GOVERNMENT OF TAMILNADU
DIRECTORATE OF TECHNICAL EDUCATION
CHENNAI – 600 025

STATE PROJECT COORDINATION UNIT

Diploma in Electrical and Electronics Engineering

Course Code: 1030
M – Scheme

e-TEXTBOOK
on
ELECTRICAL MACHINES –II
for
IV Semester DEEE

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DIPLOMA IN ELECTRICAL AND ELECTRONICS ENGINEERING

M - SCHEME

Course Name: Diploma in Electrical and Electronics Engineering

Subject Code: 1030 **Semester:**

Subject Title: ELECTRICAL MACHINES -II

Rationale:

- This subject is classified under core technology group intended to teach students facts, concepts, Principles of electrical machines such as induction motor, alternator and synchronous motor.
- Student will be able to analyze the characteristics and qualitative parameters of these machines.
- These machines are widely used in industries and for generation of electricity.
- The knowledge gained by the student is useful in the study of technological subjects such as Utilization System, Manufacturing Processes and Testing and Maintenance of Electrical machines.
- The knowledge and skills obtained will be helpful in discharging technical functions such as Supervision, controlling and as R & D technician.

Objectives:

The students should be able to

- Alternator Principle, Construction, Types, EMF Induced and cooling
- Performance of an Alternator, Testing, Characteristics, parallel operation, Load sharing etc.,
- 3-Φ Induction Motor, Principle, Construction, Types, Characteristics and Applications, starting Methods
- 1-Φ Motor types, Construction, Characteristics and Applications Synchronous Motor, Starting, Construction, Characteristics and Applications
- Special AC machines and DC machines Construction, Characteristics and Applications

DETAILED SYLLABUS

1030 - ELECTRICAL MACHINES –II (M - SCHEME)

Unit -1 ALTERNATOR PRINCIPLES AND CONSTRUCTION Page no (5-51)

Basic principle of alternators – Types of alternators – Stationary armature rotating field – advantages of rotating field –Construction details of alternator – Salient pole rotor – Cylindrical type rotor – Types of A.C. armature windings – Types of slots –Full pitch and short pitched windings – Phase spread angle and effect of distribution factor – pitch factor – relation between frequency, speed and number of poles – EMF equation – Problems – methods of obtaining sine wave – Critical speed of rotor – Ventilation of turbo alternators – advantages of hydrogen cooling and its precaution – excitation and exciters.

Unit -2 ALTERNATOR PERFORMANCE AND TESTING Page no (52-85)

Load characteristics of alternators – reason for change in terminal voltage –Qualitative treatment of armature reaction for various power factor loads – effective resistance – leakage reactance – synchronous reactance, synchronous impedance – Voltage regulation – Determination of voltage regulation by synchronous impedance method (simple problems)- MMF method – potier method. Necessity and conditions for parallel operation of alternators – synchronizing by dark lamp method, bright lamp method ,dark - bright lamp method and synchroscope method– synchronizing current, synchronizing power and synchronizing torque – load sharing of alternators –infinite bus bar .

Unit -3 THREE PHASE INDUCTION MOTOR Page no (86-135)

Rotating magnetic field – Principle of operation of three phase induction motors – slip and slip frequency – comparison between cage and slip ring induction motors –development of phasor diagram – expression for torque in synchronous watts – slip-torque characteristics – stable and unstable region – no load test and blocked rotor test – development of approximate equivalent circuit – problems on the above topics – simplified circle diagram – determination of maximum torque, slip (problems not required) – starting torque and starting current expression – relationship between starting torque and full load torque – speed control of induction motors. Starters of induction motors – direct on line starter and its merits for cage motors – star delta starter- auto transformer starter -rotor resistance starter – cogging –crawling in induction motor– double cage induction motor-induction generator.

Unit-4 A) SINGLE PHASE INDUCTION MOTOR Page no (136-162)

single phase induction motors – not self starting – methods of making itself starting – construction, working principle –phasor diagram-slip torque characteristics- split phase motor - capacitor motor - shaded pole motor - repulsion motor – universal motor – operation of three phase motor with single phase supply.

B) SYNCHRONOUS MOTOR

Principle of operation –not self starting – methods of starting–effects of excitation on armature current and power factor– 'V' curve and inverted 'V" curve of synchronous motor – the phenomenon of hunting and prevention of hunting by damper winding – comparison between synchronous motor and three phase induction motor -applications -problems on power factor improvement.

Unit -5 A) SPECIAL AC MACHINES Page no (163-201)

Permanent magnet Synchronous motors – Construction and performance – Advantages – Applications –Synchros – Constructional features – Control Transmitter – Control receiver - Applications of synchros– A.C. Servo motors – Two phase A.C. Servo motor – Linear induction motor.

B) SPECIAL DC MACHINES

Permanent Magnet D.C. Motor – Construction–Working principle – Speed control – Advantages – Applications – Servo motors – D.C. Servomotors – Stepper motors – Variable reluctance stepper motor – Permanent magnet stepper motor.

UNIT I

ALTERNATOR PRINCIPLES AND CONSTRUCTION

1.1 Basic Principle of alternator:

Alternating current generators are usually called alternators. They operate on the principle of Faraday’s laws of electromagnetic induction. This law states that whenever a conductor cuts the magnetic flux an emf is induced in it. This emf causes a current to flow if the circuit is closed. Fig 1.1 shows a simple alternator.

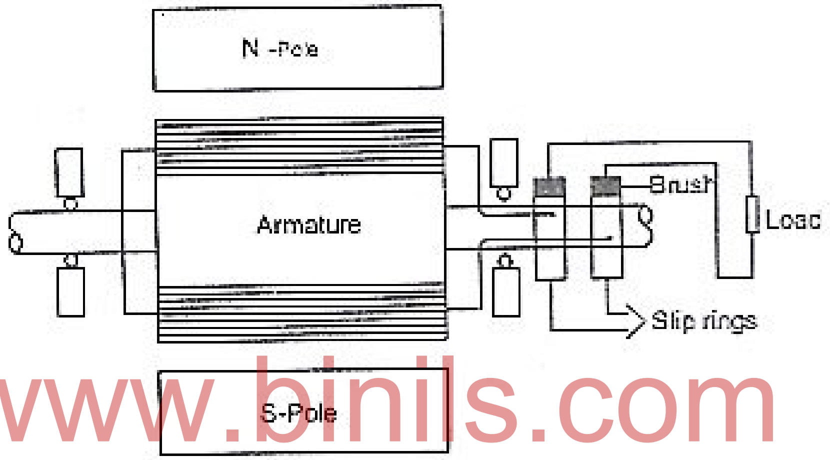


Fig 1.1

When a single turn coil rotates in a magnetic field at uniform speed, an emf is induced in it. These ends of the coil are connected to two slip rings. The induced emf can be tapped from the brushes. If the circuit is closed, a current flow through the circuit. This is the function of a simple alternator.

Fig 1.2 shows a coil rotating in clockwise direction. when the coli rotates in the field, the flux linked with it changes, thus an emf is induced. Which is proportional to the rate of change of flux linkage. At position 1, (where $\theta = 0^0$) the plane of the coil is at right angles to flux line, and the rate of change of flux linkages is minimum. In this position there is no induced emf in the coil.

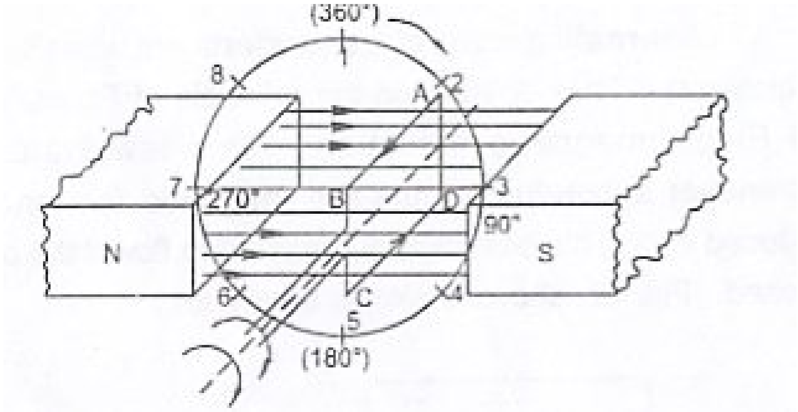


Fig 1.2

When the coil continuous rotating in the clockwise direction, the rate of change of flux linkage increases. At position 3 (where $\theta = 90^0$) the flux linked with the coil is minimum, but the rate of change of flux linkages is maximum.

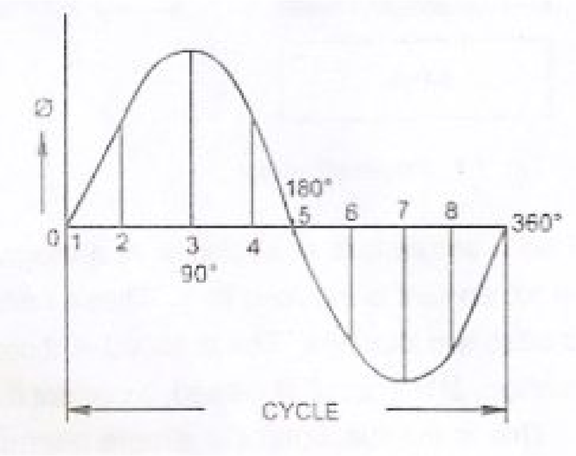


Fig 1.3

In the next quarter revolution from position 3 to position 5 (90^0 to 180^0) the flux linked with the coil gradually increases. But the rate of change of flux linkages decreases. Hence the induced emf is decreased gradually. At position 5 the emf is reduced to zero volt.

In the next half revolution, from position 5 to position 7 (180^0 to 360^0) the emf induced in the coil is in reverse direction. At position 7, negative maximum emf is induced and at position 1, minimum emf is induced. Thus an A.C emf is induced in the coil which is shown in fig 1.3

1.1.1Requirement of an Alternator:

As per the Faraday's laws of electromagnetic induction, **"whenever magnetic field is cut by a conductor an emf is induced."** Hence to produce emf, the following are required.

1. Magnetic field
2. Conductor
3. Relative motion between magnetic field and conductor

Conductors are housed in the armature slots.

1.2 Types of alternators:

To generate emf any one of the following methods may be used.

1. Stationary filed system with rotating armature
2. Stationary armature with rotating filed system

1.2.1 Revolving –armature type alternator

- It has stationary field poles and revolving armature
- It is usually of relatively small KVA capacity and low-voltage rating. It resembles a D.C generator in general appearance except that it has slip-rings instead of a commutator. The field current must be direct current and therefore, must be supplied from an external direct current source.

1.2.2 Revolving –field type alternator:

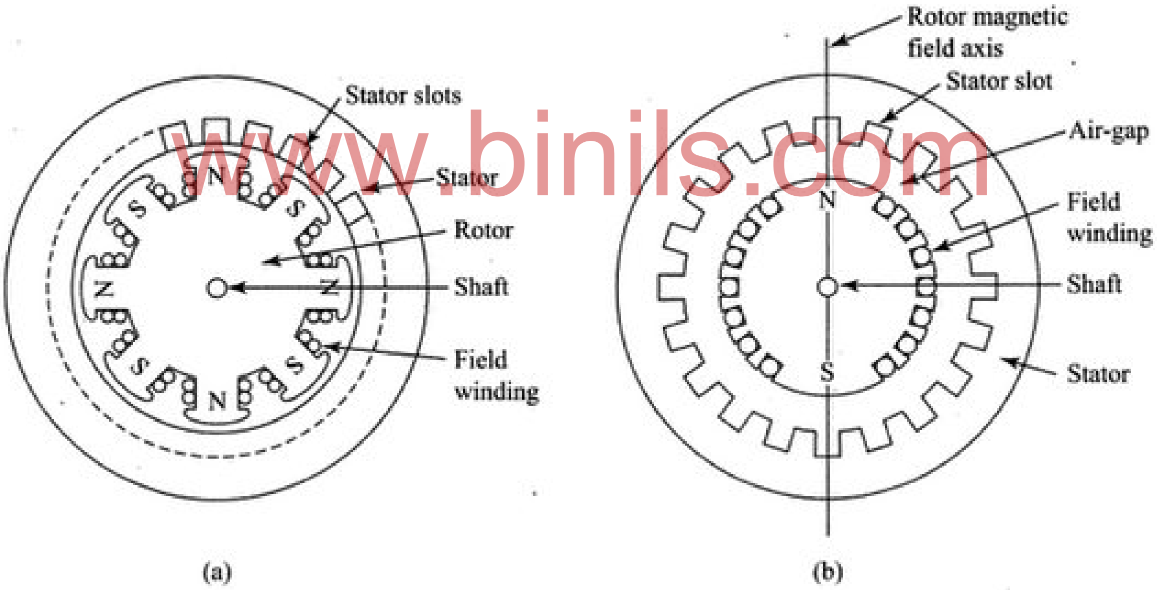
- It has a stationary armature or stator, inside of which the field poles rotate
- Most alternators are of the revolving –field type, in which the 'revolving –field structure' or 'rotor' has slip rings and brushes to supply the excitation current from on outside D.C source. The armature coils are placed in slots in a laminated core, called 'stator', which is

made up thin steel punchings or laminations securely clamped and held in place and the amount of power delivered to the field circuit is relatively small.

1.3 Advantages of stationary armature with rotating field systems:

1. For rotating field system, two slip rings are sufficient
2. Field voltage will be 110V / 220V /400V/1100V d.c. Hence, slip rings are easily insulated.
3. Current in the field system will be low. Hence, sparking in brushes will be less.
4. Field system is comparatively light weight. Hence, it can rotate fast.
5. For stationary armature conductors, coils can be easily placed in position.
6. Armature volts will be in the order of 440V, 3300V, 6600V ,11000V,22000V and 33000V Insulation of such voltage is easy in stationary armature conductors.
7. Being stationary armature conductors, there is no need for 3 or 4 slip rings.
8. Being stationary armature conductors, output current can be easily collected from the fixed terminals.
9. Armature system is of heavy weight. Hence, it is better to have stationary armature conductors.

1.4 Construction details of alternator:



(a) Salient pole alternator **(b) Cylindrical pole alternator**

Fig: 1.4

The main components of the synchronous alternator are the following

(a) Stator or armature

(b) Rotor or field magnet

1.4.1 Stator frame and stator core

The stator is a stationary armature. This consists of a core and the slots to hold the armature winding similar to the armature of a d.c. generator. The stator core uses a laminated construction. It is built up of special steel stampings insulated from each other with varnish or paper. The laminated construction is basically to keep down eddy current losses. Generally choice of material is steel to keep down hysteresis losses.

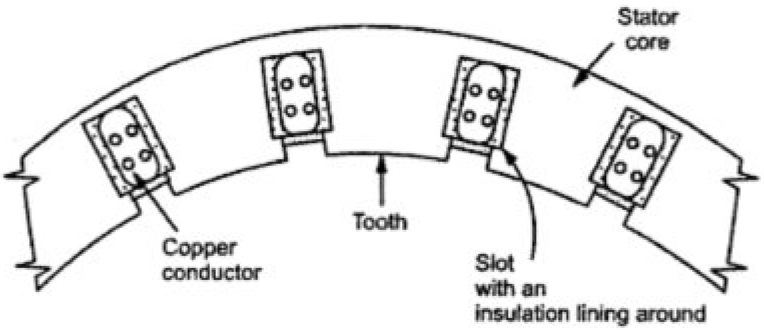


Fig. 1.5 Section of an alternator stator

The entire core is fabricated in a frame made of steel plates. The core has slots on its periphery for housing the armature conductors. Frame does not carry any flux and serves as the support to the core. Ventilation is maintained with the help of holes cast in the frame. The section of an alternators stator is shown in the Fig. 1.5

1.5 Types of rotor:

Two types of rotors are used in alternators

1. salient-pole type (Projecting pole rotor) and
2. Smooth-cylindrical type.(Non-salient pole)

1.5.1 Construction of Salient Pole Rotor:

It is used in low-and medium-speed alternators. It has a large number of projecting (salient) poles, having their cores bolted or dovetailed onto a heavy magnetic wheel of cast-iron, or steel of good magnetic quality (Fig.1.6).

Such generators are characterized by their large diameters and short axial lengths. **The poles and pole-shoes are laminated to minimize heating due to eddy currents.** In large machines, field windings consist of rectangular copper strip wound on edge.

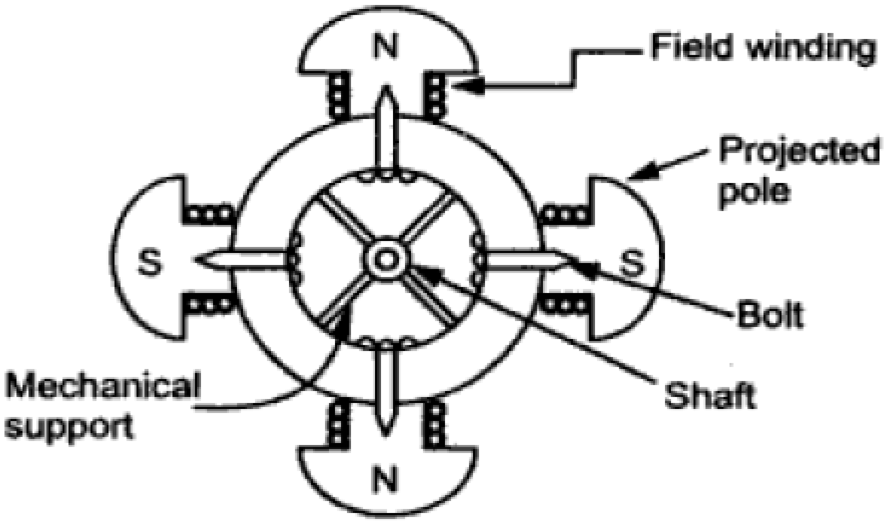


Fig1.6 Salient Pole Rotor

1.5.2 Construction of Cylindrical Type rotor:

It is used for steam turbine-driven alternators i.e. turbo alternators, which run at very high speeds. The rotor consists of a smooth solid forged steel cylinder, having a number of slots milled out at intervals along the outer periphery for accommodating field coils.

Such rotors are designed mostly for 2-pole (or 4-pole) turbo-generators running at 3000 r.p.m. (or 1500 r.p.m.). Fig.1.7 shows the structure of the cylindrical rotor.

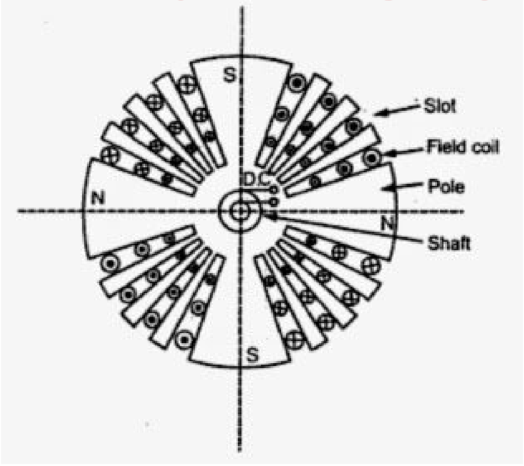


Fig. 1.7 cylindrical pole rotor

1.5.3 Comparison of Salient Pole rotor and cylindrical rotor:

S.No	Salient Pole Rotor	Cylindrical Rotor
1	Rotor is having projecting pole	Rotor is having no projecting pole
2	Rotor causes speed fluctuation	Rotor causes no speed fluctuation
3	Damper winding is provided	No need for damper winding
4	Suitable for low and medium speed operation	Suitable for high speed operation
5	Large diameter and short axial length	Small diameter and long axial length
6	Windage loss is more	Windage loss is less
7	Air gap is non-uniform	Air gap is uniform due to smooth cylindrical periphery
8	Prime mover used are water turbine, I.C engines	Prime movers used are steam turbines, electric motors.

Common Terminologies associated with ac windings

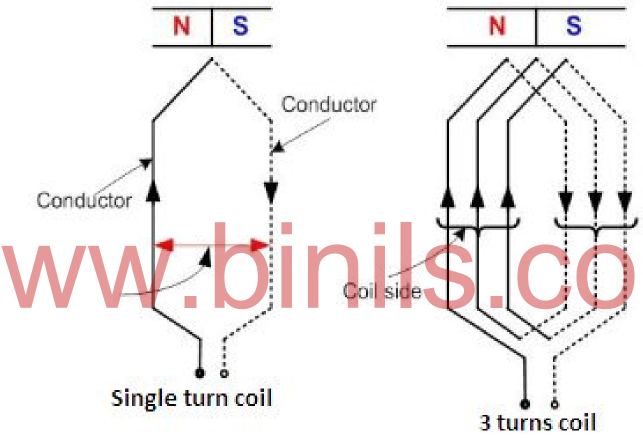


Fig 1.8

Conductor: The active length of a wire or strip in the slot.

Turn: One turn consists of two conductors.

Coil: A coil may consist of a single turn or may consist of many turns,fig:1.8 placed in almost similar magnetic position, connected in series.

Coil-Side: A coil consists of two coil sides, which are placed in two different slots, which are almost a pole pitch apart. The group of conductors on one side of the coil form one coil side while the conductors on the other side of the coil situated a pole pitch (or approximately a pole pitch apart) forms the second coil side.

Pole pitch: The distance between the centers of two adjacent poles is called pole pitch. Pole pitch is always equal to 180^{o}

Coil pitch or coil span: It is the distance between the two coil sides of a coil.

A.C. Armature winding:

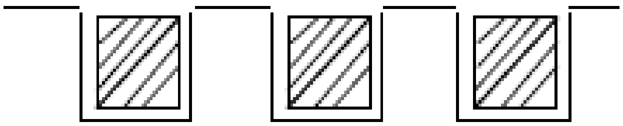
In ac machine, the alternating emf is induced in stator armature winding. The armature winding in a dc machine is closed and the closed windings are always double layer type. The winding used for armature in AC machine is open. The open winding can be either single layer or double layer type.

1.6 Types of A.C Armature windings:

1. **Single layer winding**
2. **Double layer winding**

1.6.1 Single layer winding

- Single- layer winding
  - ✓ One coil-side occupies the total slot area fig:1.9
  - ✓ Used only in small ac machines



one coil-side per slot

Fig 1.9

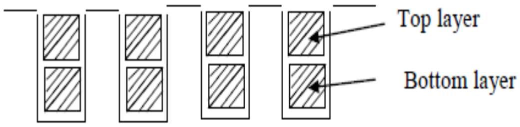
Types of single layer windings

The three most common types of single layer windings are

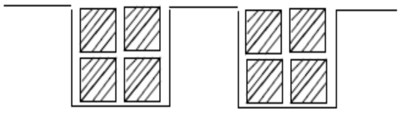
1. Concentric windings (Unequal coil span)
2. Chain windings (Equal coil span)
3. Mush windings (Equal coil span)

1.6.2 Double layer winding

- Slot contains even number (may be 2,4,6 etc.) of coil-sides in two layers fig:1.10
  - Double-layer winding is more common above about 5kW machines



Two coil –sides per slot



4-coil-sides per slot

Fig: 1.10

1.6.3 The advantages of double-layer winding over single layer winding are as follows:

- Easier to manufacture and lower cost of the coils
- Fractional-slot winding can be used
- Chorded-winding is possible
- Lower-leakage reactance and therefore , better performance of the machine
- Better emf waveform in case of generators

The windings used in rotating electrical machines can be classified as

1.6.4 (i) Concentrated Windings

All the winding turns are wound together in series to form one multi-turn coil. All the turns have the same magnetic axis

Examples of concentrated winding are

- ✓field windings for salient-pole synchronous machines
- ✓D.C. machines
- ✓Primary and secondary windings of a transformer

1.6.5 (ii) Distributed Windings

All the winding turns are arranged in several full-pitch or fractional-pitch coils .These coils are then housed in the slots spread around the air-gap periphery to form phase or commutator winding

Examples of distributed winding are

- ✓ Stator and rotor of induction machines

1.7 Types of Slots:

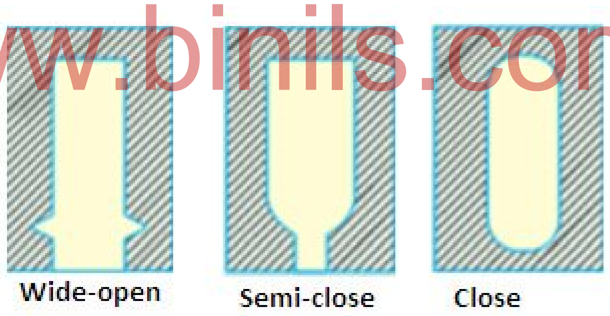


Fig 1. 11

Different shapes of armature slots are shown in Fig 1.11.The shape of the slots provided depends upon that type of winding used. Mainly they are classified into three.

1. Wide open type slots

In this type of slots, the windings can be easily done and it is easily removed in the case of repair. But it has the disadvantage of distributing the air-gap flux into bunches. Which produce ripples in the emf wave.

2. Semi closed type slot

This type of slots is better than open type in some aspects. But former wound coils are not suitable for this type of slots.

3. Closed type slots

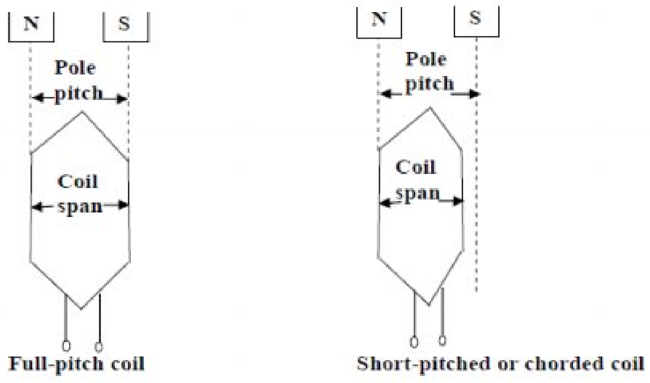
This type of slots does not disturb the air-gap flux. But they tend to increase the inductance of the windings. The armature winding has to be threaded through the slots. Hence the cost of labour and winding will be increased. The end connection of the armature winding is also completed. Hence they are rarely used.

1.8 Full pitch winding and short pitch winding

If the coil-span (or coil-pitch) is **equal** to the pole-pitch, then the coil is termed a **full-pitch coil**.fig:1.1.2a

Short pitched winding or Fractional pitched winding or chorded pitched winding fig:1.2.b

In case the coil-pitch is **less** than pole-pitch, then it is called **chorded**, **short-pitch** or **Fractional-pitch coil**



A **Fig: 1.12** **B**

1.8.1 Advantages of Chorded pitch or Short Pitch Windings:

1. Saving of copper in winding

2. Reduction of cost in winding

3. To improve the wave form of EMF. The generated EMF can be made to approximate sine wave

4. Harmonics are reduced

5. Mechanical strength of coil is increased.

6. Due to elimination of high frequency harmonics, Eddy current and hysteresis losses are reduced, thereby increasing the efficiency.

1.9 Phase Spread:

The phase spread of a winding is the proportion of circumference of armature occupied by one phase. This is normally expressed in electrical degree.

1.9.1 Slot angle: (β)

The angular displacement between any two adjacent slots in electrical degree is said to be slot angle.

$$\text{Slot angle } (\beta) = \frac{180^\circ}{\text{number of slots /pole}}$$

1.10. Pitch Factor:

The pitch factor or coil-span factor k_p or k_c is defined as

$$= \frac{\text{Vector sum of the induced emf per coil}}{\text{arthimetic sum of the induced emf per coil}}$$

It is always less than unity

Let E_S be the induced emf. in each side of the coil. If the coil were full-pitched i.e. if its two sides were one pole-pitch apart, then total induced emf in the coil would have been = $2E_S$ [Fig.1.12 (a)] If it is short-pitched by 30° (elect.) then as shown in Fig. 1.13 (b), their resultant is E which is the vector sum of two voltage 30° (electrical) apart.

$$\therefore E = 2E_s \cos\frac{30^\circ}{2} = 2E_s \cos 15^\circ$$

$$k_c = \frac{vector\,sum}{arthimetic\,sum} = \frac{E}{2E_s} = \frac{2E_s \cos 15^\circ}{2E_s} = \cos 15^\circ = 0.966$$

Hence pitch factor K_C is 0.966

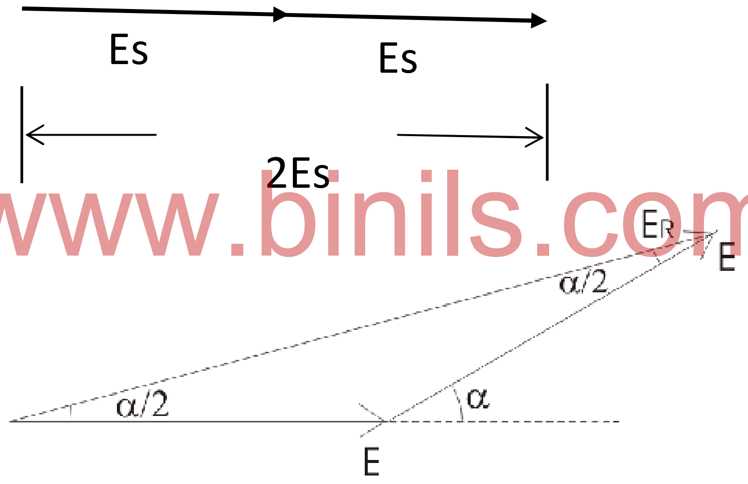


Fig1.13

In general, if the coil span falls short of full-pitch by an angle (electrical)*, α , then $k_c = \cos\frac{\alpha}{2}$

*This angle is known as chording angle and the winding employing short-pitched coils is called chorded winding.

1.10. Distribution or Breadth Factor or Winding Factor or Spread Factor:

When the coils comprising a phase of the winding are distributed in two or more slots per pole, the emf's in the adjacent coils will be out of phase with respect to one another and their resultant will be less than their algebraic sum.

The ratio of the vector sum of the e.m.f's induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the e.m.f's induced(or to the resultant of the e.m.f's induced in all the coils concentrated in one slot under one pole) is known as distributed factor kd.

$$K_d = \frac{e.m.f\ induced\ \ in\ \ a\ \ distributed\ \ winding}{e.m.f\ \ induced\ \ if\ \ the\ \ winding\ \ would\ \ have been\ \ concentrated}$$

$$k_d = \frac{vector\,sum}{arthimetic sum}$$

The distribution factor is always less than unity.

Let n = number of slots/pole

m = number of slots /pole/phase

E_s = induced emf in each coil side

β= angular displacement between the slots = $\frac{180^\circ}{n}$

mβ= phase spread angle

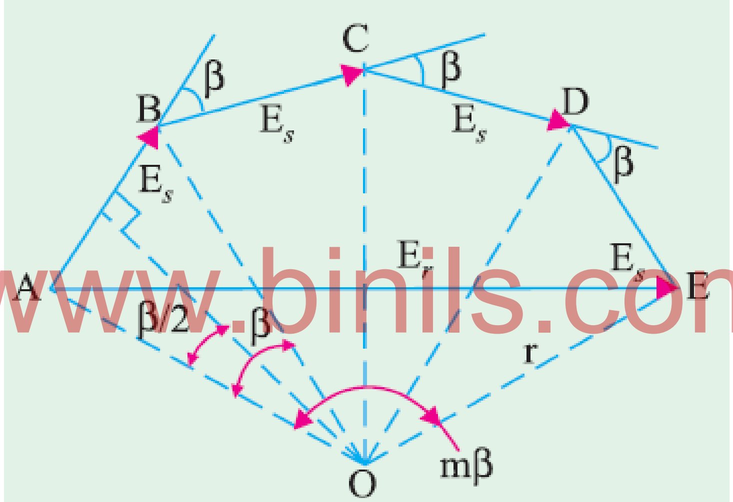


Fig 1.14

Then, the resultant voltage induced in one polar group would be mE_S . Where E_S is the voltage induced in one coil side. Fig. 1.14 illustrates the method for finding the vector sum of m voltages each of value E_S and having a mutual phase difference of β (if m is large, then the curve ABCDE will become part of a circle of radius r).

$$AB = E_s = 2r\sin\frac{\beta}{2}$$

$$Arthimetic\,sum\ \ \ is = mE_s = m\times 2r\sin\frac{\beta}{2}$$

Their vector sum = AE = $E_r = 2r\sin\frac{m\beta}{2}$

$$k_d = \frac{vector\ \ sum\ \ of\ \ coil\ \ emf's}{arithimetic\ \ sum\ \ of\ \ coil\ \ emf's}$$

$$k_d = \frac{2r \sin m\beta/2}{m \times 2r \sin \beta/2} = \frac{\sin m\beta/2}{m \sin \beta/2}$$

1.10 .Effect of the Coil span factor and distribution factor on the output and wave form on Alternator:

1.10.1 Coil Span Factor:

At the fundamental frequency this factor is $k_p = \cos\frac{\alpha}{2}$, where α is the angle in electrical degrees by which the span of the coil is less than a pole pitch.

The output at the fundamental frequency is reduced in the same ratio as this factor. The nth harmonic is reduced in the ratio $k_{pn} = \cos\frac{n\alpha}{2}$. **Short-chording can thus be used to reduce or eliminate troublesome harmonics.**

1.10.2 Distribution factor:

The effect of the distribution factor on the output of an alternator is to reduce it by an amount depending on the spread of the winding.

The vector sum of the coil emf's is less than their arithmetic sum which would be given if all the coils were located in the same slot. The distribution factor is not always the same for harmonics as for the fundamental.

For phase spread of 120° $k_d = 0$ for the third harmonic and multiples of three, which are thus eliminated from the wave form.

1.10.3 Effect of Harmonics on Pitch and Distribution Factors:

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

For third harmonic $=3\alpha$: for 5th harmonic $=5\alpha$ and so on.

$\therefore$ Pitch factor $k_c = \cos\frac{\alpha}{2}$ for fundamental

$= \cos\frac{3\alpha}{2}$ For third harmonic

$= \cos\frac{5\alpha}{2}$ For fifth harmonic

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

$$k_{dn} = \frac{\sin\frac{nm\beta}{2}}{m\sin\frac{n\beta}{2}}$$ Where n is the order of harmonics

For fundamental n=1, $$k_{d1} = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}$$

For 3rd harmonic n=3, $$k_{d3} = \frac{\sin \frac{3m\beta}{2}}{m \sin \frac{3\beta}{2}}$$

For 5th harmonic n=5, $$k_{d5} = \frac{\sin \frac{5m\beta}{2}}{m \sin \frac{5\beta}{2}}$$

Frequency is also changed. If fundamental frequency is 50 Hz i.e. $f_1 = 50$ Hz then other frequencies are: 3rd harmonic, $f_3 = 3x\ 50 = 150$ Hz, 5th harmonic, $f_5 = 5x50 = 250$ Hz etc.

Example 1.1 Determine the pitch (or coil span) factors for the following windings:

- **(i) 36 Stator slots ,4 poles, coil span 1 to 8**
- **(ii) 96 stator slots, 6 poles, coil span 1 to 12**
- **(iii) 72 stator slots ,6 poles, coil span 1 to 10**

Given Data				**To Find:**
(i)	Number of slots	=	36	Pitch factor or Coil span factor =?
(ii)	Number of poles	=	4	
(iii)	Coil Span	=	1 to 8	

Solution:

(i) 36 Stator slots ,4 poles, coil span 1 to 8

Coil span falls short by

$\left(\frac{2}{9}\right) \times 180^0 = 40^0$ I .e , $\alpha = 40^0$

Pitch factor = $K_p = \text{Cos}\ (40^0/2) = \text{Cos}\ 20^0 =$ **0.94**.

(ii) 96 stator slots, 6 poles, coil span 1 to 12

Coil span falls short by,

$\left(\frac{5}{16}\right) \times 180^0 = 56^0$ i.e ., $\alpha = 56^0$

Pitch factor = $K_p = \text{Cos}\ (56^0/2) = \text{Cos}\ 28^0 =$ **0.883**.

(iii) 72 stator slots ,6 poles, coil span 1 to 10

Coil span falls short by,

$\left(\frac{3}{12}\right) \times 180^0 = 45^0$ i.e ., $\alpha = 45^0$

Pitch factor = $K_p = \mathrm{Cos}\,(45^0/2) = \mathrm{Cos}\ 22.5^0 =$ **0.92**

Answers:

(i) **Pitch factor or Coil span factor = 0.94**
(ii) **Pitch factor or Coil span factor = 0.883**
(iii) **Pitch factor or Coil span factor = 0.924**

Example 1.2 Calculate the distribution factor for a single layer 18 slots 2-pole three-phase stator winding.

Given Data :

Number of slots = 18

Number of poles = 2

Number of phase = 3

To Find :

Distribution Factor =?

Solution:

Number of slots = 18
Number of pole, P = 2
Number of phase = 3
Distribution factor, K_d = $\frac{\sin m\beta/2}{m \sin \beta/2}$
Number of slots /pole/ phase, m = $\frac{18}{2\times 3} = 3$
Number of slots/ pole, n = $18/2 = 9$
Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

$= \frac{\sin\left(\frac{3\times 20^\circ}{2}\right)}{3\times\sin\left(\frac{20^\circ}{2}\right)}$

$= \frac{\sin 30^\circ}{3\times\sin(10^\circ)} = 0.96$

Answer

Distribution factor = 0.96

Example 1.3 Calculate the distribution factor for a 36 slot, 4 pole, single layer three phase winding.

Given Data :

Number of slots = 36

Number of poles = 4

Number of phase = 3

To Find :

Distribution Factor =?

Solution:

Number of slots = 36

Number of pole, P = 4

Number of phase = 3

Distribution factor, K_d = $\frac{\beta/2}{\beta/2}$

Number of slots /pole/ phase, m = $\frac{36}{4\times3} = 3$

Number of slots/ pole, n = $36/4 = 9$

Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

= $\frac{\sin\left(\frac{3\times20^\circ}{2}\right)}{3\times\sin\left(\frac{20^\circ}{2}\right)}$

= $\frac{\sin 30^\circ}{3\times\sin(10^\circ)} = 0.96$

Answer

Distribution factor = 0.96

Example 1.4 An armature of a three phase alternator has 120 slots. The alternator has 8 poles. Calculate its distribution factor.

Given Data :

Number of slots = 120

Number of poles = 8

Number of phase = 3

To Find :

Distribution Factor =?

Solution:

Number of slots = 120

Number of pole, P = 8

Number of phase = 3

Distribution factor, K_d = $\frac{\beta/2}{\beta/2}$

Number of slots /pole/ phase, m = $\frac{120}{8\times3} = 5$

Number of slots/ pole, n = $120/8 = 15$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{15} = 12°$

$$= \frac{\sin\left(\frac{5\times12°}{2}\right)}{5\times\sin\left(\frac{12°}{2}\right)}$$

$$= \frac{\sin 30°}{5\times\sin(6°)} = 0.957$$

Answer

Distribution factor = 0.957

Example 1.5 in a 4 pole, 3 phase star connected alternator has 48 slots. The coil span is 150 electrical degree .Determine the coil span factor and distribution factor.

Given Data :

Number of slots = 48

Number of poles = 4

Number of phase = 3

Coil span = 150 electrical degree

To Find :

Coil span factor=?

Distribution Factor =?

Solution:

Short pitched angle (α) = pole pitch – coil pitch

$= 180^0 - 150^0 = 30^0$

Coil span factor (K_P) = $\cos\frac{\alpha}{2}$

$= \cos\frac{30°}{2} = 0.966$

Number of slots = 48

Number of pole, P = 4

Number of phase = 3

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

Number of slots /pole/ phase, m = $\frac{48}{4\times3} = 4$

Number of slots/ pole, n = $48/4 = 12$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{12} = 15°$

$$= \frac{\sin\left(\frac{4\times 15^\circ}{2}\right)}{4\times\sin\left(\frac{15^\circ}{2}\right)}$$

$$= \frac{\sin 30^\circ}{4\times\sin(7.5^\circ)} = 0.957$$

Answer

Coil span factor = 0.966

Distribution factor = 0.957

Example 1.6 Determine the distribution factor and the coil span factor of a 3-phase winding of an alternator with six slots per pole per phase and the coil span of 15 slot pitches.

Given Data :			**To Find :**
Number of slots/ pole/ phase (m)	=	6	Coil span factor=?
Coil span	=	15 slot pitch	Distribution Factor =?
Number of phase	=	3	

Solution:

Number of slots /pole/ phase, m = 6

Number of slots /pole n = $6\times \text{phase} = 6\times 3 = 18$

Coil span = $\frac{180^\circ \times \text{coil span interms of slots}}{\text{Number of slots/pole}} = 180^\circ \times \frac{15}{18} = 150^\circ$

Coil span factor = $\cos\frac{(180^\circ - 150^\circ)}{2} = \cos 15^\circ = 0.966$

Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{18} = 10^\circ$

Distribution factor, K_d = $\frac{\beta/2}{\beta/2}$

$$= \frac{\sin\left(\frac{6\times 10^\circ}{2}\right)}{6\times\sin\left(\frac{10^\circ}{2}\right)} = \frac{\sin 30^\circ}{6\times\sin(5^\circ)} = 0.956$$

Answer

Coil span factor = 0.966

Distribution factor = 0.956

1.11. Relation between frequency, speed and number of poles:

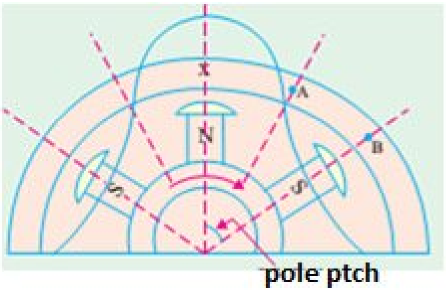


Fig: 1.15

Consider the armature conductor marked X in Fig 1.15 situated at the center of an N pole rotating in clockwise direction. The conductor being situated at the place of maximum flux density will have maximum emf induced in it

When the conductors is in the interpolar gap, as at Fig 1.15, it has minimum induced emf because flux density is minimum there. Again when is at the center of an S-pole, it has maximum emf induced in it, because flux density at B is maximum. But the direction of the emf when conductor is over an N-pole is opposite to that when is over an S-pole.

Obviously one cycle of emf is induced in a conductor when one pair of poles passes over it.

Let P = total number of magnetic poles

N = rotative speed of the rotor in r.p.m

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

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

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

Frequency (f) $= \frac{\text{Number of cycle}}{\text{Revoution}} \times \frac{\text{Number of revolution}}{\text{Second}}$

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

Frequency (f) $= \frac{PN}{120}$ Hz

Example 1.7 Determine the speed at which a four-pole synchronous generator should be driven to get a frequency of 50 Hz

Solution:

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = \mathbf{1500\ r.p.m}$$

Example 1.8 A three .50 Hz star connected synchronous generator runs at 1500 r.p.m. determine the number of poles.

Solution:

From the frequency formula $P = = \frac{120f}{N} = \frac{120 \times 50}{1500} = \mathbf{4}$ **poles**

1.12 EMF equation of an Alternator:

Let Z_p : Number of armature conductors in series per phase

P : Number of poles

ϕ : Useful flux per pole in Weber

N : Rotational speed in rpm and

f : Frequency in hertz and is equal to $\frac{NP}{120}$

The flux cut by any conductor while passing from the centre of one inter polar gap to the centre of the next is ϕ Weber and since during the movement, the emf wave completes half cycle. i.e. the time taken is $\frac{1}{2f}$ seconds.

Therefore, the average rate of cutting the flux $\frac{d\phi}{dt} = \frac{\phi}{1/2f} = 2\ \phi\ f$ wb/s

Hence average emf induced in each conductor $= 2\ \phi\ f$ volt

Average emf per phase, $E_{av}\ /\ phase$ = number of conductors in series/phase arranged in one slot/pole

X average induced emf per conductor

$= Z_p \times 2f\phi = 2T \times 2f\phi = 4\ \phi\ f\ T$ volt. ($\because Z_p = 2T$)

For distributed winding the average value of emf per phase will be k_d time above the value

$$i.e\ E_{av}\ /\ phase = 4\ k_d\ \phi\ f\ T \text{ Volt}$$

For short pitched winding the true average value of emf per phase will be k_p time above the value

$$i.e\ E_{av}/phase = 4\,k_d\,k_p\,\phi\,f\,T \text{ Volts}$$

And $$E_{rms}/phase = form\,factor\,k_f \times 4\,k_p\,k_d\,\phi\,f\,T \text{ volt}$$

For sinusoidal wave of emf, $k_f = 1.11$

$$\therefore E_{rms}/phase = 4.44\,k_p\,k_d\,\phi\,f\,T \text{ Volt}$$

If the alternator is star-connected, as is usually the case, the line voltage is $\sqrt{3}$ times the phase value.

So, the line induced emf, $E_L = \sqrt{3} \times 4.44\,k_p\,k_d\,\phi\,f\,T$ volt

For full pitch winding and concentrated windings, $K_P = 1$ and $K_d = 1$

Example 1.9 A 3 –phase ,16 pole alternator has the following data:

Number of slots = 192; Conductors /slot = 8 (conductors of each phase are connected in series); Coil span = 160 electrical degrees; Speed of the alternator = 375 r.p.m; flux/pole = 55mWb. Calculate the phase and line voltages.

Given Data :

Number of phase = 3

Number of poles, P = 16

Number of slots = 192

Number of conductor/ slot = 8

Coil span = 160 electrical degree

Speed of the alternator = 375 r.p.m

Flux /pole = 55 mWb

To Find :

Phase voltage =?

Line voltage =?

Solution:

Number of poles, P = 16

Number of slots = 192

Conductors/slot = 8

Coil span = 160^0 (electrical)

Speed of alternator = 375 r.p.m

Flux/ pole φ = 55 mWb = 0.055 Wb

Here, α = $180^0 - 160^0 = 20^0$

Pitch factor, = $\cos\frac{\alpha}{2}$

= $\cos 20/2 = \cos 10^0 = 0.9848$

Number of slots/pole, n = $\frac{192}{16} = 12$

β = $\frac{180°}{n} = \frac{180°}{12} = 15°$

m = number of slots/pole/phase = $\frac{192}{16\times 3} = 4$

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

= $\frac{\sin\left(\frac{4\times 15°}{2}\right)}{4\times \sin\left(\frac{15°}{2}\right)}$

= $\frac{\sin 30°}{4\times\sin(7.5°)} = 0.9577$

Total number of slots /phase = $\frac{192}{3} = 64$

Number of conductor /slot = 8

Total number of conductors /phase = $64\times 8 = 512$

Turns / phase, T_{ph} = $\frac{512}{2} = 256$

Frequency f = $\frac{NP}{120} = \frac{375\times 16}{120}$

f = 50Hz

Eph = 4.44fΦKpKdTph Volts

= $4.44 \times 50 \times 0.055 \times 256 \times 0.9848 \times 0.9577$

= **2948 V**

Line voltage, E_L = $\sqrt{3}\,E_{ph}$

= $\sqrt{3}\times 2948 =$ **5106 V**

Example 1.10 A 3 - phase ,star connected alternator has the following data : voltage required to be generated on open circuit = 4000 V (at 50Hz) ;speed = 500 r.p.m ; stator slot/pole/phase = 3;conductor/slot = 12;Calculate : (i) Number of poles (ii) Useful flux per pole

Assume all conductors per phase to be connected in series and coil to be full pitch.

Given Data :

Number of phase = 3

Types of connection = Star

Open circuit emf = 4000 V

Speed of the alternator = 500 r.p .m

Number of slots/pole/phase = 3

Number of conductor/ slot = 12

Full pitch coil (K_d) = 1

To Find :

Number of poles, P =?

Useful Flux /pole = ?

Solution.

Line voltage E_L = 4000 V

$E_{r.m.s}$ / phase, E_{ph} = $\frac{4000}{\sqrt{3}}$ = 2309 V

Speed of the alternator, N = 500 r.p.m

Number of slots /pole/ phase, m = 3

Number of conductors/slot = 12

Frequency, f = 50 Hz

(i) Number of poles P:

Frequency, f = $\frac{NP}{120}$

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

$$P = \frac{120 \times 50}{500} = 12 \text{ poles}$$

(ii) Useful flux per pole, φ :

Pitch factor K_p = 1

Number of slots/ pole, n = $3 \times 3 = 9$

Angular displacement between slots, $\beta = \frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

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

$$= \frac{\sin\left(\frac{3 \times 20^\circ}{2}\right)}{3 \times \sin\left(\frac{20^\circ}{2}\right)}$$

$$= \frac{\sin 30^\circ}{3 \times \sin(10^\circ)} = 0.96$$

Number of turns/phase , $T_{ph} = \frac{Zph}{2} = \frac{12 \times 9 \times 12}{2 \times 3} = 216$

Eph $= 4.44 f \Phi K p K d T p h$ Volts

$= 4.44 \times 50 \times \Phi \times 216 \times 1 \times 0.96$

Φ $= \frac{2309}{4.44 \times 50 \times 216 \times 1 \times 0.96} = 0.05 Wb$

Example 1.11 A 3-phase, 10- pole alternator has 2 slots per pole per phase on its stator with 10 conductors per slot. The air gap flux is sinusoidally distributed and equals to 0.05 Wb. The stator has double layer winding with a coil span of 150° electrical degrees. If the alternator is running at 600 r.p.m, Calculate the e.m.f generated per phase at no load.

Given Data :

Number of phase = 3

Number of poles, P = 10

Number of slots /pole/phase = 2

Number of conductor/ slot = 10

Coil span = 150 electrical degree

Speed of the alternator = 600 r.p.m

Flux /pole = 0.05 Wb

To Find :

Open circuit Phase voltage =?

Solution:

e.m.f generated per phase, E_{ph}

Number of slots/ pole, n = $2 \times 3 = 6$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{6} = 30°$

Angle of chording = $180° - 150° = 30°$

Pitch factor K_p = $\cos\left(\frac{\alpha}{2}\right)$

= $\cos\left(\frac{30°}{2}\right) = 0.9659$

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

= $\frac{\sin\left(\frac{2\times 30°}{2}\right)}{2\times\sin\left(\frac{30°}{2}\right)}$

= $\frac{\sin 30°}{2\times\sin(15°)} = 0.9659$

Number of conductors in series /phase ,Z_{ph} = $10\times\frac{\text{slots}}{\text{phase}} = 10\times(2\times 10) = 200$

Number of turns / phase, T_{ph} = $\frac{Zph}{2} = \frac{200}{2} = 100$

Eph = $4.44 f\Phi K_p K_d T_{ph}$ Volts

= $4.44\times 50\times 0.05\times 100\times 0.9659\times 0.9659$

= 1035.6 V

Example 1.12 Calculate the speed and open –circuit line and phase voltages of a 4 pole; 3 phase, 50Hz star connected alternator with 36 slots and 30 conductors per slot. The flux per pole is 0.05 Wb sinusoidally distributed.

Given Data :

Number of poles = 4

Number of phase = 3

Types of connection = Star

Number of slots = 36

Flux /pole = 0.05 Wb

Frequency = 50 Hz

Number of conductor/ slot = 30

To Find :

Speed of the alternator =?

Open circuit phase voltage =?

Open circuit line voltage=?

Assume Full pitch coil (K_p) = 1

Solution:

Speed, phase and line voltages:

Speed of alternator, N = $\frac{120f}{P}$

= $\frac{120 \times 50}{4}$ = 1500 r.p.m

Number of conductors connected in series per phase,

Z_{ph} = $\frac{\text{No. of slots} \times \text{no. of conductors per slot}}{\text{No . of phases}}$

= $\frac{36 \times 30}{3}$ = 360

Number of turns per phase ,T_{ph} = $\frac{Zph}{2} = \frac{360}{2}$ = 180

Number of slots/pole, n = $\frac{36}{4}$ = 9

Number of slots/pole/phase m = $\frac{9}{3}$ = 3

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{9}$ = 20°

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

= $\frac{\sin\left(\frac{3 \times 20°}{2}\right)}{3 \times \sin\left(\frac{20°}{2}\right)}$

= $\frac{\sin 30°}{3 \times \sin(10°)}$ = 0.96

Assuming coils to be full pitches,

Coil span factor, K_p = 1

Open circuit phase voltage, **Eph** = $4.44 f \Phi K_p K_d T_{ph}$ Volt

= $4.44 \times 50 \times 0.05 \times 180 \times 1 \times 0.96$

= 1918.1 V

Open circuit line voltage, E_L = $\sqrt{3}\, E_{ph}$

= $\sqrt{3} \times 1918.1$ = 3322.2 **V**

Example 1.13 A 4pole, 50Hz, star connected alternator has a flux per pole of 0.12Wb. It has 4 slots per pole per phase, conductors per slot being 4, If the winding coil span is $150°$,find the e.m.f .

Given Data :

Number of poles = 4

Number of phase = 3

Types of connection = Star

Flux /pole = 0.12 Wb

Number of slots /pole/phase = 4

Frequency = 50 Hz

Number of conductor/ slot = 4

Coil span = 150^{0}

To Find :

Emf = ?

Solution:

E.m.f Induced:

Number of slots per pole , n = $m \times \text{number of phases} = 4 \times 3 = 12$

Number of slots per phase = $m \times \text{number of poles} = 4 \times 4 = 16$

Number of conductors connected in series per phase ,

Z_{ph} = $\text{number ofconductor/slot} \times \text{numberof slots/phas}$

= $4 \times 16 = 64$

Number of turns per phase , T_{ph} = $\frac{Zph}{2} = \frac{64}{2} = 32$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{12} = 15°$

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

= $\frac{\sin\left(\frac{4\times 15°}{2}\right)}{4\times \sin\left(\frac{15°}{2}\right)}$

= $\frac{\sin 30°}{3 \times \sin(7.5°)} = 0.958$

Angle of chording = $180° - 150° = 30°$

Pitch factor K_p = $\cos\left(\frac{\alpha}{2}\right)$

= $\cos\left(\frac{30°}{2}\right) = 0.966$

Eph = 4.44fΦKpKdTph Volts

= $4.44 \times 50 \times 0.12 \times 0.966 \times 0.958 \times 32$

= 788.91 V

EL = $\sqrt{3}$Eph

= $\sqrt{3} \times 788.91 = 1366.4$ **V**

Example 1.14 The stator of a three-phase, 8 pole synchronous generator driven at 750 rpm has 72 slots. The winding has been made with 36 coils having 10 turns per coil. Calculate the rms value of the induced emf per phase if the flux per pole is 0.15 Wb, sinusoidally distributed. Assume that full-pitch coils have been used.

Given Data :

Number of phase = 3

Number of poles = 8

Speed = 750 rpm

Number of slots = 72

Number of coils = 36

Number of turns per coil = 10

Flux /pole = 0.15 Wb

Assume full pitch coil (K_p) = 1

To Find :

Rms value of the induced Emf / phase= ?

Solution:

Frequency, f = $\frac{NP}{120}$

= $\frac{750\times8}{120}$ = 50Hz

Number of coils per phase = $\frac{36}{3} = 12$

Number of turns per phase , T_{ph} = $12\times10 = 120$

Since full pitch coils are used , K_p = 1

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

Number of slots /pole/ phase, m = $\frac{72}{8\times3} = 3$

Number of slots/ pole, n = $72/8 = 9$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{9} = 20°$

= $\frac{\sin\left(\frac{3\times20°}{2}\right)}{3\times\sin\left(\frac{20°}{2}\right)}$

= $\frac{\sin 30°}{3\times\sin(10°)} = 0.96$

Eph = $4.44f\Phi K_pK_dT_{ph}$ Volts

= $4.44\times50\times0.15\times1\times0.96\times120$

= 3836 V

Example 1.15 A three –phase, star connected synchronous generator driven at 750 rpm is required to generate a line-line voltage of 440 V at 50 Hz on open circuit. The stator is wound with 2 slots per pole per phase and each coil has 4 turns. Calculate the useful flux per pole.

Given Data :

Number of phase = 3

Types of connection = Star

Speed of the alternator = 750 rpm

To Find :

Flux /pole = ?

Line to line voltage = 440 V

Frequency = 50 Hz

Number of slots / pole/ phase = 2

Number of turns/ coil = 4

Assume Full pitch coil (K_p) = 1

Solution:

E (line –line) = 440 V

Eph = $\frac{440}{\sqrt{3}} = 254$ V

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

= $\frac{120 \times 50}{750} = 8$

Number of slots /pole/ phase, m = 2

Total number of stator slots = $2 \times 8 \times 3 = 48$

Assuming coils to be full pitches,

Coil span factor, K_p = 1

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

Number of slots /pole/ phase, m = $\frac{48}{8 \times 3} = 2$

Number of slots/ pole, n = $48/8 = 6$

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{6} = 30°$

= $\frac{\sin\left(\frac{2 \times 30°}{2}\right)}{2 \times \sin\left(\frac{30°}{2}\right)}$

= $\frac{\sin 30°}{2 \times \sin(15°)} = 0.966$

Number of turns per coil = 4

Number of turns per phase T_{ph} = $8 \times 4 = 32$

Eph = $4.44 f \Phi K_p K_d T_{ph}$ Volts

254 = $4.44 \times 50 \times \Phi \times 1 \times 0.966 \times 32$

$\Phi = \dfrac{254}{4.44\times50\times1\times0.966\times32} = 36.9\text{.mWb}$

Example 1.16 A 3-phase, 16 –pole synchronous generator has a star –connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.03 Wb, sinusoidally distributed and the speed is 375 rpm. Calculate the frequency and line induced emf.

Given Data :

Number of phase = 3

Number of poles, P = 16

Types of connection = Star

Number of slots = 144

Number of conductor/ slot = 10

Speed of the alternator = 375 r.p.m

Flux /pole = 0.03 Wb

Assume full pitch Coil (K_p) = 1

To Find :

Frequency =?

Line induced emf =?

Solution:

Synchronous speed, $N_s = \dfrac{120f}{P}$

$f = \dfrac{N_s \times P}{120} = \dfrac{375 \times 16}{120} = 50\text{Hz}$

Assuming coils to be full pitches,
Coil span factor, $K_p = 1$

Distribution factor, $K_d = \dfrac{\sin m\beta/2}{m \sin \beta/2}$

Number of slots /pole/ phase, m $= \dfrac{144}{16\times3} = 3$

Number of slots/ pole, n = 144/16 = 9

Angular displacement between slots, β $= \frac{180°}{n} = \frac{180}{9} = 20°$

$= \frac{\sin\left(\frac{3 \times 20°}{2}\right)}{3 \times \sin\left(\frac{20°}{2}\right)}$

$= \frac{\sin 30°}{3 \times \sin(10°)} = 0.96$

Z_{ph} $= \frac{\text{No. of slots} \times \text{no. of conductors per slot}}{\text{No . of phases}}$

$= \frac{144 \times 10}{3} = \frac{1440}{3} = 480$

Number of turns per phase T_{ph} $= \frac{Zph}{2} = \frac{480}{2} = 240$

Eph $= 4.44 f \Phi K_p K_d T_{ph}$ Volts

$= 4.44 \times 50 \times 0.03 \times 1 \times 0.96 \times 240 = 1534$ V

EL $= \sqrt{3} Eph$

$= \sqrt{3} \times 1534$

$= 2657$ **V**

Example 1.17 Find the number of turns of armature conductors is series per phase required for the armature of a 3-phase, 10 pole, 50Hz, synchronous generator with 90 slots. The winding is to be star connected so as to have line voltage of 11KV. the flux per pole is 0.16 Wb

Given Data :

Number of phase = 3

Number of poles, P = 10

Frequency = 50 Hz

Number of slots = 90

Types of connection = Star

Line voltage = 11 KV

Flux /pole = 0.16 Wb

Assume full pitch Coil (K_p) = 1

To Find :

Number of turns of armature conductors=?

Solution:

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

Number of slots /pole/ phase, m = $\frac{90}{10\times3} = 3$

Number of slots/ pole, n = $90/10 = 9$

Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

= $\frac{\sin\left(\frac{3\times20^\circ}{2}\right)}{3\times\sin\left(\frac{20^\circ}{2}\right)}$

Number of slots/ pole, n = $144/16 = 9$

Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

Distribution factor, K_d = $\frac{\sin\left(\frac{3\times20^\circ}{2}\right)}{3\times\sin\left(\frac{20^\circ}{2}\right)}$

= $\frac{\sin 30^\circ}{3\times\sin(10^\circ)} = 0.96$

EL = $\sqrt{3}$Eph

= $\sqrt{3}$ 4.44fΦKpKdTph Volts

11000 = $\sqrt{3}\times4.44\times f\times\Phi\times Kp\times Kd\times Tph$

Tph = $\frac{1100}{\sqrt{3}\times4.44\times50\times0.16\times1\times0.96} = 18$

Zph = $2\times Tph$

= $2\times186 = 372$ turns

Example 1.18 A three phase ,50Hz,20 pole, salient pole alternator with star connected stator winding has 180 slots on the stator .there are 8 conductors per slot and the coils are full pitch. The flux per pole is 25 mWb. Assuming sinusoidally distributed flux, calculate (a) the speed (b) the generated emf per phase and (c) the line emf

Given Data :	**To Find :**
Number of phase = 3	Speed = ?

Frequency = 50 Hz

Number of poles = 20

Types of connection = Star

Number of slots = 180

Number of conductor/ slot = 8

Flux /pole = 0.25 mWb

Full pitch Coil (K_p) = 1

Generated emf per phase = ?

Generated line emf per phase = ?

Solution:

Speed, phase and line voltages:

Speed of alternator, N = $\frac{120f}{p} = \frac{120\times50}{20}$ = 300 r.p.m

Number of conductors connected in series per phase,

Z_{ph} = $\frac{\text{No.of slots}\times\text{no.of conductors per slot}}{\text{No .of phases}}\ \frac{180\times8}{3}$ = 480

Number of turns per phase ,T_{ph} = $\frac{Zph}{2} = \frac{480}{2}$ = 240

Number of slots/pole, n = $\frac{180}{20}$ = 9

Number of slots/pole/phase m = $\frac{9}{3}$ = 3

Angular displacement between slots, β = $\frac{180°}{n} = \frac{180}{9}$ = 20°

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

= $\frac{\sin\left(\frac{3\times20°}{2}\right)}{3\times\sin\left(\frac{20°}{2}\right)}$

= $\frac{\sin 30°}{3\times\sin(10°)}$ = 0.96

Assuming coils to be full pitches,

Coil span factor, K_p = 1

Open circuit phase voltage, **Eph** = 4.44fΦKpKdTph Volt

= $4.44 \times 50 \times 0.025 \times 1 \times 0.96 \times 240$

= 1278.72 V

Open circuit line voltage, E_L = $\sqrt{3}\, E_{ph}$

= $\sqrt{3} \times 1278.72 = 2214.8$ **V**

Example 1.19 Find the no –load phase and line voltage of a star connected 3-phase, 6 pole alternator which runs at 1200 r.p.m. having flux per pole of 0.1 Wb sinusoidally distributed. Its stator has 54 slots having double layer winding. Each coil has 8 turns and coil is chorded by 1 slot.

Given Data :			**To Find :**
Types of connection	=	Star	No -load phase voltage= ?
Number of phase	=	3	No -load line voltage= ?
Number of poles	=	6	
speed	=	1200 rpm	
Flux /pole	=	0.1 Wb	
Number of slots	=	54	
Number of turns per coil	=	8	
Coil is chorded	=	1 slots	

Solution:

Since the winding is chorded by one slot, it is short pitched by 1/9 or $180^0/9 = 20^o$

Pitch factor K_p = $\cos\left(\frac{\alpha}{2}\right)$

= $\cos\left(\frac{20^\circ}{2}\right) = 0.98$

frequency alternator, f = $\frac{NP}{120} = \frac{1200 \times 6}{120} = 60$ Hz

Number of slots/pole, n = $\frac{54}{6} = 9$

Number of slots/pole/phase m = $\frac{9}{3} = 3$

Angular displacement between slots, β = $\frac{180^\circ}{n} = \frac{180}{9} = 20^\circ$

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

= $\frac{\sin\left(\frac{3\times20^\circ}{2}\right)}{3\times\sin\left(\frac{20^\circ}{2}\right)}$

= $\frac{\sin 30^\circ}{3\times\sin(10^\circ)} = 0.96$

Z_{ph} = $\frac{\text{No.of slots} \times \text{no.of conductors per slot}}{\text{No .of phases}} = \frac{54\times8}{3} =$ 144

Number of turns per phase ,T_{ph} = $\frac{Zph}{2} = \frac{144}{2} = 72$

Open circuit phase voltage, Eph = $4.44 f \Phi KpKdTph$ Volt

$4.44 \times 60 \times 0.1 \times 0.98 \times 0.96 \times 72$

= 1805 V

Open circuit line voltage, $E_L = \sqrt{3}\, E_{ph} = \sqrt{3} \times 1805 = 3125$ **V**

Example 1.20 A 4-pole ,3 phase, 50 Hz, star connected alternator has 60 slots, with 4 conductors per slot. Coils are short- pitched by 3 slots. If the phase spread is 60° ,find the line voltage induced for a flux per pole of 0.943 Wb distributed sinusoidally in space. All the turns per phase are in series.

Given Data :

Number of poles = 4

Number of phase = 3

Types of connection = Star

Number of slots = 60

To Find :

Line voltage= ?

Number of conductor / slot = 4

Coil is short pitched = 3 slots

Phase spread = 60^0

Flux / pole = 0.943 Wb

Solution:

Phase spread mβ = 60^o

Number of slots/pole/phase m = n/phase = 15/3 = 5

Number of slots/pole, n = $\frac{60}{4} = 15$

mβ = $5 \times \beta = 60^o$

β = $\frac{60^\circ}{5} = 12^\circ$

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

$$= \frac{\sin\left(\frac{5 \times 12^\circ}{2}\right)}{5 \times \sin\left(\frac{12^\circ}{2}\right)}$$

$$= \frac{\sin 30^\circ}{5 \times \sin(6^\circ)} = 0.957$$

Since the winding is chorded by 3 slot, it is short pitched by 3/15 or $3 \times 180^0 / 15 = 36^o$

Pitch factor K_p = $\cos\left(\frac{\alpha}{2}\right)$

$$= \cos\left(\frac{36^\circ}{2}\right) = 0.951$$

Z_{ph} = $\frac{\text{No.of slots} \times \text{no.of conductors per slot}}{\text{No .of phases}} = \frac{60 \times 4}{3} = 80$

Number of turns per phase ,T_{ph} = $\frac{Zph}{2} = \frac{80}{2} = 40$

Open circuit phase voltage, **Eph** = 4.44fΦKpKdTph Volt

$$= 4.44 \times 50 \times 0.943 \times 0.95 \times 0.957 \times 40$$

= 7613 V

Open circuit line voltage, E_L = $\sqrt{3}\, E_{ph}$

= $\sqrt{3} \times 7613 = 13185$ **V**

1.13. Methods of obtaining sine wave in salient pole Alternators:

1.13.1 Skewed Pole Shoe Method:

In general, the emf induced in a conductor $e = BLV \sin\theta$, depends upon the following factors. They are,

(i) Length of the conductor in the magnetic field
(ii) Flux density of the magnetic field and
(iii) Velocity of the conductor

From the above equation, if the velocity is maintained constant, then for obtaining a sinusoidal emf, the active length of the conductor or the flux density in the air gap should be made to vary according to sine law.

In salient pole alternators, the poles are projecting types, the active length of the conductor in the pole is related to shape of the pole. If the pole shoes are skewed, the shape of the pole shoes becomes trapezoidal in shape. The skewed pole shoe and the field obtained are shown in fig1.16. In this method the flux density is constant, but the effective length of the conductor under the pole shoe is made to vary. By proper design of pole shoe a very close to a sine wave emf is obtained.

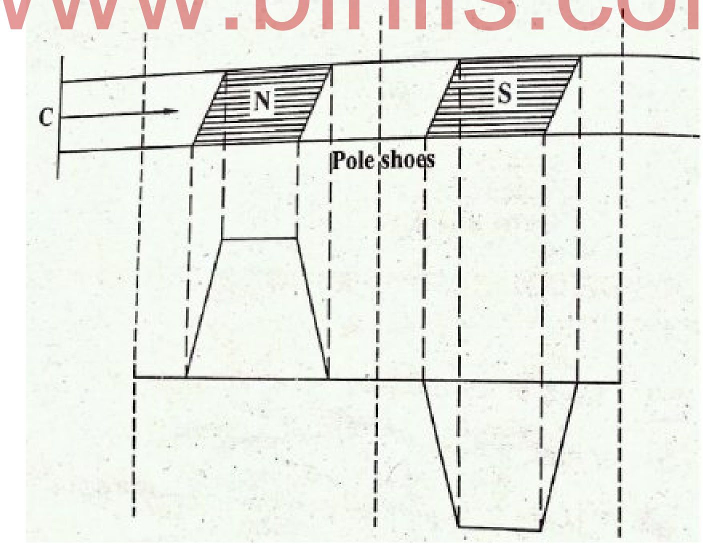


Fig.1.16 Methods adopted in Salient Pole Alternator

1.13.2 Graded Air Gap Method:

In this method, the flux density available in the air gap is varied by the way of varying the air gap length. The minimum air gap length is provided at the centre line of the pole. At pole tips, nearly double the value of air gap length as at the centre is provided. By allowing graded air gap length the field form obtained is as shown in fig1.17. In this method also a very close to a sine wave emf is obtained by providing graded air gap- length.

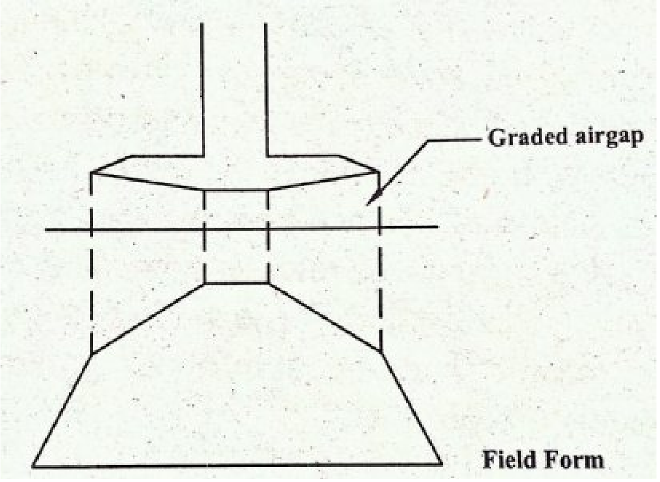


Fig.1.17 Graded Air Gap Method

1.13.3 Methods adopted in cylindrical rotor alternators:

In cylindrical rotor, the filed winding is a distributed one. The winding is distributed in rotor slots. The flux density in the air gap is increasing towards the centre of the pole. Fig.1.18 shows a rotor with three pairs of slot per pole.

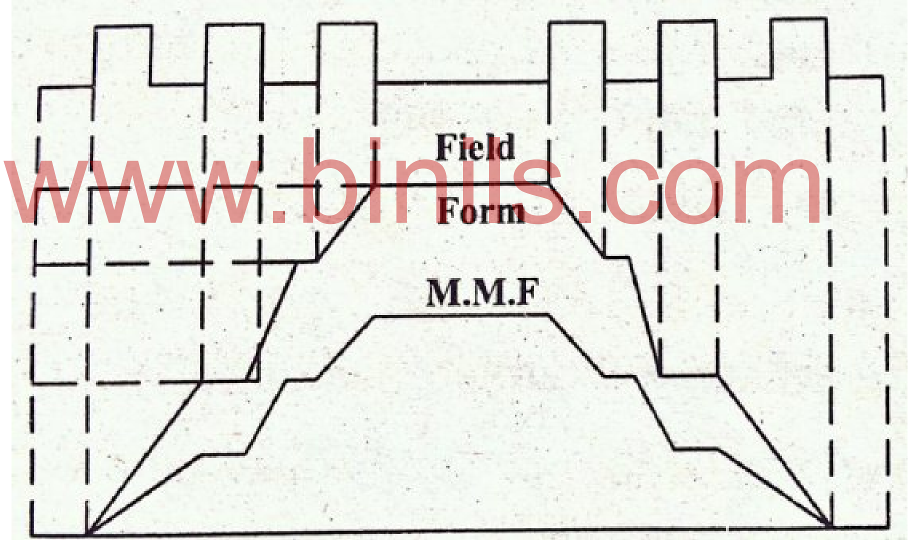


Fig.1.18 Method of obtaining sine wave in cylindrical alternator

The magneto motive force about a particular point in the air gap is proportional to the number of ampere turns acting at that point. At the centre point of the un-slotted portion of the rotor, the mmf acted is due to the ampere turns of all three pairs of slots. So that emf is maximum at the point.

In the other points of the rotor say at the first tooth, the mmf acting is due to two pairs of slot only. Hence from the central un-slotted portion to the other point on the rotor on either side the mmf acting is varying. This is shown in fig 1.18. If the un-slotted portion of the rotor is made equal to about 0.3 times pole pitch, best results are obtained.

1.14 Critical Speed of Rotor of an Alternator:

When the rotor of an alternator is rotating, at a particular speed of the rotor, considerable amount of vibration is set up in the machine. This particular speed is named as critical speed. It is corresponds to the natural frequency of transverse vibration.

In case of machines with salient pole rotor, this speed is always more than that of the running speed. But in large turbo alternators, the critical speed may be nearly equal to the running speed. In such cases the rotor is so designed such that the critical speed of rotor is lower than the running speed. The critical speed should be within the safe value. It must not be within 20 percent of the running speed. Otherwise the vibration of the machine will be dangerous. When being run up, considerable vibration is experienced as the rotor passes through its critical speed. Smooth running is obtained at the working speed.

1.15 Cooling of Alternators:

The losses produced in the core and conductors of electrical machines are converted in to heat. It raises the temperature of several parts of the machine. Hence to reduce the heat, air or hydrogen is used as cooling medium.

In the case of slow speed alternators diameter of the machine is very large and fan arrangements are provided with the rotating member of the machine. By providing proper size of fan, sufficient air can be made available for cooling. Hence cooling arrangement needed for low speed machines are simple. But for high speed alternator the natural cooling area available is very less, because the size of the alternator is very small.

1.15.1 Various cooling (Ventilation) methods are:

1. Radial Ventilation
2. Axial Ventilation
3. Radial Axial Ventilation
4. Multiple inlet system of ventilation
5. Closed Circuit Ventilation System

1.15.2 Radial Ventilation:

In case of small size turbo alternators, the length of the machine is so short. In such machines, cold air is allowed to flow inside the machine, by providing fans at the ends of the rotor. This cold air passes over the winding surface of the rotor and then reaches the air cap. Then it passes through the radial vent ducts of the stator core. This method of providing ventilation is called radial ventilation.

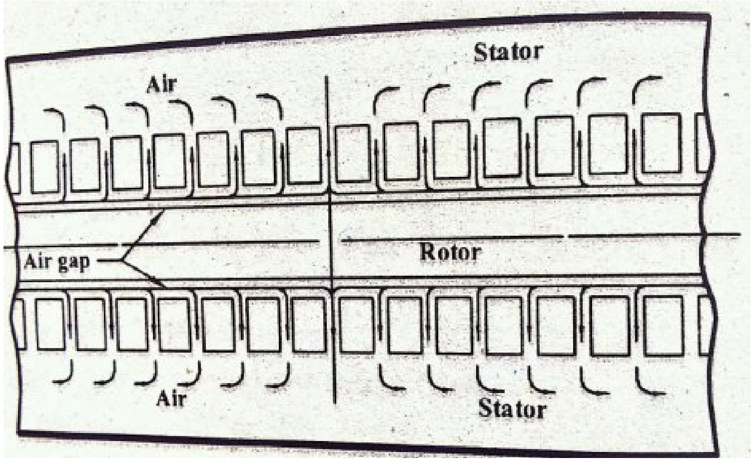


Fig.1.19 Radial Ventilation

1.15.3 Axial Ventilation:

In this method, large quantity of air is passed through narrow sub slots which are just below the main slots in the stator core. fig:1.20

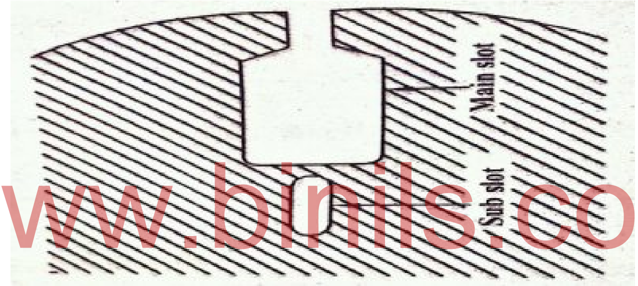


Fig.1.20 Axial Ventilation:

For larger size turbo alternators the air allowed for the purpose of circulation through the rotor and stator should be with higher pressure. Excessive amount of air is also needed. For effective circulation of air, radial and axial ducts are provided.

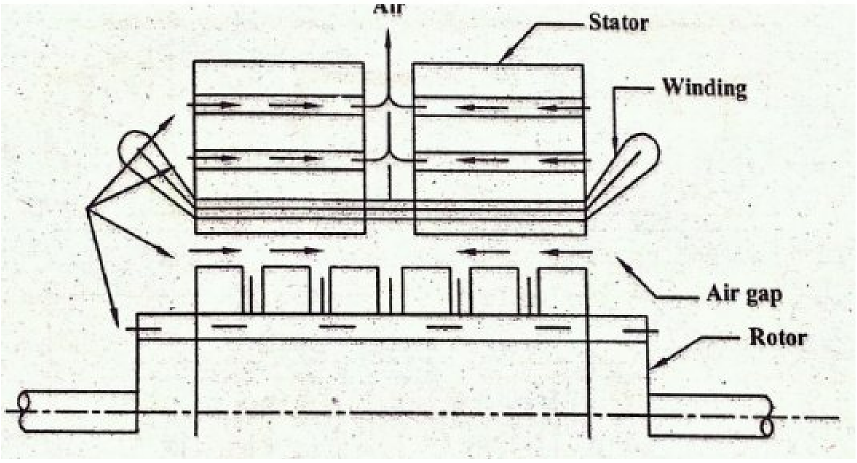


Fig.1.21 Radial –Axial Ventilation

The cold air is allowed through the axial holes of the rotor. Then it is allowed to escape through the radial vent ducts and moves across the air gap. Then this air is allowed to pass through the radial ducts in the stator core. Special care and provision should be made to cool the rotor end windings by directly allowing the air over these portions. This air is again allowed to pass through the axial holes that are provided in the stator stampings. Now the air that is passing through the axial holes and also through the radial ducts is totally discharged from the alternator.

In these methods radial and axial ventilating ducts are provided for ventilation purposes. Hence this method is called radial axial methods.fig:1.21

1.15.4 Multiple inlet system of Ventilation:

This method is adopted in case of turbo alternators having very long rotors. In such alternators there is difficulty in circulating cool air with certain pressure in all parts. To eliminate this difficulty, multiple inlet system of ventilation is adopted.

In this method, the outer stator frame is fabricated with two compartments and provisions as inlet and outlet chambers. These inlet and outlet chambers are provided alternately. The air is allowed to pass through the inlet chambers. This air passes through radially inside the stator ventilating ducts. A portion of this air passes through the axial ducts and the remaining air flows through the air gap.

From the air gap this air leaves out, through the outlet chambers. In addition to this provision air is also allowed to pass through the two ends of the rotor. This air passes through the axial ventilating ducts of the rotor and also over the stator windings. In this multiple inlet system of ventilation, the cold air is allowed to pass over all the parts of the alternator.fig:1.22

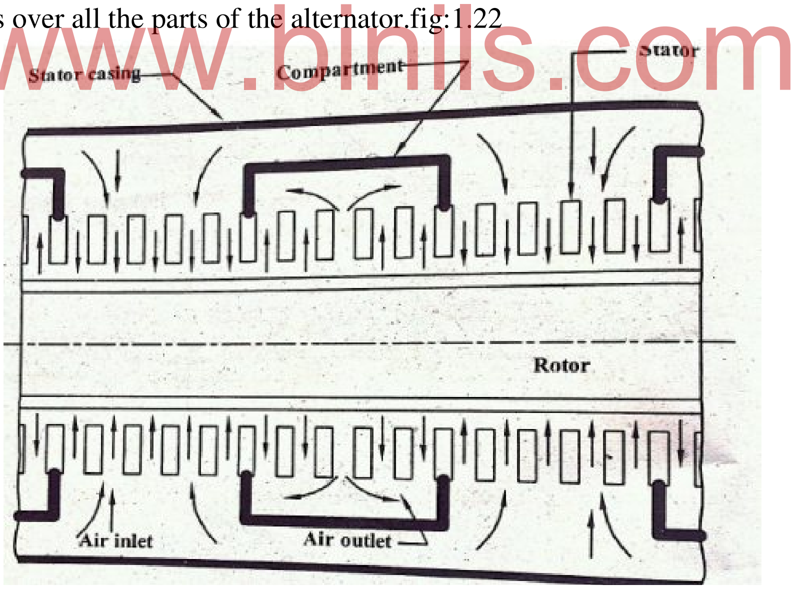


Fig.1.22 Multiple inlet system

1.15.5. Closed Circuit Ventilation System:

In closed circuit ventilation system, the coolers are mounted at the bottom of the alternators in the space provided in the foundations. The arrangement should be such that the installation of the entire unit is an air tight one.

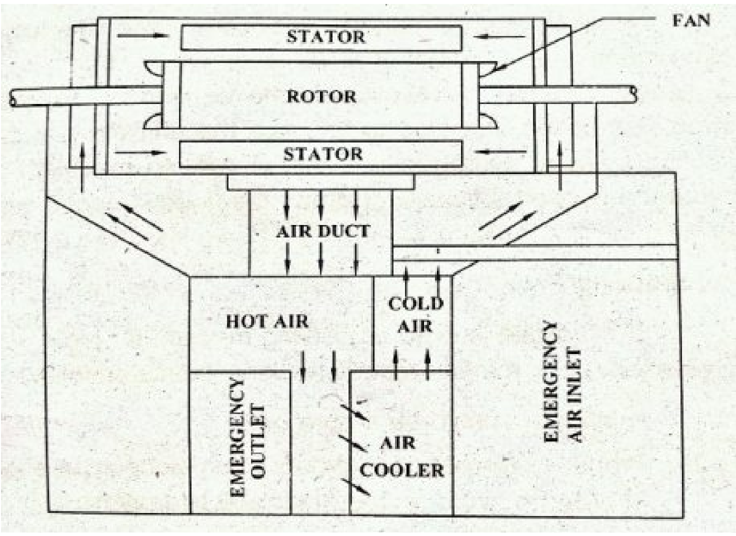


Fig.1.23 Closed Circuit Ventilation

The air is replaced by hydrogen to increase the efficiency of the cooling system. If hydrogen is used for cooling medium, the coolers and the whole alternator are designed with a gas tight casing. The special sealing device is also provided at the shaft in order to prevent the leakage of the hydrogen. The hydrogen pressure should be maintained at certain pressure higher than that of the atmosphere in order to prevent the leakage of air into the cooling system. The closed circuit ventilation system used for turbo alternators is shown in Fig.1.23

1.16 Hydrogen Cooling:

If air is used for cooling purpose in large size turbo alternators, a large quantity of air is required. For this, a large size fan is required to circulate the required air. To avoid large size of fan and also to improve the efficiency of the cooling system, hydrogen is used as cooling medium. If the hydrogen is used for cooling, it has many advantages over air as cooling medium.

1.16.1 Precautions:

If hydrogen is used as cooling medium for large size turbo alternators, the following conditions should be followed.

- Hydrogen should be a pure one
- Proper sealing devices should be provided at the shaft in order to avoid mixing of air and hydrogen.
- Hydrogen used for cooling should be maintained at certain pressure slightly above the atmospheric pressure. This helps to avoid leakage of air in to the cooling medium of hydrogen.

1.16.2 Advantages of Hydrogen Cooling:

- There is a reduction in windage loss due to the low density of gas
- As the windage loss is very low, the efficient of machine is increased.
- Since the hydrogen has 1.3 times heat transfer that of air, the heat is easily transferred in the machines.

- Due to low density of gas, noiseless operation is possible.
- There is no chance for fire accident since the hydrogen is non- inflammable

Life of the insulation is increased, due to absence of oxygen and moisture.

1.17 Excitation and exciters:

The field windings of an alternator are excited by direct current supply which may be obtained in any of the following ways:

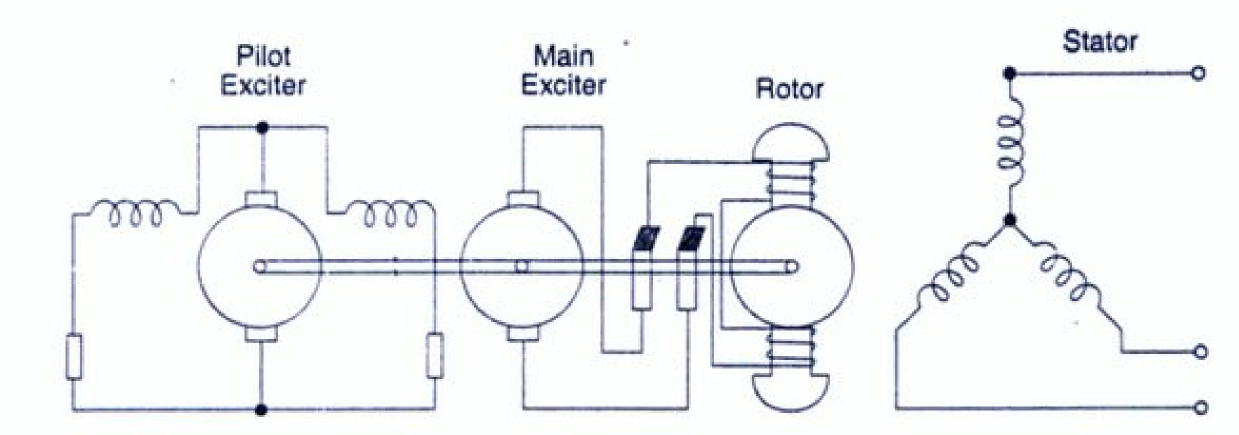


Fig: 1.24

(a) From a dc generator called exciter, mounted on the shaft extension of the alternator. For moderately rated alternators, exciters are dc shunt generators. Exciters for large alternators may be separately excited type, whose field windings are feed from another shunt generator called pilot exciter. The pilot exciter is also mounted on the same shaft as that of the alternator.

(b) Using a separate three-phase synchronous generator as exciter, mounted on the same shaft as the main synchronous generator. The output of the exciter is rectified through a bank of rectifiers and then fed to the field windings of the main generator.

REVIEW QUESTION

Part – A Questions:

1. What are the basic elements for generating emf in turbo alternators?
2. What type of rotor is adopted for high speed alternator?
3. What type of rotor is adopted for low and medium speed alternators?
4. Name the two types of alternators depending on the rotor constructions.
5. On what principle alternator works?
6. Which type of alternator is suitable for coupling with turbines and why?
7. Which type of alternator is suitable for hydro-electric power plants and why?
8. Why the stator core are laminated?
9. What is the relation between speed and frequency of an alternator?
10. What is the necessity for chording in the armature winding of a synchronous machine?
11. Why are distributed windings preferred over concentrated winding?
12. What is an exciter?
13. Which is called pilot exciter in an alternator?
14. What is the other name for distribution factor?
15. Write any two advantages of rotating field system of alternator.
16. What is full pitch and short pitch winding?
17. Define winding factor.
18. Define pitch factor.
19. Write any two advantages of hydrogen cooling.
20. What are the various ventilation methods?
21. State the advantages of stationary armature with rotating field system.
22. What is mean by single layer winding?
23. What is mean by double layer winding?
24. Define space spread.
25. List the methods to obtain sine wave in an alternator.
26. A three phase, 50 Hz star connected synchronous generator runs at 1000 r.p.m. determine the number of poles.
27. Determine the speed at which a two-pole synchronous generator should be driven to get a frequency of 50 Hz

Part- B Questions:

1. What is the working principle of an alternator? And write the basic requirements for generating emf in an alternator.
2. Draw the diagram of Projecting or salient pole rotor of an alternator.
3. Draw the diagram of a Non-salient or smooth cylindrical pole rotor of an alternator.
4. Write the advantages of rotating filed system of an alternator.
5. Draw the diagram of turbo alternator.
6. Draw the diagram of salient pole alternator.
7. Explain brief about stator core of an alternator.
8. What are the types of slot in an alternator?

9. What is mean by critical speed an alternator?
10. Write the comparison of salient pole and cylindrical type rotor.
11. Determine the pitch (or coil span) factors for the winding ,24 Stator slots ,4 poles, coil span 1 to 5
12. Determine the pitch (or coil span) factors for the winding , 96 Stator slots ,4 poles, coil span 1 to 18
13. Calculate the distribution factor for a single layer 36 slots 2-pole three-phase stator winding.
14. Calculate the distribution factor for a 96 slot, 4 pole, single layer three phase winding.
15. An armature of a three phase alternator has 144 slots. The alternator has 8 poles. Calculate its distribution factor.
16. Draw the block diagram of closed circuit ventilation system.
17. What are the precautions of hydrogen cooling?
18. Write the advantages of hydrogen cooling.
19. Draw the diagram of excitation and exciter system of alternator?
20. For a 3 phase winding with 4 slots/pole/phase and with the coil span of 10 slots pitch, calculate the values of the pitch and distribution factor.(0.966 , 0.9576)

Part – C Questions:

1. Explain the working principles of alternator.
2. Explain the construction details of salient pole and non-salient pole type of rotor.
3. Derive the expression for EMF of alternator taking into account the pitch factor and distribution factor.
4. Explain the methods of obtaining the sine wave in salient pole and non-salient pole alternators with relevant diagram.
5. Explain the various ventilation system adopted in turbo alternators.
6. A 2200 volt, 3-phase alternator is running at 300 r.p.m and has 24 poles. Find the number of the conductors in the stator winding, if the magnetic flux is 5×10^{-2} Wb/pole. Assume distribution factor as 0.96. (600)
7. A 4 pole alternator has an armature with 25 slots and 8 conductors /slot and rotates at 1500 rpm and the flux/pole is 0.05 Wb. Calculate the emf generated, if winding factor is 0.96 and all conductors are in series. (1065.6)
8. A 16-pole, 3 phase alternator has a star –connected winding with 144 slots and 10 conductors per slot .the flux per pole is 0.03 Wb. Distributed sinusoidally and the speed is 375 rpm. find the line voltage.(2658)
9. Calculate the e.m.f of a 4 pole, 3phase star connected alternator running at 1500 rpm from the following data:(1138)

   Flux per pole = 0.1 Wb
   Number of slots = 48
   Conductors/slot (2 layer) = 4
   Coil span = 150°
10. A 3 phase, 16 pole, star connected alternator has 192 stator slots with eight conductors/slot and the conductors of each phases are connected in series. The coil span is 150 electrical degrees. Determine the phase and line voltage if the machine runs at 375 r.p.m and the flux per pole is 64mWb distributed sinusoidally over pole.(3367, 5830)
11. An alternator has the following data:

   3ϕ alternator
   No of pole = 8
   Distribution factor = 0.985
   Flux/ pole = 0.040 Wb

No of slots an armature = 90
No of conductors/slot = 8
Full pitch winding
Speed of alternator = 600 rpm
Determine no load phase and line voltage.

12. A three phase star connected, 10 pole 600 rpm alternator has 90 slots and flux of 0.16 Wb per pole. Find the number of armature conductors per phase required to give a line voltage of 11 KV. Assume full pitch coil.
13. A three phase 8 pole 750 rpm star connected alternator has 72 slots, each slots is having 12 conductors. The winding is chorded by 2 slots. Calculate the induced emf between lines if the flux per pole is 0.06 wb sinusoidally distributed.
14. A 4 pole 50Hz, star connected alternators have a flux per pole of 0.12 Wb. It has 4 slots/pole/phase, conductors/slot being 4. If the winding coil span is 150^o find the emf.
15. Write the expression, showing the relationship between speed, frequency and number of poles of a synchronous machine. The speed of rotation of the turbine driving an alternator is 166.7 rpm. What should be the number of poles of the alternator if it is to generate voltage at 50Hz?
16. A 6 pole synchronous generator has the following data:

Number of slots = 30
Number of conductors/slot = 8
speed = 1000 rpm
Flux per pole = 0.06 Wb
Distribution factor = 0,965
All the conductors are in series
Determine the line voltage generated in the synchronous generator.

17. A synchronous generator has the following data:

Number of phases = 3
Armature winding is connected in star
Number of slots = 180
Number of poles = 20
Number of conductors/slot = 12
Synchronous speed = 300 rpm
Flux per pole = 0.035 Wb
Determine the line voltage generated in the synchronous generator

UNIT-II

ALTERNATOR PERFORMANCE AND TESTING

2.1 Load characteristics of an alternators:

As the load of an alternator is varied, its terminal voltage is also found to vary. This variation in terminal voltage is due to the following reasons

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

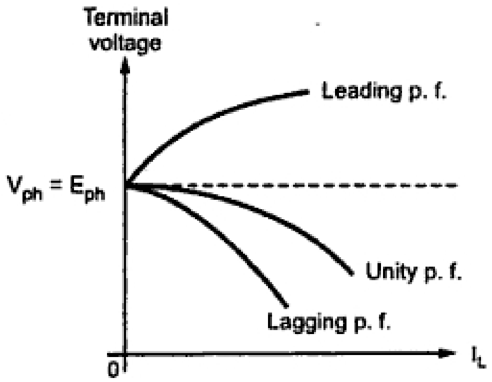


Fig: 2.1

A load characteristic of an alternator is the relation between the terminal voltage and the load current keeping the field excitation and speed as constant. The variation of terminal voltage also depends on the power factor of the load. With unity power factor load, there is a moderate voltage drop. But if there load has a lagging power factor this voltage drop is considerably increased. On the other hand, a load having a leading power factor has the reverse effect. If the load current leads the voltage by sufficient angle, the voltage drop may actually be converted into a voltage rise. The load characteristics curves for different power factors are shown in fig 2.1

2.2 Reason for change in terminal voltage or causes of voltage drop in alternators

When the armature current increases, the terminal voltage drops due to the following reasons.

- Voltage drop due to armature effective resistance (R_{eff}) of the armature winding.
- Voltage drop due to armature leakage reactance (X_L).
- Voltage drop due to armature reaction.

2.3 Armature reaction of alternators on load at various power factors

The armature winding of an alternator carries current only when the alternator is loaded. At no-load, there will be no current flowing through the armature winding. In alternators under loaded condition, there are two fluxes present in the air-gap. They are

- Flux due to the field ampere turns
- Flux due to the current flowing through the armature winding

That is, when the armature carries the load current, an armature flux (ϕ_a) is produced in the armature winding and is also present in the airgap. There is already another flux due to field current that is also present in the air-gap. Now there are two fluxes present in the air gap. But actually the machine needs only the fluxes due to field ampere turns only.

The effect of armature flux due to armature current over the main field flux is called armature reaction. This effect can be in the following forms.

They are

- The armature flux will produce a distortion over the field flux
- The armature flux will oppose the main field flux (or) will aid the main flux.

The above said armature reaction effects depends upon the p.f of the load.

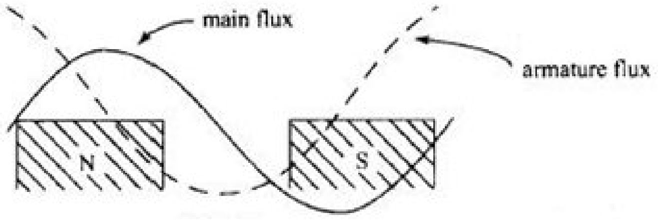


Fig 2.2 Unity p.f

Consider the load of the alternator as resistive and for which the p.f is unity. That is the load current is in phase with the terminal voltage V. at unity p.f, armature flux cross magnaetising. i..e at unity p.f of the load, the main flux and the armature flux are as shown in Fig 2.2

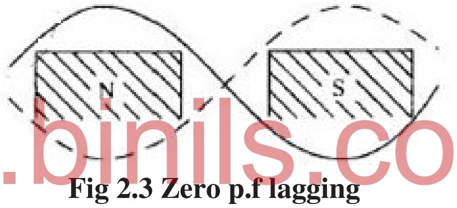


Fig 2.3 Zero p.f lagging

The result is that the flux at the leading pole tips of the pole is reduced. While it is increased at the trailing pole tips. Hence these two effects are more or less off set each other. Hence the filed strength is constant. Under unity p.f load, the armature reaction is distortional.

Consider the load of the alternator as pure inductive, and for which the p.f is zero lagging. That is the load current lags the terminal voltage by an angle 90^0 . At zero p.f lagging load, the armature flux is in direct opposition to the main flux as shown in Fig 2.3. So the main flux is decreased. For zero p.f lagging, the armature reaction is demagnetizing. It weakens the main flux. So less emf is generated. To keep the generated emf constant, field excitation has to be increased, in order to compensate the weaken flux.

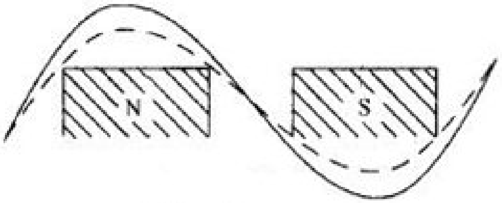


Fig 2.4 Zero p.f leading

Consider the load of the alternator is pure capacitive, and for which the p.f is zero leading. That is the load current leads the terminal voltage V by an angle 90^0. At zero p.f leading, the armature flux is in phase with the main flux as shown in Fig 2.4. The armature flux added with the main flux and hence the flux is increased. Here the armature reaction effect is magnetizing. Due to increasing of flux, the generated emf is increased. Hence to keep the generated emf constant, the field excitation has to be reduced in order to compensate the increasing flux.

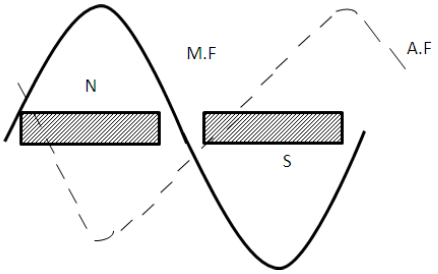


Fig 2.5 Intermediate power factor

If the p.f the load is intermediate (say 0.7 p.f lagging) the armature reaction effect is partly distortion and partly demagnetising. The effect is shown in Fig 2.5

2.4 Effective Resistance, R_{eff}:

The effective resistance of the armature is the resistance offered by the armature winding for a alternating current. It is greater than the D. C resistance due to skin effect. R_{eff} is usually assumed to be $1.6R_{DC}$. the voltage drop due to this resistance (IR_{eff}) is very low compared to other voltage drops.

2.4.1 Armature Resistance:

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

2.5 Armature Leakage Reactance:

When current flows through the armature conductors, fluxes are set up which do not cross the air-gap, but take different paths. Such fluxes are known as leakage fluxes. The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V. This leakage flux sets up an emf. of self-inductance which is known as reactance emf. and which is ahead of I by 90°.

Hence, armature winding is assumed to possess leakage reactance X_L (also known as Potier reactance X_P) such that voltage drops due to this equals IX_L. A part of the generated emf is used up in overcoming this reactance emf.

2.6 Synchronous Reactance X_s:

The synchronous reactance of an alternator is a fictitious reactance. It is equivalent to a reactance value, which is equal to the combined effects of the armature leakage reactance, X_L and a fictitious inductive reactance to represents the armature reaction X_a, synchronous reactance X_S is equal to ($X_L + X_a$)

2.7 Synchronous Impedance, Z_S :

The effective value of armature resistance R_{eff} and synchronous reactance combined together is called synchronous impedance, Z_S. it is the vector sum of armature resistance and the synchronous reactance

$Z_S =$ ohms.

2.8 Voltage Regulation:

It is clear that with change in load, there is a change in terminal voltage of an alternator. The magnitude of this change depends not only on the load but also on the load power factor. The voltage regulation of an alternator is defined as “the rise in voltage when full-load is removed (field excitation and speed remaining the same) divided by the rated terminal voltage.”

$$\therefore \%\ Regulation\ 'Up' = \frac{E_o - V}{V} \times 100$$

2.8.1 Determination of Voltage Regulation:

In the case of small machines, the regulation may be found by direct loading. The procedure is as follows:

The alternator is driven at synchronous speed and the terminal voltage is adjusted to its rated value V. The load is varied until the wattmeter and ammeter indicate the rated values at desired p.f. Then the entire load is thrown off while the speed and field excitation are kept constant. The open-circuit or no-load voltage E_0 is read. Hence, regulation can be found from

$$\% regulation = \frac{E_O - V}{V} \times 100$$

In the case of large machines, the cost of finding the regulation by direct loading becomes expensive. Hence, other indirect methods are used as discussed below. It will be found that all these methods differ mainly in the way the no-load voltage E_0 is found in each case.

- Synchronous Impedance or E.M.F. Method
- The Ampere-turn or M.M.F. Method
- Zero Power Factor or Potier Method

All these methods require:

1. Armature (or stator) resistance R_a
2. Open-circuit/No-load characteristic.
3. Short-circuit characteristic (but zero power factor lagging characteristic for Potier method).

2.8.1 To find the Value of Ra:

Armature resistance Ra per phase can be measured directly by voltmeter and ammeter method or by using Wheatstone bridge. However, under working conditions, the effective value of Ra is increased due to 'skin effect'. The value of Ra so obtained is increased by 60% or so to allow for this effect. Generally, a value 1.6 times the d.c. value is taken.

2.8.2 Open circuit characteristics

The open –circuit characteristics or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator. But it is usual to plot the curve with exciting current in X-axis and the terminal voltage in Y-axis. The test is carried out on open circuit maintaining the speed of the machine at normal.

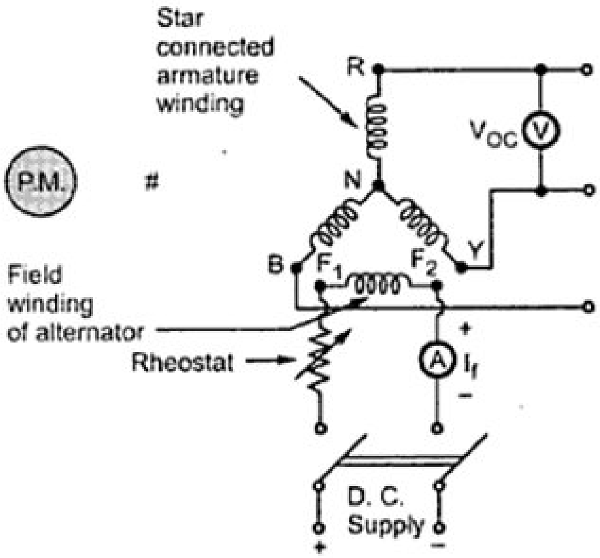


Fig 2.6

The connection in diagram for the open –circuit characteristics (O.C.C) is shown in fig.2.6 the armature terminals are left open circuited and a voltmeter is connected to show the induced emf . The ammeter connected shows the field excitation of the alternator. For various field current the induced emfs are noted and plotted the open-circuit characteristics as shown fig .2.7

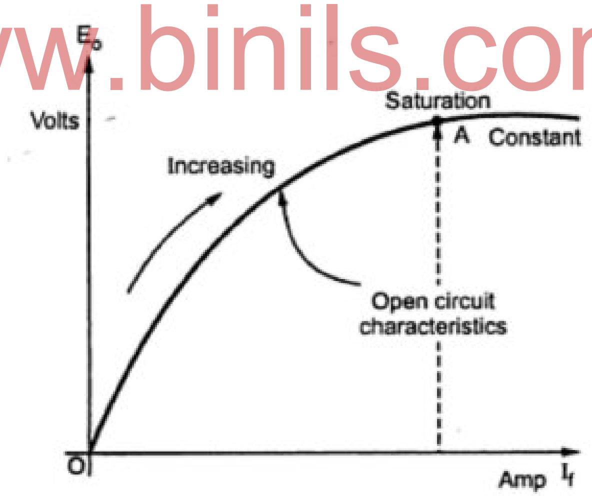


Fig 2.7

2.8.3 Short –circuit characteristics

The short –circuit characteristics, as its name implies, refers to the behavior of the alternator when its armature is short circuited. The connection diagram for conducting the short –circuit test is shown in fig 2.8. The armature terminals are short circuited through an ammeter to show the short circuit current. Another ammeter is connected in the field circuit of the alternator to show the field excitation.

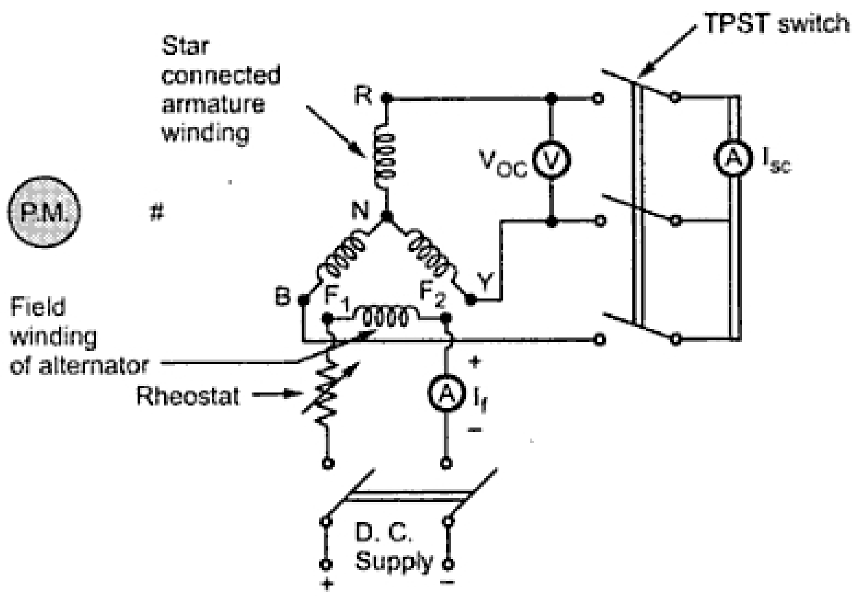


Fig: 2.8

The alternator is allowed to run at rated speed. The filed current is gradually increased till the armature current reaches its rated value. The small induced emf in the armature is equal to the voltage drop in the winding itself. This induced emf is required to circulate the short –circuit current through the armature windings.

The armature short- circuit current and the filed current are found to be proportional to each other over a wide range as shown in fig 2.9 .So the short –circuit characteristics (S.C.C) is a straight line.

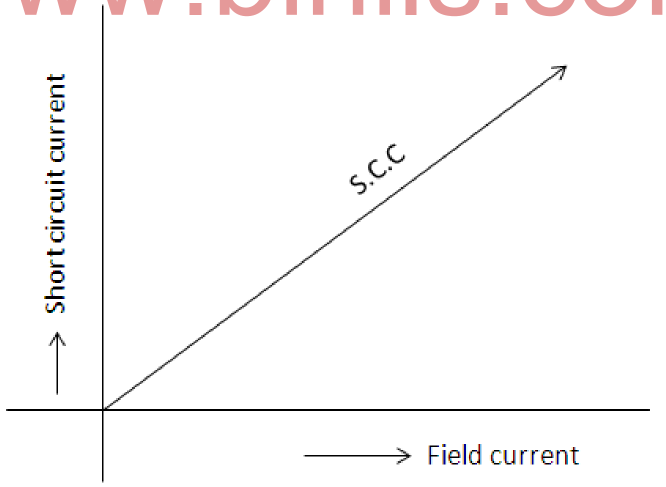


Fig: Short circuit characteristic

Fig: 2.9

2.9 Synchronous Impedance Method:

Following procedural steps are involved in this method:

1. O.C.C is plotted from the given data as shown in Fig. 2.10 (a).
2. Similarly, S.C.C. is drawn from the data given by the short-circuit test. It is a straight line passing through the origin. Both these curves are drawn on a common field-current base.

Consider a field current I_f. The O.C. voltage corresponding to this field current is E_1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedance Z_S.

$$\therefore \quad E_1 = I_1 Z_S \qquad \therefore Z_S = \frac{E_1(Open\ circuit)}{I_1(Short\ \ circuit)}$$

3. Since Ra can be found as discussed earlier $X_S = \sqrt{Z^2{}_s - R_a^2}$
4. Knowing R_a and X_S, vector diagram as shown in Fig. 2.10 (b) can be drawn for any load and any power factor.

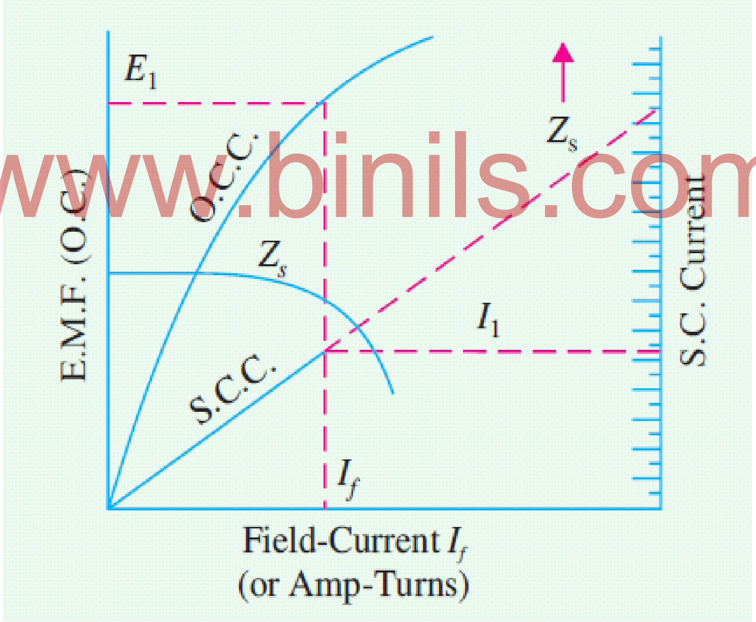


Fig.2.10 (a) OCC & SCC

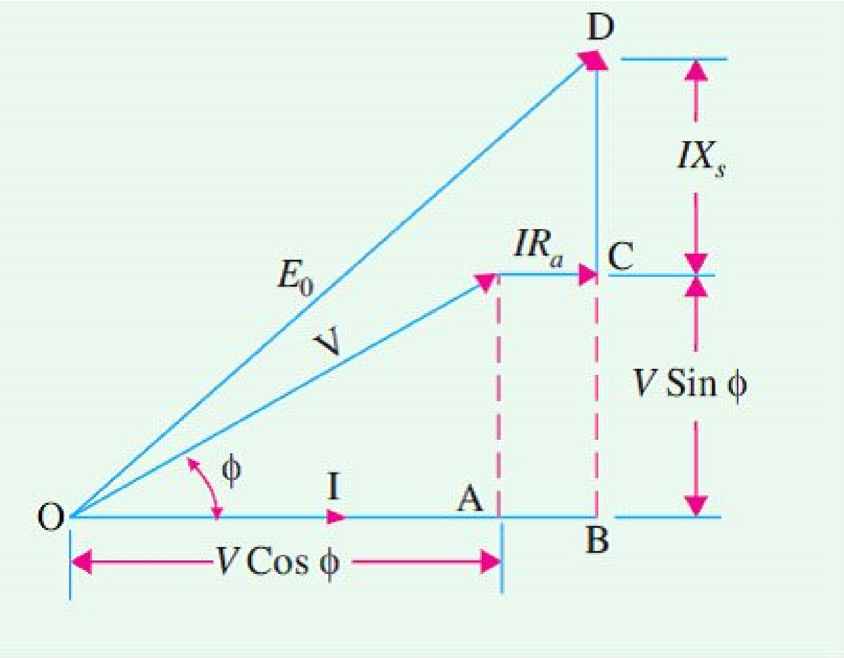


Fig.2.10 (b) Vector Diagram

Here $OD = E_O$ $\quad \therefore E_O = \sqrt{(OB^2 + BD^2)}$

or $E_O = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

$$\therefore \%\text{Re}\,gulation'Up' = \frac{E_o - V}{V} \times 100$$

This method is not accurate because the value of Z_S so found is always more than its value under normal voltage conditions and saturation. Hence, the value of regulation so obtained is always more than that found from an actual test. That is why it is called pessimistic method. The value of Z_S is not constant but varies with saturation.

At low saturation, its value is larger because then the effect of a given armature ampere-turns is much more than at high saturation. Now, under short-circuit conditions, saturation is very low, because armature m.m.f. is directly demagnetizing. Different values of Z_S corresponding to different values of field current are also plotted in Fig. 2.10 (a).

The value of Z_S usually taken is that obtained from full-load current in the short-circuit test. Here, armature reactance X_a has not been treated separately but along with leakage reactance X_L..

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

Generally, alternators are used in a power system where they are in parallel with many other alternators. It means that the alternator is connected to a live system of constant voltage and constant frequency. Often the electrical system, to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same. In that case, the alternator is said to be connected to infinite bus-bars.

Example 2.1 The effective resistance of a 2200 V, 50Hz, 440KVA, single phase alternator is 0.5Ω. On short circuit, a field current of 40 A gives the full load current of 200 A .The emf on open circuit with the same field current excitation is 1160V. Calculate the synchronous impedance and reactance.

Solution:

Synchronous impedance, $Zs = \frac{open\ circuit\ voltage}{short\ circuit\ current}$

Synchronous impedance, $Zs = \frac{1160}{200} = 5.8\Omega$

Synchronous reactance, $Xs = \sqrt{Zs^2 - Ra^2}$

$Xs = \sqrt{5.8^2 - 0.5^2} = 5.78\Omega$

Example 2.2 The effective armature resistance and synchronous reactance of a 60 KVA, star connected. 440V, 3-phase, 50 Hz alternator are 0.2Ω and 3Ω per phase respectively. Determine the percentage voltage regulation on full load at unity power factor.

Solution:

Terminal voltage per phase $= \frac{440}{\sqrt{3}} = 254\ Volts$

Full load current $= \frac{60 \times 1000}{\sqrt{3} \times 440} = 78.72\ A$

Induced emf per phase, $Eo = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

$= \sqrt{(254 \times 1 + 78.72 \times 0.2)^2 + (254 \times 0 + 78.72 \times 3)^2}$

$=$ 358.5 Volts

Percentage of voltage regulation $= \dfrac{E_o - V}{V} \times 100$

$= \dfrac{358.5 - 254}{254} \times 100 = 41\%$

Example 2.3 A 550V, 55 KVA, single phase alternator has an effective resistance of 0.2Ω. A field current of 10A produces an armature current of 200A on short circuit and an emf of 450V on open circuit. Calculate (1) the synchronous impedance and reactance (2) the full load regulation with 0.8 power factor lagging.

Solution:

Full load current $= \dfrac{55000}{550} = 100\,A$

Synchronous impedance, Zs $= \dfrac{\text{open circuit voltage}}{\text{short circuit current}} = \dfrac{450}{200} = 2.25\Omega$

Synchronous reactance, Xs $= \sqrt{Zs^2 - Ra^2}$

Xs $= \sqrt{2.25^2 - 0.2^2} = 2.24\Omega$

Induced emf per phase, Eo $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

$= \sqrt{(550 \times 0.8 + 100 \times 0.2)^2 + (550 \times 0.6 + 100 \times 2.24)^2}$

= 720 volts

Percentage of voltage regulation $= \dfrac{E_o - V}{V} \times 100$

$= \dfrac{720 - 550}{550} \times 100 = 30.92\%$

Example 2.4 Determine the voltage regulation of a 2000V, single phase alternator giving a current of 100 A at 0.71 power factor lagging from the following test results.

> ***Test Results: Full load current of 100 A is produced on short circuit by a field current of 2.5 A; an emf of 500V is produced on open circuit by the same excitation. Armature resistance is 0.8Ω.***

Solution:

Synchronous impedance, Zs = $\frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{500}{100} = 5\Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

Xs = $\sqrt{5^2 - 0.8^2} = 4.94\,\Omega$

Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

= $\sqrt{(2000\times 0.71 + 100\times 0.8)^2 + (2000\times 0.71 + 100\times 4.94)^2}$

= 2431.7 Volts

Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{2431.7 - 2000}{2000}\times 100 = 21.58\%$

Example 2.5 A 60 KVA, 220V, 50Hz, 1- φ alternator has effective armature resistance of 0.016Ω and an armature leakage reactance of 0.07Ω . Compute the voltage induced in armature when the alternator is delivering rated current at a load power factor of (a) unity (b) 0.7 lagging (c) 0.7 leading.

Solution:

Full load current = $\frac{60000}{220} = 272.2\,A$

At unity power factor Induced emf per phase, Eo = $\sqrt{(V + IR_a)^2 + (IX_L)^2}$

Eo = $\sqrt{(220+272.2\times0.016)^2+(272.2\times0.07)^2}$

= 225 V

At 0.7 lagging p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi+IX_L)^2}$

= $\sqrt{(220\times0.7+272.2\times0.016)^2+(220\times0.7+272.2\times0.07)^2}$

= 235 Volts

At 0.7 leading p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi-IX_L)^2}$

= $\sqrt{(220\times0.7+272.2\times0.016)^2+(220\times0.7-272.2\times0.07)^2}$

= 208 lts

Example 2.6 Find the synchronous impedance and reactance of an alternator in which a given field current produces an armature current of 200 A on short circuit and a generated emf of 50 V on open circuit. The armature resistance is 0.1Ω. To what induced voltage must the alternator be excited if it is to deliver a load of 100 A at a p.f. of 0.8 lagging. With terminal voltage of 200V

Solution:

Synchronous impedance, Zs = $\dfrac{open\ circuit\ voltage}{short\ circuit\ current}=\dfrac{50}{200}=0.25\Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2-Ra^2}$

Xs = $\sqrt{0.25^2-0.1^2}=0.23\ \Omega$

Induced emf per phase, Eo = $\sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi+IX_S)^2}$

$$= \sqrt{(200\times 0.8+100\times 0.1)^2+(200\times 0.6+100\times 0.23)^2}$$

$$= 222 \text{ lts}$$

Example 2.7 Determine the voltage regulation of a 2000V, single phase alternator giving a current of 100 A at (i) unity p.f (ii) 0.8 leading p.f (iii) 0.71 lagging p.f from the following test results.

Test Results: Full load current of 100 A is produced on short circuit by a field current of 2.5 A; an emf of 500V is produced on open circuit by the same excitation. Armature resistance is 0.8Ω.

Solution:

Synchronous impedance, $Zs = \frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{500}{100} = 5\Omega$

Synchronous reactance, $Xs = \sqrt{Zs^2 - Ra^2}$

$Xs = \sqrt{5^2 - 0.8^2} = 4.94\,\Omega$

At unity power factor Induced emf per phase, $Eo = \sqrt{(V+IR_a)^2+(IXs)^2}$

$$= \sqrt{(2000+100\times 0.8)^2+(100\times 4.94)^2}$$

$$= 2140 \text{ V}$$

At 0.71 lagging p.f Induced emf per phase, $Eo = \sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi+IX_S)^2}$

$$= \sqrt{(2000\times 0.71+100\times 0.8)^2+(2000\times 0.71+100\times 4.94)^2}$$

$$= 2432 \text{ Volts}$$

At 0.8 leading p.f Induced emf per phase, $Eo = \sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi-IX_S)^2}$

$$= \sqrt{(2000 \times 0.8 + 100 \times 0.8)^2 + (2000 \times 0.6 - 100 \times 4.94)^2}$$

$$= 1822 \text{ Volts}$$

At Unity p.f

Percentage of voltage regulation $= \frac{E_o - V}{V} \times 100$

$$= \frac{2140 - 2000}{2000} \times 100 = 7\%$$

At 0.8 leading p.f

Percentage of voltage regulation $= \frac{E_o - V}{V} \times 100$

$$= \frac{1820 - 2000}{2000} \times 100 = -9\%$$

At 0.71 lagging p.f

Percentage of voltage regulation $= \frac{E_o - V}{V} \times 100$

$$= \frac{2432 - 2000}{2000} \times 100 = 21.6\%$$

Example 2.8 A 100 KVA, 3000V, 50Hz, 3-phase star connected alternator has effective armature resistance of 0.2Ω. The field current of 40 A produces short circuit current of 200 A and an open circuit emf of 1040 V (line value). Calculate the full load voltage regulation at 0.8 p.f. lagging and 0.8 p.f leading.

Solution:

Synchronous impedance, $Zs = \frac{\text{open circuit voltage}}{\text{short circuit current}} = \frac{1040/\sqrt{3}}{200} = 3\Omega$

Synchronous reactance, $Xs = \sqrt{Zs^2 - Ra^2}$

$$Xs = \sqrt{3^2 - 0.2^2} = 2.99\,\Omega$$

Full load current = $\frac{100000}{\sqrt{3} \times 3000} = 19.2\,A$

Voltage per phase = $\frac{3000}{\sqrt{3}} = 1732\,V$

(i) P.f 0.8 lagging = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

At 0.8 lagging p.f Induced emf per phase , Eo

$= \sqrt{(1732 \times 0.8 + 19.2 \times 0.2)^2 + (1732 \times 0.6 + 19.2 \times 2.99)^2}$

= 1770 Volts

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

$= \frac{1770 - 1730}{1730} \times 100 = 2.2\%$

(ii) At 0.8 leading p.f = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_S)^2}$

At 0.8 leading p.f Induced emf per phase, Eo

$= \sqrt{(1730 \times 0.8 + 19.2 \times 0.2)^2 + (1730 \times 0.6 - 19.2 \times 2.99)^2}$

= 1701.31 Volts

At 0.8 leading p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

$= \frac{1701 - 1730}{1730} \times 100 = -1.8\%$

Example 2.9 A 3 –phase star connected alternator is rated at 1600 KVA, 13500 V. the armature resistance and synchronous reactance are 1.5Ω and 30Ω respectively per phase. Calculate the percentage regulation for a load of 1280 KW at 0.8 leading power factor.

Solution:

Load current = $\frac{1280 \times 10^3}{\sqrt{3} \times 13500 \times 0.8} = 68.4\,A$

Voltage per phase = $\frac{13500}{\sqrt{3}} = 7794\,V$

At 0.8 leading p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_S)^2}$

= $\sqrt{(7794 \times 0.8 + 68.4 \times 1.5)^2 + (7794 \times 0.6 - 68.4 \times 30)^2}$

= 6860 Volts

At 0.8 leading p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

= $\frac{6860 - 7795}{7795} \times 100 = -11.98\%$

Example 2.10 A 3-phase, 10 KVA, 400 V, 50Hz, Y-connected alternator supplies the rated load at 0.8 p.f lag. If armature resistance is 0.5Ω and synchronous reactance is 10 Ω. Find the voltage regulation.

Solution:

Full load current = $\frac{100000}{\sqrt{3} \times 400} = 14.4\,A$

Voltage per phase = $\frac{400}{\sqrt{3}} = 231\,V$

At 0.8 lagging p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

= $\sqrt{(231\times 0.8+14.4\times 0.5)^2+(231\times 0.6+14.4\times 10)^2}$

= 342 Volts

At 0.8 lagging p.f = $\frac{E_o - V}{V}\times 100$

Percentage of voltage regulation

= $\frac{342-231}{231}\times 100 = 48\,\%$

Example 2.11 The following test results are obtained from a 3-phase ,600 KVA, 6600V, star connected ,2 pole, 50 Hz turbo alternator:

With a field current of 125 A, the open circuit voltage is 8000 V at the rated speed. With the same field current and rated speed, the short- circuit current is 800 A. at the rated full load, the resistance drop is 3 percent. Find the regulation of the alternator on full load and at a power factor of 0.8 lagging.

Solution:

Synchronous impedance, Zs = $\frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{8000/\sqrt{3}}{800} = 5.77\Omega$

Voltage per phase = $\frac{6600}{\sqrt{3}} = 3810.5\ V$

Resistive drop = 3% of 3810.5 V

= 114.3 V

Load current = $\frac{600\times 10^3}{\sqrt{3}\times 6600} = 52.5\ A$

IR_a = 114.3

R_a = 114.3/52.5 = 2.177Ω

Synchronous reactance, X_s = $\sqrt{Zs^2 - Ra^2}$

X_s = $\sqrt{5.77^2 - 0.218^2} = 5.3435\ \Omega$

At 0.8 lagging p.f Induced emf per phase, E_o = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

$$= \sqrt{(3810 \times 0.8 + 525 \times 0.218)^2 + (3810 \times 0.6 + 525 \times 5.74)^2}$$

= 4073.23 Volts

At 0.8 lagging p.f

Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

$$= \frac{4073 - 3810}{3810} \times 100 = 6.89\,\%$$

Example 2.12 A 3-phase 50 Hz star connected 2000 KVA, 2300 V alternator gives a short circuit current of 600 A for a certain field excitation. With the same excitation, the open circuit voltage was 900 V. the resistance between a pair of terminals was 0.12Ω. Find full load regulation at (i) UPF (ii) 0.8 p.f lagging.

Solution:

Synchronous impedance, Z_s = $\frac{\text{open circuit voltage}}{\text{short circuit current}} = \frac{900/\sqrt{3}}{600} = 0.866\Omega$

Full load current = $\frac{2000 \times 10\text{^}3}{\sqrt{3} \times 2300} = 502\ A$

Resistance between the terminals is 0.12Ω . it is the resistance of two phase connected in series

Resistance /phase = $0.12 / 2 = 0.06\Omega$

Effective resistance / phase = $1.5 \times Ra$

= $1.5 \times 0.06 = 0.09\ \Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

Xs = $\sqrt{0.866^2 - 0.09^2} = 0.86\ \Omega$

Voltage per phase = $\frac{2300}{\sqrt{3}} = 1328\,V$

At unity power factor Induced emf per phase, Eo = $\sqrt{(V + IR_a)^2 + (IXs)^2}$

= $\sqrt{(1328 + 502 \times 0.06)^2 + (502 \times 0.86)^2}$

= 1425 V

Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

= $\frac{1425 - 1328}{1328} \times 100 = 7.3\%$

At 0.8 lagging p.f Induced emf per phase, Eo = $\sqrt{(V \cos\phi + IR_a)^2 + (V \sin\phi + IX_S)^2}$

= $\sqrt{(1328 \times 0.8 + 502 \times 0.06)^2 + (1328 \times 0.6 + 502 \times 0.86)^2}$

= 1644 Volts

At 0.8 lagging p.f = $\frac{E_o - V}{V} \times 100$

Percentage of voltage regulation

= $\frac{1643 - 1328}{1328} \times 100 = 23.7\%$

Example 2.13 A 500 KVA, three phase, star connected alternator has a rated line to line terminal voltage of 3300V. The resistance and synchronous reactance per phase are 0.3Ω and 4.0 Ω respectively. Calculate the voltage regulation at full load, 0.8 power factor lagging.

Solution:

Full load current = $\frac{500000}{\sqrt{3}\times 3300} = 87.5\,A$

Voltage per phase = $\frac{3300}{\sqrt{3}} = 1905\,V$

At 0.8 lagging p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$

= $\sqrt{(1905\times 0.8 + 87.5\times 0.3)^2 + (1905\times 0.6 + 87.5\times 4)^2}$

= 2152 Volts/phase

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{2152 - 1905}{1905}\times 100 = 12.96\,\%$

Example 2.14 A 1200 KVA, 3300V, 50 Hz, three phase, star connected alternator has armature resistance of 0.25Ω per phase. A field current of 40 A produces a short –circuit current of 200 A and an open –circuit emf of 1100 V line to-line. Calculate the regulation on (a) full load 0.8 power factor lagging; (b) full load 0.8 leading power factor

Solution:

Full load current = $\frac{1200000}{\sqrt{3}\times 3300} = 210\,A$

Voltage per phase = $\frac{3300}{\sqrt{3}} = 1905\,V$

Synchronous impedance, Zs = $\frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{1100/\sqrt{3}}{200} = 3.175\Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

X_s = $\sqrt{3.175^2 - 0.25^2} = 3.165\ \Omega$

(a) At 0.8 lagging p.f Induced emf per phase, E_o = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

= $\sqrt{(1905\times 0.8 + 210\times 0.25)^2 + (1905\times 0.6 + 210\times 3.165)^2}$

= 2398 Volts

At 0.8 lagging p.f

Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{2398 - 1905}{1905}\times 100 = 25.9\%$

(b) At 0.8 leading p.f Induced emf per phase, E_o = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_s)^2}$

= $\sqrt{(1905\times 0.8 + 210\times 0.25)^2 + (1905\times 0.6 - 210\times 3.165)^2}$

= 1647 Volts

At 0.8 leading p.f

Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{1647 - 1905}{1905}\times 100 = -13.54\%$

2.10 M.M.F. or Ampere-turn Method:

For determining the regulation of an alternator by Magneto Motive force (MMF) method, the open circuit test and short circuit test are to be conducted on the alternator.

In this method, the armature leakage reactance and the effect of armature reaction are treated as mmf

The following steps are followed in this method for calculating the regulation

1. MMF in terms of field currents are calculated.
2. Field current (MMF) for the voltage of the vector sum of terminal voltage (V) and IR_a drop is found out from the O.C.C . Let this field current be I_{f1}.

3. Rated armature current is known. Then from the S.C.C, the value of field current is found out in order to produce the rated full load armature current on short circuit. Let this filed current I_{f2}.
4. This is the field current or MMF necessary to send the rated current against the effect of armature leakage reactance and the armature reaction.
5. The vector sum of the two field currents I_{f1} and I_{f2} are found out and let this value be I_{fr}.
6. For this current I_{fr} ,the corresponding e.m.f . on the open circuit characteristics is found out. This e.m.f is the no load e.m.f of the alternator E.
7. Knowing the no load EMF E, the regulation can be calculated as

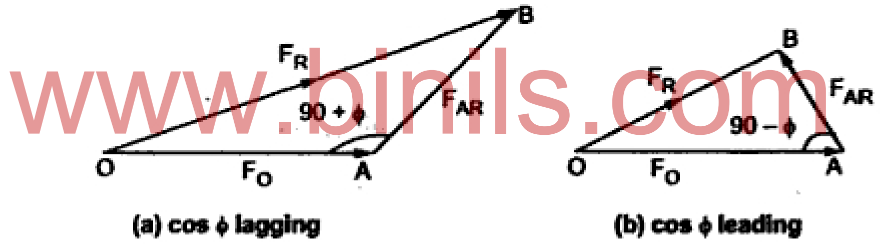
$$\%regulation = \frac{E_O - V}{V} \times 100$$

Fig 2.11 Shows the OC and SC characteristics and also the vector diagram for lagging p.f load. For lagging p.f load the I_{f2} is drawn from I_{f1} by an angle (90+θ) as shown in fig 2.12 (a). The vector sum of I_{f1} and I_{f2} is I_{fr} . For this current I_{fr} , the corresponding e.m.f on the open circuit characteristics is found out. This is no load emf (E)

Hence

$$\%regulation = \frac{E_O - V}{V} \times 100$$

Can be calculated for lagging p.f.



(a) cos ϕ lagging

(b) cos ϕ leading

Fig 2.12

For leading p.f load , I_{f2} is drawn from I_{f1} by an angle (90-θ) as shown in Fig 2.12.(b) . the vector sum of I_{f1} and I_{f2} is I_{fr} . for this current I_{fr}, the corresponding e.m.f on open circuit characteristics is found out. This e.m.f is no load e.m.f (E) . Then the

$$\%regulation = \frac{E_O - V}{V} \times 100$$

can be calculated for leading p.f

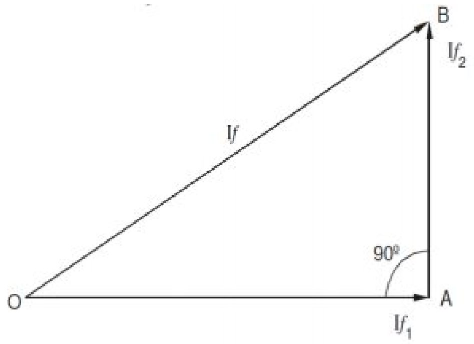


Fig 2.13

For unity p.f load ,I_{f2} is drawn 90^o from I_{f1} as shown in fig 2.13 the vector sum of I_{f1} and I_{f2} is I_{fr}. For this current I_{fr}, the corresponding e.m.f on O.C.C is found out. This e.m.f is no load e.m.f (E) . Then the

$$\%regulation = \frac{E_O - V}{V} \times 100$$

Can be calculated for unity p.f

2.11 Zero Power Factor or potier Method

This method gives more accurate results since it is based on the separation of armature leakage reactance drop and the armature reaction effects. The following experimental data is required in this method:

(i) No –load or open circuit curve
(ii) Full –load zero power factor curve (S.C.C)

The circuit diagram to conducting this test is shown in fig 2.14

From (ii) the reduction in voltage due to armature reaction is found out and volltage drop due to armature leakage reactance (also called potier reactance) X_L is found from both (i) and (ii). By combining the two, Eo can be calculated.

The above two curves are similar and displaced horizontally by the m.m.f due to armature reaction in terms of the field current.

Zero power factor test

To conduct zero power factor test, the switch 'S' is kept closed. Due to this, a purely inductive load is connected to the alternator through an ammeter. A purely inductive load has zero power factor lagging (i.e $\cos 90^o$). The machine speed is maintained constant at synchronous speed. Then by adjusting the field current such that the voltmeter reads rated voltage and by varying the inductance of the load, such that ammeter reads rated full load current.

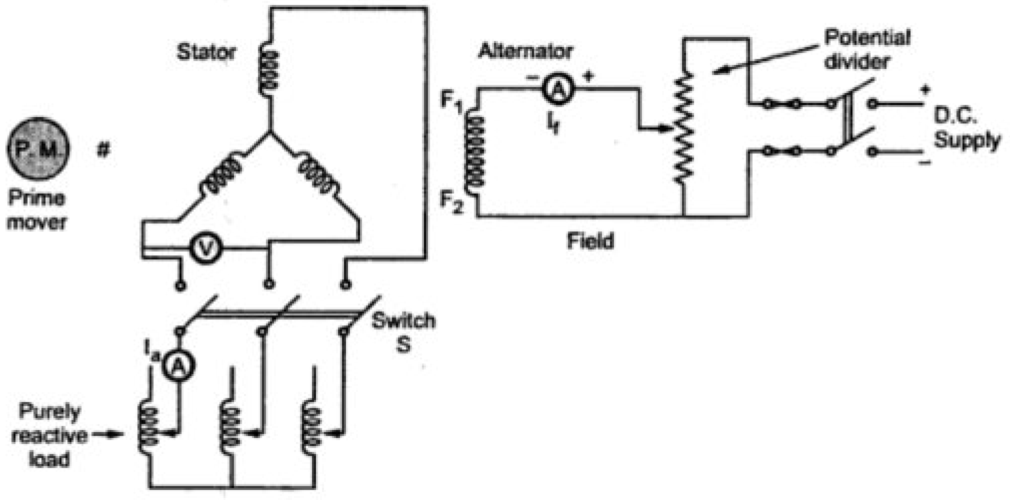


Fig 2.14

In this test there is no need to obtain number of points to obtain the curve. Only two points are enough to construct the zero power factor curve. This is the graph of terminal voltage against excitation when delivering full load zero power factor current.

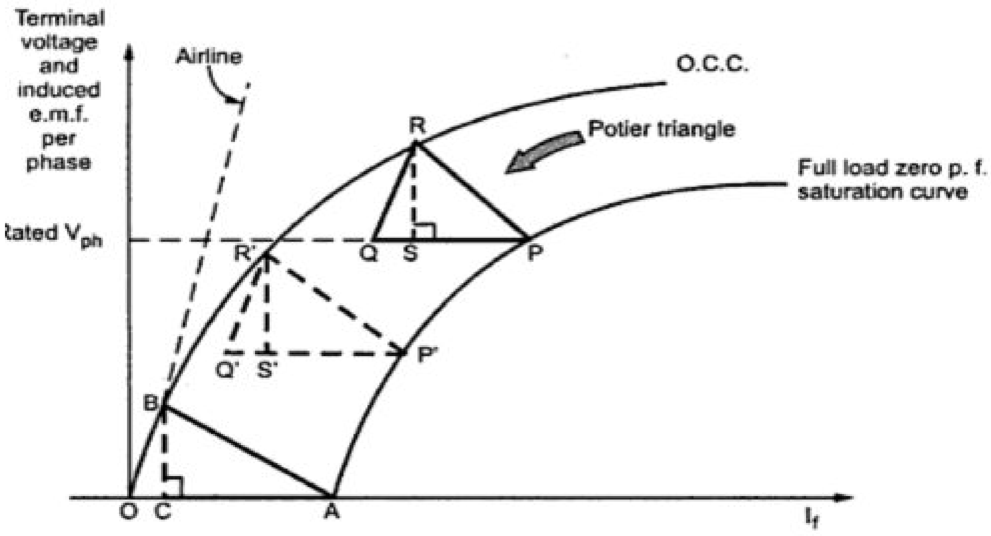


Fig 2.15

Zero power factor, full-load voltage excitation characteristics can be drawn by knowing two points A and P. point A is obtained from a short circuit test with full –load armature current. Hence OA represents field current (Excitation) required to overcome demagnetizing effect of armature reaction and to balance leakage reactance drop at full –load. Point P is obtained when full –load current flows through the armature and wattmeter reading is zero. Zero power factor curve may be drawn as follows:

(i) From P draw line PQ equal and parallel to OA.

(ii) Through point Q draw a line parallel to initial straight part of O.C.C (parallel to OB),cutting the O.C.C at R.

(iii) Join RQ and draw a perpendicular Line RS on PQ.

(iv) Impose the triangle PRS at various –points of O.C.C to obtain corresponding points on the zero power factor curve.

In triangle PRS

Length RS represents leakage reactance drop (IX_L)

Length PS represents armature reaction excitation. This shown in fig 2.15

Potier Regulation Diagram

Following is the procedure to draw potier regulation diagram:

(i) Draw OA horizontally to represent terminal voltage V on full load and OB to represent full load current (I) at a given power factor

(ii) Draw AC ($=IR_a$) ,voltage drop due to resistance (R_a) (if resistance is given)parallel to OB

(iii) Draw CD perpendicular to AC and equal to reactance drop IX_L.

Now OD represents generated e.m.f E.

(iv) From O.C.C, find the field current I_1 corresponding to this generated e.m.f E and draw OF (equal to I_1) perpendicular to OD. Draw FG parallel to load current OB (i.e . I) to represent excitation (field current) equivalent to full load armature reaction.

OG gives total field current required.

(v) If the load is thrown off, then terminal voltage will be equal to generated e.m.f corresponding to field excitation OG. Hence e.m.f E_o may be obtained from O.C.C corresponding to field excitation OG. Vector OJ will lag behind vector OG by 90^0 . DJ represents voltage drop due to armature reaction.

Now regulation may be obtained from the following relation:

$$\%regulation = \frac{E_O - V}{V} \times 100$$

2.12 Necessity for Parallel Operation of Alternators:

If the load on a single alternator at a power station becomes more than the rating of alternator, it becomes necessary to add another alternator in parallel to meet out the increasing load. For this reason, total output of a power station is supplied with a number of alternator connected in parallel to a common system of bus bars.

2.13 Condition for parallel operation:

- The terminal voltage of the incoming alternator must be the same as bus-bar voltage.
- The speed of the incoming machine must be such that its frequency (= PN/120) equals bus-bar frequency.
- The phase sequence of the alternator voltage must be identical with the phase sequence of the bus-bar voltage.

2.13.1 Advantages of Parallel operation:

- Increase the output capacity of a system beyond that of a single unit
- Serve as additional reserve power for expected demands
- Permit shutting down one machine and cutting in a standby machine without interrupting power distribution.

Methods of Synchronizing:

There are three methods of synchronizing for parallel operation

- Dark lamp Method
- Bright Lamp Method
- Synchroscope Method

2.14 synchronizing by Dark Lamp Method:

The connection for synchronizing a three phase alternator is shown in Fig 2.17 The alternator 1 is already connected with the bus-bar and is supplying power factor to the external circuit. The alternator 2 is the incoming alternator.

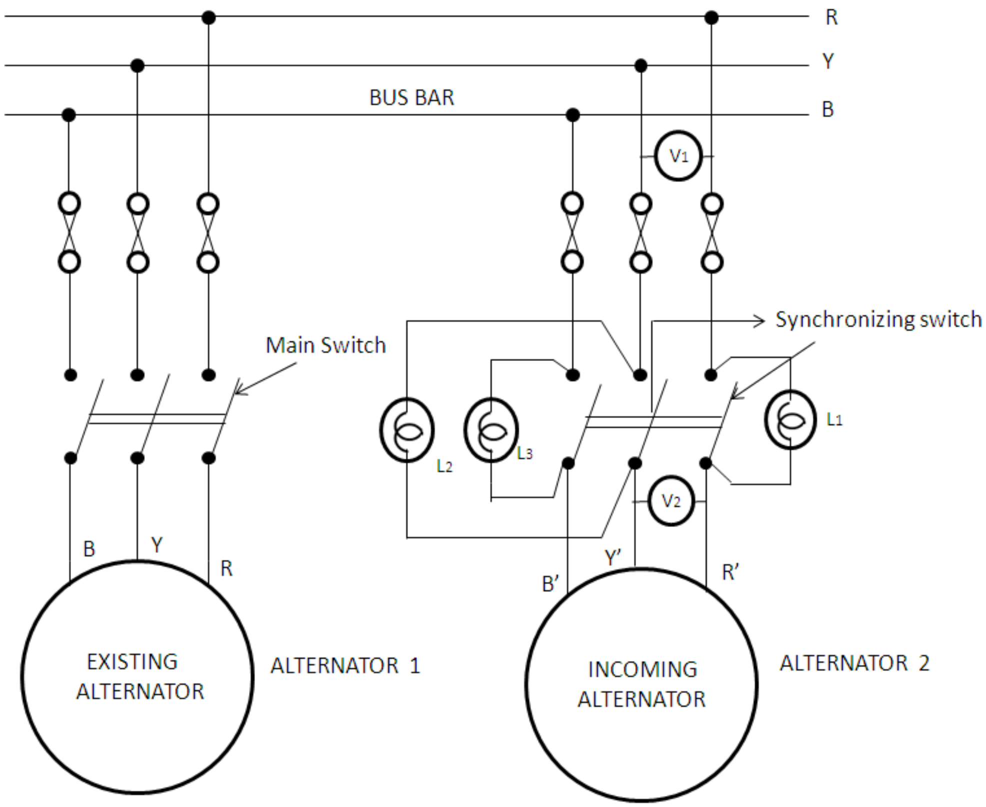


Fig : Dark lamp method

Fig 2.17

The incoming alternator started and its speed is adjusted to its rated value. Its excitation is also adjusted to generate its rated voltage. Voltmeter V_2 will indicate its voltage and voltmeter V_1 will indicate the bus-bar voltage. When the voltage V_1 and V_2 are equal, the condition 1 is satisfied.

The frequency of the incoming machine is adjusted to the bus-bar frequency by controlling the speed of the alternator 2. This fulfils the condition 2. The phase sequence also checked as mentioned above.

The synchronizing switch is closed at the middle of the lamps dark period. Now the incoming machine is connected to the bus-bar. At this stage, the generated emf of the incoming machine is just equal to the bus-bar voltage. It neither supply power nor receive power from the bus-bar, and the alternator 2 is said to be “floating on the bus-bar”.

In dark lamp method, it is not possible to judge whether the incoming alternator is fast or slow. Also, the lamp can be dark even though a small value of voltage may present across its terminals. These are the disadvantages of dark lamp method. These disadvantage may not cause much in case of slow speed alternators or small capacity alternators. But it may cause harm and disturbance in case of high speed and large capacity alternators. The bright lamp method eliminates these difficulties.

2.15 Bright Lamp Method:

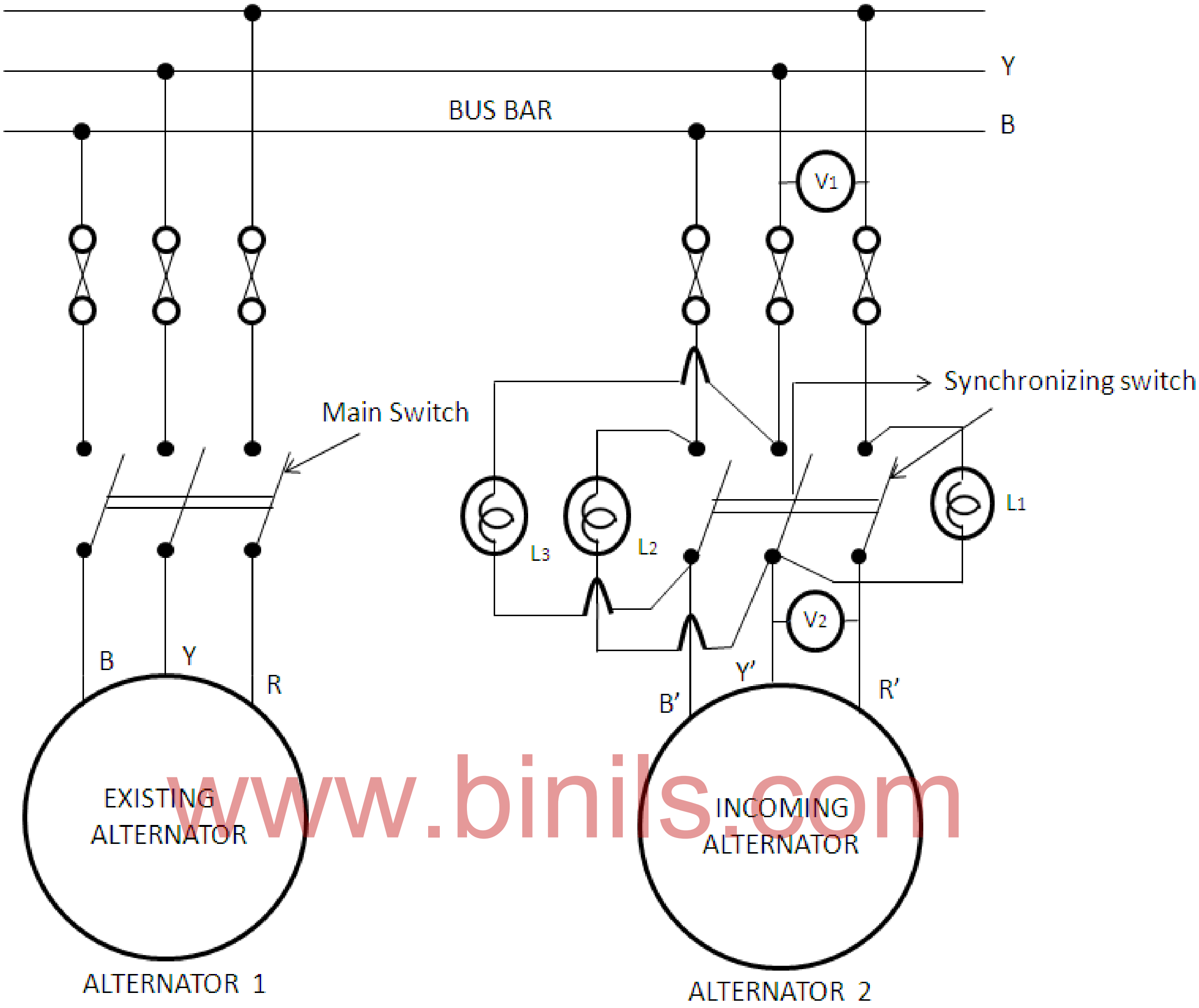


Fig : Bright lamp method

Fig 2. 18

In bright lamp method of synchronizing all three lamp connections have been reversed as shown in fig 2.18. AS in dark lamp method, the incoming machine is started, voltage and frequency are adjusted to bus-bar values. Phase sequence is checked by phase sequence indicator. Now the lamps are flickering proportional to the difference in frequencies of bus- bar and the incoming machine. The brightness of all the lamps are maximum when the voltages are in phase with the bus-bar. The synchronizing switch is closed at the middle period of the brightest period and thus the alternator is synchronized.

2.16 Two dark one bright Lamp method:

Fig 2.19 shows another method called the "rotating lamp method", in which the lamp will flicker two bright, one dark, and two dark, one bright successively. The synchronizing switch is closed when the two lamps are bright and one lamp dark

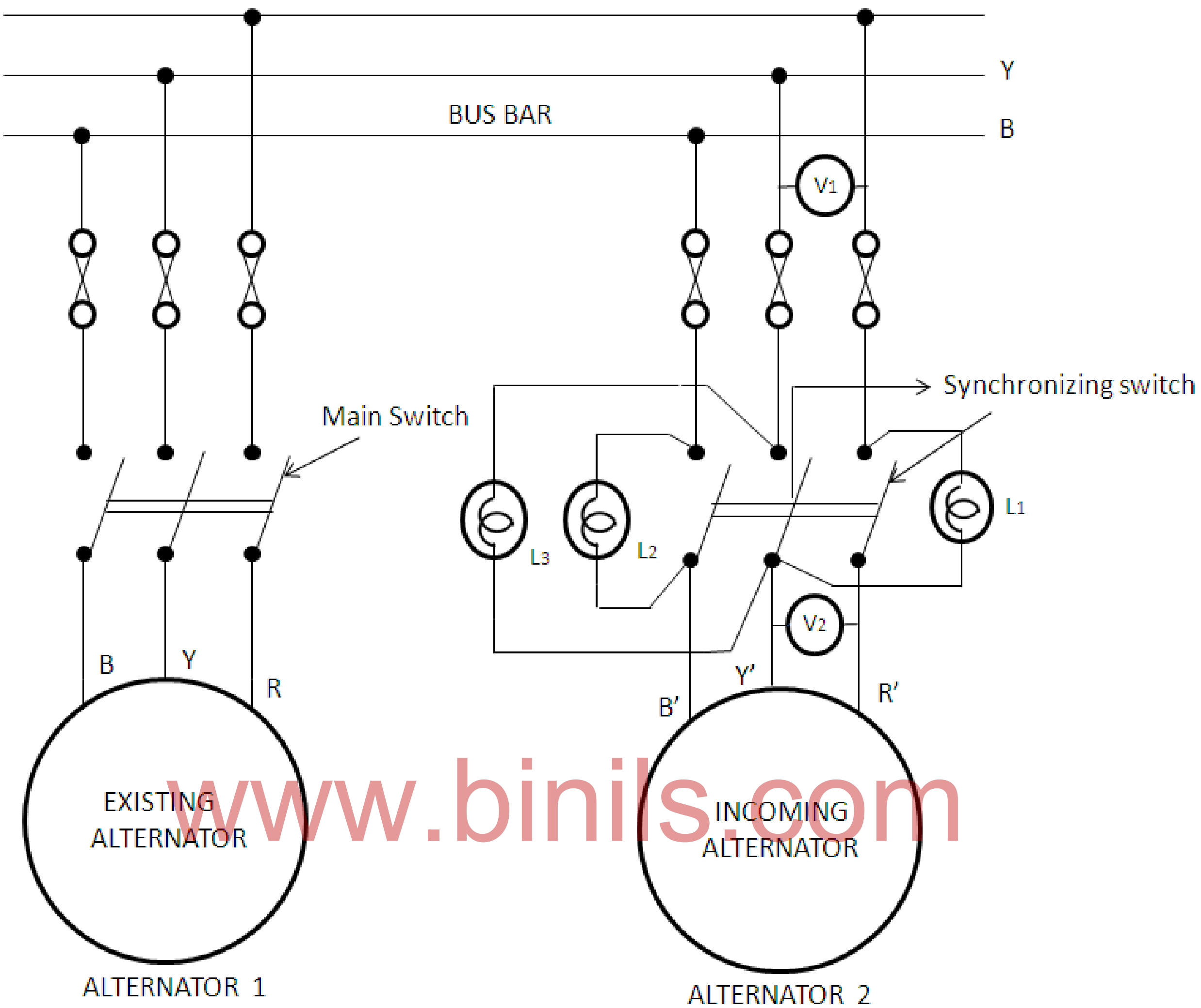


Fig : Rotating lamp method

Fig 2.19

2.17 Synchroscope Method:

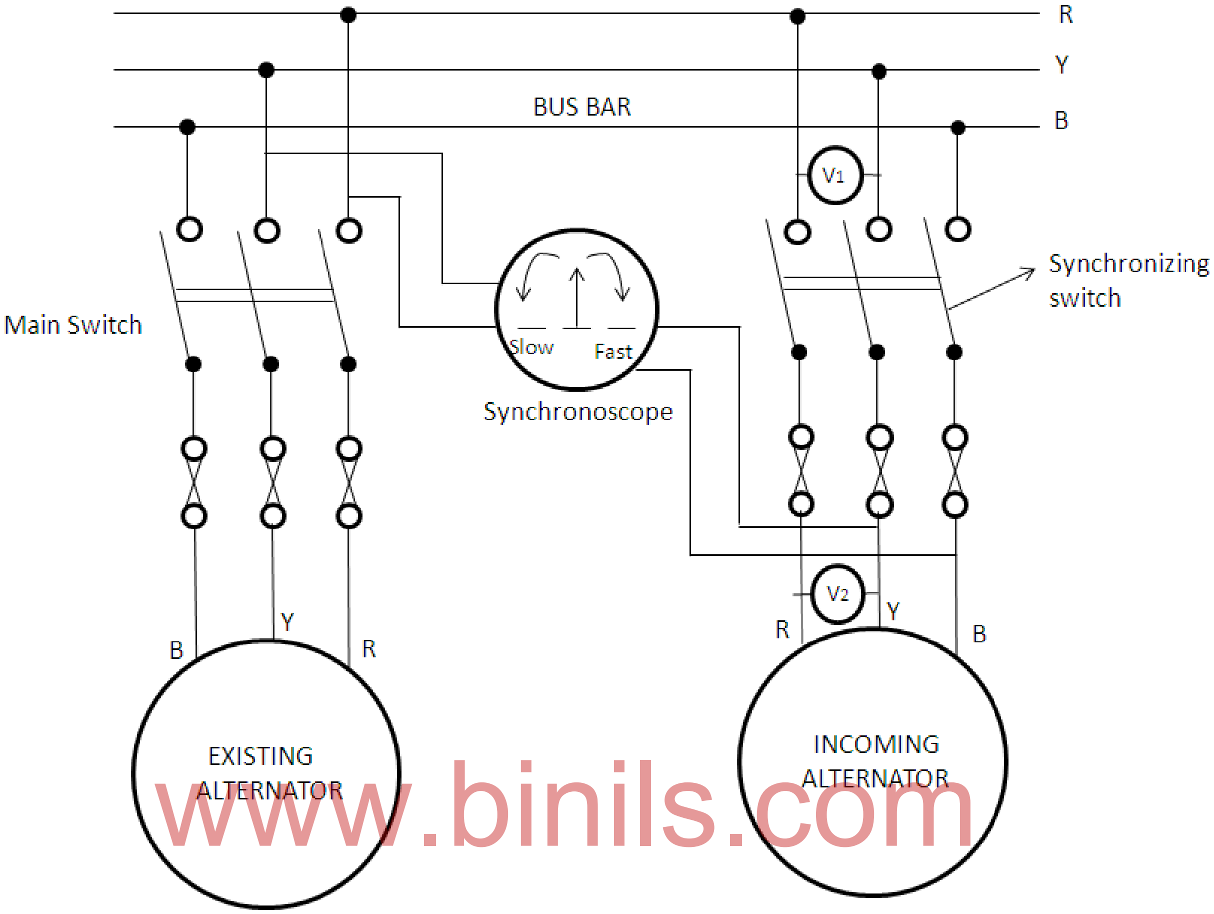


Fig : Synchroscope method

Fig 2.20

Synchronizing an alternator by using lamps is not very exact method, since it requires a correct judgment for closing the synchronizing switch. Therefore the lamps are replaced by a synchroscope. The synchroscope indicates not only the exact moment but also shows whether the incoming machine is fast or slow.

The synchroscope operates on the same principle as the power factor meter. It consist of a rotor and a stator. The rotor is connected to the incoming alternator, and the stator is connected to the bus-bar. A pointer is attached to the rotor. This pointer will indicate the correct time for closing the synchronizing switch. The correct time for synchronizing is the pointer points at 12^0 clock position.

Fig 2.20 shows the connection diagram for synchronizing the alternator by using synchroscope. In this case also, the phase sequence is checked by a phase sequence indicator or test lamp. After checking up the voltage and phase sequence as in previous cases, the incoming alternator is adjusted so that the pointer of the synchroscope rotates very slowly. If the frequencies are different values, the pointer will rotate. If the pointer rotates in the anticlockwise direction then the frequency of the incoming alternator is low. The clockwise direction of rotation of the pointer shows the frequency of the incoming alternator is higher than the frequency of the alternator 1 (Bus-bar). If the frequencies are equal, the pointer is at stationary position. The synchronizing switch is closed when the pointer is stationary at 12^0 clock position in the synchroscope. This is the correct instant for closing the switch. It is possible to parallel even the largest alternators without trouble.

2.18 Synchronizing Current:

Once a synchronous machine is synchronized, it will tend to remain in synchronism with the other alternators. Any tendency to depart from the condition of synchronism is opposed by a synchronizing torque produced due to circulating current flowing through the alternators.

When two alternators are in exact synchronism, the two alternators have equal induced emfs which are in exact phase opposition as shown in Fig.2.21 a, no circulating current flows round the local circuit.

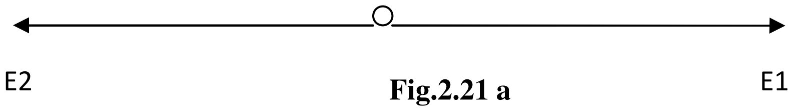


Fig.2.21 a

When the induced emfs of the two alternators are equal in magnitude but not in exact phase opposition as shown in fig.2.21 b, their resultant emf acts round the local circuit causes flow of current called the **synchronizing current, I_{sy}.**

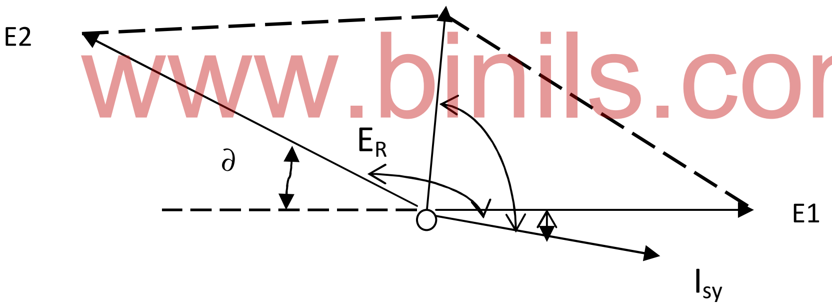


Fig.2.21b

If any alternator due to some disturbance tends to retard, E_2 falls back by a phase angle δ electrical degrees, as shown in fig.2.13b.

Now though their induced emfs E_1 and E_2 are in equal in magnitude but have a phase difference of $180^\circ - \delta$. Let each of the induced emfs E_1 and E_2 be equal to E.

$$\text{Resultant emf, } E_R = 2E\cos\left[\frac{180^\circ - \delta}{2}\right] = 2E\cos\left(90 - \frac{\delta}{2}\right) = 2E\sin\frac{\delta}{2}$$

$$= 2E \times \frac{\delta}{2} = E\delta \qquad \therefore \delta is very small$$

$$\text{Synchronizing Current, } I_{sy} = \frac{E_R}{Z_S} = \frac{E\delta}{Z_S}$$

Where, Z_S is the combined synchronous impedance per phase of the two alternators

The synchronizing current I_{SY} lags behind the resultant emf E_R by an angle θ given by $\theta = \tan^{-1}\frac{X_S}{R_e}$

Where, X_s is the combined synchronous reactance and R_e is the effective resistance of the two alternators. If resistance R_e is very small as compared to synchronous reactance Xs then,

Synchronizing Current, $I_{sy} = \frac{E\delta}{X_S}$ and lags behind E_R by 90°

2.19 Synchronizing Power:

In the parallel operation, machine no.1 supplies power equal to $E_1 I_{SY} \cos\phi_1$ and the machine no.2 receives power equal to $E_2 I_{SY} \cos(180^\circ - \phi_2)$.

The power supplied by the machine no.1= Power supplied to machine no.2 + copper loses.
The power supplied by the machine no.1 is called *synchronizing power* and is given by the expression

$$P_{SY} = E_1 I_{SY}\cos\phi_1 = E_1 I_{SY} = E \times \frac{E\delta}{X_S} = \frac{\delta E^2}{X_S} \qquad \because E_1 = E \text{ and } \phi \text{ isverysmall}$$

Total synchronizing power for 3 phases = $3P_{sy}$ = $\frac{3\delta E^2}{X_S}$

2.20 Synchronizing Torque:

If T_{sy}, be the synchronizing torque in Nm, then the total synchronizing power $3P_{SY} = T_{SY} \times \frac{2\pi N_S}{60}$

Or synchronizing torque, $T_{SY} = \frac{3P_{SY} \times 60}{2\pi N_S}$

2.21 Load Sharing Between Two Alternators:

Consider two machines with identical speed –load characteristics running in parallel with a common terminal voltage of V volts and load impedance Z.

Let the generated emfs of the two machines1 and 2 operating in parallel be E1 and E2 respectively and synchronous impedance per phase be Zs_1 and Zs_2 respectively.

$$Terminal\ Voltage\ of\ Machines 1, V = E_1 - I_1 Z_{s1} ---------- (1)$$

Similarly

$$Terminal\ Voltage\ of\ Machines 2, V = E_2 - I_2 Z_{s2} ------- (2)$$

Also

$$V = IZ = (I_1 + I_2)Z ---------------- (3)$$

From Equation (1) and (2), we have

$$I_1 = \frac{E_1 - V}{Z_{s1}} -------------- (4)$$

And

$$I_2 = \frac{E_2 - V}{Z_{s2}} ----------- (5)$$

Adding equation (4) and (5) and we have

$$I_1 + I_2 = \frac{E_1 - v}{Z_{s2}} + \frac{E_2 - V}{Z_{s2}}$$

or

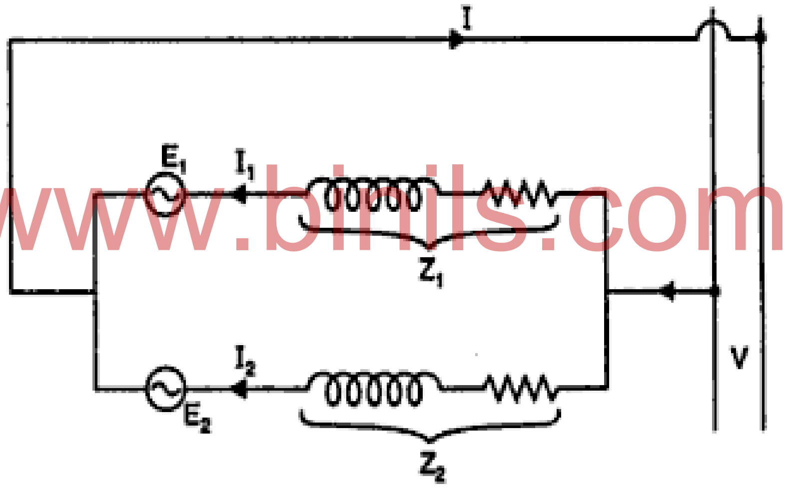


Fig.2.22 Equivalent circuit for two alternators in parallel

$$\frac{V}{Z} = \frac{E_1 - V}{Z_{s1}} + \frac{E_2 - V}{Z_{s2}}$$

From Equation (3)

$$I_1 + I_2 = \frac{V}{Z}$$

or

$$V\left(\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}\right) = \frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}$$

or

$$V = \frac{\frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}}{\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}} \text{-------------(6)}$$

2.22 Infinite Bus Bar:

It is the general practise to operate a number of alternators in parallel in the generating stations. A power system with a large number of alternators connected in parallel is called Infinite bus bar.

When large number of alternators are connected in parallel to an infinite bus-bar, the synchronous impedance of the system is reduced to a very small value.(Since all the alternators are connected in parallel). Irrespective of the changes or variations of the electrical loads on the system, the terminal voltage and the bus-bar frequency are constant in an infinite bus-bar system.

REVIEW QUESTIONS

PART -A

1. What is leakage reactance ?
2. What is armature reactance ?
3. What is synchronous impedance ?
4. Mention the methods used for synchronization?
5. What is meant by voltage regulation?
6. Write the expression for regulation of alternator?
7. What is meant by load characteristics?
8. Name the two methods for determining the voltage regulation of alternator?
9. What is meant by synchronization of alternators?
10. What is effective armature resistance?

PART – B

1. What are the advantages of parallel operation of alternators?
2. Explain the effect of load on alternator.
3. Define the term synchronous reactance and synchronous impedance?
4. Draw the circuit diagram for short circuit test of 3 phase alternator?
5. What are the advantages of parallel operation of alternators?
6. What are the causes of voltage drop in alternator?
7. Draw the load characterist of 3 phase alternator?
8. Draw the schematic diagram for synchronization of 3 alternators by synchroscope method.
9. What is synchronizing current?
10. Write the three methods of synchronizing of alternators?

PART – C

1. Explain anyone method of parallel operation of alternators. Write the points to be followed for parallel operation of alternators?
2. Discuss the load sharing of alternator in parallel?
3. Explain how to determine the regulation of alternator by zero power factor method?
4. In an alternator a given field current produces an armature current of 200 amps on short circuit and a generated emf of 50v per phase on open circuit. The armature resistance is 0.1 ohm per phase. Find the induced voltage when it delivers 100amps at 0.8 p.f. lagging with a terminal with a terminal voltage of 200 volts per phase.
5. A 3phase star connected alternator is rated 200 KVA, at 1100V. The stator winding resistance per phase is 0.5 ohm. Determine synchronous impedance per phase and voltage regulation at 0.8 p.f. lag and lead. Given that the open circuited voltage is 422 volts between the lines and short circuit current is 105 amps.
6. Explain briefly the synchronizing of two three phase alternators by dark- bright lamp method.
7. Explain synchronizing current, synchronizing power, synchronizing torque.
8. Describe the synchronizing of two three phase alternators by synchroscope method.
9. With schematic diagram explain briefly the synchronizing of two 3 phase alternators by dark lamp method.
10. Explain the EMF OR synchronous impedance method of predetermining the voltage regulation of an alternator.

Unit - 3

THREE PHASE INDUCTION MOTORS

3.1 INTRODUCTION

In the year 1821 British scientist Michael Faraday explained the conversion of electrical energy into mechanical energy by placing a current carrying conductor in a magnetic field which resulted in the rotation of the conductor due to torque produced by the mutual action of electrical current and magnetic field. Based on his principle the most primitive of machines a DC (Direct Current) machine was designed by another British scientist William Sturgeon in the year 1832. But his model was overly expensive and wasn't used for any practical purpose. Later in the year 1886 the first electrical motor was invented by scientist Frank Julian Sprague, that was capable of rotating at a constant speed under a varied range of load, and thus derived motoring action.

3.1.1 Types of AC motor

- **Classification Based On *Principle Of Operation*:**

(a) Synchronous Motors.

1. Plain

2. Super

(b) Asynchronous Motors.

1. ***Induction Motors:***

(a) Squirrel Cage

(b) Slip-Ring (external resistance).

2. ***Commutator Motors:***

(a) Series

(b) Compensated

(c) Shunt

(d) Repulsion

(e) Repulsion-start induction

(f) Repulsion induction

- Classification ***Based On no of phases:***

1. Single Phase

2. Three Phase

- Classification Based On ***Speed Of Operation:***

1. Constant Speed.

2. Variable Speed.

3. Adjustable Speed.

- Classification Based On ***Structural Features:***

1. Open

2. Enclosed

3. Semi-enclosed

4. Ventilated

5. Pipe-ventilated

6. Riveted frame-eye etc..

3.2 General principle of operation

Conversion of electrical power into mechanical power takes place in the rotating part of an electrical motor .In dc motor the electrical power is conducted directly to the armature through brushes and commentator hence in this sense a dc motor can be called as conduction motor. However in ac motor the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary that is why such motor are know as induction motors .infact a induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary as free to rotate.

3.2.1 Principles of operation of three phase induction motor:

Why a 3-Ø Induction motor is self-starting? How the rotor does rotate?

i. When a 3-Ø stator winding having a space displacement of 120° electrical is energized from a 3-Ø supply having 120° time displacement a rotating magnetic field is setup in the stator.

ii. This rotating magnetic field rotates with synchronous speed $N_S = \frac{120f}{P}$ with respect to stationary in the air gap

iii. This rotating field passes through the air gap and cuts the stationary rotor conductors

iv. Due to the relative speed between the rotating flux and the stationary rotor EMFs are induced in the rotor conductors

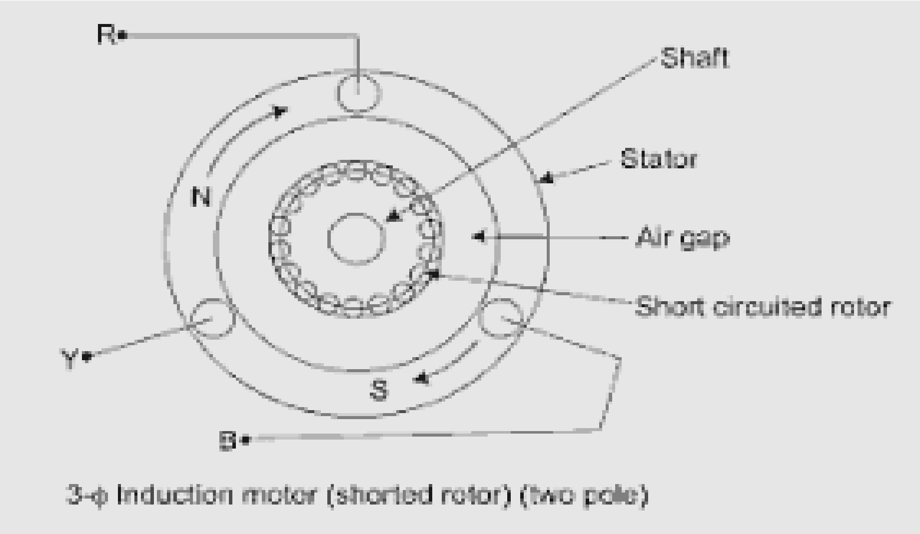
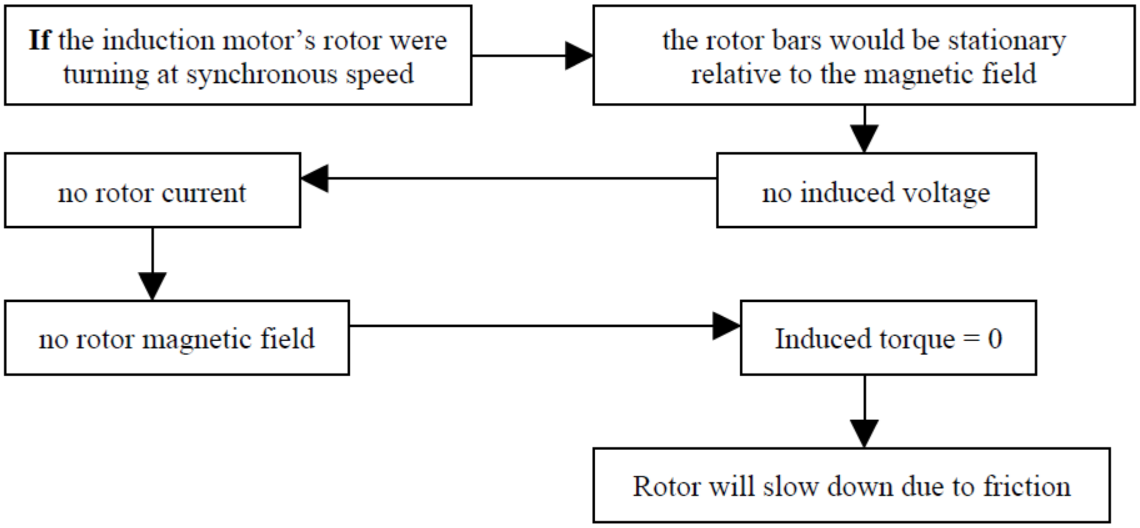


Fig 3.1

v. If the rotor conductors are short circuited, currents start flowing in the rotor conductor
vi. According to Len's law the direction of the induced current is such that it opposes the cause.
vii. Cause is the relative speed between the rotating field and stationary rotor
viii. Hence, a rotor has a tendency to reduce the relative speed
ix. So rotor begins to move in the direction of rotating field and continues towards synchronous speed and the machine runs at a speed near but below synchronous speed depending upon load on shaft
x. As the speed of rotor reaches to synchronous speed (speed of field) relative speed is zero. Hence no emf, no current and therefore no torque at synchronous speed. Hence rotor never reaches to synchronous speed.
xi. At synchronous speed current is zero in rotor conductor hence no force acting on rotor conductor and slip back, somewhat less speed than synchronous speed.

Why 3phase induction motor does not run at synchronous speed?



An induction motor can thus speed up to near synchronous speed but it can never reach synchronous speed.

Advantages

Thus the three phase induction motor is:

- Self-starting.
- Less armature reaction and brush sparking because of the absence of commutators and brushes that may cause sparks.
- Robust in construction.
- Economical.
- Easier to maintain.

Disadvantages

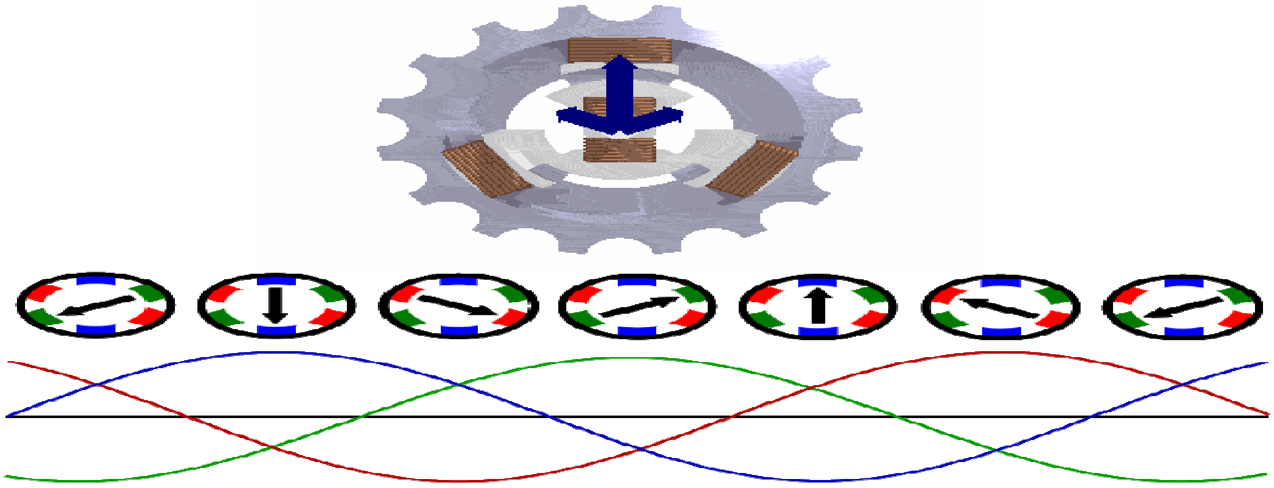
- Its speed cannot be varied without sacrificing some of its efficiency.
- Just like a dc shunt motor its speed decreases with increase in load.
- Its starting torque is somewhat inferior to that of a dc shunt motor.

3.3 Rotating Magnetic Field

The fundamental principle of operation of AC machines is the **generation of a rotating magnetic field**, which causes the rotor to turn at a speed that depends on the speed of rotation of the magnetic field.

Production of Rotating Magnetic Field

The stator of the motor consists of overlapping winding offset by an electrical angle of 120°. When the primary winding or the stator is connected to a 3 phase AC source, it establishes a rotating magnetic field which rotates at the synchronous speed.



Rotating 3-phase magnetic field

Fig 3.2

3.3.1 Rotating magnetic field produced by Three phase:

It will now be shown that when three-phase windings displaced in space by 120º, are fed by three phase currents, displaced in time by 120º, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

The principle of a 3-phase, two-pole stator having three identical windings placed 120 space degrees apart is shown in Fig. 3.4 The flux (assumed sinusoidal) due to three-phase windings is shown in Fig 3.3

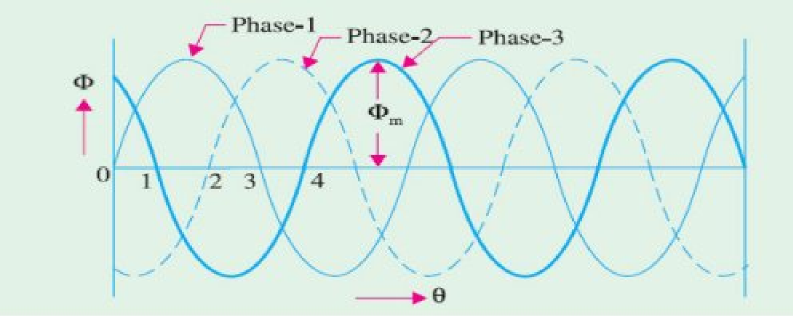


Fig.3.3

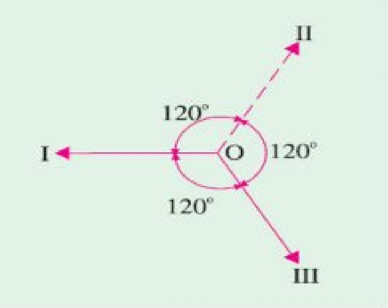


Fig.3.4

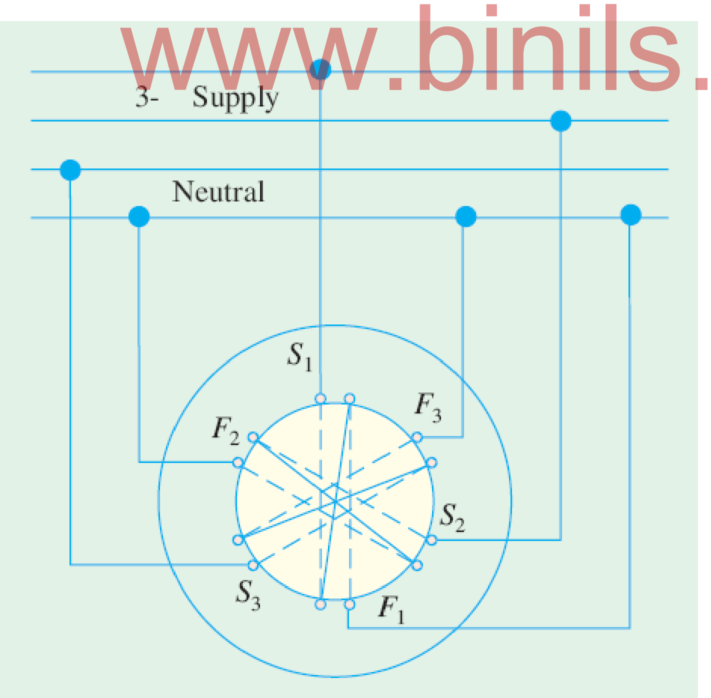


Fig 3.5

The assumed positive directions of the fluxes are shown in Fig 3.3. Let the maximum value of flux due to any one of the three phases be Φ_m.

The resultant flux Φ_r, at any instant, is given by the vector sum of the individual fluxes, Φ_1, Φ_2 and Φ_3 due to three phases. We will consider values of Φ_r at four instants 1/6th time-period apart corresponding to points marked 0, 1, 2 and 3 in Fig. 3.3.

When $\theta = 0^\circ$ i.e corresponding to point 0 in Fig.3.6. Here $\Phi_1 = 0, \Phi_2 = \frac{-\sqrt{3}}{2}\Phi_m, \Phi_3 = \frac{\sqrt{3}}{2}\Phi_m$

The vector for Φ_2 in fig 4.8 (i) is drawn in a direction opposite to the direction assumed in Fig.3.4

$$\therefore \Phi_r = 2 \times \frac{\sqrt{3}}{2}\Phi_m \cos\frac{60^\circ}{2} = \sqrt{3} \times \frac{\sqrt{3}}{2}\Phi_m = \frac{3}{2}\Phi_m$$

(i) When $\theta = 60^\circ$ i.e corresponding to point 1 in Fig.3.3.

Here $\Phi_1 = \frac{\sqrt{3}}{2}\Phi_m$ ……… drawn parallel to OI of Fig.3.4 as shown in Fig.3.6 (ii)

$\Phi_2 = -\frac{\sqrt{3}}{2}\Phi_m$ ……… drawn in opposition to OI of Fig.3.4

$\Phi_3 = 0$

$$\therefore \Phi_r = 2 \times \frac{\sqrt{3}}{2}\Phi_m \times \cos 30^\circ = \frac{3}{2}\Phi_m$$

It is found that the resultant flux is again $\frac{3}{2}\Phi_m$ but has rotated clockwise through an angle of 60º

(ii) When $\theta = 120^\circ$ i.e corresponding to point 2 in Fig.3.3

Here, $\Phi_1 = \frac{\sqrt{3}}{2}\Phi_m$, $\Phi_2 = 0$, $\Phi_3 = -\frac{\sqrt{3}}{2}\Phi_m$

It can be again proved that $\Phi r = \frac{3}{2}\Phi_m$

So that resultant is again of the same value, but has further rotated clockwise through an angle of 60° [Fig.3.6 (iii)]

(iii) When $\theta = 180^\circ$ i.e corresponding to point 3 in Fig.3.3

$\Phi_1 = 0, \Phi_2 = \frac{\sqrt{3}}{2}\Phi_m, \Phi_3 = -\frac{\sqrt{3}}{2}\Phi_m$

The resultant is $\Phi r = \frac{3}{2}\Phi_m$ and has rotated clockwise through an additional angle 60° or through an angle of 180° from the start.

Hence, we conclude that

1. The resultant flux is of constant value = $\frac{3}{2}\Phi_m$ *i.e. 1.5 times the maximum value of the flux due to any phase.*

2. The resultant flux rotates around the stator at synchronous speed given by
Ns = 120 f/P.

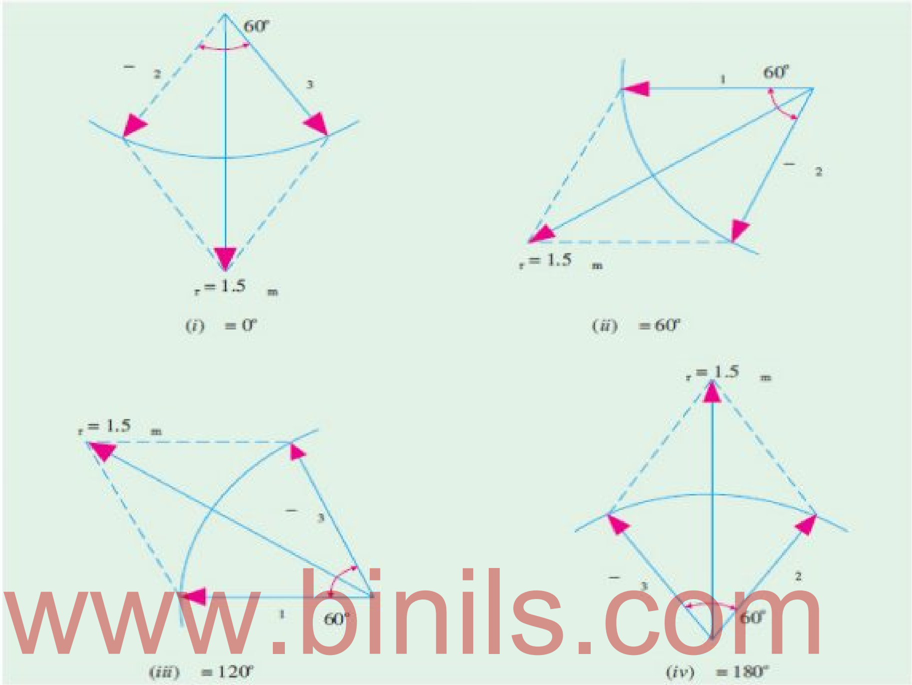


Fig.3.6

Fig. 3.7 (*a*) shows the graph of the rotating flux in a simple way. As before, the positive directions of the flux phasors have been shown separately in Fig. 3.7 (*b*).

Arrows on these flux phasors are reversed when each phase passes through zero and becomes negative.

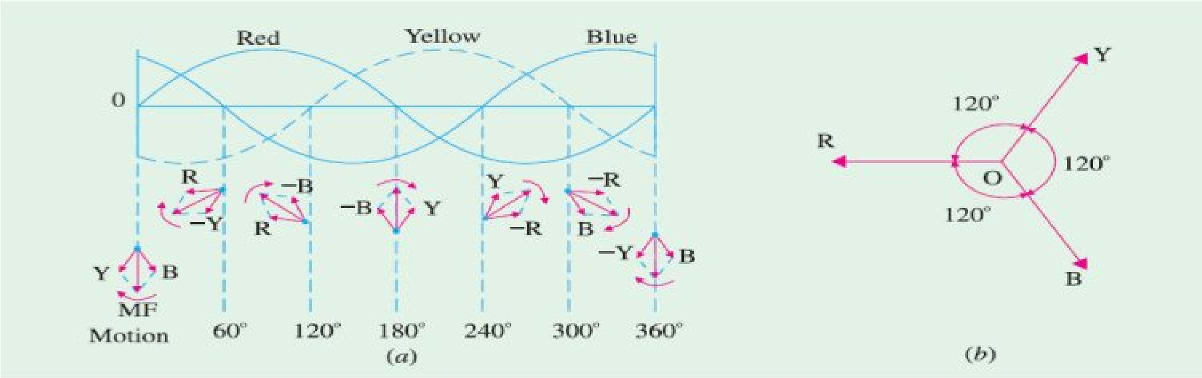


Fig.3.7

3.3.2 Construction of Three Phase Induction:

An Induction motor consists of mainly two parts:

(a) Stator **(b) Rotor**

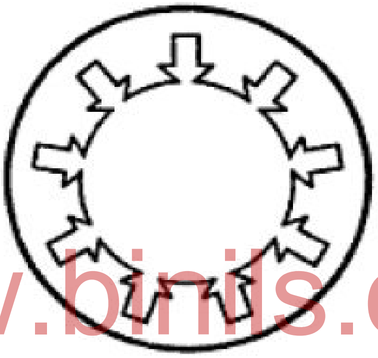
Stator:

(i) Stator core is made of laminated steel stampings and has slots and teeth on its inner periphery to house stator windings. The stampings are 04.to 0.5 mm thick.

(ii) Stator carries a 3-phase winding having space displacement of 120° electrical

(iii) The 3-phase winding is either star or delta connected and is fed from 3-phase supply

(iv) The radial ventilating ducts are provided along the length of the stator core



Stator Stamping

Rotor:

i. Rotor comprises a cylindrical laminated iron core, with slots on outer periphery
ii. Like stator, rotor lamination are punched in one piece for small Machine
iii. In larger machine the lamination are segmented
iv. If there are ventilating ducts on the stator core, an equal number of such ducts is provided on rotor core

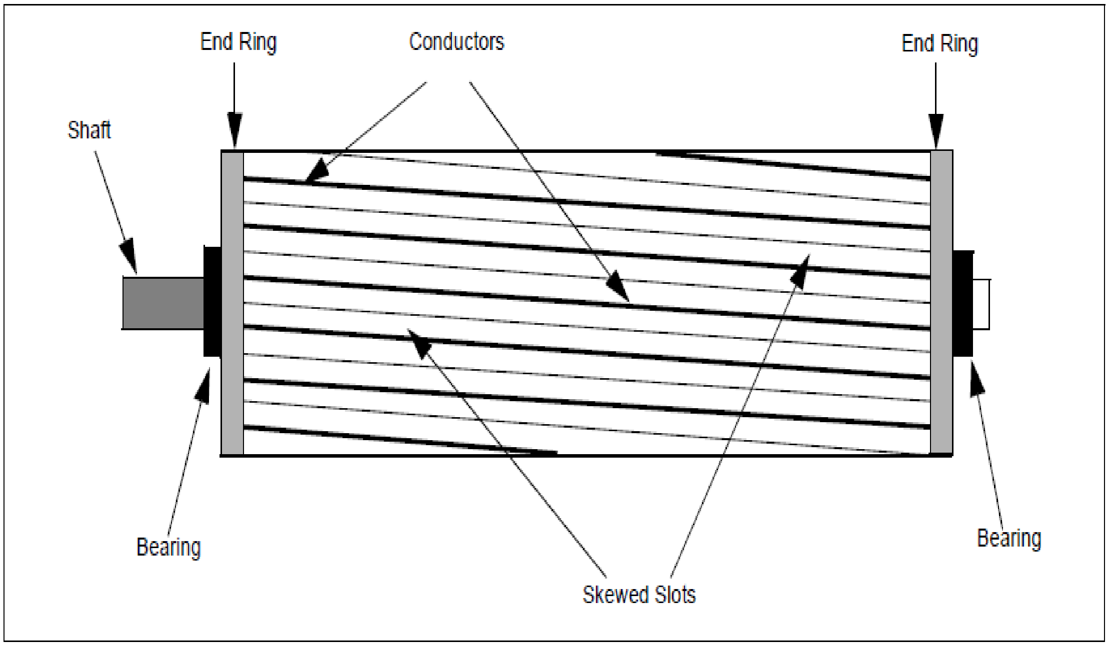
According to windings rotor are of two types:

a) Squirrel cage rotor
b) Slip ring or wound rotor

Squirrel Cage Rotor:

i. This rotor consists of a cylindrical laminated core with parallel slots
ii. Rotor slots are usually not quite parallel to the shaft but for reducing the magnetic hum and locking tendency rotor slots are slight skew
iii. In rotor slots heavy copper, aluminum or alloy bars are housed

iv. Rotor bars are permanently short circuited at the ends. This limits that no external resistance insertion is possible



Squirrel cage rotor

Advantages of squirrel cage induction rotor-

- Its construction is very simple and rugged.
- As there are no brushes and slip ring, these motors requires less maintenance.

Applications:

- Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

3.4 Slip Ring or Wound Rotor:

i. The rotor is wound for the same number of poles and number of phase as that of stator

ii. Rotor winding is either star or delta but star connection is preferred

iii. The three star terminals are connected to three brass slip ring mounted on rotor shaft

iv. These slip rings are insulated from rotor shaft

v. Slip rings connected with brushes and three brushes can further be connected externally to 3-variable rheostats

vi. This makes possible introduction to additional resistance in the rotor circuit during starting period

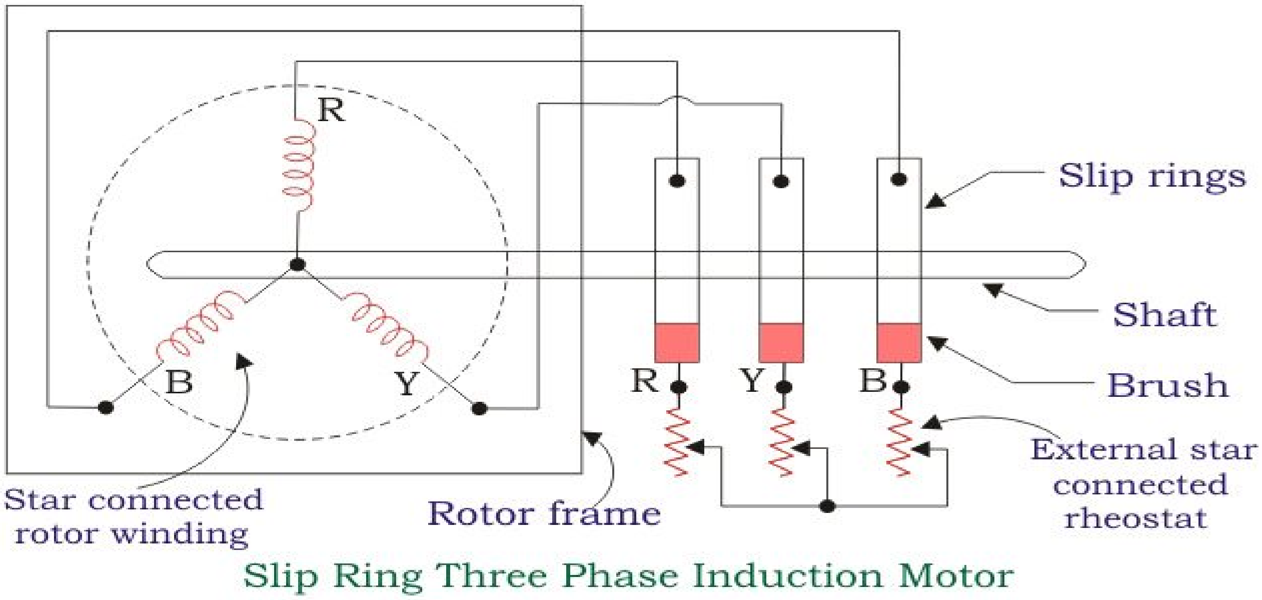


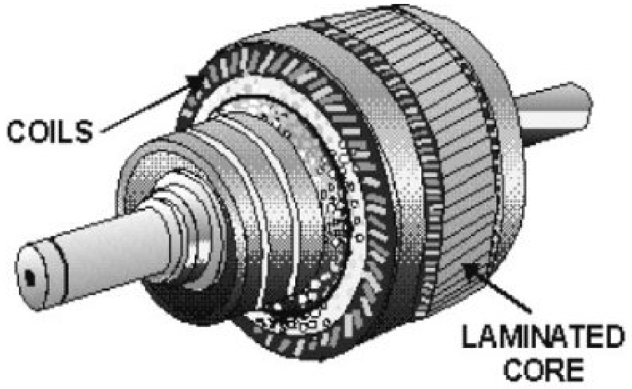
Fig.3.8 Wound rotor

Advantages of slip ring induction motor -

- It has high starting torque and low starting current.
- Possibility of adding additional resistance to control speed.

Application:

- Slip ring induction motor are used where high starting torque is required i.e. in hoists, cranes, elevator etc.



3.5 Difference between Slip Ring and Squirrel Cage Induction Motor

Slip ring or phase wound Induction motor	***Squirrel cage induction motor***
Construction is complicated due to presence of slip ring and brushes	Construction is very simple
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	Since the rotor bars are permanently shorted, it's not possible to add external resistance
Due to presence of external resistance high starting torque can be obtained	Staring torque is low and cannot be improved
Slip ring and brushes are present	Slip ring and brushes are absent
Frequent maintenance is required due to presence of brushes	Less maintenance is required
The construction is complicated and the presence of brushes and slip ring makes the motor more costly	The construction is simple and robust and it is cheap as compared to slip ring induction motor
This motor is rarely used only 10 % industry uses slip ring induction motor	Due to its simple construction and low cost. The squirrel cage induction motor is widely used
Rotor copper losses are high and hence less efficiency	Less rotor copper losses and hence high efficiency
Speed control by rotor resistance method is possible	Speed control by rotor resistance method is not possible
Slip ring induction motor are used where high starting torque is required i.e in hoists, cranes, elevator etc	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

3.6 Slip and Slip frequency:

The relative speed between the rotating magnetic field (n_s) and rotor (n_r) is called slip speed.

$$slip\ \ speed = n_s - n_r \ \ rps$$

Slip:

Percentage change in slip speed is called as slip

$$slip = \frac{n_s - n_r}{n_s} \times 100 \Rightarrow \ \ n_r = n_s(1-s)$$

When rotor is stationary $n_r = 0$, s=1 or 100%

Typical values of slip between no load and full load are about 4 to 5 percent for small motor and 1.5 to 2 percent for large motor

When the rotor is stationary, rotor emf having same frequency as stator emf

$$E_S = \sqrt{2}\pi f \quad N_1\Phi \qquad E_r = \sqrt{2}\pi f N_2 \Phi$$

Frequency $\quad = \dfrac{Poles \times relative\, speed\, or\, slip\, speed}{120}$

Frequency of the rotor induced emf

$$f_r = \frac{P(n_s - n_r)}{120}$$

$$but$$

$$s = \frac{n_s - n_r}{n_s} \Rightarrow sn_s = n_s - n_r$$

$$So$$

$$f_r = \left(\frac{Psn_s}{n_r}\right), f_{stator} = \frac{Pn_s}{120}$$

$$f_r = sf_s$$

As rotor picks up speed hence rotor current frequency decreases. When rotor is rotating

$$E_{stator} = \sqrt{2}\pi f_s N_1 \Phi k_w \; and \; f_r = sf_{stator}$$

$$E_{rotor} = \sqrt{2}\pi f_r N_2 \Phi k_w$$

$$E_r = SE_S$$

Rotor EMF:

When the rotor is at standstill, the motor is equivalent to a 3-phase transformer with secondary short circuited. So induced emf per phase E_2 in the rotor, when it is at standstill i.e. at the instant of starting is given by

$$E_2 = E_1 \times \frac{N_2}{N_1}$$

Where E_1 is applied voltage per phase to primary i.e. stator winding, N_2 and N_1 are the number of turns per phase on rotor and stator respectively.

When the rotor starts running, the relative speed of the rotor with respect to stator flux i.e. slip s drops in direct proportion with the relative speed or slip s is given by sE_2

Hence for slip s, the induced emf in the rotor is s times the induced emf in the rotor at standstill.

Example 1

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

Calculate:

a) Synchronous speed

b) Rotor speed

c) Frequency of rotor current

Solution:

Synchronous speed: $n_s = 120\,f / p = (120*60) / 6 = 1200$ rpm

Rotor speed: $n_r = (1\text{-}s)\,n_s = (1 - 0.05)\,(1200) = 1140$ rpm

Frequency of rotor current: $f_r = s\,f = (0.05)\,(60) = 3$ Hz

3.7 Phasor Diagram of Induction Motor

The phasor diagram of loaded induction motor is similar to the loaded transformer. The only difference is the secondary of induction motor is rotating and short circuited while transformer secondary is stationary and connected to load. The load on induction motor is mechanical while load on transformer is electrical. Still by finding electrical equivalent of mechanical load on the motor, the phasor diagram of induction motor can be developed.

Let Φ = Magnetic flux links with both primary and secondary.

There is self induced e.m.f. E_1 in the stator while a mutually induced e.m.f. E_{2r} in the rotor.

Let R_1 = Stator resistance per phase.

X_1 = Stator reactance per phase

The stator voltage per phase V_1 has to counter balance self induced e.m.f. $E_1$and has to supply voltage drops I_1 R_1 and I_1 X_1. So on stator side we can write,

$$\overline{V_1} = -\overline{E_1} + \overline{I_1 R_1} + j\,\overline{I_1 X_1} = \overline{E_1} + \overline{I_1}\,(R_1 + j\,X_1) = -\overline{E_1} + \overline{I_1}\overline{Z_1}$$

The rotor induced e.m.f. in the running condition has to supply the drop across impedances as rotor short circuited.

$$\therefore \qquad \bar{E}_{2r} = \overline{I_{2r}R_2} + j\overline{I_{2r}X_2} = \bar{I}_{2r}(R_2 + jX_2) = \overline{I_{2r}}\ \overline{Z_{2r}}$$

The value of E_{2r} depends on the ratio of rotor turns to stator turns.

The rotor current in the running condition is I_{2r} which lags E_{2r} by rotor p.f. angle Φ_{2r}.

The reflected rotor current I_{2r}' on stator side is the effect of load and is given by,

$$I_{2r}' = K\, I_{2r}$$

The induction motor draws no load current I_o which is phasor sum of I_c and I_m. The total stator current drawn from supply is,

$$\bar{I}_1 = \bar{I}_o + \bar{I}_{2r}'$$

The Φ_1 is angle between V_1 and I_1 and cos Φ_1 gives the power factor of the induction motor.

Thus using all above relations the phasor diagram of induction motor on load can be obtained.

The steps to draw phasor diagram are,

1. Takes Φ as reference phasor.
2. The induced voltage E_1 lags Φ by 90^o.
3. Show - E_1 by reversing voltage phasor.
4. The phasor E_{2r} is in phase with E_1. So I_{2r} show lagging E_{2r} i.e. E_1 direction by Φ_{2r}.
5. Show I_{2r} R_2 in phase with I_{2r} and I_{2r} X_{2r} leading the resistive drop by 90^o, to get exact location of.
6. Reverse I_{2r} to get I_{2r}'.
7. I_m is in phase with Φ while Ic is at leading with. Add I_m and Ic to get I_o.
8. Add I_o and I_{2r}' to get I_1.
9. From tip of - E_1 phasor, add I_1 R_1 in phase with I_1 and I_1X_1 at 90^o leading to I_1 to V_1 get phasor.
10. Angle between V_1 and I_1 is Φ_1.

The phasor diagram is shown in the Fig. 1.

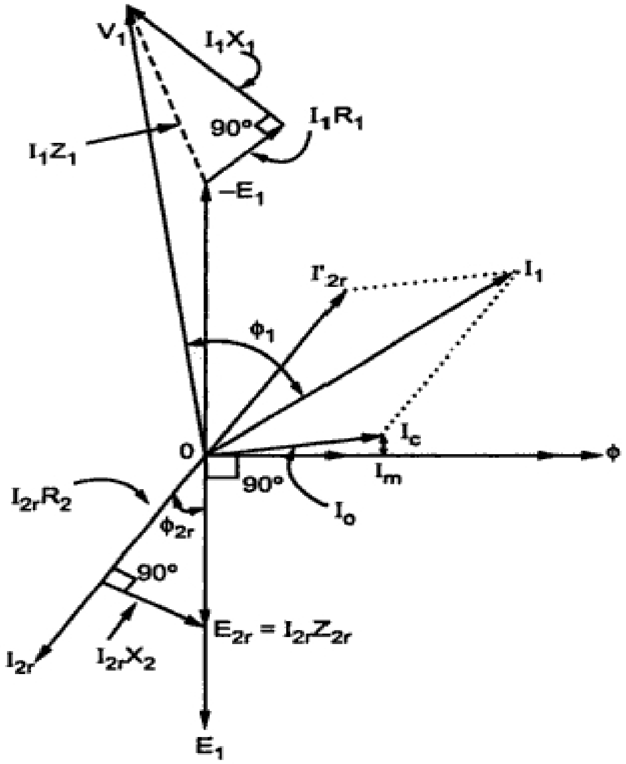


Fig. 3.9 On load phasor diagram of induction motor

3.7.1 Torque Equation of Three Phase Induction Motor

The torque produced by three phase induction motor depends upon the following three factors:Firstly the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor, lastly the power factor of rotor of the three phase induction motor.

Combining all these factors together we get the equation of torque as-

$$T \propto \phi I_2 \cos \theta_2$$

Where, T is the torque produced by induction motor,

φ is flux responsible for producing induced emf,

I_2 is rotor current,

$\cos\theta_2$ is the power factor of rotor circuit.

The flux φ produced by the stator is proportional to stator emf E1.

i.e. $\varphi \propto E_1$

We know that transformation ratio K is defined as the ratio of secondary voltage (rotor voltage) to that of primary >voltage (stator voltage).

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

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

$$or,\ E_2 = \phi$$

Rotor current I_2 is defined as the ratio of rotor induced emf under running condition , sE_2 to total impedance, Z_2 of rotor side,

$$i.e\ I_2 = \frac{sE_2}{Z_2}$$

and total impedance Z_2 on rotor side is given by ,

$$Z_2 = \sqrt{R_2^2 + (sX_2)^2}$$

Putting this value in above equation we get,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

s= slip of Induction motor

We know that power factor is defined as ratio of resistance to that of impedance. The power factor of the rotor circuit is

$$\cos\theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Putting the value of flux φ, rotor current I_2, power factor $\cos\theta_2$ in the equation of torque we get,

$$T \propto E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Combining similar term we get,

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

Removing proportionality constant we get,

$$T = KsE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

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

Where ns is synchronous speed in r. p. s, ns = Ns / 60. So, finally the equation of torque becomes,

$$T = sE_2^2 \times \frac{R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s} N - m$$

Derivation of K in torque equation.

In case of three phase induction motor, there occur copper losses in rotor. These rotor copper losses are expressed as

$$P_c = 3I_2^2R^2$$

We know that rotor current,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Substitute this value of I_2 in the equation of rotor copper losses, Pc. So, we get

$$P_c = 3R_2 \left(\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \right)^2$$

$$On\ simplifying\ P_c = \frac{3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

The ratio of P_2 : Pc : Pm = 1 : s : (1 - s)

Where, P_2 is the rotor input,

Pc is the rotor copper losses,

Pm is the mechanical power developed.

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

$$or \quad P_m = \frac{(1-s)P_c}{s}$$

Substitute the value of Pc in above equation we get,

$$P_m = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

On simplifying we get,

$$P_m = \frac{(1-s)3R_2sE_2^2}{R_2^2+(sX_2)^2}$$

The mechanical power developed Pm = Tω,

$$\omega = \frac{2\pi N}{60}$$

$$or\ P_m = T\frac{2\pi N}{60}$$

Substituting the value of Pm

$$\frac{1}{s}\times\frac{(1-s)3R_2s^2E_2^2}{R_2^2+(sX_2)^2} = T\frac{2\pi N}{60}$$

$$or\ T = \frac{1}{s}\times\frac{(1-s)3R_2s^2E_2^2}{R_2^2+(sX_2)^2}\times\frac{60}{2\pi N}$$

We know that the rotor speed N = Ns(1 - s)

Substituting this value of rotor speed in above equation we get,

$$T = \frac{1}{s}\times\frac{(1-s)3R_2s^2E_2^2}{R_2^2+(sX_2)^2}\times\frac{60}{2\pi N_s(1-s)}$$

Ns is speed in revolution per minute (rpm) and ns is speed in revolution per sec (rps) and the relation between the two is

$$\frac{N_s}{60} = n_s$$

Substitute this value of Ns in above equation and simplifying it we get

$$Toeque,\ T = \frac{s\ E_2^2R_2}{R_2^2+(sX_2)^2}\times\frac{3}{2\pi N_s}$$

$$or,\ T = KsE_2^2\frac{R_2}{R_2^2+(sX_2)^2}$$

Comparing both the equations, we get, constant K = 3 / 2πns

3.7.2 Equation of Starting Torque of Three Phase Induction Motor

Starting torque is the torque produced by induction motor when it is started. We know that at start the rotor speed, N is zero.

$$So,\ slip\ s = \frac{N_s-N}{N_s}\ becomes\ 1$$

So, the equation of starting torque is easily obtained by simply putting the value of s = 1 in the equation of torque of the three phase induction motor,

$$T = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{3}{2\pi n_s} N - m$$

The starting torque is also known as standstill torque

3.7.3 Maximum Torque Condition for Three Phase Induction Motor

In the equation of torque,.

$$T = \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s}$$

The rotor resistance, rotor inductive reactance and synchronous speed of induction motor remains constant . The supply voltage to the three phase induction motor is usually rated and remains constant so the stator emf also remains the constant. The transformation ratio is defined as the ratio of rotor emf to that of stator emf. So if statoremf remains constant then rotor emf also remains constant.

If we want to find the maximum value of some quantity then we have to differentiate that quantity with respect to some variable parameter and then put it equal to zero. In this case we have to find the condition for maximum torque so we have to differentiate torque with respect to some variable quantity which is slip, s in this case as all other parameters in the equation of torque remains constant.

So, for torque to be maximum

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

$$T = KsE_2^2 \frac{R_2}{R_2^2 + (sX_2)^2}$$

Now differentiate the above equation by using division rule of differentiation. On differentiating and after putting the terms equal to zero we get,

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

Neglecting the negative value of slip we get

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

So, when slip $s = R_2 / X_2$, the torque will be maximum and this slip is called maximum slip Sm and it is defined as the ratio of rotor resistance to that of rotor reactance.

NOTE: At starting S = 1, so the maximum starting torque occur when rotor resistance is equal to rotor reactance.

Equation of Maximum Torque

The equation of torque is

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

The torque will be maximum when slip $s = R_2 / X_2$

Substituting the value of this slip in above equation we get the maximum value of torque as,

$$T_{max} = K \frac{E_2^2}{2X_2} N - m$$

In order to increase the starting torque, extra resistance should be added to the rotor circuit at start and cut out gradually as motor speeds up.

From the above equation it is concluded that

The maximum torque is directly proportional to square of rotor induced emf at the standstill.

The maximum torque is inversely proportional to rotor reactance.

The maximum torque is independent of rotor resistance.

The slip at which maximum torque occur depends upon rotor resistance, R_2. So, by varying the rotor resistance, maximum torque can be obtained at any required slip.

3.7.4 Torque/Speed Curve:

The torque developed by a conventional 3-phase motor depends on its speed but the relation between the two cannot be represented by a simple equation.

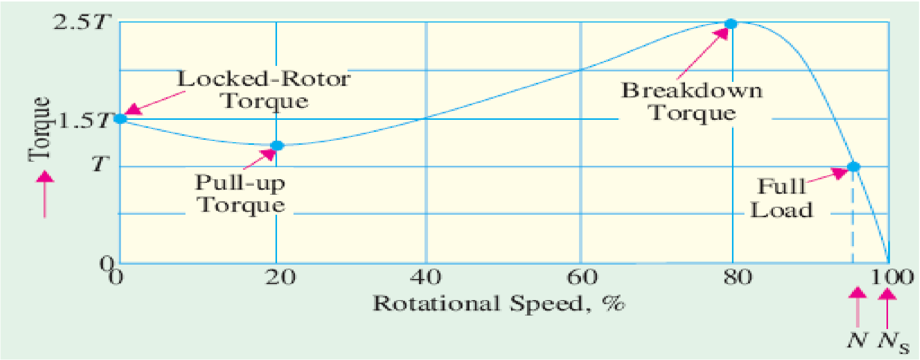


Fig.3.10

It is easier to show the relationship in the form of a curve (Fig. 3.10). In this diagram, *T* represents the nominal full-load torque of the motor. As seen, the starting torque (at *N* = 0) is 1.5 *T* and the maximum torque (also called breakdown torque) is 2.5 T

At full-load, the motor runs at a speed of *N*. When mechanical load increases, motor speed decreases till the motor torque again becomes equal to the load torque.

As long as the two torques are in balance, the motor will run at constant (but lower) speed. However, if the load torque exceeds 2.5 *T*, the motor will suddenly stop.

3.8 Determination of Equivalent Circuit Constants by Conducting No load Test and Blocked Rotor Test:

The various constants of the equivalent circuit of an induction motor is shown in fig.3.13

3.8.1 No-load Test:

The Connection diagram for no load test on three phase induction motor is shown in Fig.3.11

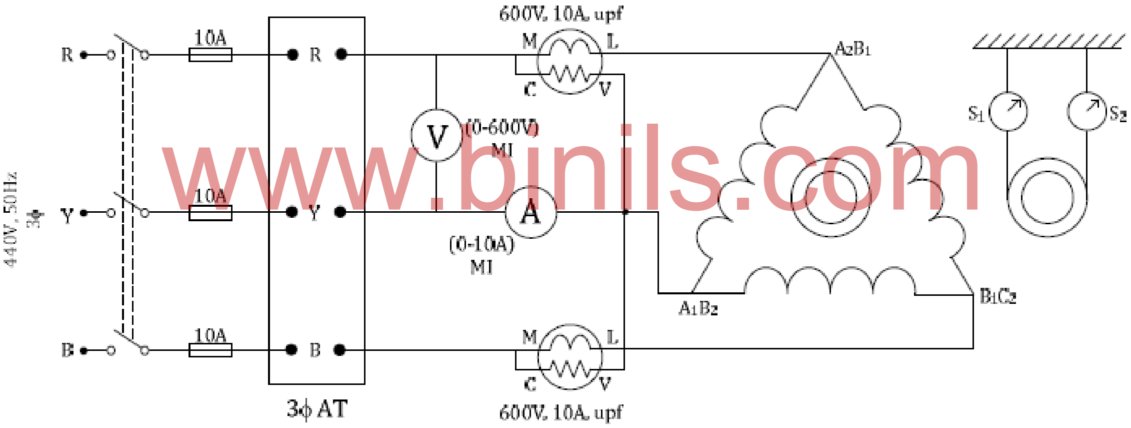


Fig.3.11

Rated voltage is given to the stator windings and the motor is allowed to run on no-load. The no load current Io, the applied voltage Vo and no load input power Po are noted.

At no load, the input power is supplied to meet out losses. The various losses are

1. Stator winding loss $(= 3I_0^2R_1)$
2. Core Loss $(3\frac{V^2}{R})$
3. Friction and Wind age loss

The core loss, friction and windage losses totally are called constant losses (Fixed Loss)

No load power factor $Cos\Phi_0 = \dfrac{P_0}{\sqrt{3}V_0 I_0}$

Where ,P_0 is no load power, V_o is no load voltage

No load current per phase = $\dfrac{I_o}{\sqrt{3}}$ (Since Stator winding is delta connected)

No load Resistance $R_0 = \dfrac{V_0}{I_W}$ ohm, I_W is watt -full current, $I_W = \dfrac{I_o}{\sqrt{3}}\cos\Phi_0$

No load Reactance $X_0 = \dfrac{V_0}{I_m}$ ohm, I_m is magnetizing current, $I_m = \sqrt{I_0^2 - I_W^2}$

3.8.2 Blocked Rotor Test:

This test is called locked rotor test (or) short circuit test. The connection diagram for blocked rotor test is shown in Fig.3.12

In this method, the rotor is locked. In case of slip ring induction motor the rotor windings are short circuited at slip rings. Reduced voltage is allowed to the stator winding by an autotransformer to flow rated full load current.

Now the voltage applied V_{SC} the short circuit current I_{SC} and the power taken by the motor P_{SC} are noted.

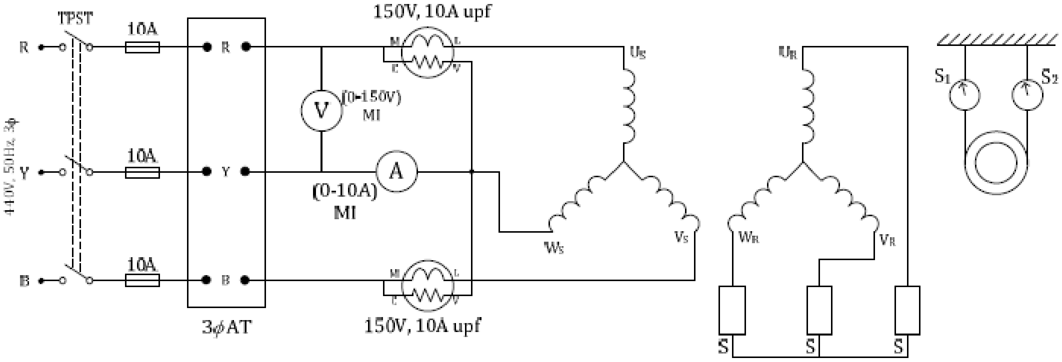


Fig.3.12

Short circuit Impedance $Z = \dfrac{V_{SC}}{I_{SC}}$ ohm,

Where V_{SC} is short circuit voltage, I_{SC} is short circuit current

Resistance/ phase referred to stator $R_{01} = \dfrac{P_{SC}}{I_{SC}^2}$ ohm

Reactance/ phase referred to stator $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$ ohm

3.9 Equivalent Circuit of Induction Motor:

The rotor current is given by $I_2 = \dfrac{\text{rotor emf}}{\text{rotor impedance}}$

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

If n is stator to rotor turns ratio then stator current,

$$I_1 = \frac{I_2}{n}$$

or

$$I_1 = \frac{sE_2}{n\sqrt{R_2^2 + s^2X_2^2}}$$

To produce I_1 current in the stator there is a requirement of voltage. i.e. $E_1=nE_2$ so that the rotor impedance referred in stator winding

$$= \frac{E_1}{I_1} = \frac{E_1}{\frac{I_2}{n}} = nE_2 \times \frac{n\sqrt{R_2^2 + s^2X_2^2}}{sE_2} = \frac{n^2}{s}\sqrt{R_2^2 + s^2X_2^2}$$

$$= \sqrt{\left(\frac{n^2R_2}{s}\right)^2 + (n^2X_2)^2}$$

The rotor resistance $\left(\frac{n^2R_2}{s}\right)$ can be divided as series combination of two resistances n^2R_2 and $n^2R_2\left(\frac{1}{s} - 1\right)$.

The n^2R_2 part remains constant and represents physical rotor resistance referred to stator side.

i.e. R'_2 . But $n^2R_2\left(\frac{1}{s} - 1\right)$.k varies from zero to infinite as s changes from unity to zero and represents the rotor output in the form of power in this resistance. The equivalent circuit referred to stator side is shown in fig.3.13

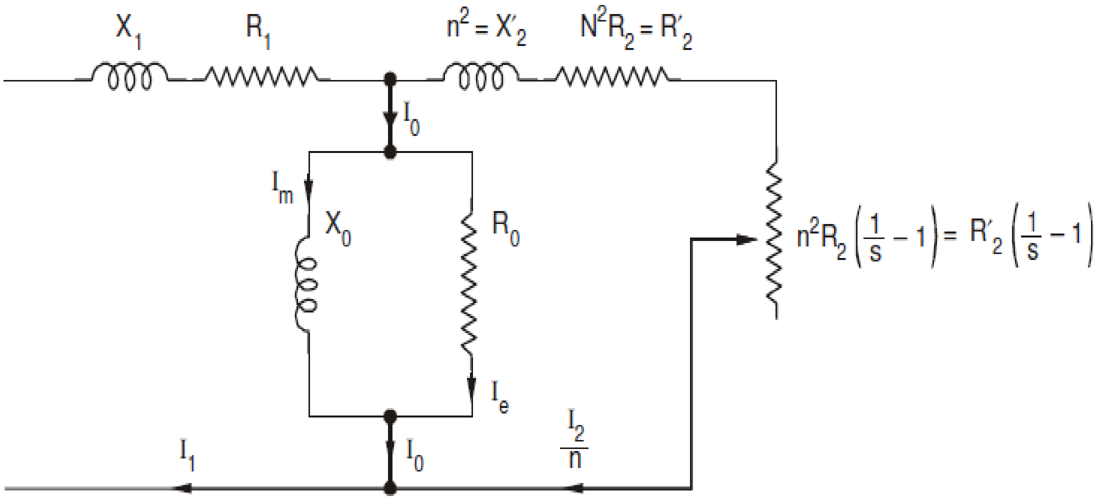


Fig. 3.13 Equivalent circuit of Induction Motor

3.10 Circle Diagram of an Induction Motor:

By using the data obtained from the no load test and the blocked rotor test, the circle diagram can be drawn using the following steps :

Step 1: Take reference Phasor V as vertical (Y-axis).

Step 2: Select suitable current scale such that diameter of circle is about 20 to 30 cm.

Step3: From no load test, I_o and are Φ_o obtained. Draw vector I_o, lagging V by angle Φ_o. This is the line OO' as shown in the Fig. 3.14

Step 4: Draw horizontal line through extremity of I_o i.e. O', parallel to horizontal axis.

Step 5: Draw the current I_{SN} calculated from I_{sc} with the same scale, lagging V by angle Φ_{sc}, from the origin O. This is Phasor OA as shown in the Fig. 3.14

Step 6: Join O'A is called output line.

Step 7: Draw a perpendicular bisector of O'A. Extend it to meet line O'B at point C. This is the centre of the circle.

Step 8: Draw the circle, with C as a centre and radius equal to O'C. This meets the horizontal line drawn from O' at B as shown in the Fig.3.14

Step 9: Draw the perpendicular from point A on the horizontal axis, to meet O'B line at F and meet horizontal axis at D.

Step 10: Torque line.

The torque line separates stator and rotor copper losses.

Note that as voltage axis is vertical, all the vertical distances are proportional to active components of currents or power inputs, if measured at appropriate scale.

Thus the vertical distance AD represents power input at short circuit i.e. W_{SN}, now which consists of core loss and stator, rotor copper losses.

Now FD = O'G

= Fixed loss

Where O'G is drawn perpendicular from O' on horizontal axis. This represents power input on no load i.e. fixed loss.

Hence AF α Sum of stator and rotor copper losses

Then point E can be located as,

AE/EF = Rotor copper loss / Stator copper loss

The line O'E under this condition is called torque line.

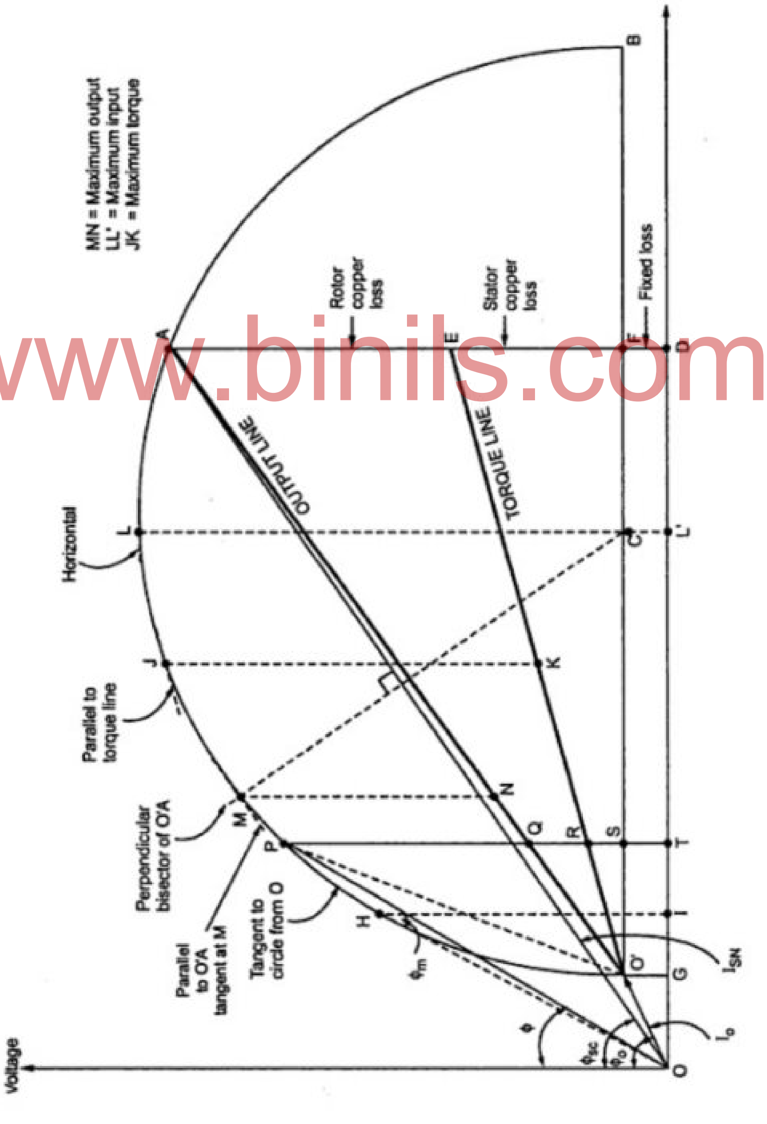


Fig.3.14 Circle Diagram of an Induction Motor

Power scale:

As AD represents W_{SN} i.e. power input on short circuit at normal voltage, the power scale can be obtained as,

Power scale = $W_{SN}/l(AD)$ W/cm

where l(AD) = Distance AD in cm

Location of Point E :

In a slip ring induction motor, the stator resistance per phase R_1 and rotor resistance per phase R_2 can be easily measured. Similarly by introducing ammeters in stator and rotor circuit, the currents I_1 and I_2 also can be measured.

∴ $K = I_1/I_2$ = Transformation ratio

Now AF/EF = Rotor copper loss / Stator copper loss = $(I_2^2 R_2)/(I_1^2 R_1) = (R_2/R_2)(I_2^2/I_1^2) = (R_2/R_2).(1/K^2)$

But $R_2' = R_2/K^2$ = Rotor resistance referred to stator

∴ $AE/EF = R_2'/R_1$

Thus point E can be obtained by dividing line AF in the ratio R_2' to R_1

In **a squirrel cage motor**, the stator resistance can be measured by conducting resistance test.

∴ Stator copper loss = $3I_{SN}^2 R_1$ where I_{SN} is phase value.

Neglecting core loss, W_{SN} = Stator Cu loss + Rotor Cu loss

∴ Rotor copper loss = $W_{SN} - 3I_{SN}^2 R_1$

∴ $AE/EF = (W_{SN} - 3I_{SN}^2 R_1)/(3I_{SN}^2 R_1)$

Dividing line AF in this ratio, the point E can be obtained and hence O'E represents torque line.

Predicting Performance from Circle Diagram:

Let motor is running by taking a current OP as shown in the Fig. 3.15. The various performance parameters can be obtained from the circle diagram at that load condition.

Draw perpendicular from point P to meet output line at Q, torque line at R, the base line at S and horizontal axis at T.

We know the power scale as obtained earlier.

Using the power scale and various distances, the values of the performance parameters can be obtained as,

Total motor input = PT x Power scale

Fixed loss = ST x power scale

Stator copper loss = SR x power scale

Rotor copper loss = QR x power scale

Total loss = QT x power scale

Rotor output = PQ x power scale

Rotor input = PQ + QR = PR x power scale

Slip s = Rotor Cu loss = QR/PR

Power factor cos = PT/OP

Motor efficiency = Output / Input = PQ/PT

Rotor efficiency = Rotor output / Rotor input = PQ/PR

Rotor output / Rotor input = 1 - s = N/N_s = PQ/PR

The torque is the rotor input in synchronous watts.

Maximum Quantities from Circle Diagram

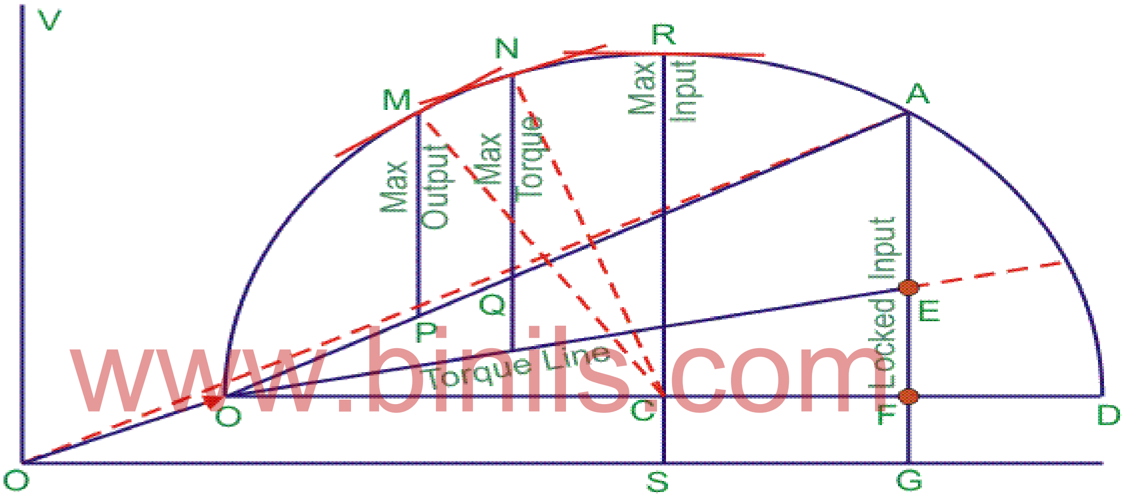


Fig 3.15

Maximum Output Power

When the tangent to the circle is parallel to the line then output power will be maximum. That point M is obtained by drawing a perpendicular line from the center to the output line and extending it to cut at M.

Maximum Torque

When the tangent to the circle is parallel to the torque line, it gives maximum torque. This is obtained by drawing a line from the center in perpendicular to the torque line AD and extending it to cut at the circle. That point is marked as N.

Maximum Input Power

It occurs when tangent to the circle is perpendicular to the horizontal line. The point is the highest point in the circle diagram and drawn to the center and extends up to S. That point is marked as R.

Example

A 480 V, 50 hp, three phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW and the rotor copper losses are 700 W. The friction loss is 600 W and the core losses are 1800 W, find:

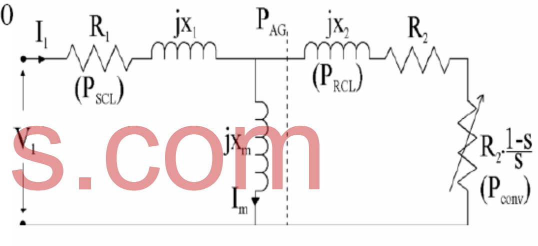
- The air gap power.
- The converted power.
- The output power.
- The efficiency of the motor.

Solution

$$\text{a) } n_s = \frac{120f}{P} = \frac{(120)(60)}{4} = 1800 \text{ rpm}$$

$$n_m = (1-s)n_s = (1-.022)(1800) = 1760 \text{ rpm}$$

$$\text{b) } Z_{total} = \left\{ \left(\frac{R_2}{s} + jx_2\right) \| (jx_m) \right\} + (R_1 + jx_1) = 14.0$$



$$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88\angle -33.6$$

$$\text{c) } p.f. = \cos(33.6) = 0.833 \textit{ lagging}$$

$$\text{d) } P_{in} = \sqrt{3}(480)(18.88)(0.833) = 12.53 \text{ kW}$$

$$P_{SCL} = 3I_1^2 R_1 = 3(18.88)^2(0.641) = 685 \text{ W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12{,}530 - 685 = 11.845 \text{kW}$$

3.11 Speed Control of Induction Motor

3.11.1 Induction Motor Speed Control From Stator Side

1. By Changing the Applied Voltage:

From the torque equation of induction motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_S} \frac{sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Rotor resistance R_2 is constant and if slip s is small then $(sX_2)^2$ is so small that it can be neglected. Therefore, $T \propto sE_2^2$ where E_2 is rotor induced emf and $E_2 \propto V$ Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

1. large change in supply voltage is required for relatively small change in speed.
2. large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

2. By Changing the supply Frequency

Synchronous speed of the rotating magnetic field of an induction motor is given by,

$$Ns = \frac{120\,f}{P} \quad (RPM)$$

where, f = frequency of the supply and P = number of stator poles. Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as N = Ns (1 - s). However, this method is not widely used. It may be used where, the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

3. Constant V/F Control Of Induction Motor

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant. This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control. Along with wide range of speed control, this method also offers 'soft start' capability.

4. Changing the Number Of Stator Poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots. For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.

For supply frequency of 50 Hz

i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM

ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

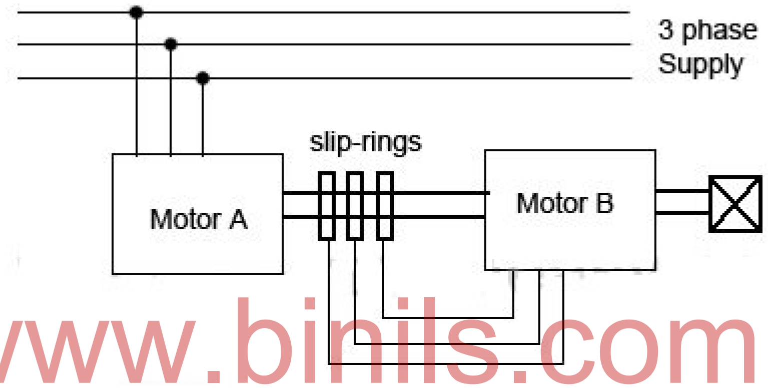
3.11.2 Speed Control from Rotor Side:

1. **Rotor Rheostat Control**

This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is notpossible.

2. **Cascade Operation**

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure.



Motor A is called the main motor and motor B is called the auxiliary motor.

Let, Ns1 =synchronous speed of motor A
Ns2 =synchronous speed of motor B
P1 =number of poles stator of motor A
P2 =number of stator poles of motor B
N=speed of the set and same for both motors
f = frequency of the supply

Now, slip of motor A, S1 = (Ns1 - N) / Ns1.

frequency of the rotor induced emf in motor A, f1 = S1f

Now, auxiliary motor B is supplied with the rotor induce emf

therefore, Ns2 =(120f1) / P2 = (120S1f) / P2.

now putting the value of S1 = (Ns1 - N) / Ns1

$$N_{s2} = \frac{120f(N_{s1} - N)}{P_2 N_{S1}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.

i.e. N = Ns2.

from the above equations, it can be obtained that

$$N = \frac{120f}{P_1 + P_2}$$

With this method, four different speeds can be obtained
1. when only motor A works, corresponding speed = .Ns1 = 120f / P_1
2. when only motor B works, corresponding speed = Ns2 = 120f / P_2
3. if commulative cascading is done, speed of the set = N = 120f / $(P_1 + P_2)$
4. if differential cascading is done, speed of the set = N = 120f $(P_1 - P_2)$

5. By Injecting EMF In Rotor Circuit

In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of the slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with the rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled. The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved. The emf can be injected by various methods such as Kramer system, Scherbius system etc.

3.12 Various starting methods of induction motors

An induction motor is similar to a poly-phase transformer whose secondary is short circuited. Thus, at normal supply voltage, like in transformers, the initial current taken by the primary is very large for a short while. Unlike in DC motors, large current at starting is due to the absence of back emf. If an induction motor is directly switched on from the supply, it takes 5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line.

3.12.1 Direct-On-Line (DOL) Starters

Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the full load torque. Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor.

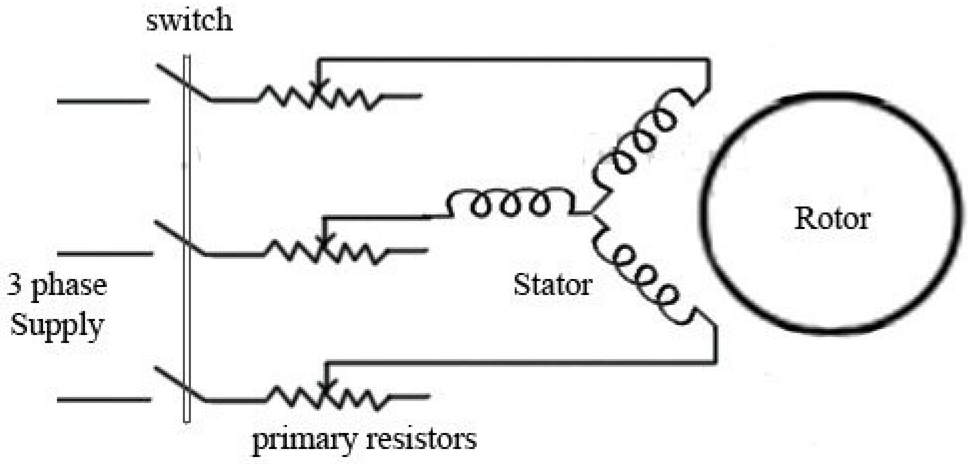
In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.

Starting Of Squirrel Cage Motors

Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator. These methods are sometimes called as reduced voltage methods for starting of squirrel cage induction motors. For this purpose, following methods are used:

1. By using primary resistors
2. Autotransformer
3. Star-delta switches

1. **Using Primary Resistors:**



Obviously, the purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. Then according to the Ohm's law (V=I/Z), the starting current will also be reduced by the same percentage. From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage. That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its normal voltage value. This method is generally used for a smooth starting of small induction motors. It is not recommended to use primary resistors type of starting method for motors with high startingtorquerequirements.

Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

2. **Auto-Transformers:**

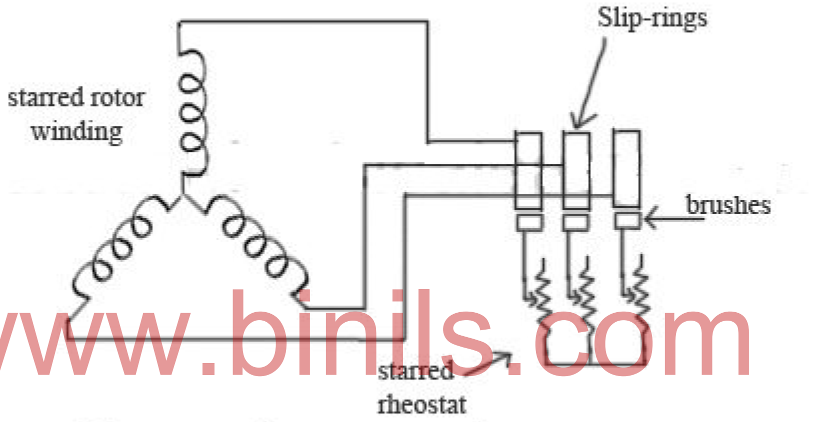
Auto-transformers are also known as auto-starters. They can be used for both star connected or delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With auto-transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio. For example, when a motor is started on a 65% tap, the applied voltage to the motor will be 65% of the line voltage and the applied current will be 65% of the line voltage starting value, while the line current will be 65% of 65% (i.e. 42%) of the line voltage starting value. This difference between the line current and the motor current is due to transformer action. The internal connections of an auto-starter are as shown in the figure. At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator. When the motor gathers an appropriate speed, say upto 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position. The switch changing the connection from start to run position may be air-break (small motors) or oil-immersed (large motors) type. There are also provisions for no-voltage and overload, with time delay circuitsonanautostarter.

3. **Star-Delta Starter:**

This method is used in the motors, which are designed to run on delta connected stator. A two way switch is used to connect the stator winding in star while starting and in delta while running at normal speed. When the stator winding is star connected, voltage over each phase in motor will be reduced by a factor 1/(sqrt. 3) of that would be for delta connected winding. The starting torque will 1/3 times that it will be for delta connected winding. Hence a star-delta starter is equivalent to an auto-transformer of ratio 1/(sqrt. 3) or 58% reduced voltage.

3.12.2 Starting Of Slip-Ring Motors

Rotor resistance starter



Phase wound rotor connections

Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic.
As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load.
The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

3.12.3 Crawling And Cogging In Induction Motors

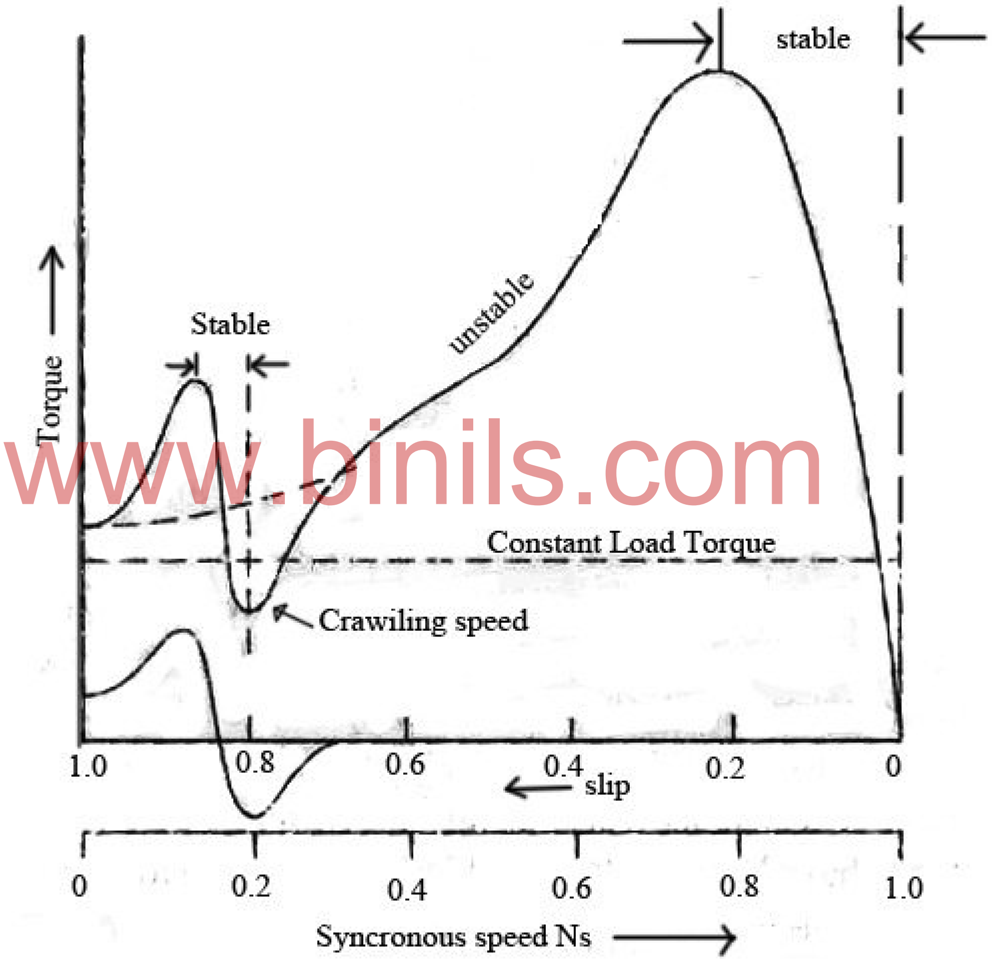
crawling and cogging both are particularly related to squirrel cage induction motors.

Crawling

Sometimes, a squirrel cage induction motor exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as **crawling of an induction motor**.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).



Now, 5th harmonic currents will have phase difference of 5 X 120 = 600° =2 X 360 - 120 = -120°. Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of 7 X 120 = 840° = 2 X 360 +120 = + 120°. Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7th of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of of its normal speed. This phenomenon is called as **crawling in induction motors.**

3.12.4 Cogging (Magnetic Locking Or Teeth Locking)

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum, that is why the rotor tends to remain fixed. This phenomenon is called cogging or **magnetic locking of induction motor**.

3.12.5 Double Squirrel Cage Motor / Deep Bar Double Cage Induction Motor

Why starting torque is poor in squirrel cage induction motor?

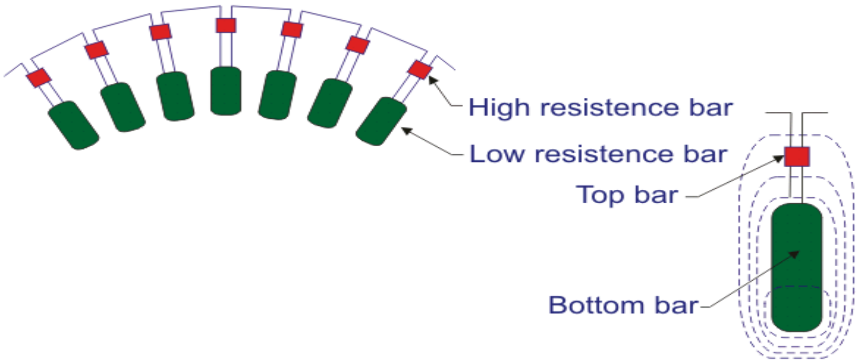
The resistance cannot be varied in squirrel cage rotor as it is possible in slip ring induction motor. The fixed resistance of the rotor of the squirrel cage induction motor is very low. At the starting moment, the induced voltage in the rotor has same frequency as the frequency of the supply. Hence the starting inductive reactance gets higher value at stand still condition. The frequency of the rotor current gets same frequency as the supply frequency at standstill. Now the case is that the rotor induced current in spite of having higher value lags the induced voltage at a large angle. So this causes poor starting torque at the stand still condition. This torque is only 1.5 times of the full load torque though the induced current is 5 to 7 times of the full load current. Hence, this squirrel cage single bar single cage rotor is not being able to apply against high load. We should go for deep bar double cage induction motor to get higher starting torque

3.12.6 Construction of Deep Bar Double Cage Induction Motor

In deep bar double cage rotor bars are there in two layers.

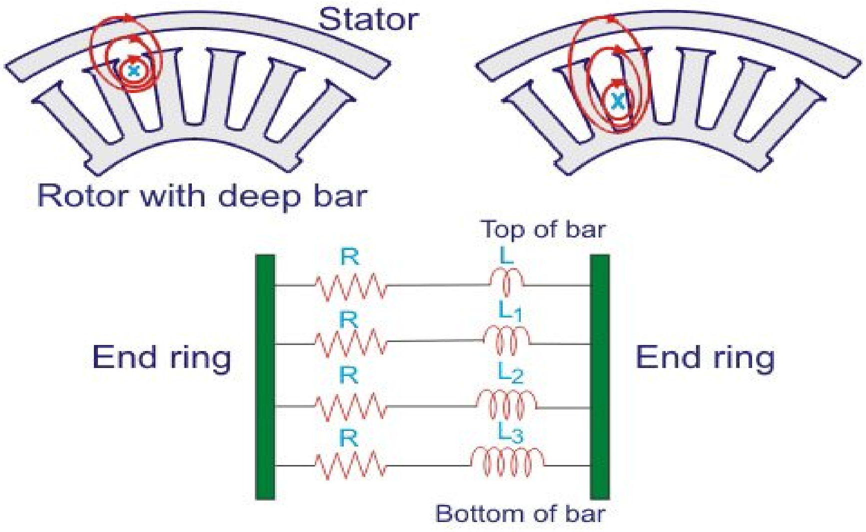
Outer layer has the bars of small cross sections. This outer winding has relatively large resistance. The bars are shorted at the both ends. The flux linkage is thus very less. And hence inductance is very low. Resistance in outer squirrel cage is relatively high. Resistance to inductive reactance ration is high.

Inner layer has the bars of large cross section comparatively. The resistance is very less. But flux linkage is very high. The bars are thoroughly buried in iron. As flux linkage is high the inductance is also very high. The resistance to inductive reactance ration is poor.



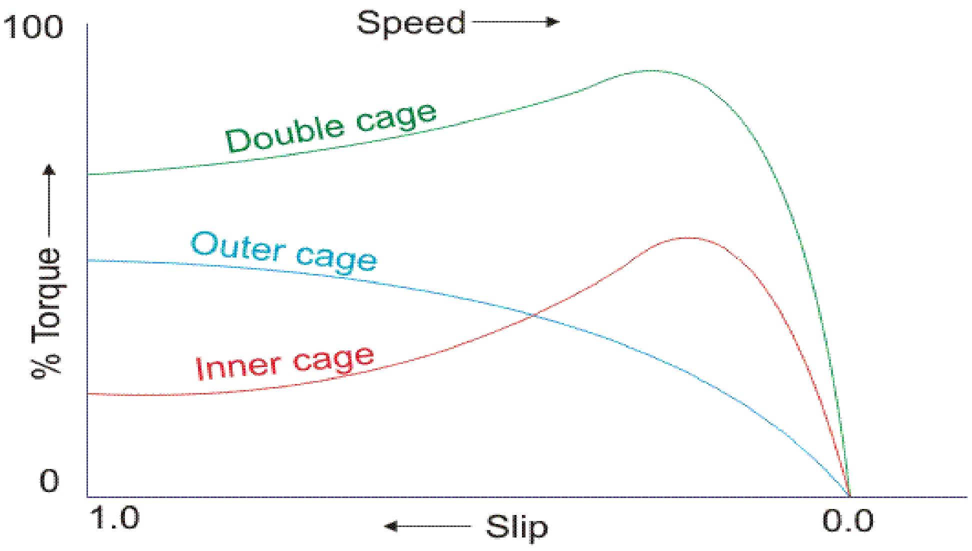
3.12.7 Operational Principle and Construction of Deep Bar Double Cage Induction Motor

At the stand still condition the inner and outer side bars get induced with voltage and current with the same frequency of the supply. Now the case is that the inductive reactance ($X_L = 2\pi fL$) is offered more in the deep bars or inner side bars due to skin effect of the alternating quantity i.e. voltage and current. Hence the current tries to flow through the outer side rotor bars.



The outer side rotor offers more resistance but poor inductive reactance. The ultimate resistance is somewhat higher than the single bar rotor resistance. The higher valued rotor resistance results more torque to be developed at the starting. When the speed of the rotor of the deep bar double cage induction motor increases, the frequency of the induced EMF and current in the rotor gets gradually decreased. Hence the inductive reactance (X_L) in the inner side bars or deep bars gets decreased and the current faces less inductive reactance and less resistance as a whole. Now no need for more torque because the rotor already has arrived to its full speed with running torque.

Speed Torque Characteristics of Deep Rotor IM



where R_2 and X_2 are the rotor resistance and inductive reactance at starting respectively, E_2 is the rotor induced EMF and $k = \frac{3}{2\pi N_s}$ N_s is the RPS speed of synchronous stator flux and S is the slip of the rotor speed. The above speed-torque graph shows that the higher valued resistance offers higher torque at the stand still condition and the max torque will be achieved at higher valued slip. Comparison between single cage and double cage motors:

1. A double cage rotor has low starting current & high starting torque. Therefore, it is more suitable for direct on line starting.
2. Since effective rotor resistance of double cage motor is higher, there is larger rotor heating at the time of starting as compared to that of single cage rotor.
3. The high resistance of the outer cage increases the resistance of double cage motor. So full load copper losses are increased & efficiency is decreased.
4. The pull out torque of double cage motor is smaller than single cage motor.
5. The cost of double cage motor is about 20-30 % more than that of single cage motor of same rating.

3.13 Induction generator

Induction machine is sometimes used as a generator. It is also called Asynchronous Generator. What are the conditions when the poly phase (here three phase) induction machine will behave as an induction generator? The following are conditions when the induction machine will behave as an induction generator are written below:

(a) Slip becomes negative due to this the rotor current and rotor emf attains negative value.

(b) The prime mover torque becomes opposite to electric torque.

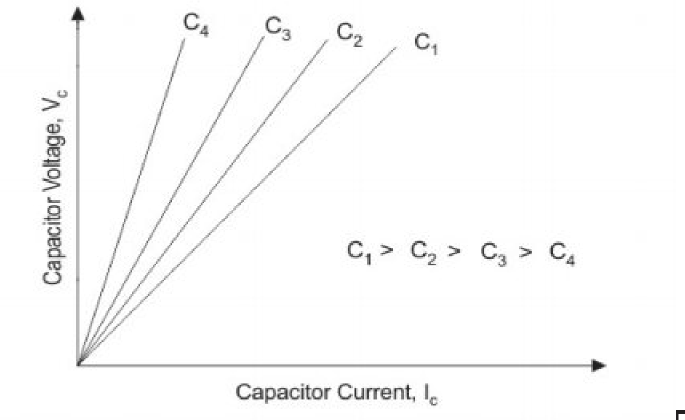
Now let us discuss how we can achieve these conditions. Suppose that an induction machine is coupled with the prime mover whose speed can be controlled. If the speed of the prime mover is increased such that the slip becomes negative (i.e. speed of the prime mover becomes greater than the synchronous speed).Due to this, all the conditions that we have mentioned above will become fulfilled and 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 effect of the generator vanishes. Clearly the speed of the induction generator during the whole operation is not synchronous, therefore the induction generation is also called a synchronous generator.

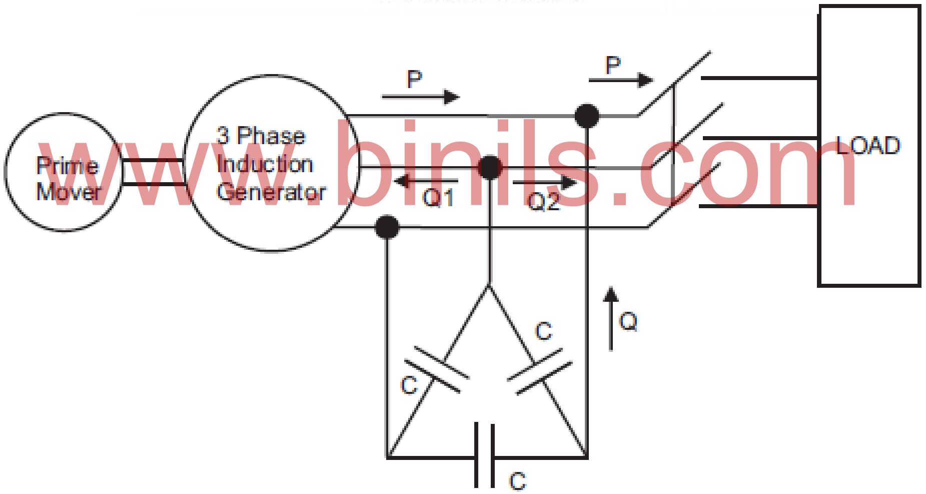
Induction generator is not a self excited machine therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizing current and reactive power from the various sources like the supply mains or it may be another synchronous generator. The 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* in one case if we will use capacitor bank for reactive power supply instead of AC supply system. So let us discuss **isolated induction generator** in detail,

3.14 Isolated Induction Generator

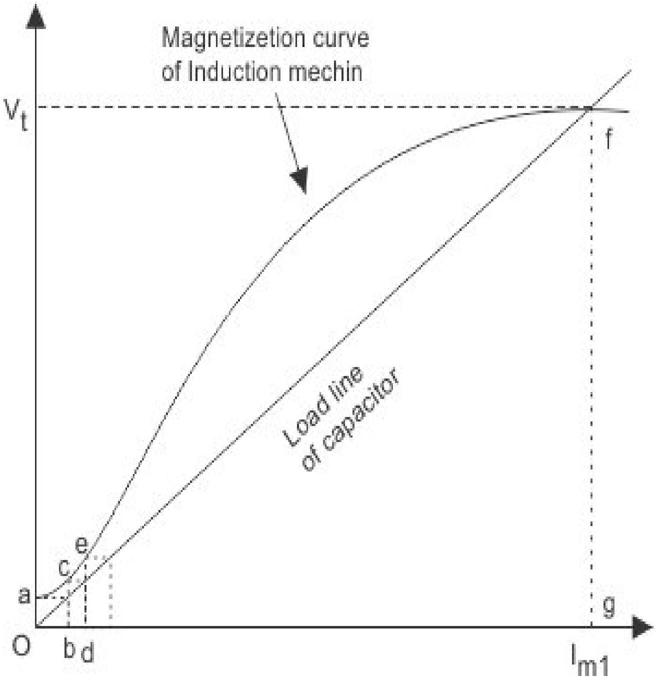
This type of generator is also known as self excited generator. Now why it is called self excited? It is because it uses capacitor bank which is connected across its stator terminals as shown in the diagram given below,

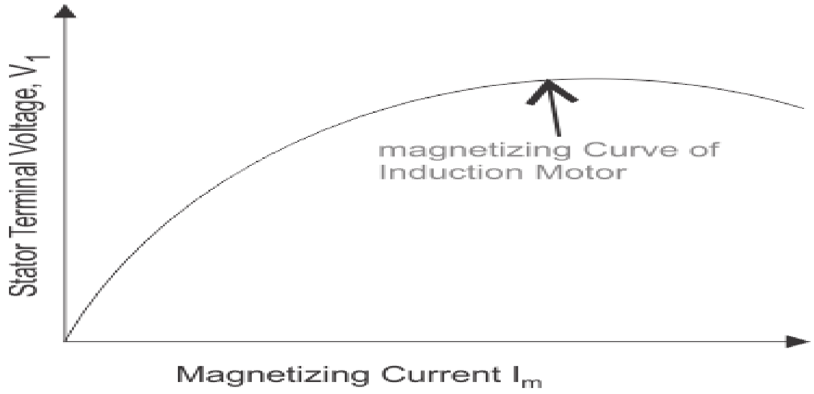
The function of the capacitor bank is to provide the lagging reactive power to the induction generator as well as load. So mathematically we can write total reactive power provided by the capacitor bank is equals to the summation of the reactive power consumed by the induction generator as well as the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





There is generation of small terminal voltage oa (as in figure given below) across the stator terminal due the residual magnetism when the rotor of the induction machine runs at the required speed. Due to this voltage oa the capacitor current ob is produced. The current bc sends current od which generates the voltage de. The cumulative process of voltage generation continues till





the saturation curve of the induction generator cuts the capacitor load line at some point. This point is marked as f in the given curve.

3.14.1 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.

As an example, consider the use of a 10 hp, 1760 r/min, 440 V, three-phase induction motor as an asynchronous generator. The full-load current of the motor is 10 A and the full-load power factor is 0.8.

Required capacitance per phase if capacitors are connected in delta:

Apparent power $S = \sqrt{3}\, E\, I = 1.73 \times 440 \times 10 = 7612$ VA
Active power $P = S \cos \theta = 7612 \times 0.8 = 6090$ W
Reactive power $Q = \sqrt{(S^2 - P^2)} = 4567$ VAR

For a machine to run as an asynchronous generator, capacitor bank must supply minimum 4567 / 3 phases = 1523 VAR per phase. Voltage per capacitor is 440 V because capacitors are connected in delta.

Capacitive current $I_c = Q/E = 1523/440 = 3.46$ A
Capacitive reactance per phase $X_c = E/I_c = 127\ \Omega$

Minimum capacitance per phase:

$C = 1 / (2*\pi*f*X_c) = 1 / (2 * 3.141 * 60 * 127) = 21$ microfarads.

If the load also absorbs reactive power, capacitor bank must be increased in size to compensate.

Prime mover speed should be used to generate frequency of 60 Hz:

Typically, slip should be similar to full-load value when machine is running as motor, but negative (generator operation):

if Ns = 1800, one can choose N=Ns+40 rpm
Required prime mover speed N = 1800 + 40 = 1840 rpm.

3.14.2 Advantages of Induction Generator

1. It has robust construction requiring less maintenance. Also it is relatively cheaper.
2. It has small size per KW output power.
3. It runs in parallel without hunting
4. No synchronization to the supply line is required like a synchronous generator.

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

Problems

Ques1: A 3 φ 4 pole 50 hz induction motor runs at 1460 r.p.m. find its %age slip.
Solution
N_s = 120f/p = 120*50/4 = 1500r.p.m.
Running speed of motor = n= 1460r.p.m.
Slip S=(N_s–N)/ N_s*100 =(1500-1460) x 100 / 1500 = 2.667%

Ques2: A 12 pole 3 φ alternator driver at speed of 500 r.p.m. supplies power to an 8 pole 3 φ induction motor. If the slip of motor is 0.03p.u, calculate the speed.
Solution
Frequency of supply from alternator, f=PN/120
=12*500/120 = 50hz

where P= no of poles on alternatev
N=alternator speed is r.p.m.
Synchronous speed of 3 φ induction motor
N=120f/Pm
=120*50/8 = 750 r.p.m.
Speed of 3 φ induction motor N=Ns (1-s)
=750(1-0.03) = 727.5 r.p.m.
Ques3: A motor generates set used for providing variable frequency ac supply consists of a 3-φ synchronous and 24 pole 3 φ synchronous generator. The motor generate set is fed from 25hz, 3 φ ac supply. A 6 pole 3 φ induction motor is electrically connected to the terminals of the synchronous generator and runs at a slip of 5%. Find
i) the frequency of generated voltage of synchronous generator
ii) the speed at which induction motor is running
Solution
Speed of motor generator set
N_s=(120*f_1(supply freq))/(no of pole on syn motor)
=120*25/10=300 r.p.m.

(1) frequency of generated voltage
f_z=speed of motor gen set voltage *no of poles on syn gen/120
= 300*24/120 = 60hz
(2) Speed of induction motor , N_m=N_s(1-s)
=120 f_z /P_m(1-s) = 120*60/6(1-0.05) = 1140r.p.m.
Ques4: A 3-φ 4 pole induction motor is supplied from 3φ 50Hz ac supply. Find
(1) synchronous speed
(2) rotor speed when slip is 4%
(3) the rotor frequency when runs at 600r.p.m.
Sulution
1) N_s =120f/p
=120*50/4 = 1500 r.p.m.

2) speed when slip is 4% or .04
N=N_s (1-s)
=1500(1-0.04) = 1440 r.p.m.
3) slip when motor runs at 600 r.p.m.
S'=(N_s –N)/N_s
=(1500-600)/1500 = 0.6

Rotor frequency f’ = S’f = 0.6*50 = 30Hz.

Ques5: A 12 pole 3-φ alternator is coupled to an engine running at 500r.p.m. If supplied a 3φ induction motor having full speed of 1440r.p.m.

Find the %age slip, frequency of rotor current and no of poles of rotor.

Ans

Frequency of supply from alternator $f=P_a*N_a/120$

=12*500/120 = 50Hz

Full load speed N_f =1440 r.p.m.

The no of poles (nearest to and higher than full load speed of motor =1440) should be in even nos.

P=120f/n = 120*50/1440 = 4

$N_s = 120f/P_m$ = 120*50/4 = 1500 r.p.m.

% Slip s = $(N_s-N)/N_s$ x 100 =(1500-1440) x 100 / 1500 = 4%

Rotor frequency f’ = sf = 0.04*50 = 2Hz

No A poles of the motor = 4

Ques6: The rotor of 3φ induction motor rotates at 900r.p.m. when states is connected to 3φ supply .find the rotor frequency.

Solution N_r =980 r.p.m., f=50Hz, N_s=120f/p

When P=2, N_s=3000r.p.m.,P=4, N_s=1500

P=6, Ns=1000, P=8, Ns=750r.p.m.

As we know that synchronous speed is slightly greater than rotor speed.

N_s=1000 r.p.m. P=6

Fr=Sf=(Ns-N)/Ns*f=Sf = (1000-980) x 50 / 1000

Ques7: A 3 φ 50Hz induction motor has a full load speed of 960 r.p.m

(a) find slip

(b) No of poles

(c) Frequency of rotor induced e.m.f

(d) Speed of rotor field w.r.t. rotor structure

(e) Speed of rotor field w.r.t. Stator structure

(f) Speed of rotor field w.r.t. stator field

Solution:

Given f = 50 Hz(supply frequency)

N = 960r.p.m

The no. of pole will be 6 only(because at P=6, Ns = 1000 which is nearer nad greater then 960 r.p.m.)

(a) Slip, S = $(N_s-N)/N_s$ * 100 = (1000 – 960) / 1000 * 100 = 4%

(b) No of poles = 6

(c) Frequency of rotor induced emf = f_r = SF = .04 * 50 = 2Hz

(d) Speed of rotor field w.r.t rotor structure = $120f_r/p$ = 120*2/6 = 40 r.p.m.

(e) Speed of rotor field w.r.t. stator structure os actually the speed of stator filed w.r.t stator structure, N_s = 1000r.p.m

(f) Speed of rotor field w.r.t stator field is zero

Ques8: A 3 φ, 400V wound rotor has delta connected stator winding and star connected rotor winding. The stator has 48 turns/phase while rotor has 24 turns per phase. Find the stand still or open circuited voltage across the slip rings

Solution

Stator e.m.f/phase E1 = 400V
Statur turns/phase N1 = 48
Rotor turns/phase N2 = 24
K= N2/N1 = 24/48 = 1/2

Rotor e.m.f/phase = KE_1 = 1/2 * 400 = 200V
Voltage between slip rings = Rotor line voltage = √ 3 x 200 = 346 volt

Ques9: A 6 pole 3 φ 50Hz induction motor is running at full load with a slip of 4%. The rotor is star connected and its resistance and stand still reactance are 0.25 ohm and 1.5 ohm per phase. The e.m.f between slip ring is 100V. Find the rotor current per phase and p.f, assuming the slip rings are short circuited.

Solution

Rotor e.m.f./phase at stand still $E_2 = 100\sqrt{3} = 57.7$V
Rotor e.m.f./phase at full load = sE_2 = 0.04 * 57.7 = 2.31 V
Rotor reactance/phase at full Load = SX_2 = .04 * 1.5 = .06 ohm
Rotor impedance/phase at full load = $\sqrt{((0.25)^2 + (0.06)^2)}$ = .257 ohm
Full load Rotor current/phase = 2.31/0.257 = 9A
Rotor P.f = 0.25/0.257 = 0.97 lag

Quest10: A 50 Hz, 8 pole induction motor has full load slip of 4%. The rotor resistance and stand still reactance are 0.01 ohm and 0.1 ohm per phase respectively. Find:

i) The speed at which maximum torque occurs
ii) The ratio of maximum torque to full load torque

Solution:

Synchronous speed N_s = 120f/P = 120*50/8 = 750r.p.m.
Slip at which maximum torque occurs = R_2/X_2 = 0.01/0.1 = 0.1
Rotor speed at maximum torque = (1-0.1) N_s = (1- 0.1) 750 = 675 r.p.m. $T_m/T_f = (a^2 + s^2)/2as$
Where s = Full load slip = 0.04

a = R_2/X_2 = 0.01/0.1 = 0.1
$T_m/Tf = ((0.1)^2 + (0.04)^2)/(2*0.1*0.04) = 1.45$

Ques 11: An 8 pole 3 φ, 50 Hz induction motor has rotor resistance of 0.025 ohm/phase and rotor standstill reactance of 0.1ohm/phase. At what speed is the torque maximum? What proportion of maximum torque is the starting torque?

Solution

N_s = 120f/P = 120*50/8 = 750 r.p.m.
$R_2 = SX_2$ ------------ for maximum torque
S = R_2/X_2 = 0.025/0.1 = 0.25
Corresponding speed N = (1-s)Ns = (1 – 0.25)750 = 562.5 r.p.m.

ii) $T_s/T_m = 2a/(a^2+1) = 0.47$ where a = R_2/X_2 = 0.025/0.1 = 0.25

Ques12: A 500 V, 3 φ, 50 Hz induction motor develops an output of 15 KW at 950 r.p.m. If the input p.f. is 0.86 lagging, Mechanical losses are 7.30 W and stator losses 1500W, Find

i) the slip
ii) the rotor Cu loss
iii) the motor input
iv) the line current

Solution:

VL = 500V, motor output Pr = 15KW
N = 950 r.p.m. P.f. = cos Ø = 0.86lags
Mech. Loss = 730 W
Stator loss = 1500 W
Ns = 120f/P = 120 * 50/6 = 1000r.p.m.
i) S = (Ns-N)/Ns * 100 = (1000 – 960)/1000 *100 = 0.05*100 = 5%
ii) Rotor output = Motor output + Mechanical output = 15 + .730 watt = 15.73 KWatt
There fore (Rotor Cu loss)/(Rotor output) = s/(s-1)
Or Rotor Cu loss = 15.73 * (0.05)/(1-0.05) = 827.89 watt

Power flow diagram for finding the motor input

Motor input = 15kw + 730 + 1500 + 827.89 = 18.058KW
Line Current = $\sqrt{3}V_2I_2\cos\varphi$
I2 = 24.25A
Ques13: A 6 pole 3φ induction motor develops 30hp including 2 hp mechanical losses at a speed of 950 r.p.m. on 550V, 50Hz Mains. The P.F. is 0.88 lagging. Find:
1) Slip
2) Rotor Cu loss
3) Total input if stator losses are 2kw
4) η
5) Line current

Solution
N_s = 120f/P = 120 * 50/6 = 1000 r.p.m.
1) S = (N_s – N)/N_s = (1000 – 950)/1000 = 0.05
Rotor output P_{mech} = 30hp = 30 * 735.5 = 22065 watt
Power input to rotor = P_{mech}/(1-S) = 22065/(1-0.05) = 23,226
2) Rotor Cu loss = s * rotor input = 0.05 * 23226 = 1161 Watt
3) Total input = Power input to rotor + stator losses = 23226 + 2000 = 25226 Watt

Motor output = Rotor output – Mech loss = 30 – 2 = 28 HP = 28 * 735.5 = 20594 Watt
4) η = (Motor output)/(Motor input) * 100 = 81.64%
5) I_L = (Motor Input)/(√3 * 550 * 0.88) = 30A
Ques14: A 4 pole 50 Hz 3 φ induction motor running at full load, develops a torque of 160N-m, when rotor makes 120 complete cycles per minute, find what power output
Solution
Supply frequency f = 50Hz
Rotor e.m.f. frequency = f = 120/60 = 2Hz
Slip S = f'/f = 2/50 = 0.04
N_s = 120f/p = 120 *50/4 = 1500 r.p.m.
Shaft power output = T_{sh} * 2πN/160 = 160 * 2 π * 1440/60 = 24127W

Ques15: The power input to a 500V 50Hz, 6 pole, 3 φ squirrel case inductor motor running at 975 r.p.m. is 40kw. The stator losses are 1 kw and friction and windage losses are 2kw. Find:
1) Slip
2) Rotor Cu loss
3) Brake hp
Solution:
i) N_s = 120f/P = 120*50/6 = 1000 r.p.m.
S= (N_s – N)/N_s = (1000 – 975)/1000 = 0.025

Power input to station P_1 = 40Kw
Stator output power = P_1 – stator losses = 40 -1 = 39kw
Power input to rotor P_2 = Stator output power = 39 KW
ii) Rotor Cu loss = sP_2 = 0.025 * 39 = 0.975KW
$P_{mech} = P_2 – P_{cu}$ = 39 – 0.975 = 38.025
iii) Motor output = P_{mech} – friction and windage loss = 38.025 – 2 = 36.025KW

Ques16: A 480V, 60 Hz, 6-pole, three-phase, delta-connected induction motor has the following parameters:

$R_1=0.461\ \Omega$, $R_2=0.258\ \Omega$, $X_1=0.507\ \Omega$, $X_2=0.309\ \Omega$, $X_m=30.74\ \Omega$

Rotational losses are 2450W. The motor drives a mechanical load at a speed of 1170 rpm. Calculate the following information:

i. Synchronous speed in rpm

ii. slip

iii. Line Current

iv. Input Power

v. Airgap Power

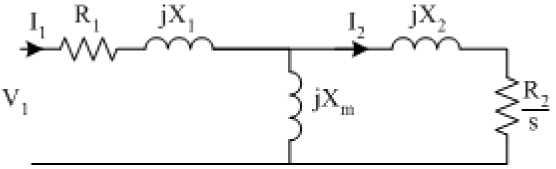
vi. Torque Developed

vii. Output Power in Hp

viii. Efficiency

Solution

This machine has no iron loss resistance, so the equivalent circuit is as follows:



i. Synchronous speed is given by:

$$n_s = \frac{120 f_e}{p}$$

Therefore

n_s = 1200 rpm

ii. Slip is given by

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

Using the rpm equation,

$s = (1200\text{-}1170)/1200 = 0.025$

iii. Now, phase current is given by

$$I_1 = \frac{V_1}{Z_{in}}$$

where phase impedance is given by

$$Z_{in} = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2}{s} + jX_2\right)}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}$$

Using the above equation, $Z_{in} = 9.57 + j3.84\ \Omega$
And noting that the machine is delta connected, $V_1 = V_{LL} = 480V$

$I_1 = 43.1 - j17.4\ A.$ $|I_1| = 46.6\ A,$ $\theta = -21.9°$
Therefore $I_L = \sqrt{3} \times 46.6 = 80.6\ A$

iv. Input power is given by:

$$P_{in} = \sqrt{3}V_{LL}I_L\cos\theta = 3V_1I_1\cos\theta$$

Therefore:

$P_{in} = 62.2\ kW$

v. To find airgap power, There are two possible approaches:

a. Airgap power is the input power minus stator losses. In this case the core losses are grouped with rotational loss. Therefore

$$P_{gap} = P_{in} - 3I_1^2R_1$$

$P_{gap} = 62.2\ kW - 3\times 46.6^2 \times 0.461$
$P_{gap} = 59.2\ kW$

b. Airgap Power is given by

$$P_{gap} = \frac{3I_2^2R_2}{s}$$

This approach requires rotor current to be found. With no core loss resistance:

$$\mathbf{I}_2 = \frac{jX_m}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}\mathbf{I}_1$$

$$I_2 = \left|\frac{jX_m}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}\right| I_1$$

Giving $I_2 = 43.7\ A$. Substituting into the power equation

$P_{gap} = 59.2kW$

vi. Torque developed can be found from

$$\tau = \frac{P_{gap}}{\omega_s}$$

where synchronous speed in radians per second is given by

$$\omega_s = \frac{4\pi f_e}{p}$$

giving

$\tau = 471\ Nm$

vii. Output power in horsepower is the output power in Watts divided by 746. (there are 746 W in one Hp).

$$P_{out} = P_{conv} - P_{rotational}$$

and

$$P_{conv} = \left(1 - s\right)P_{gap}$$

Therefore output power in Watts is: $P_{out} = 55.3kW$

$P_{out} = 74.1\ Hp$

viii. Efficiency is given by

$$\eta = \frac{P_{out}}{P_{in}}$$

Therefore

$\eta = 55.3/62.2 = 88.9\%$

Ques17: A three-phase, 6-pole, 10 HP, 400 Hz induction motor has a slip of 3% at rated output power. Friction and windage losses are 300 W at rated speed. The rated condition total core losses are 350 W. $R_1 = R_2' = 0.05\ \Omega$. $X_1 = X_2' = 0.15\ \Omega$. If the motor is operating at rated output power, speed, and frequency, find (*a*) rotor speed, (*b*) frequency of rotor currents, (*c*) total power across the air gap, (*d*) efficiency, and (*e*) applied line voltage. Use the approximate equivalent circuit for analysis.

(*a*)

$$n_s = \frac{120f}{p} = \frac{(120)(400)}{6} = 8000 \text{ rpm}$$

$$n_m = (1-s)n_s = (1-0.03)(8000) = 7760 \text{ rpm}$$

(*b*)

$$f_r = sf = (0.03)(400) = 12 \text{ Hz}$$

(*c*)

$$3P_d = P_s + P_{FW} = (10)(746) + 300 = 7760 \text{ W}$$

$$3P_g = \frac{3P_d}{(1-s)} = \frac{7760}{1-0.03} = 8000 \text{ W}$$

(*d*) The reflected secondary current is found by

$$I_2' = \left[\frac{sP_g}{R_2'}\right]^{1/2} = \sqrt{\frac{(0.03)(8000/3)}{0.05}} = 40 \text{ A}$$

$$\text{Losses} = 3(I_2')^2(R_1 + R_2') + 3P_c + P_{FW}$$

$$= 3(40)^2(0.05+0.05) + 350 + 300 = 1130 \text{ W}$$

$$\eta = \frac{P_s(100)}{P_s + \text{losses}} = \frac{(10)(746)(100)}{(10)(746)+1130} = 88.94\%$$

(*e*)

$$V_1 = I_2'\left|R_1 + \frac{R_2'}{s} + jX_{eq}\right| = 40\left|0.05 + \frac{0.05}{0.03} + j0.3\right| = 69.71 \text{ V}$$

$$V_L = \sqrt{3}V_1 = \sqrt{3}(69.71) = 120.7 \text{ V}$$

REVIEW QUESTIONS

2marks and 3 marks

1. Why are 3-phase induction motors very popular as drives for industrial applications?

2. What are the various types of 3-phase induction motors as per the rotor construction?

3. List the differences between squirrel cage and slip ring rotor.

4. Define slip of induction motor.

5. A 3-phase induction motor does not run at synchronous speed. Why?

6. Why is the no-load current drawn by 3-phase induction motor so high?

7. Compare the efficiency and operating power factor of single phase induction motor with 3-phase induction motor.

8. How to change the direction of induction motor?

9. What are the advantages of induction generator?

10. What do you meant by cogging?

11. What do you meant by crawling?

12. Write the application of induction generator?

13. Write the application of slip ring induction motor?

14. Draw the torque-speed characteristics of a 3-phase induction motor.

15. List the various losses that take place in an induction motor.

10marks

1. With the help of diagrams, explain how a rotating magnetic field is produced in the air gap of a 3-phase induction motor.

2. Explain the principle of operation of 3-phase induction motor.

3. Explain with neat diagram of construction of squirrel cage induction motor.

4. Draw and Explain the construction of Double Squirrel Cage Motor

5. Derive a general expression for the torque developed in a 3-phase induction motor.

6. Draw and explain the phasor diagram of a 3-phase induction motor.

7. Develop the equivalent circuit of a 3-phase induction motor.

8. i)Why do we need a starter for starting a 3-phase induction motor?

ii) Draw a neat diagram showing the connections of 3-phase induction motor with star-delta starter. Explain how the above starter reduces the starting current.

9. Draw the diagram of an auto-transformer starter used for 3-phase induction motor and explain its operation.

10. Describe the no-load test and blocked rotor test to determine the parameters of equivalent circuit of 3-phase induction motor.

11. Explain the various techniques used for speed control of 3-phase induction motor.

12. Explain rotor resistance speed control of 3-phase induction motor.

13. Draw and explain the development of circle diagram.

14. Explain with neat sketch the Construction of Deep Bar Double Cage Induction Motor.

Unit-IV

SINGLE PHASE MOTOR AND SYNCHRONOUS MOTOR

SINGLE PHASE MOTOR

4.1 Introduction

Single phase power system is widely used as compared to three phase system for domestic purpose, commercial purpose and to some extent in industrial purpose. As the single phase system is more economical and the power requirement in most of the houses, shops, offices are small, this can be easily met by single phase motor. The single phase motors are simple in construction, cheap in cost, reliable and easy to repair and maintain. Due to all these advantages the single phase motor finds its application in vacuum cleaner, fans, washing machine, centrifugal pump, blowers, washing machine, small toys etc.

4.1.1 Types of single phase induction motor

Single phase motor are generally built in the fractional horse power range and may be classified in to the following four basic types

1. **Single phase induction motor**
    - (i) Split phase type
    - (ii) Capacitor type
    - (iii) Shaded pole type
2. **AC series motor or universal motor**
3. **Repulsion motors**
    - (i) Repulsion start induction run motor
    - (ii) Repulsion induction motor
4. **Synchronous motor**
    - (i) Reluctance motor
    - (ii) Hysteresis motor

4.1.2Construction of Single Phase Induction Motor

Like any other electrical motor single phase induction motor also have two main parts namely rotor and stator.

4.1.2(a)Stator:

As its name indicates stator is a stationary part of induction motor. A single phase ac supply is given to the stator of single phase induction motor.

4.1.2(b)Rotor:

The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft. The rotor in single phase induction motor is of squirrel cage rotor type. The construction of single phase induction motor is almost similar to the squirrel cage three phase motor except that in case of asynchronous motor the stator have two windings instead of one as compare to the single stator winding in three phase induction motor.

(a)Stator of Single Phase Induction Motor

The stator of the single phase induction motor has laminated stamping to reduce **eddy current** losses on its periphery. The slots are provided on its stamping to carry stator or main winding. In order to reduce the hysteresis losses, stamping are made up of silicon steel. When the stator winding is given a single phase ac supply, the magnetic_field is produced and the motor rotates at a speed slightly less than the synchronous speed N_s which is given by

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

Where, f = supply voltage frequency,

P = No. of poles of the motor.

The construction of the stator of asynchronous motor is similar to that of three phase induction motor except there are two dissimilarity in the winding part of the single phase induction motor.

- Firstly the single phase induction motors are mostly provided with concentric coils. As the number of turns per coil can be easily adjusted with the help of concentric coils, the mmf distribution is almost sinusoidal.
- Except for shaded pole motor, the asynchronous motor has two stator windings namely the main winding and the auxiliary winding. These two windings are placed in space quadrature with respect to each other.

(b)Rotor of single phase induction motor

The construction of the rotor of the single phase induction motor is similar to the squirrel cage three phase induction motor. The rotor is cylindrical in shape and has slots all over its periphery. The slots are not made parallel to each other but are bit skewed as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of induction motor more smooth and quieter i.e. less noise. The squirrel cage rotor consists of aluminum, brass or copper bars. These aluminum or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor. The rotor conductors are permanently shorted by the copper or aluminum rings called the end rings.

In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as squirrel cage induction motor. As the bars are permanently shorted by end rings, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars are permanently shorted. The absence of slip ring and brushes make the construction of single phase induction motor very simple and robust.

4.1.3Working Principle of Single Phase Induction Motor

We know that for the working of any electrical motor whether its ac or DC motor, we require two fluxes as, the interaction of these two fluxes produced the required torque, which is desired parameter for any motor to rotate.

When single phase ac supply is given to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors. According to the Faraday's law of electromagnetic induction, emf gets induced in the rotor. As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its own flux called rotor flux. Since this flux is produced due to induction principle so, the motor working on this principle got its name as induction motor. Now there are two fluxes one is main flux and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

4.1.4Why Single Phase Induction Motor is not Self Starting?

According to double field revolving theory, any alternating quantity can be resolved into two components, each component have magnitude equal to the half of the maximum magnitude of the alternating quantity and both these component rotates in opposite direction to each other.

For example

A flux, φ can be resolved into two components

$$\frac{\phi_m}{2}\ and\ -\frac{\phi_m}{2}$$

Each of these components rotates in opposite direction i.e. if one φ_m / 2 is rotating in clockwise direction then the other φ_m / 2 rotate in anticlockwise direction. When a single phase ac supply is given to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude φ_m /2. Each of these components will rotate in opposite direction, with the synchronous speed, N_s. Let us call these two components of flux as forward component of flux, φ_f and backward component of flux, φ_b. The resultant of these two components of flux at any instant of time, gives the value of instantaneous stator flux at that particular instant.

$$i.e.\phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2}\ or\ \phi_r = \phi_f + \phi_b$$

Now at starting, both the forward and backward components of flux are exactly opposite to each other. Also both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at starting is zero. So, the single phase induction motors are not self starting motors.

4.1.5 Methods for Making Single Phase Induction as Self Starting Motor

From the above topic we can easily conclude that the single phase induction motors are not self starting because they produced stator flux is alternating in nature and at the starting the two components of this flux cancel each other and hence there is no net torque. The solution to this problem is that **if the stator flux is made rotating type, rather than alternating type, which rotates in one particular direction only**. Then the induction motor will become self starting.

Now for producing this rotating magnetic field we require two alternating flux, having some phase difference angle between them. When these two fluxes interact with each other they will produce a resultant flux. This resultant flux is rotating in nature and rotates in space in one particular direction only. Once the motor starts running, the additional flux can be removed. The motor will continue to run under the influence of the main flux only.

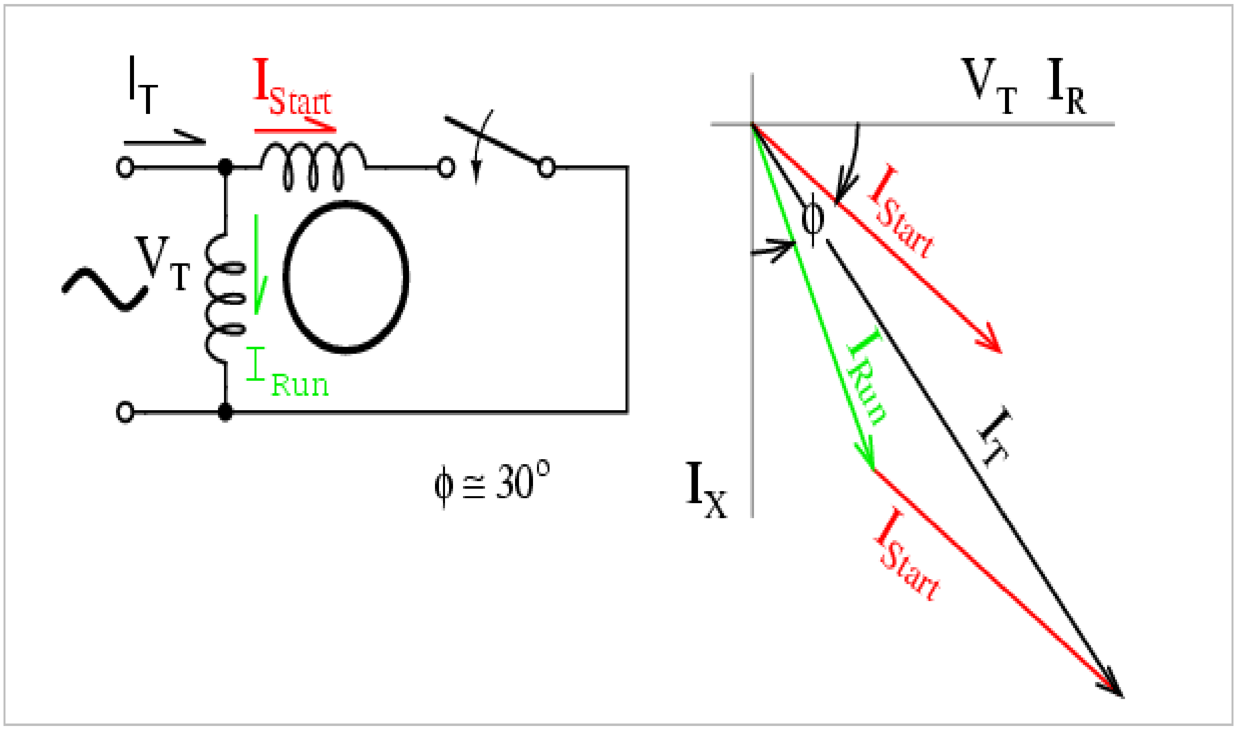
4.1.6 Comparison between Single Phase and Three Phase Induction Motors

1. **Single phase induction motors** are simple in construction, reliable and economical for small power rating as compared to three phase induction motors.
2. The **electrical power factor** of single phase induction motors is low as compared to three phase induction motors.
3. For same **size**, the single phase induction motors develop about 50% of the output as that of three phase induction motors.
4. The **starting torque** is also low for asynchronous motors / single phase induction motor.
5. The **efficiency** of single phase induction motors is less as compare it to the three phase induction motors.

Single phase induction motors are simple, robust, reliable & cheaper for small ratings. They are generally available up to 1 KW rating

4.1.7. (a) Split Phase Induction Motor

In addition to the main winding or running winding, the stator of single phase induction motor carries another winding called auxiliary winding or starting winding. A centrifugal switch is connected in series with auxiliary winding. The purpose of this switch is to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to 75 to 80% of the synchronous speed. We know that the running winding is inductive in nature. Our aim is to create the phase difference between the two winding and this is possible if the starting winding carries high resistance. Let us say I_{run} is the current flowing through the main or running winding, I_{start} is the current flowing in starting winding, and V_T is the supply voltage.



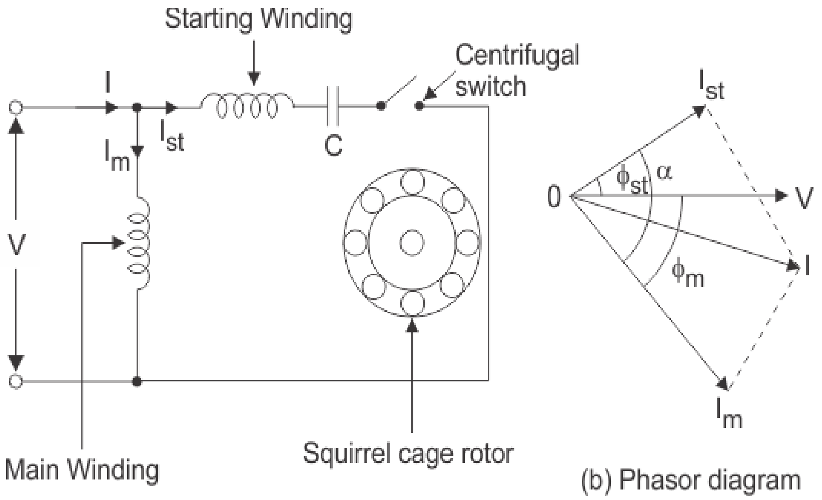
We know that for highly resistive winding the current is almost in phase with the voltage and for highly inductive winding the current lag behind the voltage by large angle. The starting winding is highly resistive so, the current flowing in the starting winding lags behind the applied voltage by very small angle and the running winding is highly inductive in nature so, the current flowing in running winding lags behind applied voltage by large angle. The resultant of these two current is I_T. The resultant of these two current produce rotating magnetic field which rotates in one direction. In **split phase induction motor** the starting and main current get splitted from each other by some angle so this motor got its name as split phase induction motor.

Applications of Split Phase Induction Motor

Split phase induction motors have low starting current and moderate starting torque. So these motors are used in fans, blowers, centrifugal pumps, washing machine, grinder, lathes, air conditioning fans, etc. These motors are available in the size ranging from 1 / 20 to 1 / 2 KW.

4.1.7(b)Capacitor Start IM and Capacitor Start Capacitor Run IM

The working principle and construction of Capacitor start induction motors and capacitor start capacitor run induction motors are almost the same. We already know that single phase induction motor is not self starting because the magnetic field produced is not rotating type. In order to produce rotating magnetic field there must be some phase difference. In case of split phase induction motor we use resistance for creating phase difference but here we use capacitor for this purpose. We are familiar with this fact that the current flowing through the capacitor leads the voltage. So, in **capacitor start inductor motor** and **capacitor start capacitor run induction motor** we are using two winding, the main winding and the starting winding. With starting winding we connect a capacitor so the current flowing in the capacitor i.e I_{st} leads the applied voltage by some angle, φ_{st}.



(b) Phasor diagram

(a) Schematic representaion

The running winding is inductive in nature so, the current flowing in running winding lags behind applied voltage by an angle, φ_m. Now there occur large phase angle differences between these two currents which produce an resultant current, I and this will produce a rotating magnetic field. Since the torque produced by these motors depends upon the phase angle difference, which is almost 90°. So, these motors produce very high starting torque. In case of **capacitor start induction motor**, the centrifugal switch is provided so as to disconnect the starting winding when the motor attains a speed up to 75 to 80% of the synchronous speed but in case of **capacitor start capacitors run induction motor** there is no centrifugal switch so, the >capacitor remains in the circuit and helps to improve the power factor and the running conditions of single phase induction motor.

Application of Capaitor Start IM and Capacitor Start Capacitor Run IM

These motors have high starting torque hence they are used in conveyors, grinder, air conditioners, compressor, etc. They are available up to 6 KW.

4-1-7(c)Permanent Split Capacitor (PSC) Motor

It has a cage rotor and stator. Stator has two windings – main and auxiliary winding. It has only one capacitor in series with starting winding. It has no starting switch.

Advantages and Applications

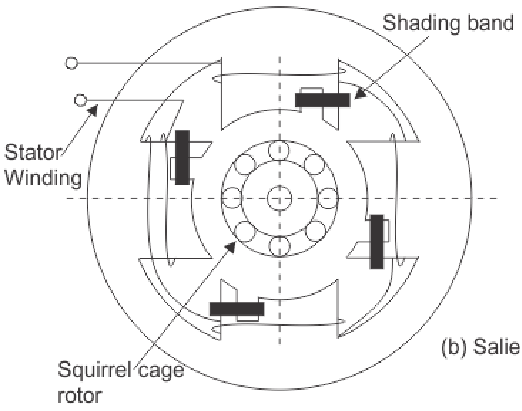
No centrifugal switch is needed. It has higher efficiency and pull out torque. It finds applications in fans and blowers in heaters and air conditioners. It is also used to drive office machinery.

4.1.7(d)Shaded Pole Single Phase Induction Motors

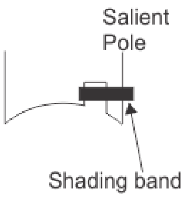
The stator of the **shaded pole single phase induction motor** has salient or projected poles. These poles are shaded by copper band or ring which is inductive in nature. The poles are divided into two unequal halves. The smaller portion carries the copper band and is called as shaded portion of the pole.

When a single phase supply is given to the stator of shaded pole induction motor an alternating flux is produced. This change of flux induces emf in the shaded coil. Since this shaded portion is short circuited, the current is produced in it in such a direction to oppose the main flux. The flux in shaded pole lags behind the flux in the unshaded pole. The phase difference between these two fluxes produces resultant rotating flux. We know that the stator winding current is alternating in nature and so is the flux produced by the stator current. In order to clearly understand the working of shaded pole induction motor consider three regions-

1. When the flux changes its value from zero to nearly maximum positive value.
2. When the flux remains almost constant at its maximum value.
3. When the flux decreases from maximum positive value to zero.



(a) 4-pole shaded pole construction



(b) Salient pole with shading band

REGION 1:

When the flux changes its value from zero to nearly maximum positive value – In this region the rate of rise of flux and hence current is very high. According to Faraday's law whenever there is change in flux emf gets induced. Since the copper band is short circuit the current starts flowing in the copper band due to this induced emf. This current in copper band produces its own flux. Now according to Lenz's law the direction of this current in copper band is such that it opposes its own cause i.e rise in current. So the shaded ring flux opposes the main flux, which leads to the crowding of flux in non shaded part of stator and the flux weaken in shaded part. This non uniform distribution of flux causes magnetic axis to shift in the middle of the non shaded part.

REGION 2:

When the flux remains almost constant at its maximum value- In this region the rate of rise of current and hence fluxes remains almost constant. Hence there is very little induced emf in the shaded portion. The flux produced by this induced emf has no effect on the main flux and hence distribution of flux remains uniform and the magnetic axis lies at the center of the pole.

REGION 3:

When the flux decreases from maximum positive value to zero - In this region the rate of decrease in the flux and hence current is very high. According to Faraday's law whenever there is change in flux emf gets induced. Since the copper band is short circuit the current starts flowing in the copper band due to this induced emf. This current in copper band produces its own flux. Now according to Lenz's law the direction of the current in copper band is such that it opposes its own cause i.e decrease in current. So the shaded ring flux aids the main flux, which leads to the crowding of flux in shaded part of stator and the flux weaken in non shaded part. This non uniform distribution of flux causes magnetic axis to shift in the middle of the shaded part of the pole. This shifting of magnetic axis continues for negative cycle also and leads to the production of rotating magnetic field. The direction of this field is from non shaded part of the pole to the shaded part of the pole.

Advantages and Disadvantages of Shaded Pole Motor

The advantages of shaded pole induction motor are

- Very economical and reliable.
- Construction is simple and robust because there is no centrifugal switch.

The disadvantages of shaded pole induction motor are

- Low power factor.
- The starting torque is very poor.
- The efficiency is very low as, the copper losses are high due to presence of copper band.
- The speed reversal is also difficult and expensive as it requires another set of copper rings.

Applications of Shaded Pole Motor

Applications of Shaded pole motors induction motor are- Due to their low starting torques and reasonable cost these motors are mostly employed in small instruments, hair dryers, toys, record players, small fans, electric clocks etc. These motors are usually available in a range of 1/300 to 1/20 KW.

4.1.8 Universal motor - construction, working and characteristics

A **universal motor** is a special type of motor which is designed to run on either DC or single phase AC supply. These motors are generally series wound (armature and field winding are in series), and hence produce high starting torque (See characteristics of DC motors here). That is why, **universal motors** generally comes built into the device they are meant to drive. Most of the universal motors are designed to operate at higher speeds, exceeding 3500 RPM. They run at lower speed on AC supply than they run on DC supply of same voltage, due to the reactance voltage drop which is present in AC and not inDC.

There are two **basic types of universal motor** :

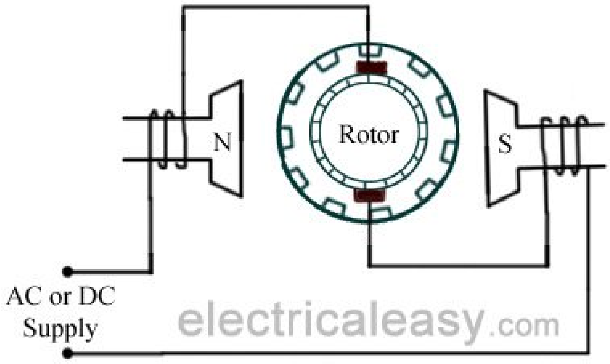
(i) Compensated type and

(ii)Uncompensated type

Construction of Universal Motor

Construction of a universal motor is very similar to the construction of a DC machine. It consists of a stator on which field poles are mounted. Field coils are wound on the field poles. However, the whole magnetic path (stator field circuit and also armature) is laminated. Lamination is necessary to minimize the eddy currents which induce while operating on AC. The rotary armature is of wound type having straight or skewed slots and commutator with brushes resting on it. The commutation on AC is poorer than that for DC. because of the current induced in the armature coils. For that reason brushes used are having high resistance.

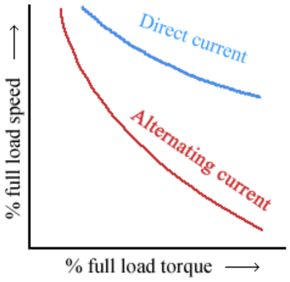
Working of Universal Motor



A universal motor works on either DC or single phase AC supply. When the universal motor is fed with a DC supply, it works as a DC series motor. (see working of a DC series motor here). When current flows in the field winding, it produces an electromagnetic field. The same current also flows from the armature conductors. When a current carrying conductor is placed in an electromagnetic field, it experiences a mechanical force. Due to this mechanical force, or torque, the rotor starts to rotate. The direction of this force is given by Fleming's left hand rule.

When fed with AC supply, it still produces unidirectional torque. Because, armature winding and field winding are connected in series, they are in same phase. Hence, as polarity of AC changes periodically, the direction of current in armature and field winding reverses at the same time. Thus, direction of magnetic field and the direction of armature current reverses in such a way that the direction of force experienced by armature conductors remains same. Thus, regardless of AC or DC supply, universal motor works on the same principle that DC series motor works.

Speed/Load Characteristics



A speed/load characteristic of a universal motor is similar to that of DC series motor. The **speed of a universal motor** is low at full load and very high at no load. Usually, gears trains are used to get the required speed on required load. The speed/load characteristics are (for both AC as well as DC supply) areshowninthefigure.

Applications of Universal Motor

- Universal motors find their use in various home appliances like vacuum cleaners, drink and food mixers, domestic sewing machine etc.
- The higher rating universal motors are used in portable drills, blenders etc.

4.1.9 Operation of three phase motor with single phase supply

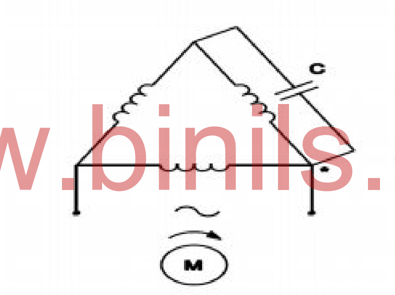
How to use three phase motor in single phase power supply? Actually three phase motor can operate in single phase power supply with the help of a permanent CAPACITOR. Normally 3-phase induction motor will have star or delta connection

How to install and wiring capacitor for three phase motor with single phase power supply?

1) **Wiring of capacitor for FORWARD rotation**

-For FORWARD rotation, we must install capacitor in DELTA connection as per drawing below.

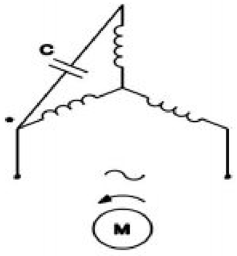
* Symbol –> The change of the connection terminal * of the capacitor allows to invert the turning sense of the motor.



2) **Wiring of capacitor for REVERSED rotation**

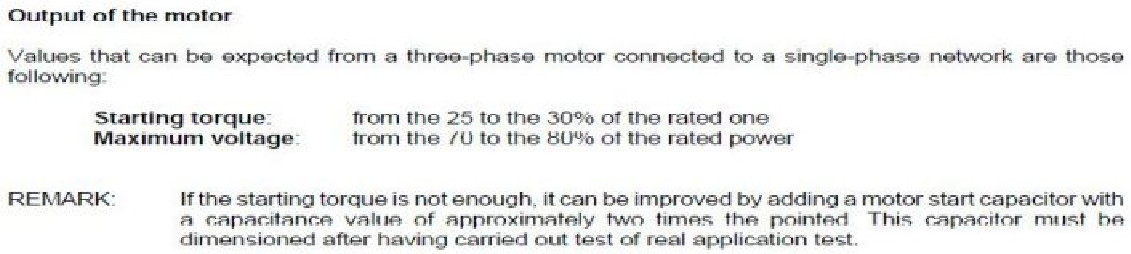
– For REVERSED rotation,we must install capacitor in any two phase of winding in STAR (Y) connection as per drawing below.

* symbol –> The change of the connection terminal * of the capacitor allows to invert the turning sense of the motor.



Output of Motor

We must to consider the output of motor when we converted from three phase to single phase power supply to match and suitable with our application. But we cannot get the actual value due to so many aspects we must calculate and it’s so complicated. So we can estimate the approximate value of motor output as per percentage (%) below:-



Output of the motor

Values that can be expected from a three-phase motor connected to a single-phase network are those following:

Starting torque:	from the 25 to the 30% of the rated one
Maximum voltage:	from the 70 to the 80% of the rated power

REMARK: If the starting torque is not enough, it can be improved by adding a motor start capacitor with a capacitance value of approximately two times the pointed. This capacitor must be dimensioned after having carried out test of real application test.

B.) SYNCHRONOUS MOTOR

4.2 Introduction

A Dc generator can be run as DC motor likewise an alternator may operate as a motor by connecting its armature winding to a 3 phase supply. It is then called as synchronous motor .as a name implies a synchronous motor runs at synchronous speed (NS=120f/P) i.e., in synchronism with the revolving field produced by the 3 phase supply. The speed of the rotation is ,therefore tied to the frequency of the source .since the frequency is fixed ,the motor speed stays constant irrespective of the load or voltage of 3-phase supply .However, synchronous motors are not used so much because they runs at constant speed (i.e., synchronous speed) but because they posses other unique electrical properties. In such Synchronous motors are called so because the speed of the rotor of this motor is same as the rotating magnetic field. It is basically a fixed speed motor because it has only one speed, which is synchronous speed, and therefore no intermediate speed is there or in other words it’s in synchronism with the supply frequency. Synchronous speed is given by

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

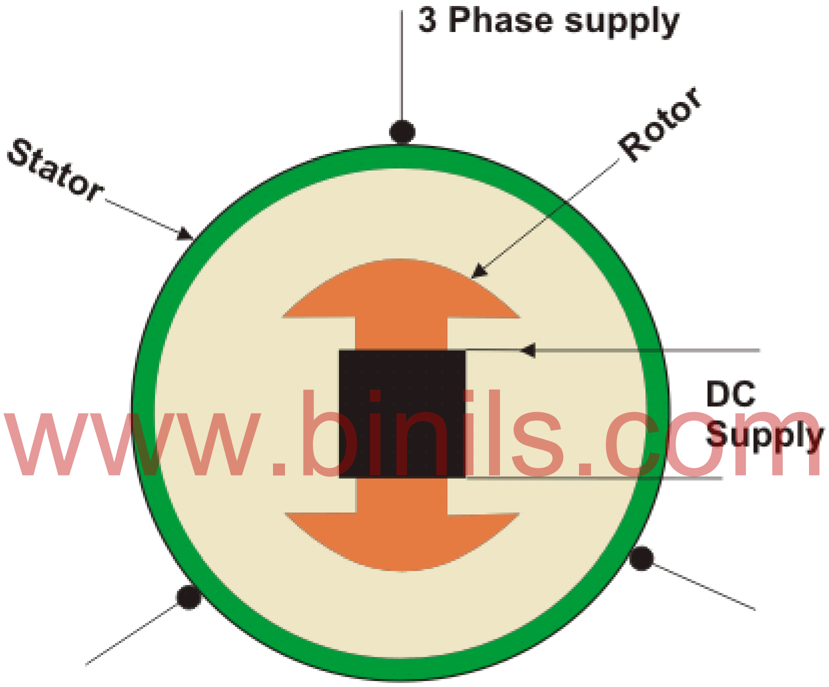
where f = supply frequency & p = no. of poles

4.2.1Construction of Synchronous Motor

Normally it's construction is almost similar to that of a 3 phase induction motor, except the fact that the rotor is given DC supply, the reason of which is explained later. Now, let us first go through the basic construction of this type of motor. From the above picture, it is clear that how this type of motors are designed. The stator is given is given three phase supply and the rotor is given dc supply.

Main Features of Synchronous Motors

- **Synchronous motors** are inherently not self starting. They require some external means to bring their speed close to synchronous speed to before they are synchronized.
- The speed of operation of is in synchronism with the supply frequency and hence for constant supply frequency they behave as constant speed motor irrespective of load condition
- This motor has the unique characteristics of operating under any electrical power factor. This makes it being used in electrical power factor improvement.



Synchronous Motor

4.2.2 Principle of Operation Synchronous Motor

`Synchronous motor is a doubly excited machine i.e two electrical inputs are provided to it. It's stator winding which consists of a 3 phase winding is provided with 3 phase supply and rotor is provided with DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. Considering the frequency to be 50 Hz, from the above relation we can see that the 3 phase rotating flux rotates about 3000 revolution in 1 min or 50 revolutions in 1 sec. At a particular instant rotor and stator poles might be of same polarity (N-N or S-S) causing repulsive force on rotor and the very next second it will be N-S causing attractive force. But due to inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Hence it is not self starting. To overcome this inertia, rotor is initially fed some mechanical input which rotates it in same direction as magnetic field to a speed very close to synchronous speed. After some time magnetic locking occurs and the synchronous motor rotates in synchronism with the frequency.

4.2.3 Methods of Starting of Synchronous Motor

1. **Motor starting with an external prime Mover :**

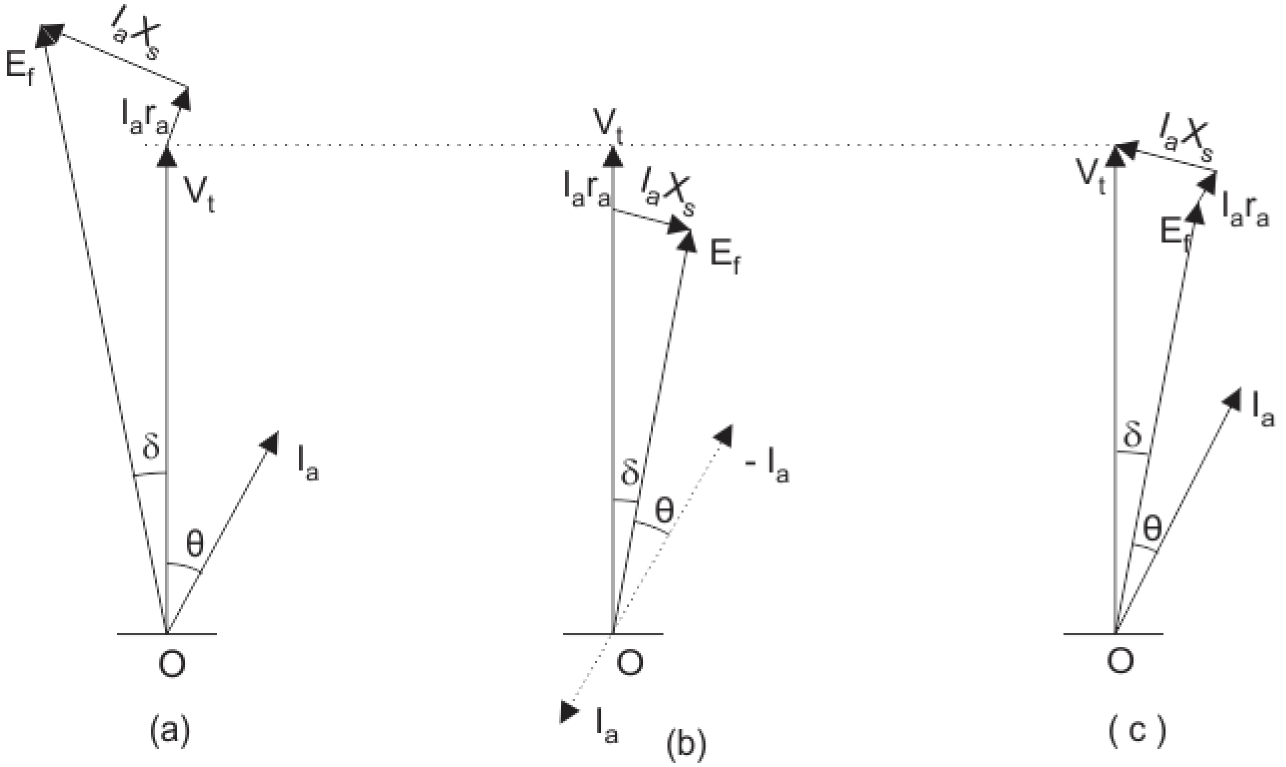
Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or DC shunt motor. DC excitation is not fed initially. It is rotated at speed very close to its synchronous speed and after that DC excitation is given. After some time when magnetic locking takes place supply to the external motor is cut off.

2. **Damper winding :**

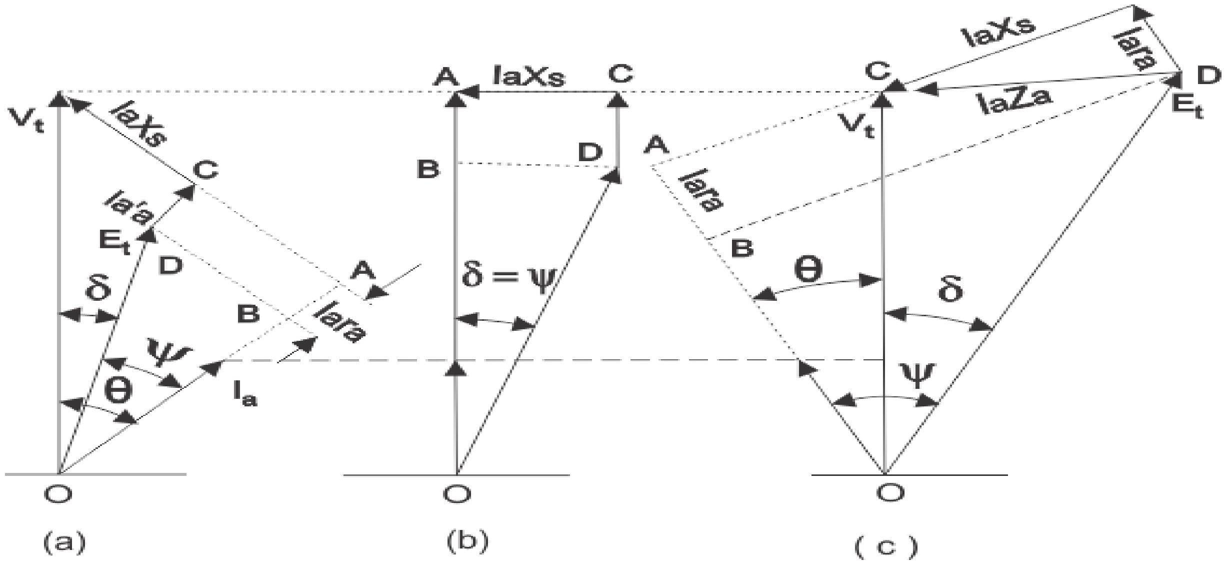
In case, synchronous motor is of salient pole type, additional winding is placed in rotor pole face. Initially when rotor is standstill, relative speed between damper winding and rotating air gap flux in large and an emf is induced in it which produces the required starting torque. As speed approaches synchronous speed, emf and torque is reduced and finally when magnetic locking takes place, torque also reduces to zero. Hence in this case synchronous is first run as three phase induction motor using additional winding and finally it is synchronized with the frequency.

4.2.4 Phasor Diagram for Synchronous Motor

We will discuss here the simplest way of drawing the **phasor diagram for synchronous motor** and we will also discuss advantages of drawing the phasor diagram. Before we draw phasor diagram, let us write the various notations for each quantity at one place. Here we will use:E_f to represent the excitation voltage V_t to represent the terminal voltage I_a to represent the armature current Θ to represent the angle between terminal voltage and armature current Ψ to represent the angle between the excitation voltage and armature current δ to represent the angle between the excitation voltage and terminal voltage r_a to represent the armature per phase resistance. We will take V_t as the reference phasor in order to **phasor diagram for synchronous motor**. In order to draw the phasor diagram one should know these two important points which are written below: **(1)** We know that if a machine is made to work as a asynchronous motor then direction of armature current will in phase opposition to that of the excitation emf. **(2)** Phasor excitation emf is always behind the phasor terminal voltage. Above two points are sufficient for drawing the phasor diagram for synchronous motor. The Phasor diagram for the synchronousmotorisgivenbelow,



In the phasor one the direction of the armature current is opposite in phase to that of the excitation emf.It is usually customary to omit the negative sign of the armature current in the phasor of the synchronous motor so in the phasor two we have omitted the negative sign of the armature current. Now we will draw complete phasor diagram for the synchronous motor and also derive expression for the excitation emf in each case. We have three cases that are written below:



(a) Motoring operation at lagging power factor.
(b) Motoring operation at unity power factor.
(c) Motoring operation at leading power factor.

(a) Motoring operation at lagging power factor:

In order to derive the expression for the excitation emf for the lagging operation we first take the component of the terminal voltage in the direction of armature current I_a. Component in the direction of armature current is $V_t\cos\Theta$.

As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be $-I_a r_a$ hence the total voltage drop is ($V_t\cos\Theta$ - $I_a r_a$) along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be ($V_t\sin\theta$ - $I_a X_s$). From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 - (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta - I_a \times X_s)^2$$

(b) Motoring operation at unity power factor:

In order to derive the expression for the excitation emf for the unity power factor operation we again first take the component of the terminal voltage in the direction of armature current I_a. But here the value of theta is zero and hence we have $\Psi = \delta$. From the triangle BOD in the second phasor diagram we can directly write the expression for excitation emf as

$$E_f^2 = (V_t - I_a \times r_a)^2 + (I_a \times X_s)^2$$

(c) Motoring operation at leading power factor:

In order to derive the expression for the excitation emf for the leading power factor operation we again first take the component of the terminal voltage in the direction of armature current Ia. Component in the direction of armature current is $V_t\cos\Theta$. As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be ($-I_a r_a$) hence the total voltage drop is ($V_t\cos\Theta$ - $I_a r_a$) along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be ($V_t\sin\theta + I_a X_s$). From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta + I_a \times X_s)^2$$

4.2.5Advantages of Drawing Phasor Diagrams for Synchronous Motor

(1) Phasors are highly useful for gaining physical insight into the operation of the synchronous motors.
(2) We can derive mathematical expressions for various quantities easily with the help of phasor diagrams.

4.2.6Synchronous Motor Excitation

Prior to understanding this **synchronous motor excitation**, it should be remembered that any electromagnetic device must draw a magnetizing current from the AC source to produce the required working flux. This magnetizing current lags by almost 90° to the supply voltage. In other words, the function of this magnetizing current or lagging VA drawn by the electromagnetic device is to set up the flux in the magnetic circuit of the device. The synchronous motor is doubly fed electrical motor Synchronous converts electrical energy to mechanical energy via magnetic circuit. Hence, it comes under electromagnetic device. It receives 3 phase ac electrical supply to its armature winding and DC supply is provided to rotor winding. **Synchronous motor excitation** refers to the DC supply given to rotor which is used to produce the required flux. One of the major and unique characteristics of this motor is that it can be operated at any electrical power factor leading, lagging or unity and this feature is based on the excitation of the synchronous motor.

When the synchronous motor is working at constant applied voltage V, the resultant air gap flux as demanded by V remains substantially constant. This resultant air gap flux is established by the co operation of both AC supply of armature winding and DC supply of rotor winding.

CASE 1:

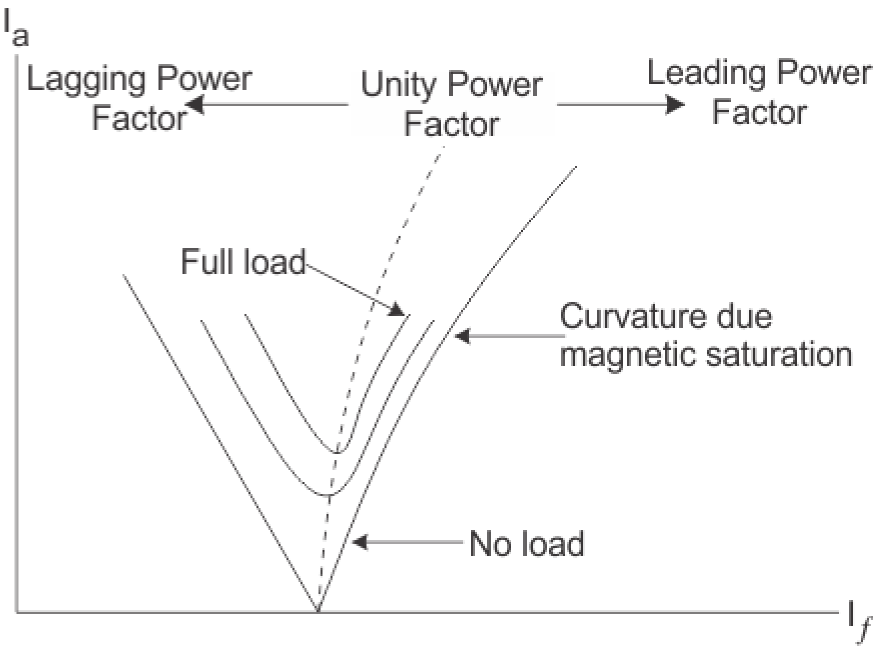
When the field current is sufficient enough to produce the air gap flux, as demanded by the constant supply voltage V, then the magnetizing current or lagging reactive VA required from ac source is zero and the motor operate at unity power factor. The field current, which causes this unity power factor is called normal excitation or normal field current.

CASE 2:

If the field current is not sufficient enough to produce the required air gap flux as demanded by V, additional magnetizing current or lagging reactive VA is drawn from the AC source. This magnetizing current produces the deficient flux (constant flux- flux set up by dc supply rotor winding). Hence in this case the motor is said to operate under lagging power factor and the is said to be under excited.

CASE 3:

If the field current is more than the normal field current, motor is said to be over excited. This excess field current produces excess flux (flux set up by DC supply rotor winding – resultant air gap flux) which must be neutralized by the armature winding. Hence the armature winding draws leading reactive VA or demagnetizing current leading voltage by almost 90^o from the AC source. Hence in this case the motor operate under leading power factor. This whole concept of excitation and power factor of synchronous motor can be summed up in the following graph. This is called V curve of synchronous motor.



V curves for a synchronous motor with variable excitation

An overexcited synchronous motor operate at leading power factor, under-excited synchronous motor operate at lagging power factor and normal excited synchronous motor operate at unity power factor.

4.2.7 Application of Synchronous Motor

- Synchronous motor having no load connected to its shaft is used for power factor improvement. Owing to its characteristics to behave at any electrical power factor, it is used in power system in situations where static capacitors are expensive.
- Synchronous motor finds application where operating speed is less (around 500 rpm) and high power is required. For power requirement from 35 kW to 2500 KW, the size, weight and cost of the corresponding three phase induction motor is very high. Hence these motors are preferably used. Ex- Reciprocating pump, compressor, rolling mills etc.

4.2.8 Hunting in Synchronous Motor

We come across the term **HUNTING** when we study about three phase synchronous motor operations. The word hunting is used because after sudden application of load the rotor has to search or hunt for its new equilibrium position. That phenomena is referred as **hunting in synchronous motor**. Now let us know what is the condition of equilibrium in synchronous motor.A steady state operation of synchronous motor is a condition of equilibrium in which the electromagnetic torque is equal and opposite to load torque. In steady state , rotor runs at synchronous speed thereby maintaining constant value of torque angle (δ). If there is sudden change in load torque, the equilibrium is disturbed and there is resulting torque which changes speed of the motor.

What is Hunting?

Unloaded synchronous machine has zero degree load angle. On increasing the shaft load gradually load angle will increase. Let us consider that load P_1 is applied suddenly to unloaded machine shaft so machine will slow down momentarily.

Also load angle (δ) increases from zero degree and becomes δ_1. During the first swing electrical power developed is equal to mechanical load P_1. Equilibrium is not established so rotor swings further. Load angle exceeds δ_1 and becomes δ_2. Now electrical power generated is greater than the previous one. Rotor attains synchronous speed. But it does not stay in synchronous speed and it will continue to increase beyond synchronous speed. As a result of rotor acceleration above synchronous speed the load angle decreases. So once again no equilibrium is attained. Thus rotor swings or oscillates about new equilibrium position. This phenomenon is known as hunting or phase swinging. Hunting occurs not only in synchronous motors but also in synchronous generators upon abrupt change in load.

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Causes of Hunting in Synchronous Motor

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

Effects of Hunting in Synchronous Motor

1. It may lead to loss of synchronism.
2. Produces mechanical stresses in the rotor shaft.
3. Increases machine losses and cause temperature rise.
4. Cause greater surges in current and power flow.
5. It increases possibility of resonance.

Reduction of Hunting in Synchronous Motor

Two techniques should be used to reduce hunting.

These are –

1. Use of Damper Winding : It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. Damper winding damps out hunting by producing torque opposite to slip of rotor. The magnitude of damping torque is proportional to the slip speed.
2. Use of Flywheels: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.

4.2.9 Difference between Synchronous Motor and Induction Motor

AC motors can be divided into two main categories –

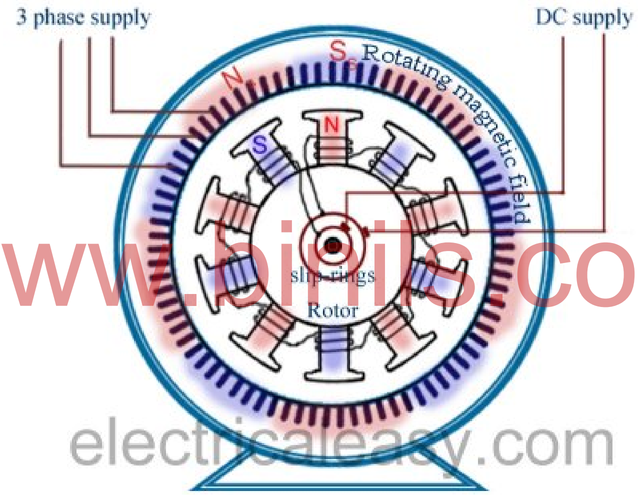
(i) **Synchronous motor** and

(ii) **Asynchronous motor**. An asynchronous motor is popularly called as Induction motor. Both the types are quite different from each other. Major differences between a synchronous motor and an induction motor are discussed below.

(a)Constructional Difference

- **Synchronous motor**:

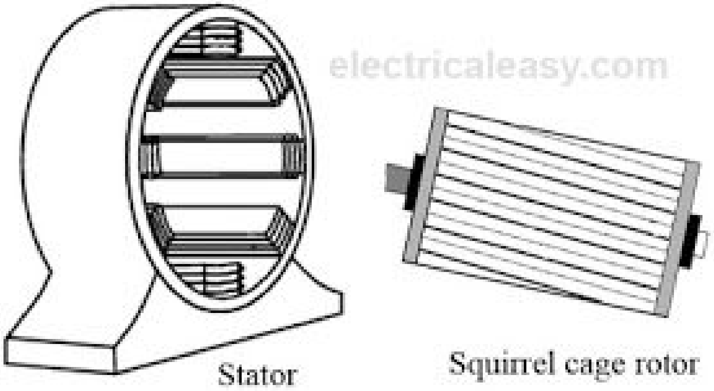
  Stator has axial slots which consist stator winding wound for a specific number of poles. Generally a salient pole rotor is used on which rotor winding is mounted. Rotor winding is fed with a DC supply with the help of slip rings. A rotor with permanent magnets can also be used.



Synchronous motor

- **Induction motor**:

  Stator winding is similar to that of a synchronous motor. It is wound for a specific number of poles. A squirrel cage rotor or a wound rotor can be used. In squirrel cage rotor, the rotor bars are permanently short-circuited with end rings. In wound rotor, windings are also permanently short-circuited, hence no slip rings are required.



Induction motor

(b)Difference In Working

- **Synchronous motor**:

  Stator poles rotate at the synchronous speed (Ns) when fed with a three phase supply. The rotor is fed with a DC supply. The rotor needs to be rotated at a speed near to the synchronous speed during starting. If done so, the rotor poles get magnetically coupled with the rotating stator poles, and thus the rotor starts rotating at the synchronous speed.

  Synchronous motor always runs at a speed equal to its synchronous speed. i.e. Actual speed = Synchronous speed
  or $N = Ns = 120f/P$
  .

- **Induction motor**:

  When the stator is fed with two or three phase AC supply, a Rotating Magnetic Field (RMF) is produced. The relative speed between stator's rotating magnetic field and the rotor will cause an induced current in the rotor conductors. The rotor current gives rise to the rotor flux. According to Lenz's law, the direction of this induced current is such that it will tend to oppose the cause of its production, i.e. relative speed between stator's RMF and the rotor. Thus, the rotor will try to catch up with the RMF and reduce the relative speed.

  Induction motor always runs at a speed which is less than the synchronous speed. i.e. $N < Ns$
  .

(c)Other Differences

- Synchronous motors require an additional DC power source for energizing rotor winding. Induction motors do not require any additional power source.

- Slip rings and brushes are required in synchronous motors, but not in Induction motors (except wound type induction motor in which slip ring motors are used to add external resistance to the rotor winding).

- Synchronous motors require additional starting mechanism to initially rotate the rotor near to the synchronous speed. No starting mechanism is required in induction motors.

- The power factor of a synchronous motor can be adjusted to lagging, unity or leading by varying the excitation, whereas, an induction motor always runs at lagging power factor.

- Synchronous motors are generally more efficient than induction motors.

- Synchronous motors are costlier.

4.2.10 comparison of synchronous and induction motors

S.NO	**PARAMETERS**	**SYNCHRONOUS MOTOR**	**3-PHASE INDUCTION MOTOR**
1	**Speed**	Remains constant from no load to full load	Decreases with load
2	**Power factor**	Can be made to operate from lagging to leading power factor	Operate at lagging power factor
3	**Excitation**	Requires DC excitation at rotor	No excitation for rotor
4	**Economy**	Economical for speeds below 300RPM	Economical for speeds above 600RPM
5	**Self starting**	No self starting torque	Self starting
6	**Construction**	Complicated	Simple
7	**Starting torque**	More	Less

REVIEW QUESTIONS

Q1: Where do we require single-phase induction motors?
Ans: Single-phase induction motors are required where
(i) 3 phase supply is not available
(ii) efficiency is of lesser importance
(iii) Rating is less than one H.P.
(iv) Equipment is portable

Q2: Why is the power factor of a single-phase induction motor low?
Ans: It is due to the large magnetizing current which ranges from 60% to 70% of full-load current. As a result, even at no-load, these motors reach temperatures close to the full-load temperature.

Q3: What is the function of centrifugal starting switch in a single-phase induction motor?
Ans: The centrifugal switch is connected in series with the starting winding. The primary function of the centrifugal switch is to produce rotating flux in conjunction with main winding at the time of starting. When the motor has started and reaches nearly 75% of synchronous speed, it produces its own rotating field from the cross field effect. The starting winding now has no function to perform and is removed from the circuit by a centrifugally operated switch.

Q4: What happens when the centrifugal starting switch fails to open?
Ans: If the starting switch fails to open when needed, then the starting winding will overheat and burn out and motor will not start next time.

Q5: What happens when the centrifugal switch fails to close when needed?
Ans: If the centrifugal starting switch fails to close, the motor will overheat the main winding without any failure of the main winding.

Q6: Why are resistance split-phase inductions motors most popular?
Ans: These motors are most popular due to their low cost. They are used where moderate starting torque is required and where the starting periods are not frequent. They drive fans, pumps, washing machines, small machine tools etc. They have power ranting between 60 watts and 250 watts.

Q7: What is the draw back of the resistance split-phase induction motor?
Ans: The starting winding has a relatively small number of turns of fine wire and its resistance is higher than that of the main winding. Therefore the current density is high and the winding heats up quickly. If the starting period lasts for more than 5 seconds, the winding begins to smoke and may burn out unless the motor is protected by a built-in-thermal relay.

Q8: Why is the starting torque of a resistance split-phase induction motor not high?
Ans: The starting torque is given as, $T_s = K\, I_m\, I_s \sin \Phi$
Where
K = constant whose magnitude depends upon the design of the motor
(i) The angle between Is and Im is small (approximately 25 degree) in a resistance split-phase induction motor, so the starting torque is small.
(ii) Since currents Is and Im are not equal in magnitude, the rotating magnetic field is not uniform and the starting torque produced is small.

Q9: Why is the starting torque of a capacitor start induction motor high?
Ans: The capacitor C in the starting winding is so chosen that Is leads Im by 75 degree. Since the starting torque is directly proportional to Sin Φ, and it is quite high in capacitor-start induction motor.

Q10: Why do we use capacitor-start induction motors in applications requiring high starting torque in preference to repulsion induction motors?
Ans: Capacitors are easily available, cheaper and reliable. Repulsion-induction motors posses a special commutator and brushes that require maintenance. Most manufacturers have stopped making them.

Q11: What is the principle of operation of shaded-pole induction motor?
Ans: A shaded-pole motor is basically a small single-phase squirrel cage motor in which the starting winding is composed of short-circuited copper ring (called shading coil) surrounding one-third of each pole. The effect of the shading coil is to cause a flux to sweep across the pole faces, from unshaded to shaded portion of the pole, producing a weak rotating magnetic field. As a result, the rotor is set in motion due to induction principle.
Q12: Which type of torque is developed in single phase motors?
Ans: Pulsating torque is produced.

Q13: If a single phase motor is driven in any direction by any means, it starts running in that direction. Explain why?
Ans: Actually a pulsating torque has two components which are equal in magnitude and rotate in opposite direction with synchronous speed at unity slip. Now if the motor rotates in any direction, the slip decreases and the torque component in this direction increases than the other component and hence motor runs in that direction.

Q14: What is a fractional H.P. motor?
Ans: A small motor having H.P. less than unit is called fractional H.P. motor.

Q15: Which type of rotor is used in single phase motors?
Ans: Squirrel cage type

Q16: How the starting winding produce rotation in a single phase resistance start induction motor?
Ans: The starting winding is highly resistive and the main winding is inductive. So the phase difference between the two currents becomes nearly 90 degree and hence the motor start as two phase motor.

Q17: How the starting winding is made resistive?
Ans: It consists of only few turns of smaller diameter.

Q18: How the speed of rotation of a split phase induction motor is reversed?
Ans: The terminal connections of the starting windings are reversed with respect to main running windings.

Q19: What will happen if the centrifugal switch fails to open the starting winding?
Ans: Excessive heat will be produced due to high resistance of the starting winding due to which stator temperature will rise and eventually both windings will burn.

Q20: How speed control is made in single phase motors?
Ans: It is usually controlled by applying a variable voltage from tapped transformers, variacs, potentio meters, and tapped reactors.

Q21: Is there any relation between the capacitances of two capacitors used in two value capacitor motor?
Ans: Starting capacitor has about 10 – 15 times high capacity than the value of running capacitor.

Q22: What is size of shaded-pole motor?
Ans: These are usually built in small fractional H.P, not exceed 1/4 H.P.

Q23: Why shaded-pole single phase induction motor does not need any special starting technique like capacitors and auxiliary winding etc.
Ans: Because it is inherently self started motor. The construction of the poles is such that they give a sweep to the magnetic flux and motor starts rotating.

Q24: How can a universal motor be reversed?
Ans: By reversing either the field leads or armature leads but not both.

Q25: What are applications of Stepper motors?
Ans: (i) Paper feed motors in typewriters and printers
(ii) Positioning of print heads
(iii) Pens in XY-plotters
(iv) Recording heads in computer disc drives etc.

Q26: Why do we use capacitor-start induction motors in applications requiring high starting torque in preference to repulsion induction motors?
Ans: Capacitors are easily available, cheaper and reliable. Repulsion-induction motors posses a special commutator and brushes that require maintenance. Most manufacturers have stopped making them.

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Ans: The terminal connections of the starting windings are reversed with respect to main running windings.

SYNCHRONOUS MOTOR QUESTION AND ANSWER

Q1: Why synchronous motor is not self starting?
Synchronous motor is a doubly excited machine i.e two electrical inputs are provided to it. It's stator winding which consists of a 3 phase winding is provided with 3 phase supply and rotor is provided with DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. At a particular instant rotor and stator poles might be of same polarity (N-N or S-S) causing repulsive force on rotor and the very next second it will be N-S causing attractive force. But due to inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Hence it is not self starting.

Q2: What are the methods of starting synchronous motor?

1. Pony motor starting(using ac or dc motor)
2. Starting as squirrel cage Induction motor or using damper winding
3. Starting as slip ring Induction motor or synchronous motor
4. Using dc machine coupled to it.

Q3: What is pony motor starting?
In this method the rotor is made to rotate by some external device called pony motors. Once the rotor attains synchronous speed, the DC excitation to the rotor is switched on. Once synchronism is established the pony motor is decoupled. The synchronous motor continuously runs at synchronous speed.

Q4: Why damper windings are used in synchronous motor? Or How synchronous motor is started as squirrel cage motor?
The damper winding consists of short circuited copper bars embedded in the the face of the rotor poles. When an ac supply is provided to stator of a 3-phase synchronous motor, stator winding produces rotating magnetic field. Due to the damper winding present in the rotor winding of the synchronous motor, emf is induced in damper winding and hence currents starts to flow. Hence torque acts on rotor. Damper windings in synchronous motor will carryout the same task of induction motor rotor windings. Therefore due to damper windings synchronous motor starts as induction motor and continue to accelerate. When the motor attains about 95% of the synchronous speed, the rotor windings is connected to exciter terminals and the rotor is magnetically locked by the rotating magnetic field of stator and it runs as a synchronous motor. Now as the rotor rotates at synchronous speed the relative motion between rotating magnetic field and damper winding is zero. Hence there will be no emf induced in damper winding.

Q5: What is the function of damper winding?
To provide starting torque
To prevent or minimize hunting

What is hunting?
The sudden changes of load on synchronous motor set up oscillations in the rotor. Such oscillation of rotor about its new equilibrium position is called hunting.

Q6: What are the effects of hunting?
Loses synchronism
Develops mechanical stress on rotor shaft
Increase machine losses
Increase temperature of machine

Q7: What is pull in torque?
The torque which is required to pull the motor into synchronism when it is running as induction motor is called pull in torque.

Q8: What is pull out torque?
The maximum torque developed by the motor without pulling out of synchronism is called pull out torque. Its value varies from 1.5 to 3.5 times full load torque.

Q9. What is the effect on speed if the load is increased on a 3 phase synchronous motor?
The speed of operation remains constant from no load to maximum load in the motor operating at constant frequency bus bars.

Q10.Why a synchronous motor is a constant speed motor?
When load increase in synchronous motor the load angle δ also increases but speed remains constant. The further increase in load cause further increase in load angle. When load angle reaches 90 degree electrical then the motor comes out of synchronism. Hence the motor rotates at synchronous speed otherwise it comes out of synchronism.

Q11: What is normal excitation?
The excitation for which power factor of the synchronous motor is lagging and the back emf is equal to supply voltage.

Q12: What is under excitation?
The excitation for which power factor of the synchronous motor is lagging and the back emf is less than supply voltage.

Q13: What is over excitation?
The excitation for which power factor of the synchronous motor is leading and the back emf is greater than supply voltage.

Q14: What is critical excitation?
The excitation for which power factor of the synchronous motor is unity and the back emf is equal to supply voltage.

Q15. What is synchronous condenser?
An over-excited synchronous motor under no load , used for the improvement of power factor is called as synchronous condenser because, like a capacitor it takes a leading current.

Q16. Distinguish between synchronous phase modifier and synchronous condenser
A synchronous motor used to change the power factor or power factor in the supply lines is called synchronous phase modifier.
A synchronous motor operated at no load with over excitation condition to draw large leading reactive current and power is called a synchronous condenser.

Q17. How the synchronous motor can be used as s synchronous condenser?
Synchronous motor is operated on over excitation so as to draw leading reactive current and power from the supply lines. This compensates the lagging current and power requirement of the load making the system power factor to become unity. The motor does the job of capacitors and hence called as synchronous condenser.

Q18. What are V and inverted V curves of synchronous motor ?
The variation of magnitude of line current with respect to the field current is called V curve .

The variation of power factor with respect to the field current is called inverted V curve.

Q19 Write the applications of synchronous motor.

a. Used for power factor improvement in sub-stations and in industries.
b. As synchronous condenser
c. Used for constant speed applications

Q20. State the characteristic features of synchronous motor.

a. the motor is not inherently self starting
b. The speed of operation is always in synchronous with the supply frequency irrespective of load conditions
c. The motor is capable of operating at any power factor.

Q21. In what way synchronous motor is different from other motors?
All dc and ac motors work on the same principle. Synchronous motor operates due to magnetic locking taking place between stator and rotor magnetic fields.

Q22 A synchronous motor starts as usual but fails to develop its full torque. What could it be due to?

a. Exciter voltage may be too low.
b. Field spool may be reversed
c. There may be either open-circuit or short-circuit in the field.

Q23 What could be the reasons if a 3-phase synchronous motor fails to start?
It is usually due to the following reasons

a. Voltage may be too low.
b. Too much starting load.
c. Open circuit in one phase or short circuit.
d. Field excitation may be excessive

Unit –V

SPECIAL MACHINES

5.1 PERMANENT MAGNET SYNCHRONOUS MOTOR

INTRODUCTION

A permanent magnet synchronous motor is also called as brushless permanent magnet sine wave motor. A sine wave motor has a

1. Sinusoidal or quasi-sinusoidal distribution of magnetic flux in the air gap.

2. Sinusoidal or quasi-sinusoidal current wave forms.

3. Quasi-sinusoidal distribution of stator conductors (i.e.) short-pitched and distributed or concentric stator windings.

The quasi sinusoidal distribution of magnetic flux around the air gap is achieved by tapering the magnet thickness at the pole edges and by using a shorter magnet pole arc typically 120º. The quasi sinusoidal current wave forms are achieved through the use of PWM inverters and this may be current regulated to produce the best possible approximation to a pure sine wave. The use of short pitched distributed or concentric winding is exactly the same as in ac motors.

5.1.1 CONSTRUCTION AND PRINCIPLE OF OPERATION

Permanent magnet synchronous machines generally have same operating and performance characteristics as synchronous machines. A permanent magnet machine can have a configuration almost identical to that of the conventional synchronous machines with absence of slip rings and a field winding.

Construction

Fig. 5.1 shows a cross section of simple permanent magnet synchronous machines. It consists of the stationary member of the machine called stator. Stator laminations for axial air gap machines are often formed by winding continuous strips of soft steel. Various parts of the laminations are the teeth slots which contain the armature windings. Yoke completes the magnetic path. Lamination thickness depends upon the frequency of the armature source voltage and cost. Armature windings are generally double layer (two coil side per slot) and lap wound. Individual coils are connected together to form phasor groups. Phasor groups are connected together in series/parallel combinations to form star, delta, two phase (or) single windings.

AC windings are generally short pitched to reduce harmonic voltage generated in the windings. Coils, phase groups and phases must be insulated from each other in the end-turn regions and the required dielectric strength of the insulation will depend upon the voltage ratings of the machines.

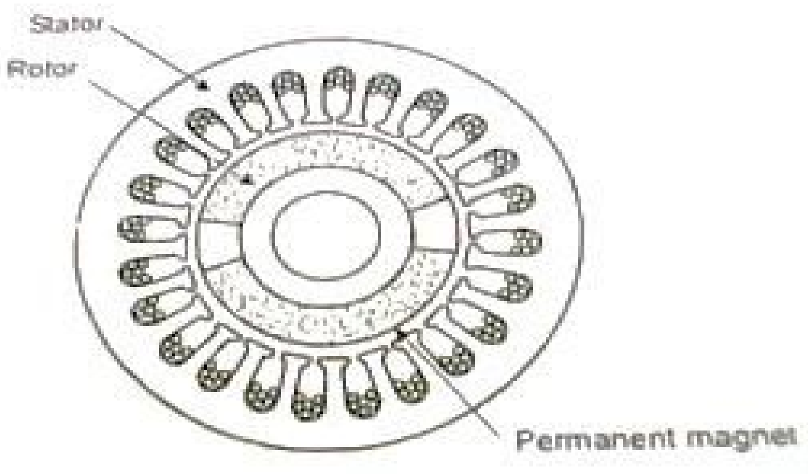


Fig. 5.1 structure of the stator and rotor

In a permanent magnet machines the air gap serves an role in that its length largely determines the operating point of the permanent magnet in the no-load operating condition of the machines .Also longer air gaps reduce machines wind age losses.

The permanent magnets form the poles equivalent to the wound field pole of conventional synchronous machines. Permanent magnet poles are inherently ―salient‖ and there is no equivalent to the cylindrical rotor pole configurations used in many convectional synchronous machines.

Many permanent magnet synchronous machines may be cylindrical or ―smooth rotor‖ physically but electrically the magnet is still equivalent to a salient pole structure. Some of the PMSM rotors have the permanent magnets directly facing the air gap as in fig. 5.2

Rotor yoke is the magnetic portion of the rotor to provide a return path for the permanent magnets and also provide structural support. The yoke is often a part of the pole structure

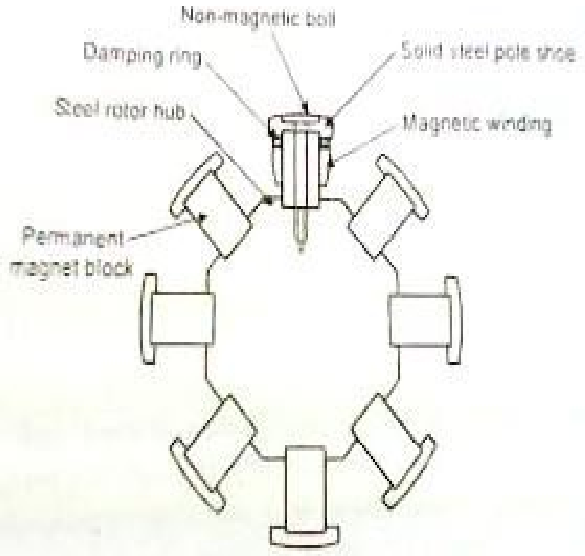


Fig. 5.2 PMSM rotor

Damper winding is the typical cage arrangement of conducting bars, similar to induction motor rotor bars and to damper bars used on many other types of synchronous machines. It is not essential for all permanent magnet synchronous machines applications, but is found in most machines used in power applications.

The main purpose is to dampen the oscillations about synchronous speed, but the bars are also used to start synchronous motors in many applications. The design and assembly of damper bars in permanent magnet machines are similar to the other types of synchronous machines.

Synchronous machines are classified according to their rotor configuration. There are **four general types of rotors in permanent magnet synchronous machines**. They are

1. **Peripheral rotor**
2. **Interior rotor**
3. **Claw pole or lundell rotor.**
4. **Transverse rotor.**

Peripheral rotor

The permanent magnets are located on the rotor periphery and permanent magnet flux is radial.

Interior rotor

The permanent magnets are located on the interior of the rotor and flux is generally radial.

Claw pole or Lund ell

The permanent magnets are generally disc shaped and magnetized axially. Long soft iron extensions emanate axially from periphery of the discs like claws or Lund ell poles. There is set of equally spaced claws on each disc which alternate with each other forming alternate north and south poles.

Transverse rotor

In this type the permanent magnets are generally between soft iron poles and the permanent magnet flux is circumferential. In this soft iron poles at as damper bars. Magnetically this configuration is similar to a reluctance machine rotor, since the permeability of the permanent magnet is very low, almost the same as that of a non-magnetic material. Therefore, reluctance torque as well as torque resulting from the permanent magnet flux is developed. Thus BLPM sine waves (SNW) motor is construction wise the same as that of BLPM square wave (SQW) motor. The armature winding and the shape of the permanent magnet are so designed that flux density distribution of the air gap is sinusoidal(i.e.) .The magnetic field setup by the permanent magnet in the air gap is sinusoidal

Construction and Performance

Such motors have a cage rotor having rare-earth permanent magnets instead of a wound field. Such a motor starts like an induction motor when fed from a fixed-frequency supply. A typical 2-pole 4-pole surface-mounted versions of the rotor are shown in Fig. 5.3. Since no d.c. supply is needed for exciting the rotor, it can be made more robust and reliable. These motors have outputs ranging from about 100 W upto 100 kW. The maximum synchronous torque is designed to be around 150 per cent of the rated torque. If loaded beyond this point, the motor loses synchronism and will run either as an induction motor or stall.

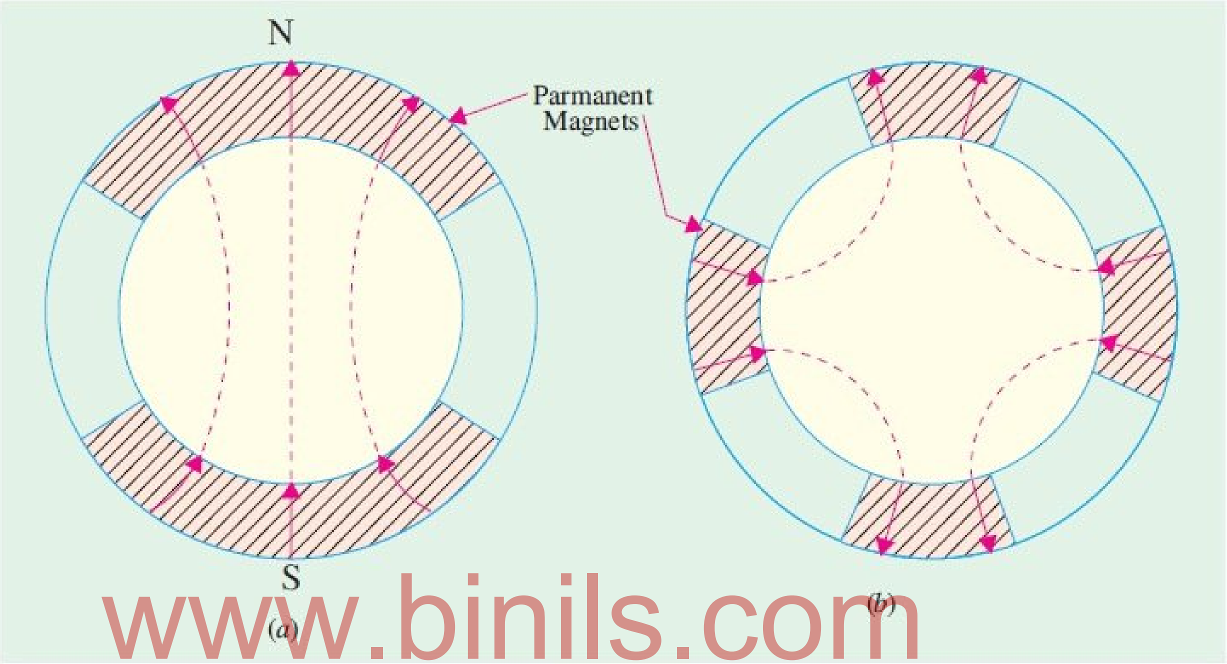


Fig 5.3

These motors are usually designed for direct-on-line (DOL) starting. The efficiency and power factor of the permanent-magnet excited synchronous motors are each 5 to 10 points better than their reluctance motor counterparts

Advantages

Since there are no brushes or slip-rings, there is no sparking. Also, brush maintenance is eliminated. Such motors can pull into synchronism with inertia loads of many times their rotor inertia.

Applications

These motors are used where precise speed must be maintained to ensure a consistent product. With a constant load, the motor maintains a constant speed. Hence, these motors are used for synthetic-fibre drawing where constant speeds are absolutely essential.

5.2 Synchros

It is a general name for self-synchronizing machines which, when electrically energized and electrically interconnected, exert torques which cause two mechanically independent shafts either to run in synchronism or to make the rotor of one unit follow the rotor position of the other. They are also known by the trade names of selsyns and autosyns. Synchros, in fact, are small cylindrical motors varying in diameter from 1.5 cm to 10 cm depending on their power output. They are low-torque devices and are widely used in control systems for transmitting shaft position information or for making two or more shafts to run in synchronism. If a large device like a robot arm is to be positioned, synchros will not work. Usually, a servomotor is needed for a higher torque.

5.2.1 Types of Synchros

There are many types of synchros but the four basic types used for position and error-voltage applications are as under :

(i) Control Transmitter (denoted by CX) – earlier called generator

(ii) Control Receiver (CR) – earlier called motor

(iii) Control-Transformer (CT) and

(iv) Control Differential (CD).

It may be further subdivided into control differential transmitter (CDX) and control differential receiver (CDR).

All of these synchros are single-phase units except the control differential which is of three-phase construction.

Synchros

Constructional Features

(a) Control Transmitter

Its constructional details are shown in Fig. 5.4 (a). It has a three-phase stator winding similar to that of a three-phase synchronous generator. The rotor is of the projecting-pole type using dumbbell construction and has a single-phase winding. When a single-phase ac voltage is applied to the rotor through a pair of slip rings, it produces an alternating flux field along the axes of the rotor. This alternating flux induces three unbalanced single phase/voltage in the three stator windings by transformer action. If the rotor is aligned with the axis of the stator winding 2, flux linkage of this stator winding is maximum and this rotor position is defined as the electrical zero. In Fig. 5.4(b), the rotor axis is displaced from the electrical zero by an angle displaced 120º apart.

(b) Control Receiver (CR)

Its construction is essentially the same as that of the control transmitter shown in Fig. 5.4(a). It has three stator windings and a single-phase salient-pole rotor. However, unlike a CX, a CR has a mechanical viscous damper on the shaft which permits CR rotor to respond without overshooting its mark. In normal use, both the rotor and stator windings are excited with single-phase currents. When the field of the rotor conductors interacts with the field of the stator conductors, a torque is developed which produces rotation.

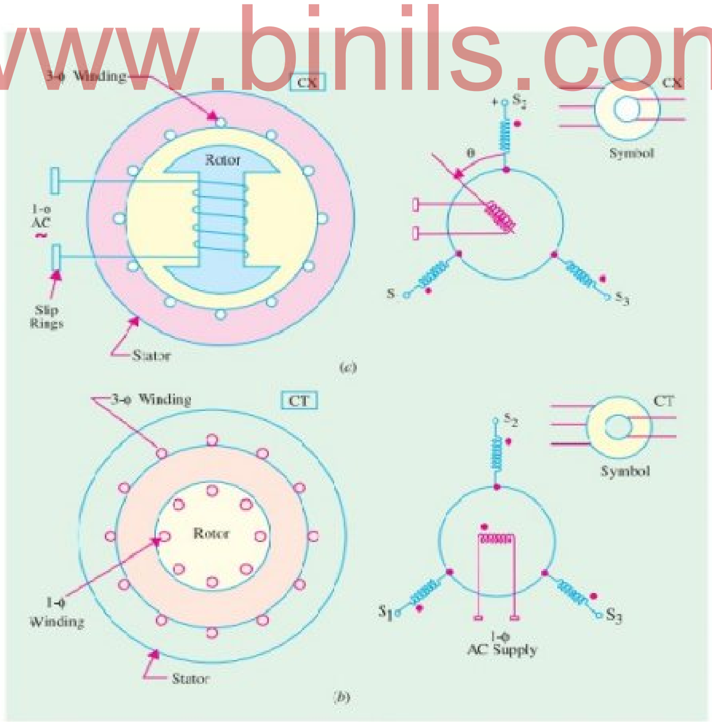


Fig 5.4

(c) Control Transformer (CT)

As shown in Fig. 5.4 (b) its stator has a three-phase winding whereas the cylindrical rotor has a single-phase winding. In this case, the electrical zero is defined as that position of the rotor that makes the flux linkage with winding 2 of the stator zero. This rotor position has been shown in Fig. 5.4 (b) and is different from that of a control transmitter.

(d) Control Differential (CD)

The differential synchro has a balanced three-phase distributed winding in both the stator and the rotor. Moreover, it has a cylindrical rotor as shown in Fig.5.5 (b). Although three-phase windings are involved, it must be kept in mind that these units deal solely with single-phase voltages. The three winding voltages are not polyphase voltages. Normally, the three-phase voltages are identical in magnitude but are separated in phase by 120º. In synchros, these voltages are in phase but differ in magnitude because of their physical orientation

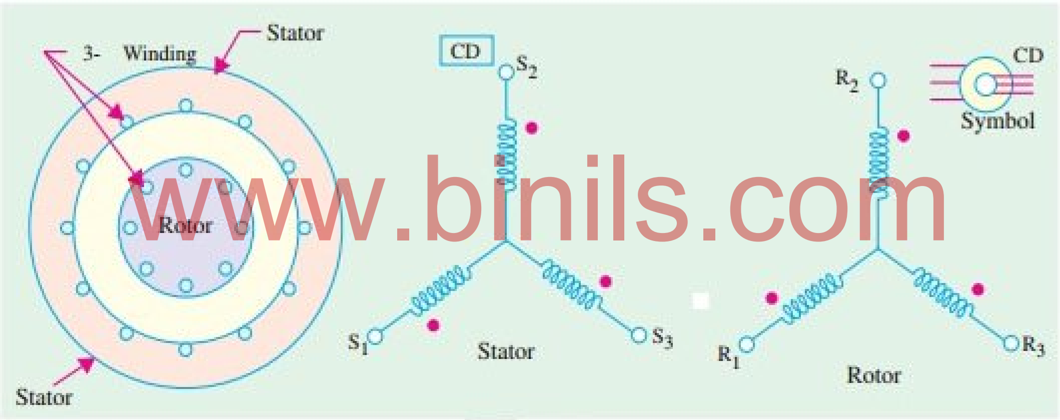


Fig 5.5

(e) Voltage Relations

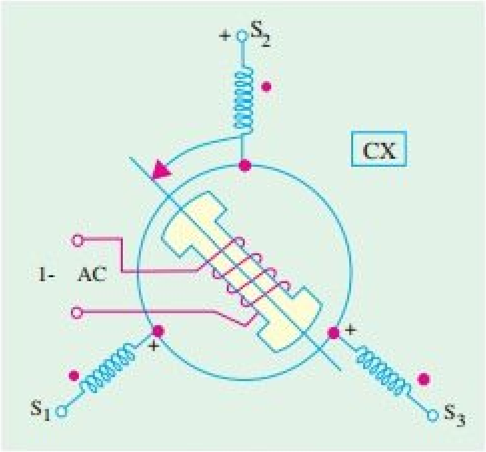


Fig 5.6

Consider the control transmitter shown in Fig. 5.6. Suppose that its rotor winding is excited by a single-phase sinusoidal ac voltage of rms value Er and that rotor is held fast in its displaced position from the electrical zero. If K = stator turns / rotor turns, the rms voltage induced in the stator winding is E = KEr

. However, if we assume K = 1, then E = Er

. The rms value of the induced emf in stator winding 2 when the rotor displacement is 'a' is given by

E2s = Er cos α.

Since the axis of the stator winding 1 is located 120º ahead of the axis of winding 2, the rms value of the induced emf in this winding is

E1s = Er cos (α – 120º).

In the same way since winding 3 is located behind the axis of winding 2 by 120º, the expression for the induced emf in winding 3 becomes E3s = Er cos (α + 120º).

We can also find the values of terminal induced voltages as

$$
\begin{aligned}
E_{12} &= E_{1s} + E_{s2} = E_{1s} - E_{2s} \\
&= E_r \cos\alpha \cos 120^\circ + E_r \sin\alpha \sin 120^\circ - E_r \cos\alpha \\
&= E_r \left(-\frac{3}{2} \cos\alpha + \frac{\sqrt{3}}{2} \sin\alpha \right) \\
&= \sqrt{3}\ E_r \left(-\frac{1}{2} \cos\alpha + \frac{1}{2} \sin\alpha \right) \\
&= \sqrt{3}\ E_r \cos(\alpha - 150^\circ) \\
E_{23} &= E_{2s} + E_{s3} = E_{2s} - E_{3s} \\
&= E_r \left(\frac{3}{2} \cos\alpha + \frac{\sqrt{3}}{2} \sin\alpha \right) = \sqrt{3}\ E_r \left(\frac{\sqrt{3}}{2} \cos\alpha + \frac{1}{2} \sin\alpha \right) = \sqrt{3}\ E_r \cos(\alpha - 30^\circ) \\
E_{31} &= E_{3s} + E_{s1} = E_{3s} - E_{1s} \\
&= E_r \cos(\alpha + 120^\circ) - E_r \cos(\alpha - 120^\circ) \\
&= -\sqrt{3}\ E_r \sin\alpha = \sqrt{3}\ E_r \cos(\alpha + 90^\circ)
\end{aligned}
$$

5.2.2 Applications of Synchros

The synchros are extensively used in servomechanism for torque transmission, error detection and for adding and subtracting rotary angles. We will consider these applications one by one.

(a) Torque Transmission

Synchros are used to transmit torque over a long distance without the use of a rigid mechanical connection. Fig.5.7 represents an arrangement for maintaining alignment of two distantly-located shafts. The arrangement requires a control transmitter (CX) and a control receiver (CR) which acts as a torque receiver. As CX is rotated by an angle α, CR also rotates through the same angle α. As shown, the stator windings of the two synchros are connected together and their rotors are connected to the same single-phase ac supply.

Working.

Let us suppose that CX rotor is displaced by an angle α and switch S W1 is closed to energize the rotor winding. The rotor winding flux will induce an unbalanced set of three single-phase voltages (in time phase with the rotor voltage) in the CX stator phase windings which will circulate currents in the CR stator windings. These currents produce the CR stator flux field whose axis is fixed by the angle α. If the CR rotor winding is now energized by closing switch S W2, its flux field will interact with the flux field of the stator winding and thereby produce a torque. This torque will rotate the freely-moving CR rotor to a position which exactly corresponds with the CT rotor i.e. it will be displaced by the same angle α as shown in Fig.5.7. It should be noted that if the two rotors are in the same relative positions, the stator voltages in the two synchros will be exactly equal and opposite. Hence, there will be no current flow in the two stator windings and so no torque will be produced and the system will achieve equilibrium. If now, the transmitter rotor angle changes to a new value, then new set of voltages would be induced in the transmitter stator windings which will again drive currents through the receiver stator windings. Hence, necessary torque will be produced which will turn the CR rotor through an angle corresponding to that of the CT rotor. That is why the transmitter rotor is called the master and the receiver rotor as the slave, because it follows its master. It is worth noting that this master-slave relationship is reversible because when the receiver rotor is displaced through a certain angle, it causes the transmitter rotor to turn through the same angle.

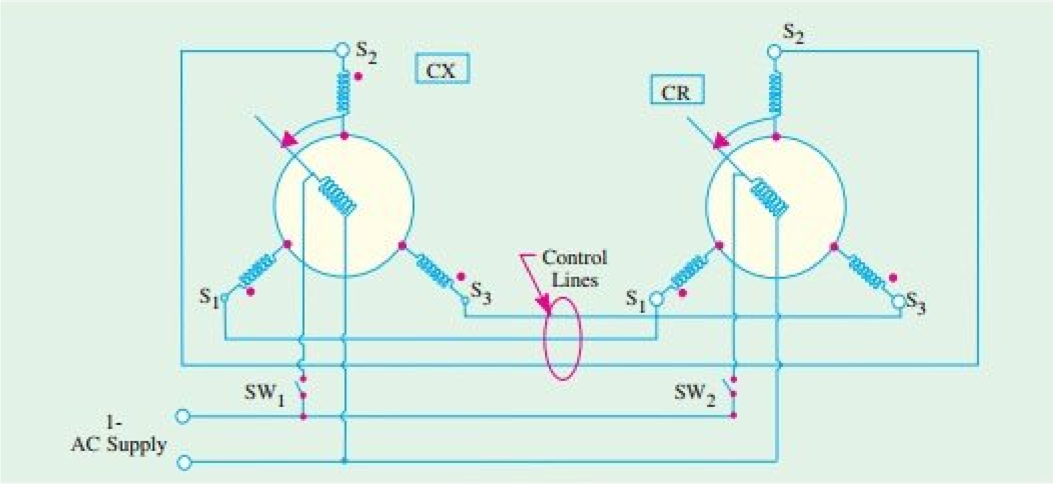


Fig 5.7

(b) Error Detection

Synchros are also used for error detection in a servo control system. In this case, a command in the form of a mechanical displacement of the CX rotor is converted to an electrical voltage which appears at the CT rotor winding terminals which can be further amplified by an amplifier.

For this purpose, we require a CX synchro and a CT synchro as shown in Fig. 5.8. Only the CX rotor is energized from the single-phase ac voltage supply which produces an alternating air-gap flux field. This time-varying flux field induces voltages in the stator windings whose values for $\alpha = 30^\circ$ are as indicated in the Fig.5.8. The CX stator voltages supply magnetizing currents in the CT stator

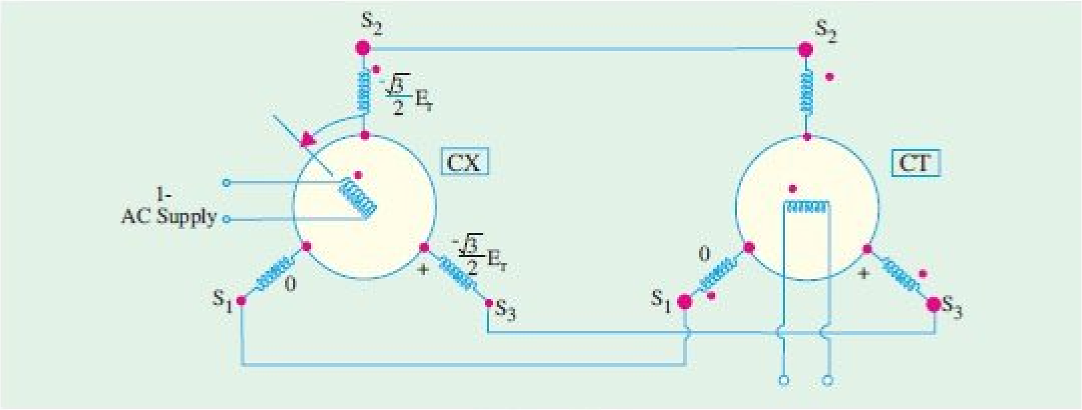


Fig 5.8

windings which, in turn, create an alternating flux field in their own air-gap. The values of the CT stator phase currents are such that the air-gap flux produced by them induces voltages that are equal and opposite to those existing in the CX stator. Hence, the direction of the resultant flux produced by the CX stator phase currents is forced to take a position which is exactly identical to that of the rotor axis of the CT.

If the CT rotor is assumed to be held fast in its electrical zero position as shown in Fig.5.8, then the rms voltage induced in the rotor is given by E = Emax sin α, where Emax is the maximum voltage induced by the CT air-gap flux when coupling with the rotor windings is maximum and α is the displacement angle of the CT rotor.

In general, the value of the rms voltage induced in the CT rotor winding when the displacement of the CX rotor is αx and that of the CT rotor is αT is given by

$$E = E_{max} \sin(\alpha x - \alpha T)$$

Ac servo motors

5.3 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.

5.3.1 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.

AC Servo Motor

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.

Synchronous-type AC servo motor

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.

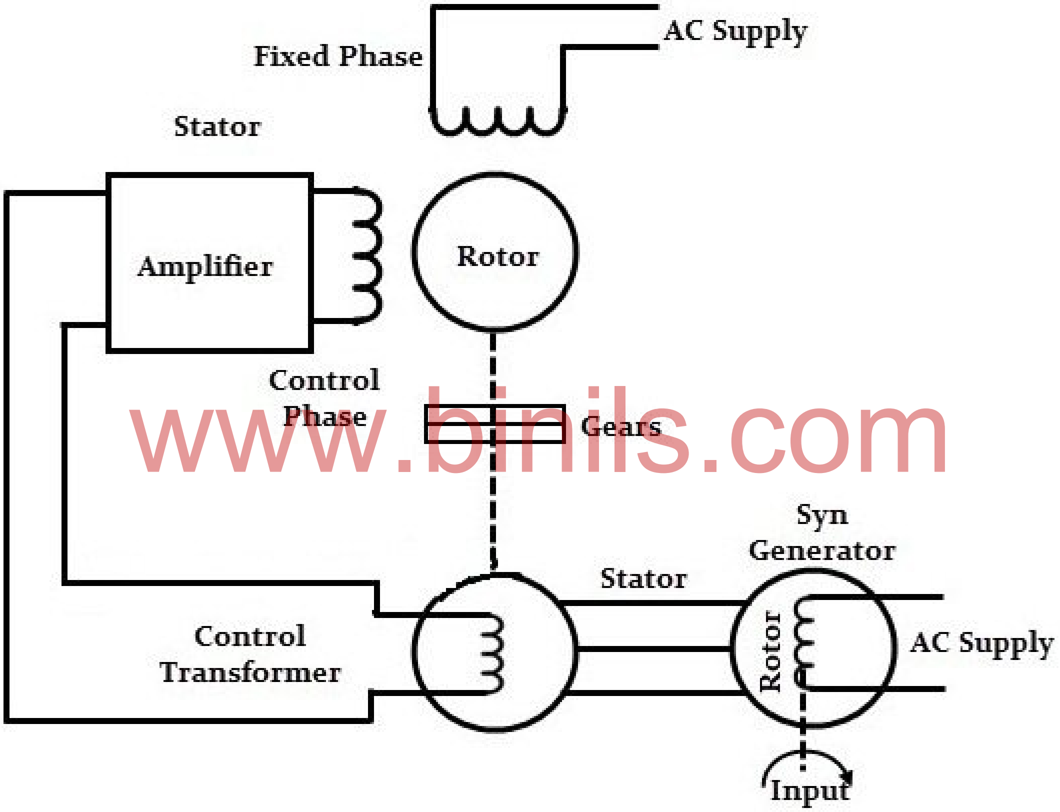
The induction-type AC servo motor structure is identical with that of general motor. In this motor, stator consists of stator core, armature winding and lead wire, while rotor consists of shaft and the rotor core that built with a conductor as similar to squirrel cage rotor.

INDUCTION-TYPE AC SERVO MOTOR

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.



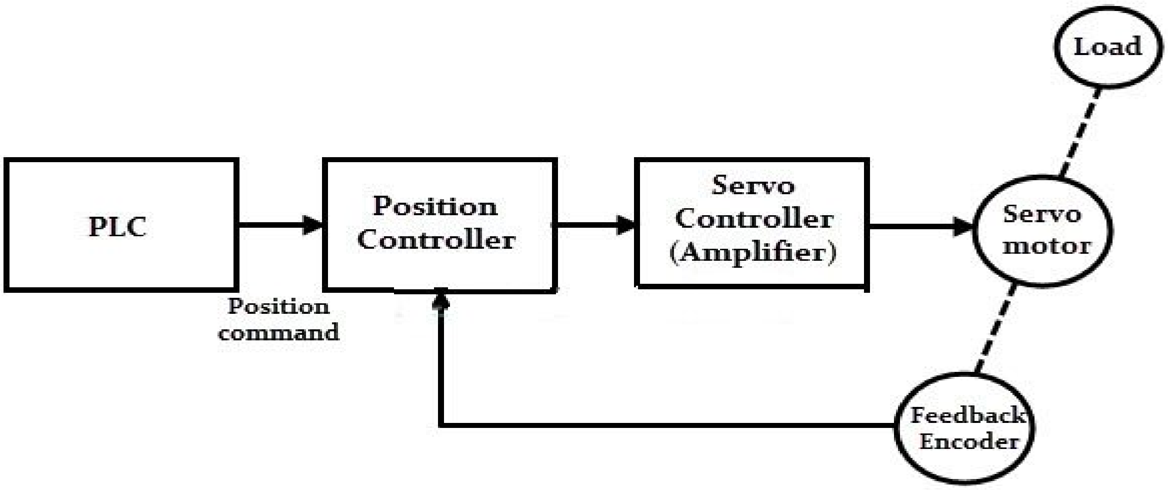
The three stator terminals of a synchro generator are connected correspondingly to the terminals of control transformer. The angular position of the two-phase motor is transmitted to the rotor of control transformer through gear train arrangement and it represents the control condition alpha.

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.



5.4 Two-phase AC Servomotor

Such motors normally run on a frequency of 60 Hz or 400 Hz (for airborne systems). The stator has two distributed windings which are displaced from each other by 90º (electrical). The main winding (also called the reference or fixed phase) is supplied from a constant voltage source, V m ∠ 0º (Fig. 5.9). The other winding (also called the control phase) is supplied with a variable voltage of the same frequency as the reference phase but is phase-displaced by 90º (electrical). The control phase voltage is controlled by an electronic controller. The speed and torque of the rotor are controlled by the phase difference between the main and control windings. Reversing the phase difference from leading to lagging (or vice-versa) reverses the motor direction.

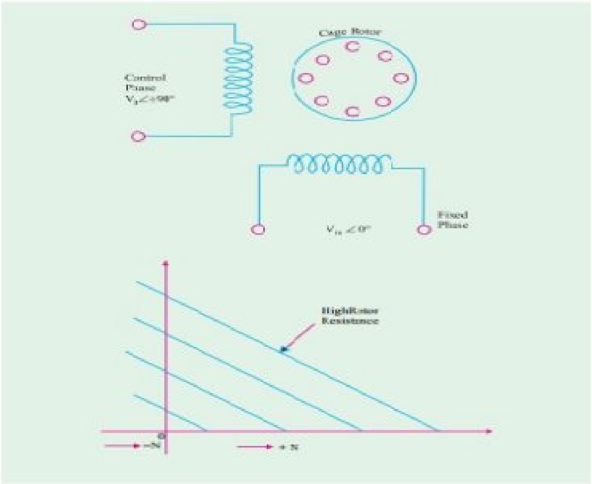


Fig 5.9

Since the rotor bars have high resistance, the torque-speed characteristics for various armature voltages are almost linear over a wide speed range particularly near the zero speed. The motor operation can be controlled by varying the voltage of the main phase while keeping that of the reference phase constant.

5.5 Three-phase AC Servomotors

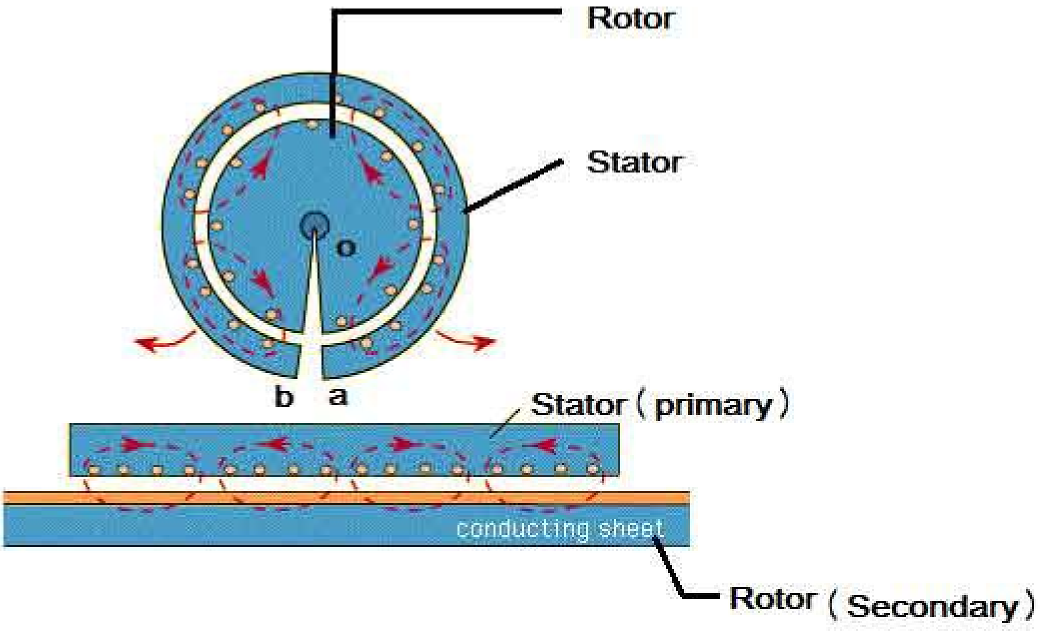
A great deal of research has been to modify a three-phase squirrel-cage induction motor for use in high power servo systems. Normally, such a motor is a highly non-linear coupled-circuit device. Recently, this machine has been operated successfully as a linear decoupled machine (like a d.c. machine) by using a control method called vector control or field oriented control. In this method, the currents fed to the machine are controlled in such a way that its torque and flux become decoupled as in a dc machine. This results in a high speed and a high torque response.

5.6 Linear Induction Motor

Linear Induction motor abbreviated as **LIM**, is basically a special purpose motor that is in use to achieve rectilinear motion rather than rotational motion as in the case of conventional motors. This is quite an engineering marvel, to convert a general motor for a special purpose with more or less similar working principle, thus enhancing its versatility of operation. Let us first look into the construction of a LIM.

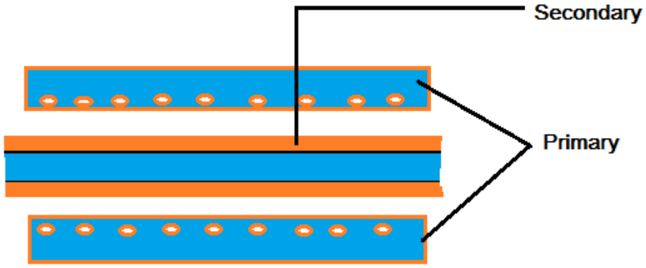
5.6.1 Construction of a Linear Induction Motor

Construction wise a LIM is similar to three phase induction motor in more ways than one as it has been depicted in the figure below.



In LIM stator and rotor are called primary and secondary respectively. If the stator of the poly phase induction motor shown in the figure is cut along the section aob and laid on a flat surface, then it forms the primary of the LIM housing the field system, and consequently the rotor forms the secondary consisting of flat aluminum conductors with ferromagnetic core for effective flux linkage.

There is another variant of LIM also being used for increasing efficiency known as the double sided linear induction motor or DLIM, as shown in the figure below.



Dual Linear induction motor（DLIM）

Which has a primary winding on either side of the secondary, for more effective utilization of the induced flux from both sides.

5.6.2 Working of a Linear Induction Motor

When the primary of an LIM is excited by a balanced three phase power supply, a traveling flux is induced in the primary instead of rotating 3 φ flux, which will travel along the entire length of the primary. Electric current is induced into the aluminum conductors or the secondary due to the relative motion between the traveling flux and the conductors. This induced current interacts with the traveling flux wave to produce linear force or thrust F. If the secondary is fixed and the primary is free to move, the force will move the primary in the direction of the force, resulting in the required rectilinear motion. When supply is given, the synchronous speed of the field is given by the equation:

$$n_s = \frac{2f_s}{p}$$

Where, f_s is supply frequency in Hz, and p = number of poles, n_s is the synchronous speed of the rotation of magnetic field in revolutions per second.

The developed field will results in a linear traveling field, the velocity of which is given by the equation,

$$V_s = 2tf_s \ m/sec$$

where, v_s is velocity of the linear traveling field, and t is the pole pitch. For a slip of s, the speed of the LIM is given by

$$V = (1 - s)V_s$$

5.6.3 Application of Linear Induction Motor

A linear induction motor is not that widespread compared to a conventional motor, taking its economic aspects and versatility of usage into consideration. But there are quite a few instances where the LIM is indeed necessary for some specialized operations.

Few of the applications of a LIM have been listed below.

1. Automatic sliding doors in electric trains.
2. Mechanical handling equipment, such as propulsion of a train of tubs along a certain route.
3. Metallic conveyor belts.
4. Pumping of liquid metal, material handling in cranes, etc.

B. SPECIAL DC MACHINES

5.7 Permanent Magnet D.C. Motor

A permanent-magnet d.c. (PMDC) motor is similar to an ordinary d.c. shunt motor except that its field is provided by permanent magnets instead of salient-pole wound-field structure. Fig. 5.7.1 (a) shows 2-pole PMDC motor whereas Fig. 5.7.1 (b) shows a 4-pole wound-field d.c. motor for comparison purposes.

Permanent magnet DC - motor

5.7.1 Construction

As shown in Fig.5.10 , the permanent magnets of the PMDC motor are supported by a cylindrical steel stator which also serves as a return path for the magnetic flux. The rotor (i.e. armature) has winding slots, commutator segments and brushes as in conventional d.c. machines.

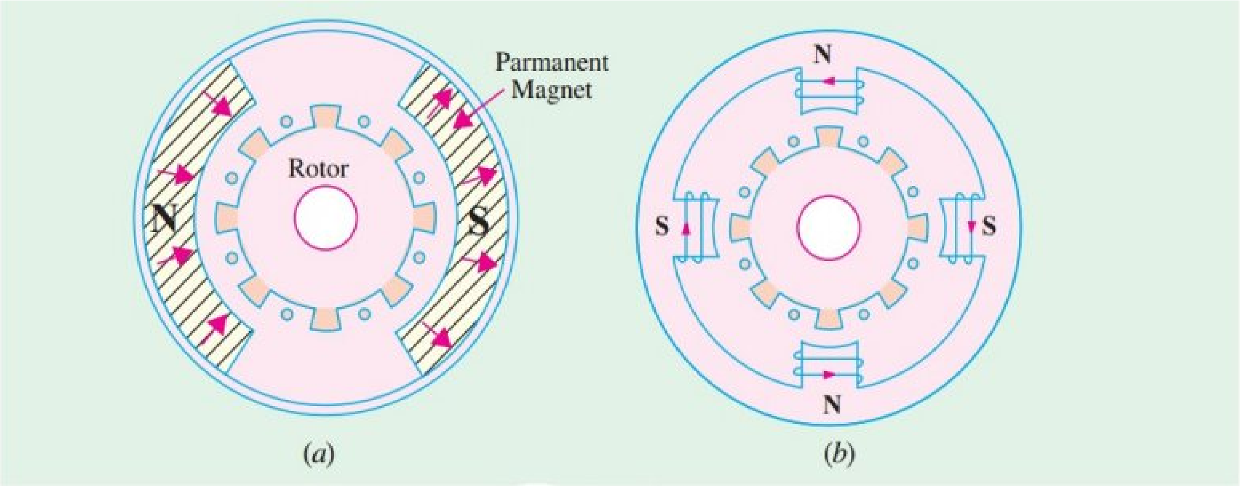


Fig 5.10

There are three types of permanent magnets used for such motors. The materials used have residual flux density and high coercivity.

(i) Alnico magnets – They are used in motors having ratings in the range of 1 kW to 150 kW.

(ii) Ceramic (ferrite) magnets – They are much economical in fractional kilowatt motors.

(iii) Rare-earth magnets – Made of samarium cobalt and neodymium iron cobalt which have the highest energy product. Such magnetic materials are costly but are best economic choice for small as well as large motors.

Another form of the stator construction is the one in which permanent-magnet material is cast in the form of a continuous ring instead of in two pieces as shown in Fig. 5.10 (a).

5.7.2 Working

Most of these motors usually run on 6 V, 12 V or 24 V dc supply obtained either from batteries or rectified alternating current. In such motors, torque is produced by interaction between the axial current-carrying rotor conductors and the magnetic flux produced by the permanent magnets.

5.7.3 Performance

Fig. 5.11 shows some typical performance curves for such a motor. Its speed-torque curve is a straight line which makes this motor ideal for a servomotor. Moreover, input current increases linearly with load torque. The efficiency of such motors is higher as compared to wound-field dc motors because, in their case, there is no field Cu loss.

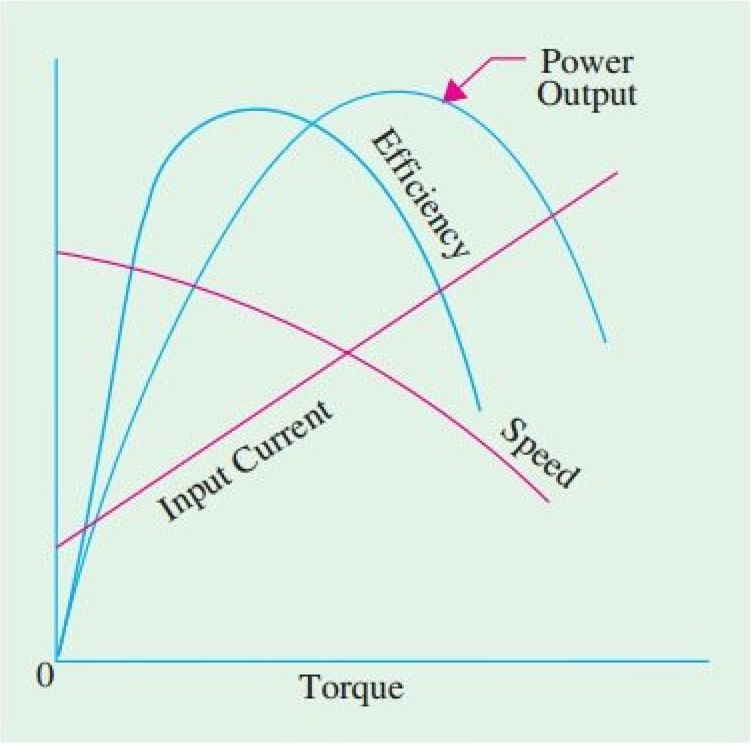


Fig 5.11

Speed Control

Since flux remains constant, speed of a PMDC motor cannot be controlled by using Flux Control Method (fig 5.11). The only way to control its speed is to vary the armature voltage with the help of an armature rheostat (fig 5.11) or electronically by using x-choppers. Consequently, such motors are found in systems where speed control below base speed only is required.

5.7.4 Advantages

(i) In very small ratings, use of permanent-magnet excitation results in lower manufacturing cost.

(ii) In many cases a PMDC motor is smaller in size than a wound-field d.c. motor of equal power rating.

iii) Since field excitation current is not required, the efficiency of these motors is generally higher than that of the wound-field motors.

(iv) Low-voltage PMDC motors produce less air noise.

(v) When designed for low-voltage (12 V or less) these motors produced very little radio and TV interference

5.7.5 Disadvantages

(i) Since their magnetic field is active at all times even when motor is not being used, these motors are made totally enclosed to prevent their magnets from collecting magnetic junk from neighbourhood. Hence, as compared to wound-field motors, their temperature tends to be higher. However, it may not be much of a disadvantage in situations where motor is used for short intervals.

(ii) A more serious disadvantage is that the permanent magnets can be demagnetized by armature reaction mmf causing the motor to become inoperative. Demagnetization can result from (a) improper design (b) excessive armature current caused by a fault or transient or improper connection in the armature circuit (c) improper brush shift and (d) temperature effects.

5.7.6 Applications

(i) Small, 12-V PMDC motors are used for driving automobile heater and air conditioner blowers, windshield wipers, windows, fans and radio antennas etc. They are also used for electric fuel pumps, marine engine starters, wheelchairs and cordless power tools.

(ii) Toy industry uses millions of such motors which are also used in other appliances such as the toothbrush, food mixer, ice crusher, portable vacuum cleaner and shoe polisher and also in portable electric tools such as drills, saber saws and hedge trimmers etc.

5.8 What are Servo Motors?

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. Then how do servo motors work?

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.

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.

5.8.1 DC Servo Motors

A DC servo motor consists of a small DC motor, feedback potentiometer, gearbox, motor drive electronic circuit and electronic feedback control loop. It is more or less similar to the normal DC motor.

The stator of the motor consists of a cylindrical frame and the magnet is attached to the inside of the frame.

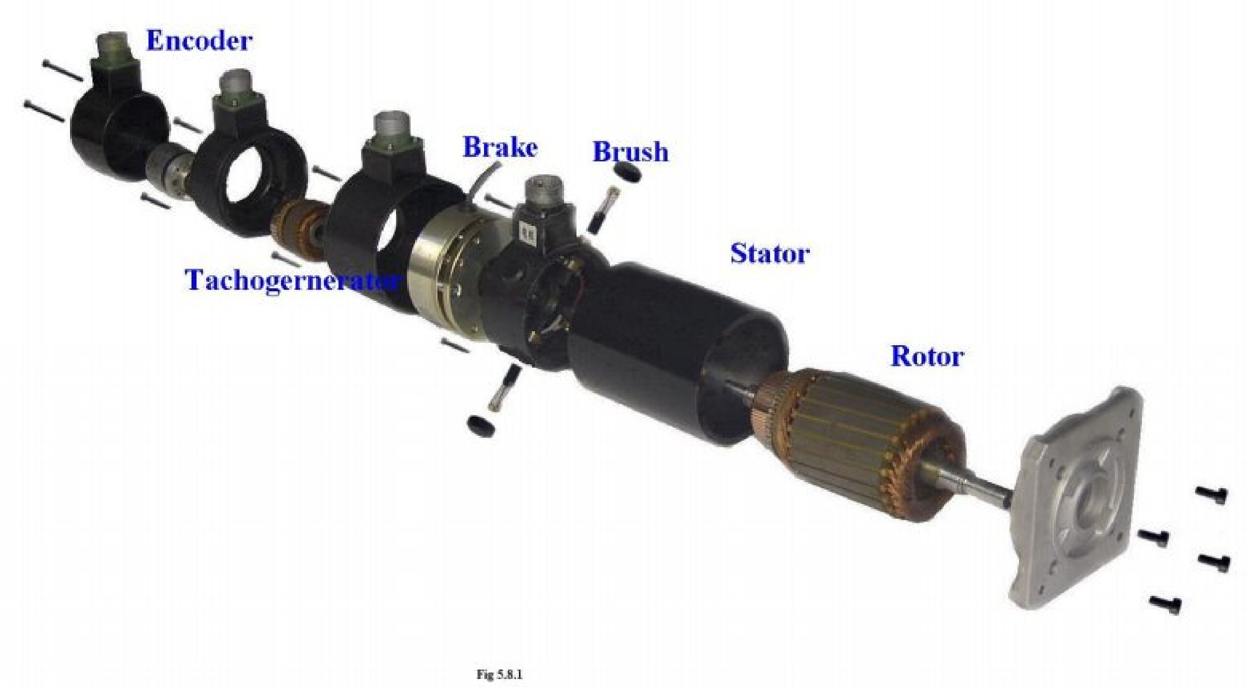


Fig 5.8.1

DC SERVO MOTOR

The rotor consists of brush and shaft. A commutator and a rotor metal supporting frame are attached to the outside of the shaft and the armature winding is coiled in the rotor metal supporting frame.

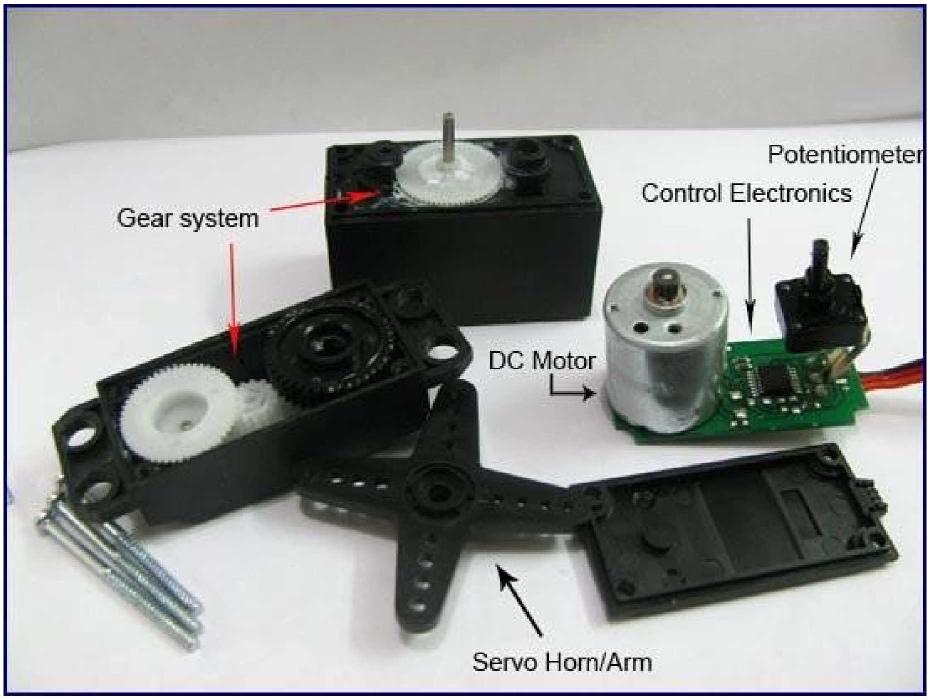
A brush is built with an armature coil that supplies the current to the commutator. At the back of the shaft, a detector is built into the rotor in order to detect the rotation speed.

With this construction, it is simple to design a controller using simple circuitry because the torque is proportional to the amount of current flow through the armature.

And also the instantaneous polarity of the control voltage decides the direction of torque developed by the motor. Types of DC servo motors include series motors, shunt control motor, split series motor, and permanent magnet shunt motor.

Working Principle of DC Servo Motor

A DC servo motor is an assembly of four major components, namely a DC motor, a position sensing device, a gear assembly, and a control circuit. The below figure shows the parts that consisting in RC servo motors in which small DC motor is employed for driving the loads at precise speed and position.



Internal diagram

A DC reference voltage is set to the value corresponding to the desired output. This voltage can be applied by using another potentiometer, control pulse width to voltage converter, or through timers depending on the control circuitry.

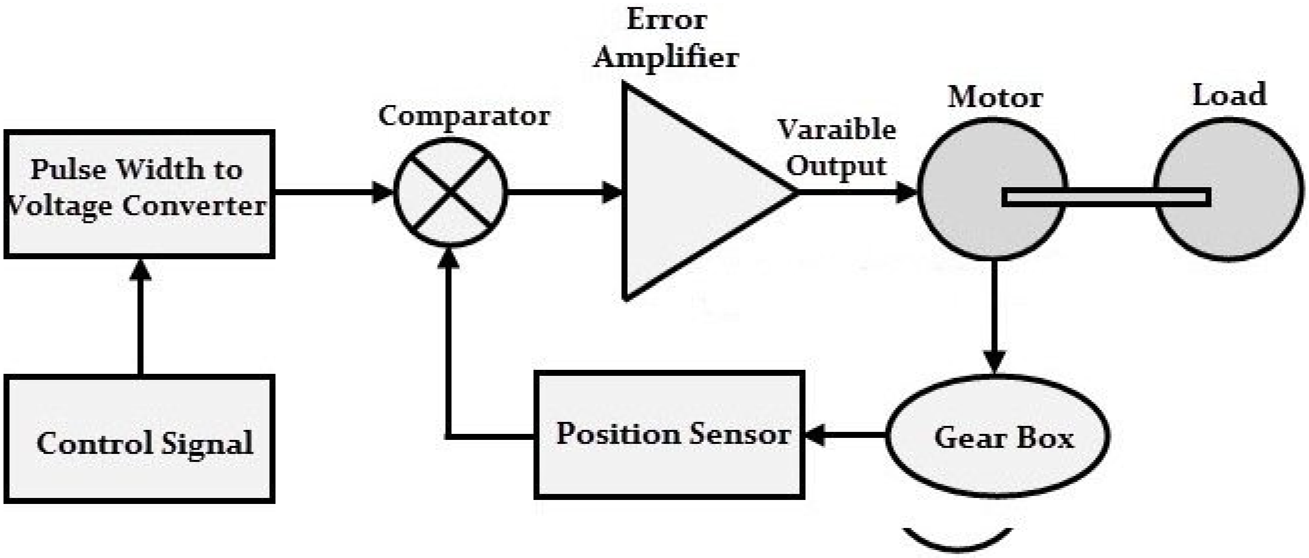
The dial on the potentiometer produces a corresponding voltage which is then applied as one of the inputs to error amplifier.

In some circuits, a control pulse is used to produce DC reference voltage corresponding to desired position or speed of the motor and it is applied to a pulse width to voltage converter.

In this converter, the capacitor starts charging at a constant rate when the pulse high. Then the charge on the capacitor is fed to the buffer amplifier when the pulse is low and this charge is further applied to the error amplifier.

So the length of the pulse decides the voltage applied at the error amplifier as a desired voltage to produce the desired speed or position.

In digital control, microprocessor or microcontroller are used for generating the PWM pluses in terms of duty cycles to produce more accurate control signals.



The feedback signal corresponding to the present position of the load is obtained by using a position sensor. This sensor is normally a potentiometer that produces the voltage corresponding to the absolute angle of the motor shaft through gear mechanism. Then the feedback voltage value is applied at the input of error amplifier (comparator).

The error amplifier is a negative feedback amplifier and it reduces the difference between its inputs. It compares the voltage related to current position of the motor (obtained by potentiometer) with desired voltage related to desired position of the motor (obtained by pulse width to voltage converter), and produces the error either a positive or negative voltage.

This error voltage is applied to the armature of the motor. If the error is more, the more output is applied to the motor armature.

As long as error exists, the amplifier amplifies the error voltage and correspondingly powers the armature. The motor rotates till the error becomes zero. If the error is negative, the armature voltage reverses and hence the armature rotates in the opposite direction.

5.9 Difference between the DC and AC Servo Motors

DC SERVO MOTOR	**AC SERVO MOTOR**
It delivers high power output	Delivers low output of about 0.5 W to 100 W
It has more stability problems	It has less stable problems
It requires frequent maintenance due to the presence of commutator	It requires less maintenance due to the absence of commutator
It provides high efficiency	The efficiency of AC servo motor is less and is about 5 to 20%

The life of DC servo motor depends on the life on brush life	The life of AC servo motor depends on bearing life
It includes permanent magnet in its construction	The synchronous type AC servo motor uses permanent magnet while induction type doesn't require it.
These motors are used for high power applications	These motors are used for low power applications

5.10 Stepper Motor

These motors are also called stepping motors or step motors. The name stepper is used because this motor rotates through a fixed angular step in response to each input current pulse received by its controller. In recent years, there has been widespread demand of stepping motors because of the explosive growth of the computer industry. Their popularity is due to the fact that they can be controlled directly by computers, microprocessors and programmable controllers.

Stepper Motor

Fig 5.10

As we know, industrial motors are used to convert electric energy into mechanical energy but they cannot be used for precision positioning of an object or precision control of speed without using closed-loop feedback. Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems. Apart from stepping motors, other devices used for the above purposes are synchros and resolvers as well as dc/ac servomotors (discussed later).

The unique feature of a stepper motor is that its output shaft rotates in a series of discrete angular intervals or steps, one step being taken each time a command pulse is received. When a definite number of pulses are supplied, the shaft turns through a definite known angle. This fact makes the motor well-suited for open-loop position control because no feedback need be taken from the output shaft.

Such motors develop torques ranging from 1 μN-m (in a tiny wrist watch motor of 3 mm diameter) upto 40 N-m in a motor of 15 cm diameter suitable for machine tool applications. Their power output ranges from about 1 W to a maximum of 2500 W. The only moving part in a stepping motor is its rotor which has no windings, commutator or brushes. This feature makes the motor quite robust and reliable.

Step Angle

The angle through which the motor shaft rotates for each command pulse is called the step angle β. Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained. The step angles can be as small as 0.72º or as large as 90º. But the most common step sizes are 1.8º, 2.5º, 7.5º and 15º.

The value of step angle can be expressed either in terms of the rotor and stator poles (teeth) Nr and Ns respectively or in terms of the number of stator phases (m) and the number of rotor teeth.

$$\beta = \frac{(N_s - N_r)}{N_s \,.\, N_r} \times 360^\circ$$

or $$\beta = \frac{360^\circ}{m\,N_r} = \frac{360^\circ}{\text{No. of stator phases} \times \text{No. of rotor teeth}}$$

For example, if $N_s = 8$ and $N_r = 6$, $\beta = (8 - 6) \times 360 / 8 \times 6 = 15^\circ$

Resolution is given by the number of steps needed to complete one revolution of the rotor shaft. Higher the resolution, greater the accuracy of positioning of objects by the motor

∴ Resolution = No. of steps / revolution = 360º / β

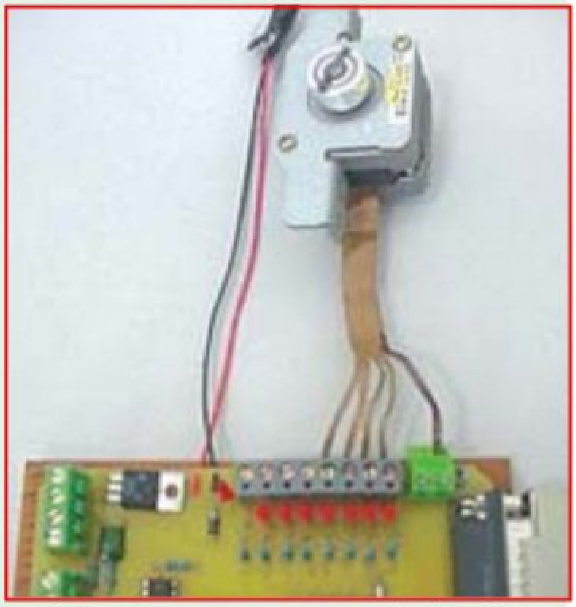
A stepping motor has the extraordinary ability to operate at very high stepping rates (upto 20,000 steps per second in some motors) and yet to remain fully in synchronism with the command pulses.

When the pulse rate is high, the shaft rotation seems continuous. Operation at high speeds is called ‘slewing’. When in the slewing range, the motor generally emits an audible whine having a fundamental frequency equal to the stepping rate. If f is the stepping frequency (or pulse rate) in pulses per second (pps) and β is the step angle, then motor shaft speed is given by

n = β × f / 360 rps = pulse frequency resolution.

If the stepping rate is increased too quickly, the motor loses synchronism and stops. Same thing happens if when the motor is slewing, command pulses are suddenly stopped instead of being progressively slowed.

Stepping motors are designed to operate for long periods with the rotor held in a fixed position and with rated current flowing in the stator windings. It means that stalling is no problem for such motors whereas for most of the other motors, stalling results in the collapse of back emf (Eb) and a very high current which can lead to a quick burn-out.



Connecting a stepper motor to the interface

Applications :

Such motors are used for operation control in computer peripherals, textile industry, IC fabrications and robotics etc. Applications requiring incremental motion are typewriters, line printers, tape drives, floppy disk drives, numerically-controlled machine tools, process control systems and X-Y plotters. Usually, position information can be obtained simply by keeping count of the pulses sent to the motor thereby eliminating the need for expensive position sensors and feedback controls. Stepper motors also perform countless tasks outside the computer industry. It includes commercial, military and medical applications where these motors perform such functions as mixing, cutting, striking, metering, blending and purging. They also take part in the manufacture of packed food stuffs, commercial end-products and even the production of science fiction movies.

Example 1. A hybrid VR stepping motor has 8 main poles which have been castleated to have 5 teeth each. If rotor has 50 teeth, calculate the stepping angle.

Solution. $N_s = 8 \times 5 = 40; N_r = 50$

$\therefore \beta = (50 - 40) \times 360 / 50 \times 40 = 1.8^\circ$.

Example 2. A stepper motor has a step angle of 2.5°. Determine (a) resolution (b) number of steps required for the shaft to make 25 revolutions and (c) shaft speed, if the stepping frequency is 3600 pps.

Solution. (a) Resolution $= 360^\circ / \beta = 360^\circ / 2.5^\circ = 144$ steps / revolution.

(b) Now, steps / revolution = 144. Hence, steps required for making 25 revolutions $= 144 \times 25 = 3600$.

(c) $n = \beta \times f / 360^\circ = 2.5 \times 3600 / 360^\circ = 25$ rps

5.10.1 Types of Stepper Motors

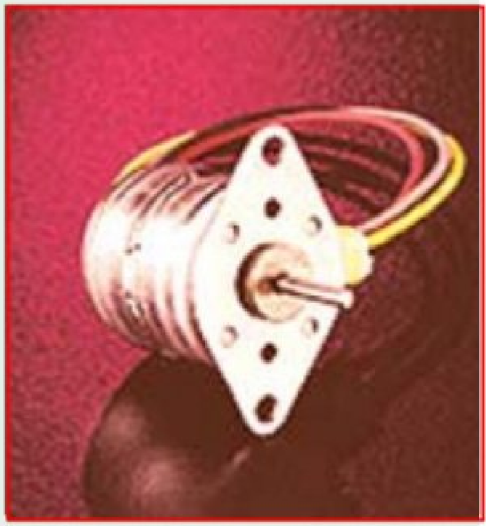
There is a large variety of stepper motors which can be divided into the following three basic categories :

(i) Variable Reluctance Stepper Motor

It has wound stator poles but the rotor poles are made of a ferromagnetic material as shown in Fig. 5.12(a). It can be of the single stack type (Fig.5.12) or multi-stack type, which gives smaller step angles. Direction of motor rotation is independent of the polarity of the stator current. It is called variable reluctance motor because the reluctance of the magnetic circuit formed by the rotor and stator teeth varies with the angular position of the rotor.

(ii) Permanent Magnet Stepper Motor

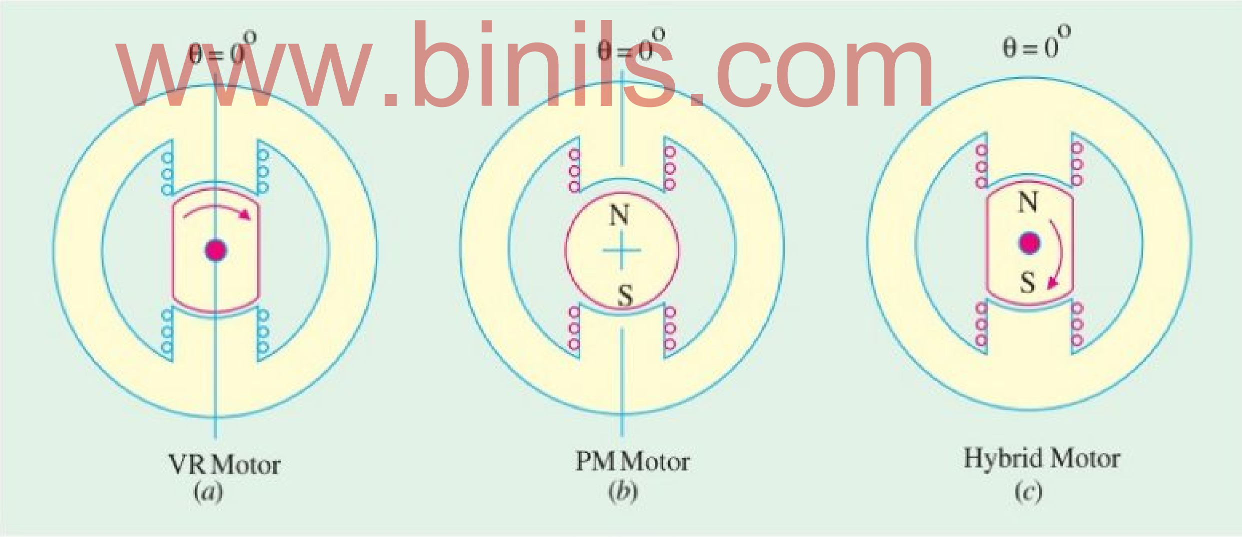
It also has wound stator poles but its rotor poles are permanently magnetized. It has a cylindrical rotor as shown in Fig. 5.12(b). Its direction of rotation depends on the polarity of the stator current.



Permanent magnet stepper motor

(iii) Hybrid Stepper Motor

It has wound stator poles and permanently-magnetized rotor poles as shown in Fig.5.12(c). It is best suited when small step angles of 1.8º, 2.5º etc. are required



VR Motor
(*a*)

PM Motor
(*b*)

Hybrid Motor
(*c*)

Fig 5.12

As a variable speed machine, V R motor is sometime designed as a switched-reluctance motor. Similarly, PM stepper motor is also called variable speed brushless dc motor. The hybrid motor combines the features of VR stepper motor and PM stepper motor. Its stator construction is similar to the single-stack VR motor but the rotor is cylindrical and is composed of radially magnetized permanent magnets.

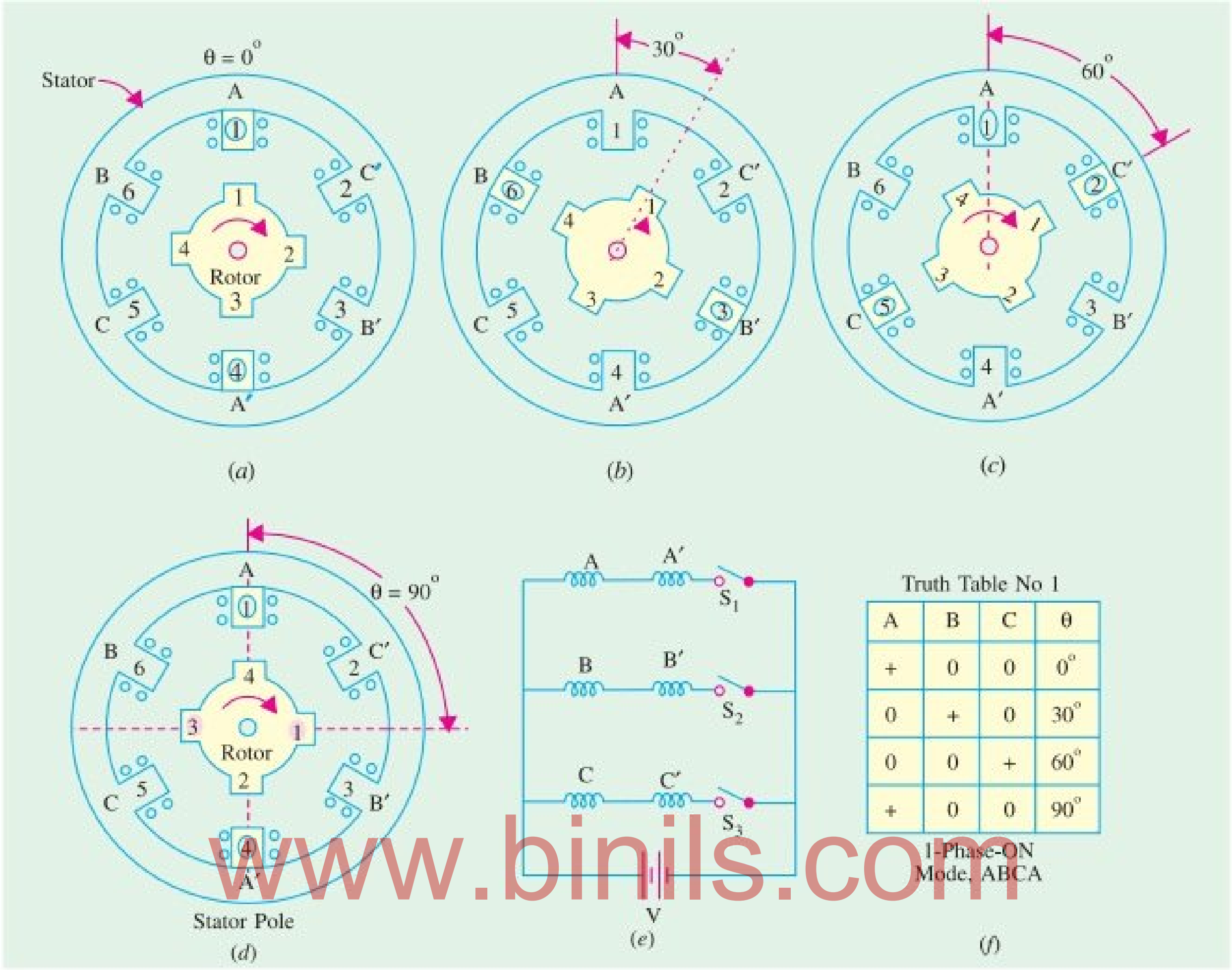
A recent type uses a disc rotor which is magnetized axially to give a small stepping angle and low inertia.

5.10.2 Variable Reluctance Stepper Motors

Construction :

Variable reluctance motor

A variable-reluctance motor is constructed from ferromagnetic material with salient poles as shown in Fig. 5.13. The stator is made from a stack of steel laminations and has six equally-spaced projecting poles (or teeth) each wound with an exciting coil. The rotor which may be solid or laminated has four projecting teeth of the same width as the stator teeth. As seen, there are three independent stator circuits or phases A, B and C and each one can be energised by a direct current pulse from the drive circuit (not shown in the figure). A simple circuit arrangement for supplying current to the stator coils in proper sequence is shown in Fig. 5.13 (e). The six stator coils are connected in 2-coil groups to form three separate circuits called phases. Each phase has its own independent switch. Diametrically opposite pairs of stator coils are connected in series such that when one tooth becomes a N-pole, the other one becomes a S-pole. Although shown as mechanical switches in Fig. 5.13 (e), in actual practice, switching of phase currents is done with the help of solid-state control. When there is no current in the stator coils, the rotor is completely free to rotate. Energising one or more stator coils causes the rotor to step forward (or backward) to a position that forms a path of least reluctance with the magnetized stator teeth. The step angle of this three-phase, four rotor teeth motor is $\beta = 360/ 4 \times 3 = 30^\circ$



A	B	C	θ
+	0	0	0°
0	+	0	30°
0	0	+	60°
+	0	0	90°

Fig 5.13

Working.

The motor has following modes of operation :

(a) 1-phase-ON or Full-step Operation

Fig. 5.13 (a) shows the position of the rotor when switch S1 has been closed for energising phase A. A magnetic field with its axis along the stator poles of phase A is created. The rotor is therefore, attracted into a position of minimum reluctance with diametrically opposite rotor teeth 1 and 3 lining up with stator teeth 1 and 4 respectively. Closing S2 and opening S1 energizes phase B causing rotor teeth 2 and 4 to align with stator teeth 3 and 6 respectively as shown in Fig. 5.13

(b). The rotor rotates through full-step of 30º in the clockwise (CW) direction. Similarly, when S3 is closed after opening S2, phase C is energized which causes rotor teeth 1 and 3 to line up with stator teeth 2 and 5 respectively as shown in Fig. 5.13

(c). The rotor rotates through an additional angle of 30º in the clockwise (CW) direction. Next if S3 is opened and S1 is closed again, the rotor teeth 2 and 4 will align with stator teeth 4 and 1 respectively thereby making the rotor turn through a further angle of 30º as shown in Fig. 5.13

(d). By now the total angle turned is 90º. As each switch is closed and the preceding one opened, therotor each time rotates through an angle of 30º. By repetitively closing the switches in the sequence 1-2-3-1 and thus energizing stator phases in sequence ABCA etc., the rotor will rotate clockwise in 30º steps. If the switch sequence is made 3-2-1-3 which makes phase sequence CBAC (or ACB), the rotor will rotate anticlockwise. This mode of operation is known as 1-phase-ON mode or full-step operation and is the simplest and widely-used way of making the motor step. The stator phase switching truth table is shown in Fig. 5.13 (f). It may be noted that the direction of the stator magnetizing current is not significant because a stator pole of either magnetic polarity will always attract the rotor pole by inducing opposite polarity.

(b) 2-phase-ON Mode

In this mode of operation, two stator phases are excited simultaneously. When phases A and B are energized together, the rotor experiences torques from both phases and comes to rest at a point mid-way between the two adjacent full-step positions. If the stator phases are switched in the sequence A B, BC, CA, A B etc., the motor will take full steps of 30º each (as in the 1-phase-ON mode) but its equilibrium positions will be interleaved between the full-step positions. The phase switching truth table for this mode is shown in Fig. 5.14 (a).

Truth Table No. 2

A	B	C	
+	+	0	15°
0	+	+	45°
+	0	+	75°
+	+	0	105°

2 Phase-ON Mode
AB, BC, CA, AB

Truth Table No. 3

	A	B	C		
A	+	0	0	0°	
	+	+	0	15°	AB
B	0	+	0	30°	
	0	+	+	45°	BC
C	0	0	+	65°	
	+	0	+	75°	CA
A	+	0	0	90°	

Half-Stepping Alternate
1-Phase-On &
2-Phase-on Mode
A, AB, B, BC, C, CA, A

Fig 5.14

The 2-phase-ON mode provides greater holding torque and a much better damped single-stack response than the 1-phase-ON mode of operation.

(c) Half-step Operation

Half-step operation or ‘half-stepping’ can be obtained by exciting the three phases in the sequence A, AB, B, BC, C etc. i.e. alternately in the 1-phase-ON and 2-phase-ON modes. It is sometime known as ‘wave’ excitation and it causes the rotor to advance in steps of 15º i.e. half the full-step angle. The truth table for the phase pulsing sequence in half-stepping is shown in Fig. 5.15 (b).

Half-stepping can be illustrated with the help of Fig. 39.4 where only three successive pulses have been considered. Energizing only phase A causes the rotor position shown in Fig. 5.15 (a). Energising phases A and B simultaneously moves the rotor to the position shown in Fig. 5.15 (b) where rotor has moved through half a step only. Energising only phase B moves the rotor through another half-step as shown in Fig. 5.15 (c). With each pulse, the rotor moves 30 / 2 = 15º in the CCW direction. It will be seen that in half-stepping mode, the step angle is halved thereby doubling the resolution. Moreover, continuous half-stepping produces a smoother shaft rotation

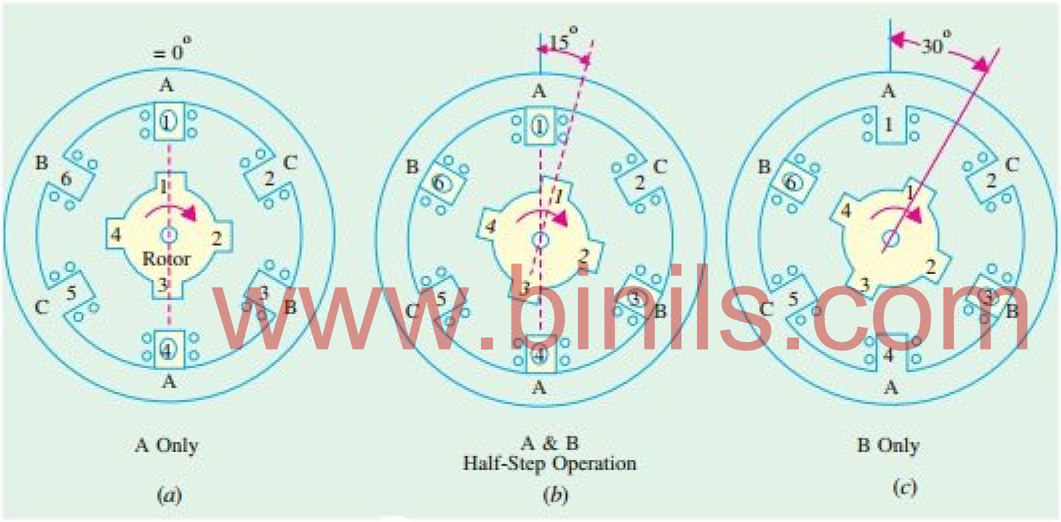


Fig 5.15

(d) Microstepping

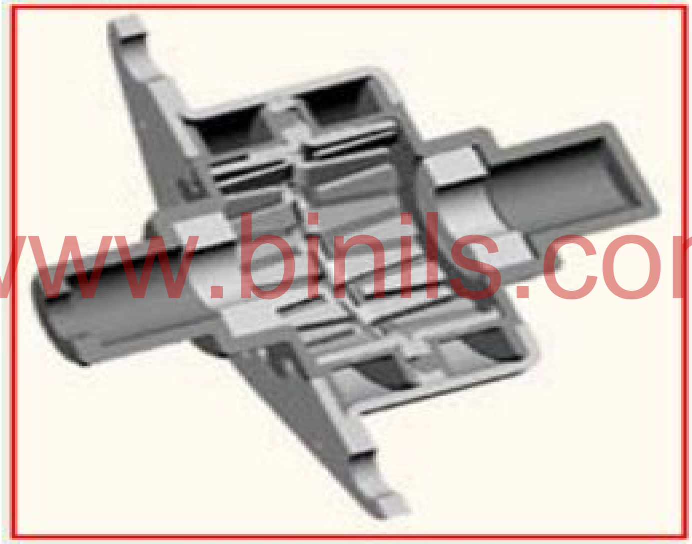
It is also known as mini-stepping. It utilizes two phases simultaneously as in 2-phase-ON mode but with the two currents deliberately made unequal (unlike in half-stepping where the two phase currents have to be kept equal). The current in phase A is held constant while that in phase B is increased in very small increments until maximum current is reached. The current in phase A is then reduced to zero using the same very small increments. In this way, the resultant step becomes very small and is called a microstep. For example, a VR stepper motor with a resolution of 200 steps / rev ($\beta = 1.8^\circ$) can with microstepping have a resolution of 20,000 steps / rev ($\beta = 0.018^\circ$). Stepper motors employing microstepping technique are used in printing and phototypesetting where very fine resolution is called for. As seen, microstepping provides smooth low-speed operation and high resolution. Torque. If Ia is the d.c. current pulse passing through phase A, the torque produced by it is given by T = (1 / 2) Ia 2 dL / dθ. VR stepper motors have a high (torque / inertia) ratio giving high rates of acceleration and fast response. A possible disadvantage is the absence of detent torque which is necessary to retain the rotor at the step position in the event of a power failure.

5.10.3 Permanent-Magnet Stepping Motor

(a) **Construction.** Its stator construction is similar to that of the single-stack V R motor discussed above but the rotor is made of a permanent-magnet material like magnetically ‘hard’ ferrite. As shown in the Fig.5.16 (a), the stator has projecting poles but the rotor is cylindrical and hasradially magnetized permanent magnets. The operating principle of such a motor can be understood with the help of Fig. 5.16 (a) where the rotor has two poles and the stator has four poles. Since two stator poles are energized by one winding, the motor has two windings or phases marked A and B.

The step angle of this motor $\beta = 360^\circ / mN_r = 360^\circ / 2 \times 2$

$= 90^\circ$ or $\beta = (4 - 2) \times 360^\circ / 2 \times 4 = 90^\circ$.



Permanent magnet stepper motor

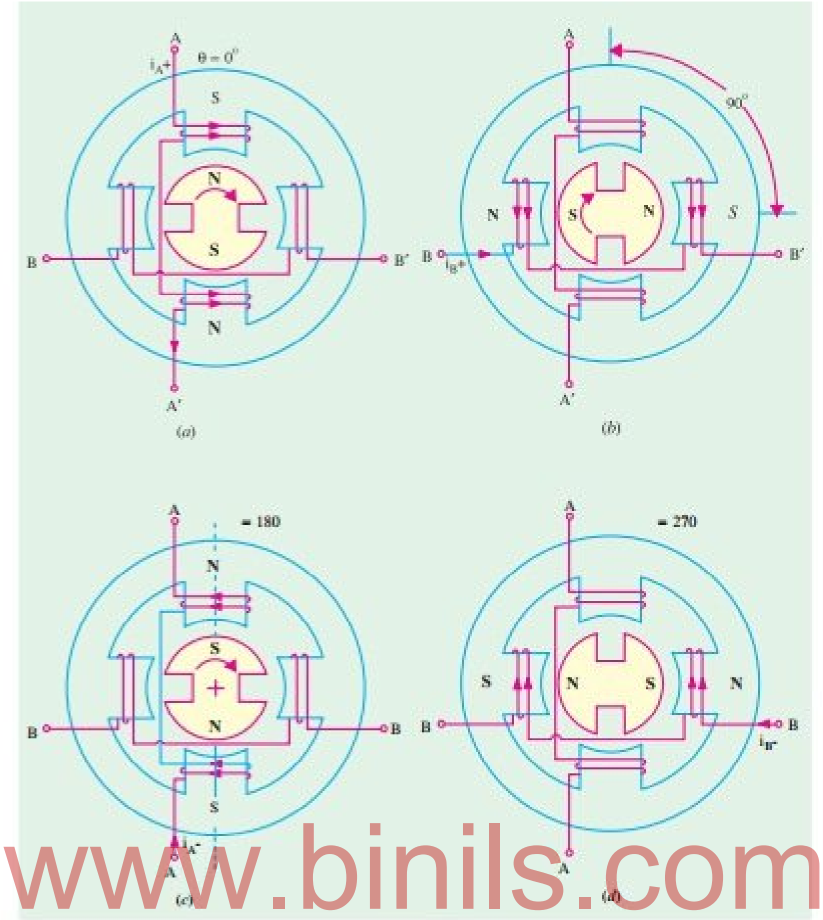
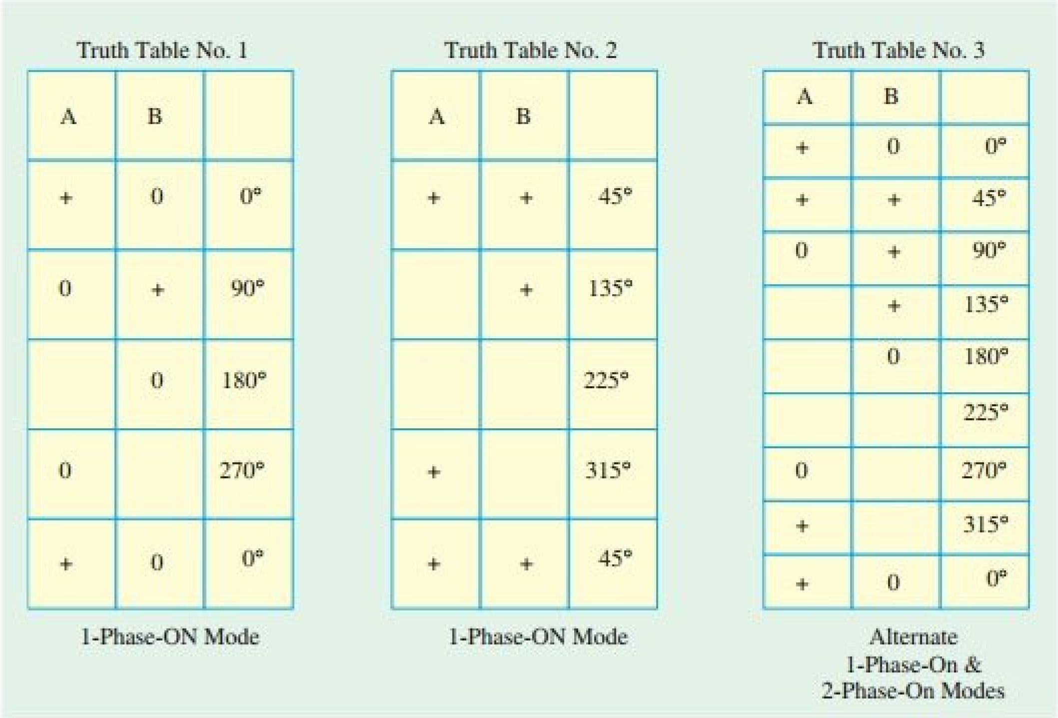


Fig 5.16

Working.

When a particular stator phase is energized, the rotor magnetic poles move into alignment with the excited stator poles. The stator windings A and B can be excited with either polarity current (A+ refers to positive current I A+ in the phase A and A– to negative current I A –). Fig.5.16 (a) shows the condition when phase A is excited with positive current iA+. Here, θ = 0º.

If excitation is now switched to phase B as in Fig. 5.16 (b), the rotor rotates by a full step of 90º in the clockwise direction. Next, when phase A is excited with negative current I A–, the rotor turns through another 90º in CW direction as shown in Fig. 5.16 (c). Similarly, excitation of phase B with B– further turns the rotor through another 90º in the same direction as shown in Fig. 5.16 (d). After this, excitation of phase A with I A+ makes the rotor turn through one complete revolution of 360º.



Truth Table No. 1

A	B	
+	0	0°
0	+	90°
	0	180°
0		270°
+	0	0°

1-Phase-ON Mode

Truth Table No. 2

A	B	
+	+	45°
	+	135°
		225°
+		315°
+	+	45°

1-Phase-ON Mode

Truth Table No. 3

A	B	
+	0	0°
+	+	45°
0	+	90°
	+	135°
	0	180°
		225°
0		270°
+		315°
+	0	0°

Alternate
1-Phase-On &
2-Phase-On Modes

Fig 5.17

It will be noted that in a permanent-magnet stepper motor, the direction of rotation depends on the polarity of the phase currents as tabulated below :

i_A+; i_B+; i_A-; i_B-; i_A+; ....
$A^+; B^+; A^-; B^-; A^+;$ .... for clockwise rotation
i_A+; i_B-; i_A-; i_B+; i_A+; ....
$A^+; B^-; A^-; B^+; A^+;$ .... for CCW rotation

Truth tables for three possible current sequences for producing clockwise rotation are given in Fig. 5.17. Table No.1 applies when only one phase is energized at a time in 1-phase-ON mode giving step size of 90º. Table No.2 represents 2-phase-ON mode when two phases are energised simultaneously. The resulting steps are of the same size but the effective rotor pole positions are midway between the two adjacent full-step positions. Table No.3 represents half-stepping when 1-phase-ON and 2-phase□ON modes are used alternately. In this case, the step size becomes half of the normal step or one□fourth of the pole-pitch (i.e. 90º / 2 = 45º or 180º / 4 = 45º). Microstepping can also be employed which will give further reduced step sizes thereby increasing the resolution.

5.10.4 Advantages and Disadvantages.

Since the permanent magnets of the motor do not require external exciting current, it has a low power requirement but possesses a high detent torque as compared to a VR stepper motor. This motor has higher inertia and hence slower acceleration. However, it produces more torque per ampere stator current than a VR motor. Since it is difficult to manufacture a small permanent-magnet rotor with large number of poles, the step size in such motors is relatively large ranging from 30º to 90º. However, recently disc rotors have been manufactured which are magnetized axially to give a small step size and low inertia.

Example 1.

A four-stack VR stepper motor has a step angle of 1.8º. Find the number of its rotor and stator teeth.

Solution. A four-stack motor has four phases. Hence, m = 4.

∴ 1.8º = 360º / 4 × Nr

; ∴ Nr = 50.

Since in multi-stack motors, rotor teeth equal the stator teeth, hence Ns = 50.

Example 2

A single-stack, 3-phase VR motor has a step angle of 15º. Find the number of its

rotor and stator poles.

Solution.

Now, β = 360º / mNr or 15º = 360º / 3 × Nr

; ∴ Nr = 8.

For finding the value of Ns , we will use the relation β = (Ns – Nr) × 360º / Ns . Nr

(i) When Ns > Nr

. Here, β = (Ns – Nr) × 360º / Ns . Nr

or 15º = (Ns – 8) × 360º / 8 Ns

; ∴ Ns = 12

(ii) When Ns < Nr

. Here,15º = (8 – Ns) × 360º / 8 Ns

; ∴ Ns = 6.

REVIEW QUESTIONS

2 Marks and 3 Marks

1. What is permanent magnet synchronous motor?

2. What are the advantages and disadvantages of PMSM?

3. What are the applications of PMSM?

4. What are the types of synchros?

5. What is stepper motor?

6. Define step angle.

7. Define slewing.

8. What are the types of stepper motor?

9. Mention some application of stepper motor.

10. Mention some applications of synchros?

11. What are the advantages of Permanent magnet DC motor?

12. Write short notes on control transmitter

13. Write short notes on control receiver.

14. Mention some application of linear induction motor.

15. Difference between the DC and AC Servo Motors

10 Marks

1. Explain the construction and operation of PMSM.
2. Explain the construction and working of Permanent Magnet Dc motor.
3. Explain with neat sketch the working of DC Servo motor.
4. Explain the construction and working of variable reluctance stepper motor.
5. Explain the construction and operation of Permanent magnet stepper motor .
6. Explain the construction working of linear induction motor.
7. Explain the constructional features of synchros.