follows:-

- **The main application of the LIM is in transportation and in electric traction system. The primary is mounted on the vehicle and the secondary is laid on the track.**
- **It is used in the cranes**
- **Pumping of liquid metals**
- **Actuators for the movement of doors**
- **Used in High voltage circuit breakers and also in accelerators.**

Universal motor

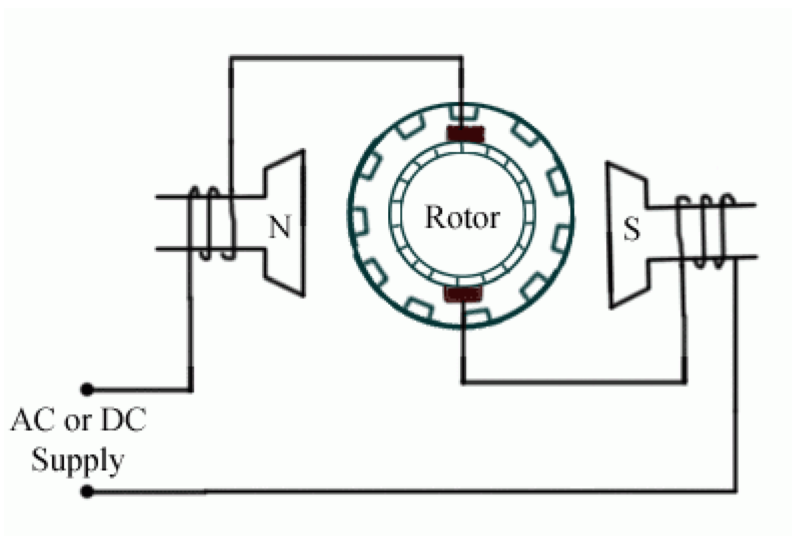

Fig.17 Universal motor

A universal motor is modified form of a DC motor and is widely used in home appliances like mixers and in machine tools. In this article I am discussing about working principle of universal motor.

If AC single phase supply is connected to a DC series motor, the motor gives circular rotation. During one-half cycle of current, it would pass through series winding as well as armature winding in a certain direction. Its magnitude, of course, would vary from

zero to maximum and then back to zero. Electromagnetic torque will be produced throughout this half cycle. This torque will act to produce rotation of the armature in the same direction throughout all of the half cycles.

Now during the next half cycle, the current through both the series winding as well as armature winding is reversed. Since current in both armature and field have been reversed, the torque developed in this half cycle will tend to produce rotation of armature in the same direction as throughout the preceding half cycle. It means the direction of the armature is a circular rotation type.

Torque in DC series motor, T α $\varphi_s I_a$

where φ_s is the series field winding flux and Ia is the armature current.

Also, T α $(-\varphi_s)(-I_a)$ for lower half cycle.

Or T α $\varphi_s I_a$

So a DC series motor, if connected to AC single phase supply produces a torque in same direction.

Construction of Universal Motor

The construction of universal motor is very similar to a two pole DC series motor. It consists two field coils wound on laminated core connected in series with armature. The iron structure of field, yoke and armature are laminated to reduce the eddy current losses. Such a motor is so designed that it can be operated either on AC or DC supply. For this reason, it is called a universal motor.

Universal Motor Working Principle

Since the field winding and the armature winding, both are connected is series, the same current passes through them when the motor is connected to either AC or DC supply.The magnetic fluxes of series field and armature produced by this current react with each other and, hence produce rotation. Because the series field magnetic flux and armature current reverse at the same time, the torque always acts in the same direction. Since universal motors are series wound, they have high starting torque. They run at dangerously high speed at no load. That is why they are always directly coupled to the device they derive.

Characteristics of Universal Motor

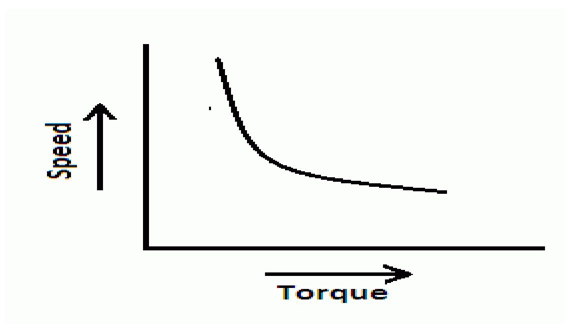

Fig.18 Characteristics of Universal Motor

- **Typical speed-torque characteristics of the universal motor have been shown in the figure. The torque varies as the square of current and speed varies inversely as the current approximately.**
- **Universal motors have high speed and large starting torque. They can, therefore, be used to derive high-speed vacuum cleaners, drills and machine tools etc.**
- **The efficiency will not be as good as that of corresponding DC machine because of greater eddy current loss and effects of p.f.**

AC series motors

They are also known as the modified DC series motor as their construction is very similar to that of the DC series motor. Before we discuss these modifications, here it is essential to discuss what is the need and where do we need to do modifications. In order to understand this, consider this question. What will happen when we give an AC supply to DC series motor? Answer to this question is written below:

1. **An AC supply will produce an unidirectional torque because the direction of both the currents (i.e. armature current and field current) reverses at the same time.**
2. **Due to presence of alternating current, eddy currents are induced in the yoke and field cores which results in excessive heating of the yoke and field cores.**
3. **Due to the high inductance of the field and the armature circuit, the power factor would become very low.**
4. **There is sparking at the brushes of the DC series motor.**

Now in order to reduce the eddy currents there is need to laminate the yoke and field coil. The power factor is directly related to reactance of the field and armature circuit and we can reduce the field winding reactance by reducing the number of turns in the field winding.

But there is one problem: on reducing the number of turns, field mmf will decrease and due to this the air gap flux decrease. The overall result of this is that there is an increase in the speed of the motor but decrease in the motor torque which is not desired. Now how to overcome this problem? The solution to this problem is the use of compensating winding. On the basis of the usage of compensating winding we have two types of motor and they are written below:

1. **Conductively compensated type of motors.**
2. **Inductively compensated type of motors.**

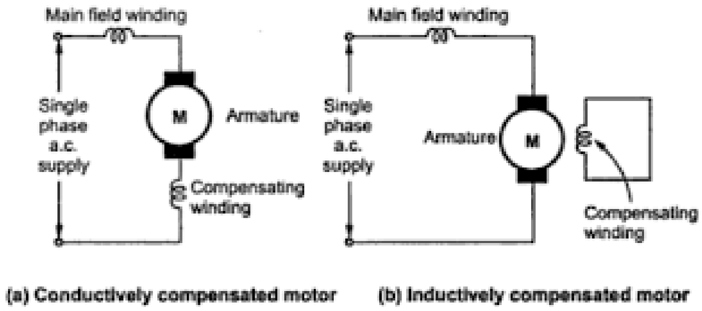

Fig.19 AC series motors

Conductively Compensated Type of Motors

In conductively compensated type of motors, the compensating winding is connected in series with the armature circuit. The winding is put in the stator slots. The axis of the compensating winding is 90^o (electrical) with main field axis.

Inductively Compensated Type of Motors

. In this type of motor, the compensating winding has no interconnection with the armature circuit of the motor. In this case, a transformer action will take place as the armature winding will act as primary winding of the transformer and the compensation winding will acts as a secondary winding. The current in the compensating winding will be in phase opposition to the current in the armature winding.

Given below is the complete schematic diagram of the single phase AC series motor with all the modifications (i.e. compensating winding and inter pole).

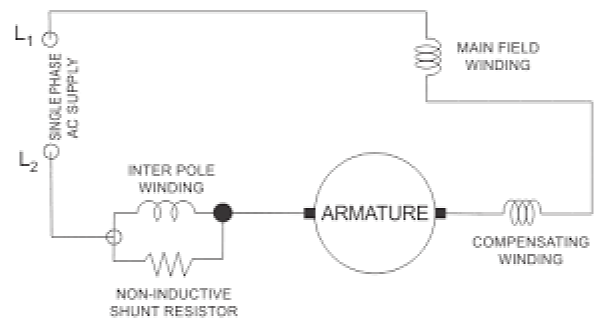

Fig.20 **Inductively Compensated Type of Motors**

Speed control of this type of motor is best obtained by solid state device. The motor has numerous applications such as portable drills, hair dryers, table fans, kitchen appliances, etc. We have already discussed the advantage of having compensating winding. Let us discuss what is the use of the inter pole? The main function of the inter poles is to improve the performance of the motor in terms of higher efficiency and a greater output from the given size of the armature core. We have taken very high reactive voltage drop of series field as compared to either armature or the compensating field in order to reduce the series filed inductance. The winding of the inter pole circuit is connected in parallel with the non inductive shunt .

AC SERVO MOTOR

A servo motor is one of the widely used variable speed drives in industrial production and process automation and building technology worldwide.

Although servo motors are not a specific class of motor, they are intended and designed to use in motion control applications which require high accuracy positioning, quick reversing and exceptional performance.

A servo motor is a linear or rotary actuator that provides fast precision position control for closed-loop position control applications. Unlike large industrial motors, a servo motor is not used for continuous energy conversion.Servo motors have a high speed response due to low inertia and are designed with small diameter and long rotor length.

Servo motors work on servo mechanism that uses position feedback to control the speed and final position of the motor. Internally, a servo motor combines a motor, feedback circuit, controller and other electronic circuit.

Servo motors

It uses encoder or speed sensor to provide speed feedback and position. This feedback signal is compared with input command position (desired position of the motor corresponding to a load), and produces the error signal (if there exist a difference between them).

The error signal available at the output of error detector is not enough to drive the motor. So the error detector followed by a servo amplifier raises the voltage and power level of the error signal and then turns the shaft of the motor to desired position.

Types of Servo Motors

Basically, servo motors are classified into AC and DC servo motors depending upon the nature of supply used for its operation. Brushed permanent magnet DC servo motors are used for simple applications owing to their cost, efficiency and simplicity.

These are best suited for smaller applications. With the advancement of microprocessor and power transistor, AC servo motors are used more often due to their high accuracy control.

AC Servo Motors

AC servo motors are basically two-phase squirrel cage induction motors and are used for low power applications. Nowadays, three phase squirrel cage induction motors have been modified such that they can be used in high power servo systems.

The main difference between a standard split-phase induction motor and AC motor is that the squirrel cage rotor of a servo motor has made with thinner conducting bars, so that the motor resistance is higher.

Based on the construction there are two distinct types of AC servo motors, they are synchronous type AC servo motor and induction type AC servo motor.

Synchronous-type AC servo motor consist of stator and rotor. The stator consists of a cylindrical frame and stator core. The armature coil wound around the stator core and the coil end is connected to with a lead wire through which current is provided to the motor.

The rotor consists of a permanent magnet and hence they do not rely on AC induction type rotor that has current induced into it. And hence these are also called as brushless servo motors because of structural characteristics.

When the stator field is excited, the rotor follows the rotating magnetic field of the stator at the synchronous speed. If the stator field stops, the rotor also stops. With this permanent magnet rotor, no rotor current is needed and hence less heat is produced.

Also, these motors have high efficiency due to the absence of rotor current. In order to know the position of rotor with respect to stator, an encoder is placed on the rotor and it acts as a feedback to the motor controller.

The induction-type AC servo motor structure is identical with that of general motor. In this motor, stator consists of stator core, armature winding and lead wire, while rotor consists of shaft and the rotor core that built with a conductor as similar to squirrel cage rotor.

The working principle of this servo motor is similar to the normal induction motor. Again the controller must know the exact position of the rotor using encoder for precise speed and position control.

Working Principle of AC Servo Motor

The schematic diagram of servo system for AC two-phase induction motor is shown in the figure below. In this, the reference input at which the motor shaft has to maintain at a certain position is given to the rotor of synchro generator as mechanical input theta. This rotor is connected to the electrical input at rated voltage at a fixed frequency.

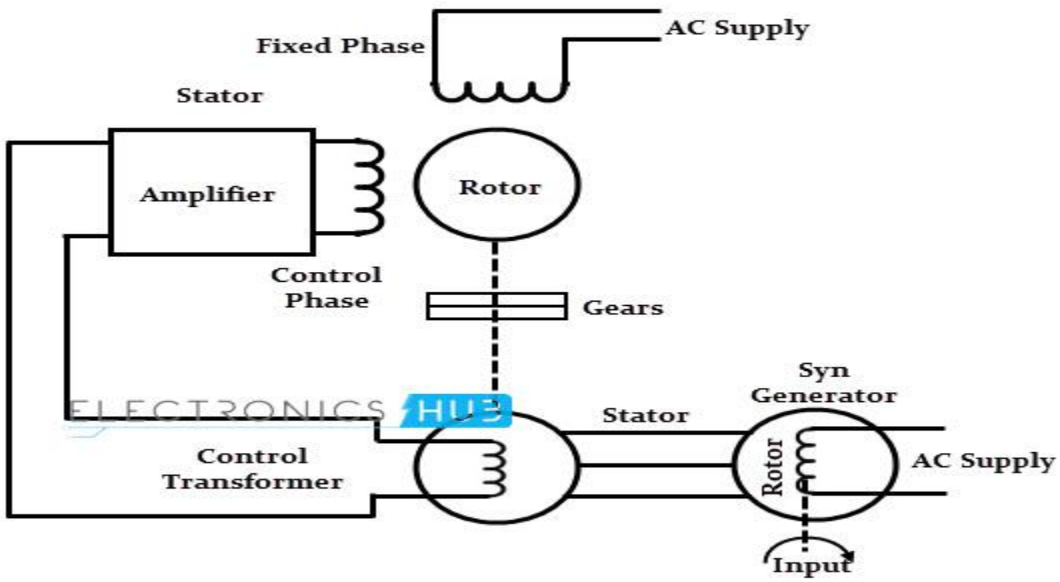

Fig.21 AC Servo Motors

The three stator terminals of a synchro generator are connected correspondingly to the terminals of control transformer. The angular position of the two-phase motor is transmitted to the rotor of control transformer through gear train arrangement and it represents the control condition alpha.

Initially, there exist a difference between the synchro generator shaft position and control transformer shaft position. This error is reflected as the voltage across the control transformer. This error voltage is applied to the servo amplifier and then to the control phase of the motor.

With the control voltage, the rotor of the motor rotates in required direction till the error becomes zero. This is how the desired shaft position is ensured in AC servo motors.

Alternatively, modern AC servo drives are embedded controllers like PLCs, microprocessors and microcontrollers to achieve variable frequency and variable voltage in order to drive the motor.

Mostly, pulse width modulation and Proportional-Integral-Derivative (PID) techniques are used to control the desired frequency and voltage. The block diagram of AC servo motor system using programmable logic controllers, position and servo controllers is given below.

Hysteresis Motor

Hysteresis motor is defined as a synchronous motor that is having cylindrical rotor and works on hysteresis losses induced in the rotor of hardened steel with high retentivity. It is a single phase motor and its rotor is made of ferromagnetic material with non magnetic support over the shaft.

Hysteresis Motor Construction

A hysteresis motor is constructed of five main components:

1. **Stator**
2. **Single phase stator winding**
3. **Rotor**
4. **Shaft**
5. **Shading coil**

The two most important components of the hysteresis motor are the stator and rotor:

- **Stator: Stator of hysteresis motor is designed in a particular manner to produce synchronous revolving field from single phase supply. Stator carries two**

windings, (a) main winding (b) auxiliary winding. In another type of design of hysteresis motor the stator holds the poles of shaded type.

- **Rotor: Rotor of hysteresis motor is made of magnetic material that has high hysteresis loss property. Example of this type of materials is chrome, cobalt steel or alnico or alloy. Hysteresis loss becomes high due to large area of hysteresis loop.**

  Rotor does not carry any winding or teeth. The magnetic cylindrical portion of the rotor is assembled over shaft through arbor of non magnetic material like brass.

  Rotor is provided with high resistance to reduce eddy current loss.

Working Principle of Hysteresis Motor

Starting behavior of a hysteresis motor is like a single phase induction motor and running behavior is same as a synchronous motor. Step by step its behavior can be realized in the working principle that is given below.

t the Starting Condition

- **When stator is energized with single phase AC supply, rotating magnetic field is produced in stator.**
- **To maintain the rotating magnetic field the main and auxiliary windings must be supplied continuously at start as well as in running conditions.**
- **At the starting, by induction phenomenon, secondary voltage is induced in the rotor by stator rotating magnetic field. Hence eddy current is generated to flow in the rotor and it develops rotor.**
- **Thus eddy current torque is developed along with the hysteresis torque in the rotor. Hysteresis torque in the rotor develops as the rotor magnetic material is with high hysteresis loss property and high retentivity.**
- **The rotor goes under the slip frequency before going to the steady state running condition.**
- **So it can be said that when the rotor starts to rotate with the help of these eddy current torque due to induction phenomenon, it behalves like a single phase induction motor.**

At Steady State Running Condition

- **When the speed of the rotor reaches near about the synchronous speed, the stator pulls the rotor into synchronism.**
- **At the condition of synchronism, the relative motion between stator field and rotor field vanishes. So there is no further induction phenomenon to continue. Hence no eddy current to generate in the rotor. Thus the torque due to eddy-currents vanishes.**
- **At the time of rotor's rotation at the synchronous speed, rotating magnetic field flux in the stator produces poles on the rotor by induction; they are named as north (N) and south (S) poles. Thus rotor behaves as a permanent magnet having rotor axis as the induced magnetic axis.**
- **For high residual magnetism or retentivity the rotor pole strength remains sustainable or unchanged. Again higher the retentivity, higher is the hysteresis torque and the hysteresis torque is independent of the rotor speed always. The high retentivity enables the continuous magnetic locking between stator and rotor and thus the motor rotates at synchronous speed.**
- **The maximum work done to establish the hysteresis losses under the magnetization cycle in the rotor is equal to the surface area inside B-H hysteresis curve.**
- **In lower load torque, the needed work done to rotate the rotor is equal to maximum magnetizing work of hysteresis phenomenon available already in the rotor. So induced magnetic pole axis always follows the rotating magnetic field axis of stator without any lag angle.**
- **But when the load torque is sufficiently high, the maximum magnetizing work in rotor by hysteresis phenomenon cannot fulfill the work done needed to rotate the rotor.**
- **So the induced magnetic field axis or rotor pole axis lags the rotating magnetic field axis of the stator at an angle δ_h. Hence the rotor pole axis tries to catch up the stator magnetic field axis.**
- **If the load torque is increased, this lagging angle will be increased up to δ_{max} before dropping below the synchronous condition.**

- **The rotor poles are attracted towards the moving stator poles and runs at synchronous speed.**

- **As there is no slip at steady state running condition, only hysteresis torque is present to keep the rotor running at synchronous speed and it behaves like a synchronous motor.**

What is Hysteresis Power Loss, P_h in Hysteresis Motor?

Hysteresis power loss in the rotor of the hysteresis motor is given by

Where,

f_r is the frequency of flux reversal in the rotor (Hz)
B_{max} is the maximum value of flux density in the air gap (T)
P_h is the heat-power loss due to hysteresis (W)
k_h is the hysteresis constant. Hysteresis torque is independent of frequency and speed.

Types of Hysteresis Motors

There are various types of hysteresis motor by construction. They are:

1. **Cylindrical hysteresis motors: It has cylindrical rotor.**
2. **Disk hysteresis motors: It has annular ring shaped rotor.**
3. **Circumferential-Field hysteresis motor: It has rotor supported by a ring of non magnetic material with zero magnetic permeability.**
4. **Axial-Field hysteresis motor: It has rotor supported by a ring of magnetic material with infinite magnetic permeability.**

Advantages of Hysteresis Motor

The main advantages of hysteresis motor are given below:

- **As no teeth and no winding in rotor, no mechanical vibrations take place during its operation.**
- **Its operation is quiet and noiseless as there is no vibration.**
- **It is suitable to accelerate inertia loads.**
- **Multi-speed operation can be achieved by employing gear train.**

Disadvantages of Hysteresis Motor

The disadvantages of hysteresis motor are given below:

- **Hysteresis motor has poor output that is one-quarter of output of an induction motor with same dimension.**
- **Low efficiency**
- **Low torque.**
- **Low power factor**
- **This type of motor is available in very small size only.**

Applications of Hysteresis Motor

Hysteresis motors have many applications, including:

1. **Sound producing equipments**
2. **Sound recording instruments**
3. **High quality record players**
4. **Timing devices**
5. **Electric clocks**
6. **Teleprinters**

Repulsion Motor

A motor is an electrical device that converts electrical input into mechanical output, where electrical input can be in current or voltage form and the mechanical output can be in torque or force form. Motor consist of two main parts namely stator and rotor, where the stator is a stationary part of the motor and the rotor is a rotatory part of the motor. A motor that works on the principle of repulsion is known as a repulsion motor, where the repulsion takes place between two magnetic fields of either stator or a rotor. Repulsion motor is a single-phase motor.

Definition: A repulsion motor is a single-phase electric motor that operates by providing input AC (alternating current). The main application of repulsion

motor is electric trains. It starts as a repulsion motor and runs as an induction motor, where the starting torque should be high for repulsion motor and very good running characteristics for induction motor.

Construction of Repulsion Motor

It is a single-phase AC motor, which consists of a pole core that is the north pole and south pole of a magnet. The construction of this motor is similar to the split-phase induction motor and DC series motor. The rotor and stator are the two main components of the motors which are inductively coupled. The field winding (or a distributed type winding or the stator) is similar to the main winding of the split-phase induction motor. Hence the flux is evenly distributed and the gap between stator and rotor is decreased and the reluctance is also decreased, which in turn improves the power factor.

The rotor or armature is similar to the DC series motor which is provided with a drum-type winding connected to the commutator, where the commutator is in-turn connected to carbon brushes which are short-circuited. A brush holder mechanism provides variable crankshaft to change the direction or alignment of brushes along the axis. Hence the torque produced during this process helps to control the speed. The energy in the repulsion motor is transferred through the transformer action or by the induction action (where the emf is transferred between stator to the rotor).

Working Principle

Repulsion motor works on the principle of repulsion where two poles of a magnet repel. The working principle of repulsion motor can be explained from 3 cases of α, depending on the position of the magnet as follows.

Case(i) : When $\alpha = 90^0$

Assume brushes 'C and D' are aligned vertically at 90 degrees and rotor aligned horizontally along the d-axis (field axis) which is the direction of current flow. From the principle of Lenz's law, we know that the emf induced mainly depends on the stator flux and the current direction (which is based on the alignment of brushes). Therefore, the net emf of brush from 'C to D' is '0' as shown in the diagram, which is represented as 'x' and '.' there is no current flow in the rotor, so Ir = 0. When no current passes in

the rotor, then it acts as an open-circuited transformer. Therefore, stator current Is = less. The direction of the magnetic field is in along brush axis direction, where the stator and rotor field axis are 180 degrees phase-shifted, the torque generated is '0' and the mutual induction induced in the motor is '0'.

Case (ii) : When $\alpha = 0^0$

Now the brushes 'C and D' are oriented along the d-axis and are short-circuited. Therefore the net emf induced in the motor is very high, which generates the flux between windings. The net emf can be represented as 'x' and '.' as shown in the figure. It is similar to a short-circuited transformer. Where the stator current and the mutual induction are maxima which means Ir = Is = maximum. From the figure, we can observe that the stator and rotor fields are 180 degrees opposite in phase, which means the torque generated will oppose each other, so the rotor cannot rotate.

Graphical Representation

Practically this is a problem this can be shown in a graphical format, where the x-axis is represented as 'α' and the y-axis is represented as 'current'.

- **From the graph, we can observe that the current is directly proportional to α**
- **The current value is 0 when $\alpha = 90^0$ which is similar to open circuit transformer**
- **The current is maximum when $\alpha = 0^0$ which is similar to the short circuit transformer as shown in the graph.**
- **Where Is is the stator current.**
- **The torque equation can be given as Ґ α K I 2s N 2s Sin2 α.**
- **Practically it is observed that torque is maximum if α is ranging between 150 – 300.**

Classification of Repulsion Motor

There are three types of repulsion motor they are,

Compensated Type

It consists of an additional winding namely compensating winding and an additional pair of brushes are placed between the (short-circuited) brushes. Both compensating

winding and a pair of brushes are connected in series for improving the power and speed factors. A compensated type motor is used where there is required for high power at the same speed.

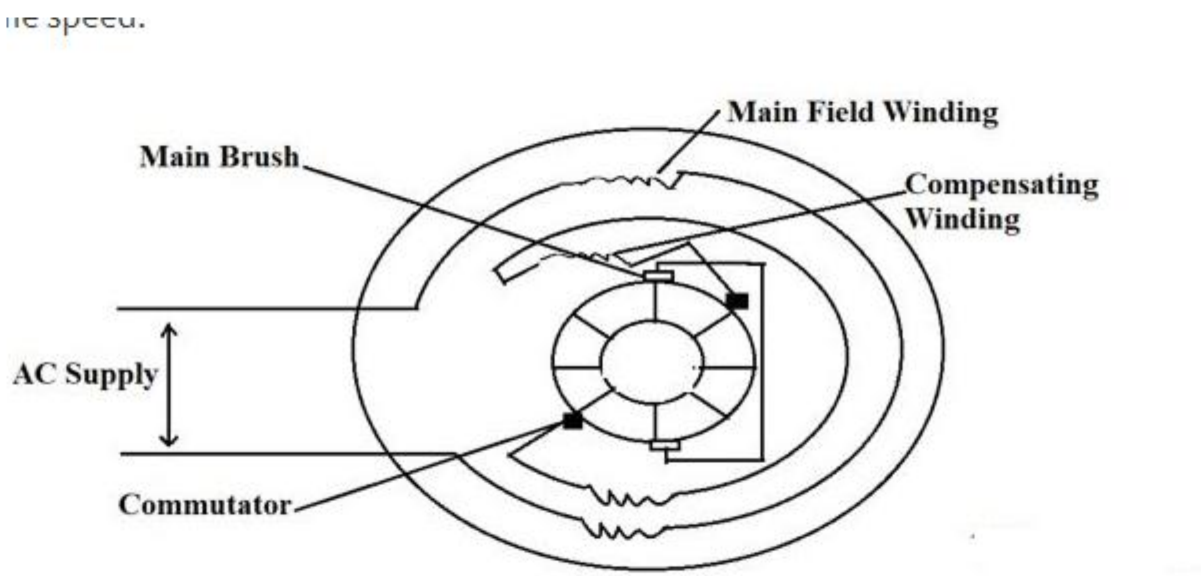

Fig.22 Compensated Type

Repulsion Start Induction Type

It starts with the repulsion of coils and runs with the induction principle, where speed is maintained constant. It has a single stator and rotor similar to DC armature and a commutator where a centrifuge mechanism short-circuits the commutator bars and has higher torque (6 times) than the current in the load. The operation of repulsion can be understood from the graph that is, when the frequency of synchronous speed increases, the percentage of full torque load starts decreasing, where at a point the magnet poles experience a repulsive force and switches into induction mode. Here we can observe the load that is inversely proportional to speed.

es into induction mode. Here we can observe the load that is inversel

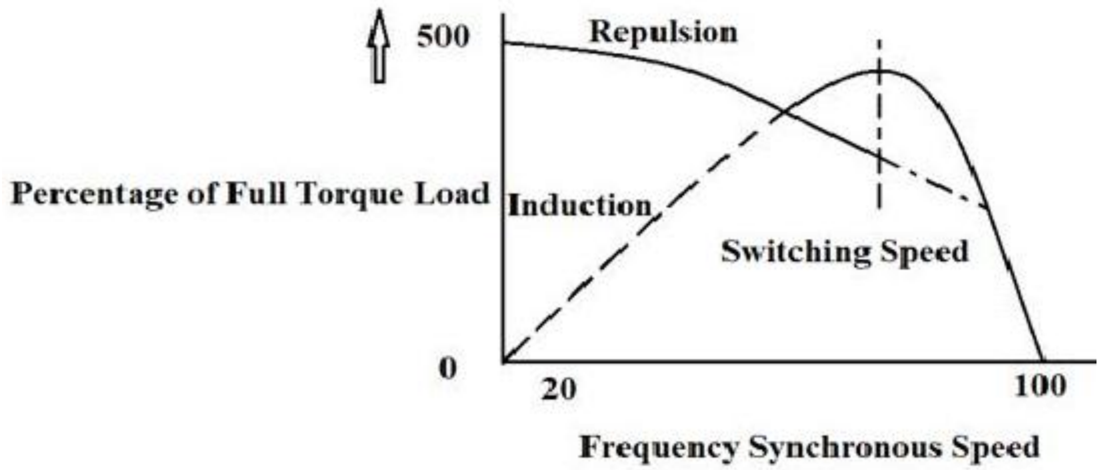

Fig. 23 Repulsion-start-induction-motor-graph

Repulsion-start-induction-motor-graph

Repulsion Type

It works on the principle of repulsion and induction, which consists of a stator winding, 2 rotors winding (where one is squirrel cage and other DC winding). These windings are shorted to commutator and two brushes. It operates in a condition where the load can be adjustable and whose starting torque is 2.5-3.

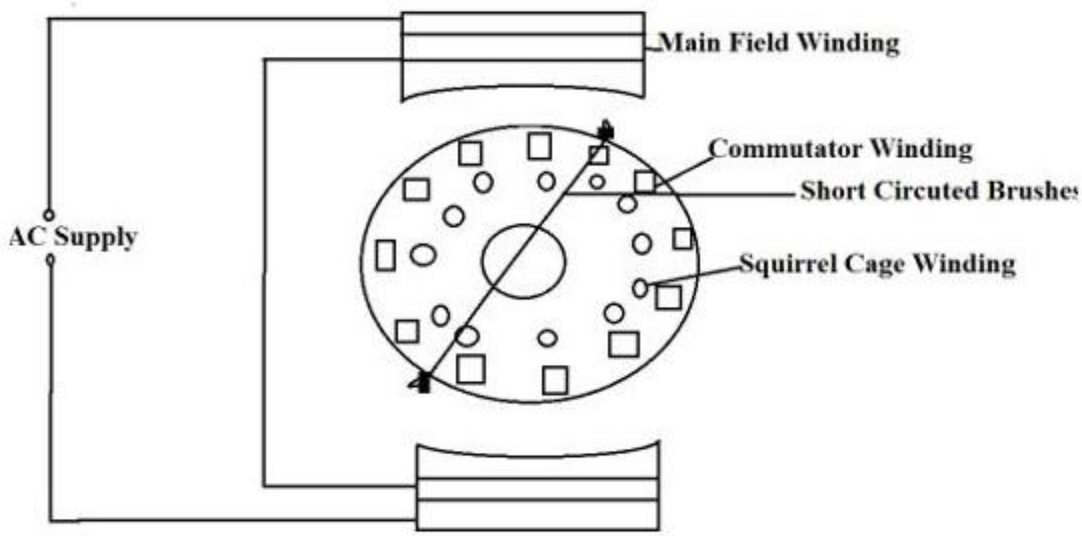

Fig. 24 Repulsion-type

Advantages

The advantages are

- **The high value of starting torque**
- **The speed is not limited**
- **By adjusting the value of 'α' we can adjust the torque, where we can increase the speed based on adjustment of torque.**
- **By adjusting the position brushes, we can control the torque and speed easily.**

Disadvantages

The disadvantages are

- **Speed varies with variation in the load**
- **The power factor is less except for high speeds**
- **The cost is high**
- **High maintenance.**

Applications

The applications are

- **They are used where there is a need for starting torque with high-speed equipment's**
- **Coil Winders: Where we can adjust speed flexibly and easily and direction can also be changed by reversing the brush axis direction.**
- **Toys**
- **Lifts etc.**

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