CONTENTS

KEE–503 : ELECTRICAL MACHINES - II

1 UNIT Synchronous Machine-I

PART-1

Constructional Features, Armature Winding, EMF Equation, Winding Coefficients.

CONCEPT OUTLINE : PART-1

- **Synchronous Machine :** 3-phase balanced stator currents produce a field rotating at synchronous speed. Rotor with DC excited poles (same number as stator poles), when rotating in same direction and same speed producing a torque proportional to sine of electrical angle between resultant air-gap flux and rotor poles.

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

- **Armature Windings :**

1. $\theta_{\text{electrical}} = \dfrac{P}{2}\,\theta_{\text{mechanical}}$
2. One pole pitch = $180°_{\text{(electrical degree)}} = \dfrac{360°_{\text{(mechanical degree)}}}{P}$
3. Coil span-factor or Pitch-factor, $K_c = \cos\dfrac{\alpha}{2}$
4. Distribution factor or Breadth factor, $K_d = \dfrac{\sin\dfrac{m\beta}{2}}{m\sin\dfrac{\beta}{2}}$
5. Winding factor, $K_w = K_c K_d$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.1. **Discuss the construction of 3ϕ synchronous machines.**

Answer

i. **Stator :**

1. The stator is a stationary armature. This consists of a core and the slots to hold the armature winding.
2. The stator core has a laminated construction. It is built up of special steel stampings insulated from each other with varnish or paper.

3. The laminated construction is basically to keep down eddy current losses. Generally choice of material is steel to keep down hysteresis losses. The entire core is fabricated in a frame made of steel plates.
4. 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.
5. Ventilation is maintained with the help of holes cast in the frame.

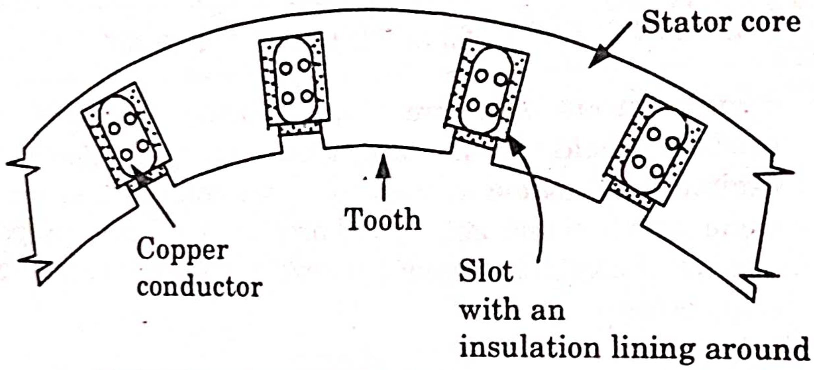

Fig. 1.1.1. Section of an alternator stator.

ii. **Rotor :**

There are two types of rotors used in alternators :

a. **Salient pole type :**

1. This is also called projected pole type as all the poles are projected out from the surface of the rotor.
2. The poles are built up of thick steel laminations. The poles are bolted to the rotor as shown in the Fig. 1.1.2. The pole face has been given a specific shape. The field pole winding is provided on the pole shoe.
3. These rotors have large diameters and small axial lengths.

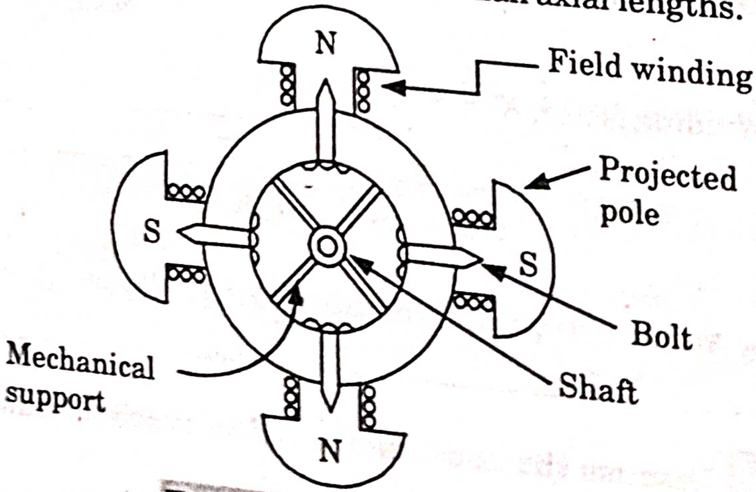

Fig. 1.1.2. Salient pole rotor.

b. **Smooth cylindrical type :**

1. This is also called non-salient type or non-projected pole type of rotor. The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coil.

2. The slots are covered at the top with the help of steel manganese wedges. The unslotted portions of the cylinder itself act as the poles.
3. The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor.
4. These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits.

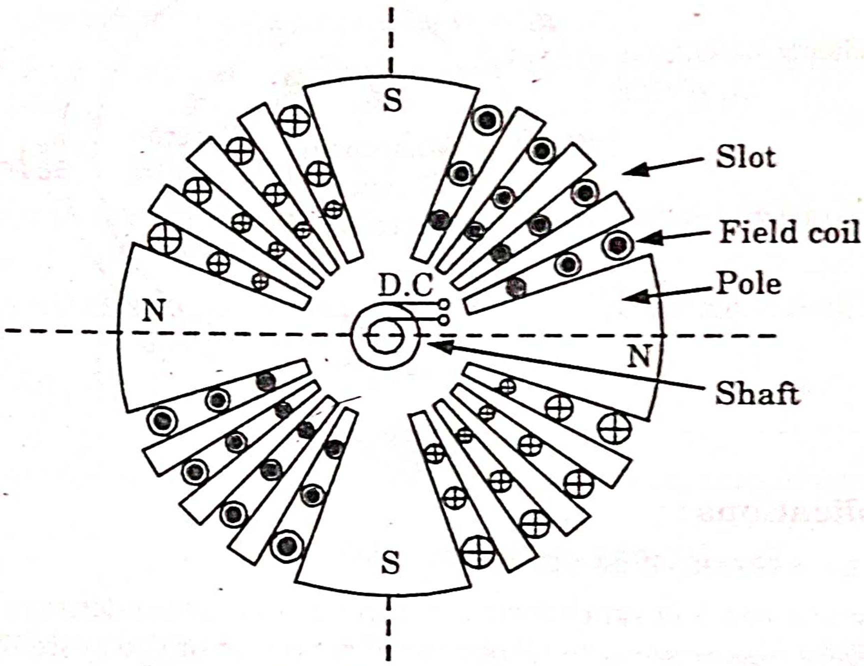

Fig. 1.1.3. Smooth cylindrical rotor.

Que 1.2. **Explain working principle of 3ϕ synchronous machine. Also give its applications.**

Answer

A. Working principle :

1. It works on the principle of electromagnetic induction *i.e.*, when the magnetic flux is cut by a conductor, an emf is induced in the conductor.
2. In 3ϕ synchronous machines, the stator housing the 3ϕ armature windings produces a rotating magnetic field, rotating at synchronous speed as shown.
3. The rotor on the other hand houses field windings carrying direct current and produces a stationary and constant magnetic field analogous to a permanent magnet.
4. Due to interaction of the two magnetic fields, an electromagnetic torque acts on rotor in clockwise direction and on stator in anticlockwise direction in case of synchronous motor.

5. However, in case of synchronous generator, the mechanical motion is to be enforced against the electromagnetic torque so as to produce electric power thus the rotor is to be driven in anticlockwise direction opposite to the electromagnetic torque.

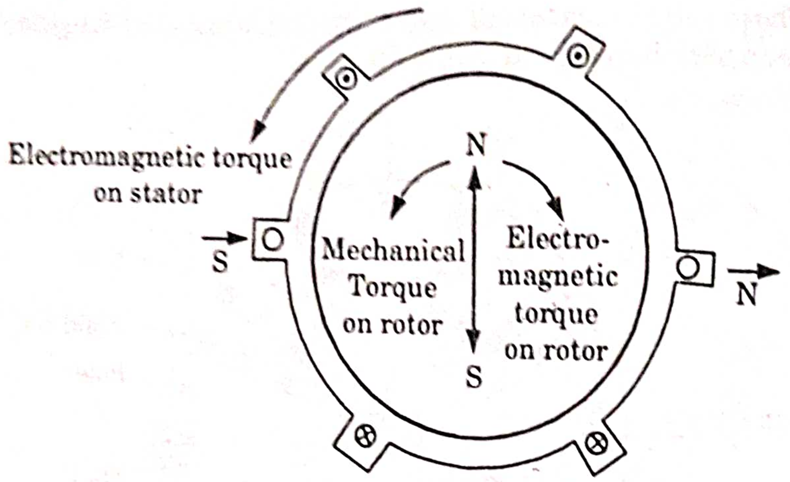

Fig. 1.2.1.

B. Applications :

1. For generation of 3ϕ power.
2. They are used as synchronous compensators or condensers to generate reactive power so as to improve power factor of the system.
3. Used in large low head pumps, reciprocating pumps and compressors, rolling mills, ball mills, crushers, pulp grinders, etc.

Que 1.3. **Explain why 3ϕ synchronous machines run at constant speed such as synchronous speed $\left(N_s = \dfrac{120f}{P}\right)$, where the symbols having their usual meanings ?**

AKTU 2013-14, Marks 10

Answer

A. Reason :

1. When the synchronous machine stator is supplied with three-phase balanced voltages and the rotor field is excited with DC current, then in the air gap there will be an mmf (magneto motive force) which is sinusoidally distributed and rotate at synchronous speed defined by the frequency of the applied voltage.
2. The rotor field is also sinusoidally distributed in the air gap due to the shaping of the poles and is stationary with respect to rotor. If the rotor is rotated at synchronous speed, then the rotor field also rotates at the same speed.

3. The interaction of stator mmf and the rotor flux generates unidirectional torque in the direction of motion of rotor. This is the principle of working of synchronous motor. The motor runs at constant speed defined by the stator frequency.
4. If the rotor rotates at any other speed, then the stator mmf sweeps past the rotor due to the relative speed between the two (*i.e.*, stator and rotor) and the angle between mmf and flux will be changing with time. The torque generated will be oscillatory with zero average.
5. Therefore for proper operation of synchronous motor, stator supply should be given only when the rotor is moving at synchronous speed.

B. Expression for synchronous speed :

1. In a 2-pole machine, the rotating field travels a distance covered by two poles (*i.e.*, two pole pitches) in one cycle.
2. For a 4-pole machine, the rotating field will travel a distance covered by two poles, *i.e.*, $\frac{1}{2}\left(=\frac{1}{4/2}\right)$ revolution in one cycle.
3. For a 6-pole machine, the rotating field will travel a distance covered by two poles, *i.e.*, $\frac{1}{3}\left(=\frac{1}{6/2}\right)$ revolution in one cycle and so on.
4. This process reveals that the rotating field speed, for a P-pole machine, is $\frac{1}{P/2}$ revolution in one cycle and therefore $\frac{f}{P/2}$ revolutions in f cycles.
5. In other words $\frac{f}{P/2}$ revolutions in one second, because f cycles are completed in one second. Here f is the frequency of the 3ϕ currents.
6. If n_s denotes the rotating field speed in revolutions per sec, then

$$n_s = \frac{f}{P/2} = \frac{2f}{P}$$

$$N_s = \frac{120f}{P} \text{ rpm} \qquad \text{...(1.3.1)}$$

where, n_s = Speed in rps

N_s = Speed in rpm

F = Frequency

P = Number of poles

7. The speed at which rotating magnetic field revolves is called the synchronous speed.

Que 1.4. **Why a rotating field system preferred against a stationary field in a synchronous machine ? A 2 pole alternator rotates at 3000 rpm. What is the frequency of the generated emf ?**

AKTU 2012-13, Marks 05

Answer

A. Rotating field is preferred over stationary field due to following reasons :

1. A stationary armature is more easily insulated for the high voltage for which the alternator is designed. This generated voltage may be as high as 33 kV.
2. The armature windings can be braced better mechanically against high electromagnetic forces due to large short-circuit currents when the armature windings are in the stator.
3. The armature windings, being stationary, are not subjected to vibration and centrifugal forces.
4. The output current can be taken directly from fixed terminals on the stationary armature without using slip ring, brushes, etc.
5. The weight of the armature windings is greater than the winding of the field poles. The size of the machine, is therefore, reduced.
6. Rotating field is comparatively light and can be constructed for high speed rotation.
7. The stationary armature may be cooled easily.

B. Numerical :

Given : Speed of machine, $N_s = 3000$ rpm, Number of poles, $P = 2$
To Find : Frequency of generated emf, f.

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

2. $$f = \frac{N_s P}{120} = \frac{3000 \times 2}{120}$$
$$f = 50 \text{ Hz}$$

Que 1.5. **Explain following terms :**

A. Pole pitch
B. Coil pitch
C. Fractional pitched coil
D. Coil span factor
E. Distribution factor.

Answer

A. Pole pitch :

It is defined as the distance between two adjacent poles and measured in terms of armature slots. In Fig. 1.5.1, the pole pitch = 6 slots. One pole pitch = 180° electrical.

B. Coil pitch :

1. It is defined as the distance between two sides of a coil. It is measured in terms of slots.
2. If the coil is put in such way that at one instant its one side is at a particular point under *N* pole and other side is under the exact similar point under *S* pole then the coil is called as a full-pitched coil. In such case, coil pitch = pole pitch = 180° electrical.

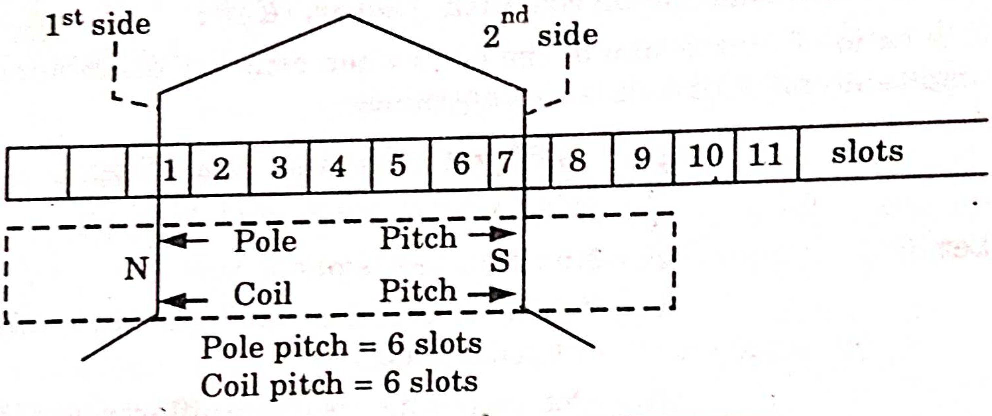

Fig. 1.5.1. Pole pitch and coil pitch.

C. Fractional pitched coil (or Short pitched coils) :

This indicates the pitch less than full pitch *i.e.*, less than pole pitch (*i.e.*, less than 180° electrical).

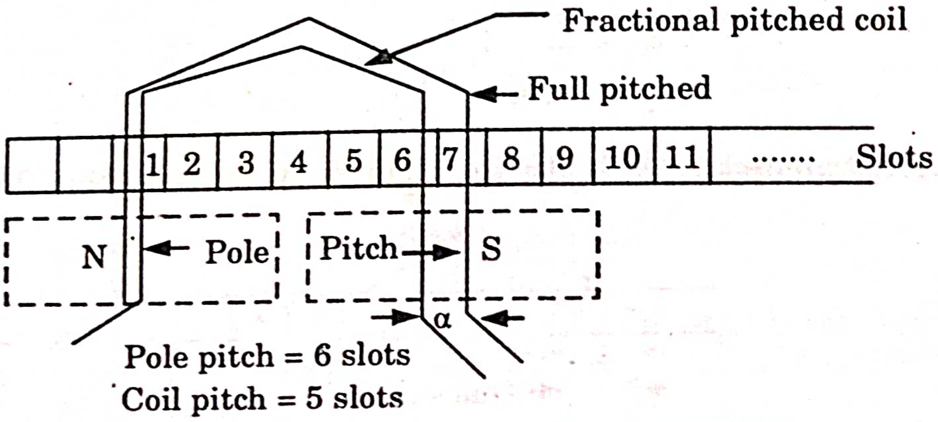

Fig. 1.5.2. Fractional pitched coil.

D. Coil span factor :

1. Coil span factor (K_c) is the ratio of vector sum of emfs to the arithmetical sum of emf induced in coil sides.

$$\therefore \quad K_c = \frac{\text{Vector sum of the induced emf/coil}}{\text{Arithmetic sum of induced emf/coil}}$$

$$= \frac{2\,E_S \cos\frac{\alpha}{2}}{2\,E_S} = \cos \alpha/2$$

$$\therefore \quad K_c = \cos\frac{\alpha}{2}$$

Thus K_c is less than unity and α is the angle by which the coil pitch falls short.

2. If coil is full pitch coil then, vector sum of induced emf/coil = Arithmetic sum of induced emf/coil.

Thus $\quad K_c = 1$

E. Distribution factor or Breadth Factor, (K_d) :

1. It is ratio of vector sum of the emfs when coils are distributed to the resultant emf with coils is concentrated.

$$\therefore \quad K_d = \frac{\text{EMF with distributed winding}}{\text{EMF with concentrated winding}}$$

2. Let
m = Number of slots/phase/pole
E_s = Voltage induced in each of the two coil sides of one polar group
β = Slot angle which is phase difference contributed by one slot in degree electrical.

$$= \frac{180°}{\text{slots/pole}}$$

$$\therefore \quad K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{m\beta}{2}\right)}$$

3. The distributed factor is also less than unity and it is about 0.9.

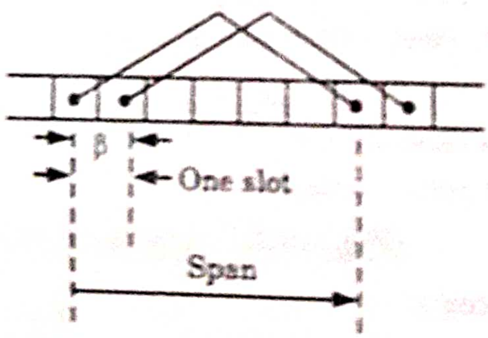

Fig. 1.5.3. Distributed coil.

Que 1.6. **Discuss types of armature winding in synchronous machine.**

Answer

A. **Single layer and double layer winding :**

1. If a slot consists of only one coil side, winding is said to be single layer. This is shown in the Fig. 1.6.1(*a*).
2. If there are two coil sides per slot, one at the bottom and one at the top the winding is called double layer as shown in the Fig. 1.6.1(*b*).

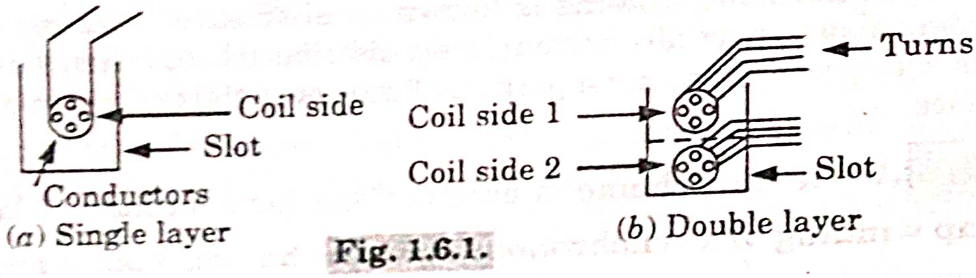

Fig. 1.6.1.

B. **Full pitch and short pitch winding :**

1. If coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from first slot, the winding is said to be full pitch winding and coil is called full pitch coil.
2. So if coil side in slot no. 1 is connected to coil side in slot no. $(n + 1)$ such that two slots no. 1 and slot no. $(n + 1)$ are one pole pitch or n slots or 180° electrical apart, the coil is called full pitch coil.

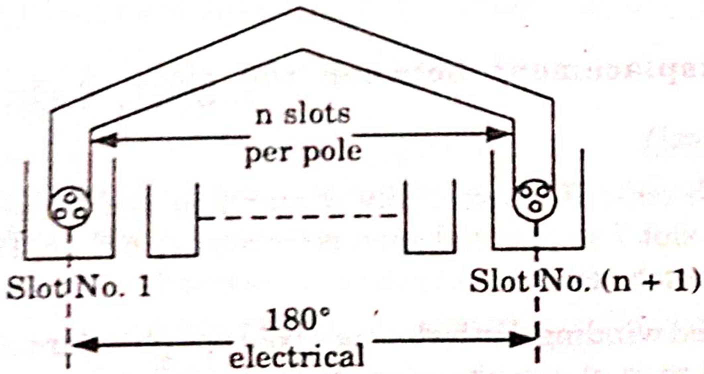

Fig. 1.6.2. Full pitch coil.

3. If coils are used in such a way that coil span is slightly less than a pole pitch *i.e.*, less than 180° electrical, the coils are called, short pitched coils or fractional pitched coils.

C. **Concentrated winding and distributed winding :** If one slot per pole or slots equal to number of poles are employed then, concentrated winding is obtained. Such windings gives maximum induced emf for a given number of conductors.

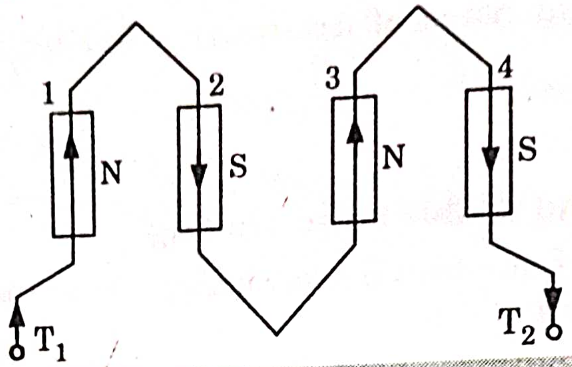

Fig. 1.6.3. Skelton wave winding (example of concentrated winding).

Distributed winding : If the conductors are placed in several slots under one pole, the winding is known as distributed winding. The winding may be partially or completely distributed accordingly as the slots are spread over only a portion of it or over the entire armature surface.

Que 1.7. **Write the scheme of connections for a 3-phase, 1-layer stator lap winding of a synchronous machine having 6 poles and 36 slots.**

AKTU 2012-13, Marks 05

Answer

1. Number of slots per pole, $n = \dfrac{36}{6} = 6.$
2. Number of slots per pole per phase, $m = \dfrac{n}{3} = \dfrac{6}{3} = 2.$
3. Angular displacement between the slots, $\beta = \dfrac{180°}{n} = \dfrac{180°}{6}$ $= 30°$ (electrical).
4. For full pitch coils if phase 1 say R starts in slot 1 then it must be connected in slot 7 so that coil span is 6 slots *i.e.*, $6\beta°$ *i.e.* 180°. Thus the coils are full pitch coils.
5. For distributed winding, both slots per pole per phase are available to be used. And all coils of one phase are to be in series.
6. So from slot 7, connect it to coil in slot 2 for lap winding and second end of slot 2 to coil in slot 8 and so on.
7. After finishing all slots per pole per phase available under first pair of poles connect coil to slot 13 under next pole and the winding will be repeated there on in similar fashion.
8. The starting end R_s and final end R_f for R phase are taken out finally. The connections for R phase are shown in the Fig. 1.7.1.

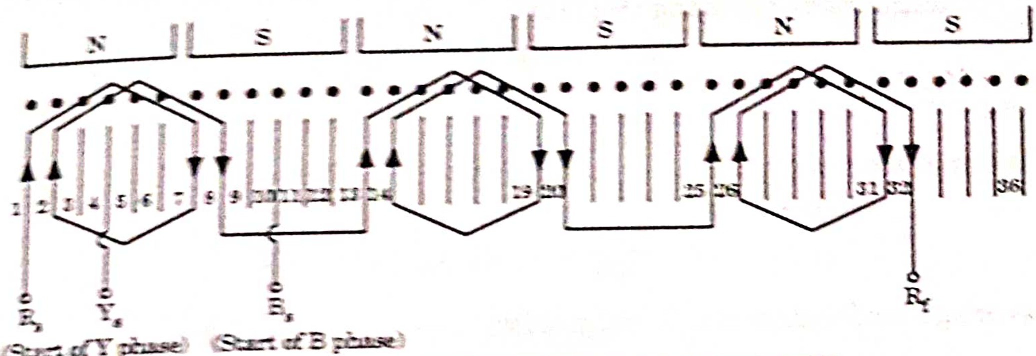

Fig. 1.7.1. Winding scheme for phase R.

9. There must be phase difference of 120° between R and Y. Each slot contributes 30° so start of Y phase should be 120° apart from R_s *i.e.*, 4 slots away from R_s *i.e.*, in slot 5.
10. Similarly start of B phase is further 120° away from Y phase *i.e.*, 4 slots away from Y_s *i.e.*, in slot 9. Finally all six ends R_s, R_f, Y_s, Y_f and B_s, B_f are brought out which are connected in star or delta to complete the winding.

Que 1.8. **Derive an expression for generated emf for an alternator.**

OR

Discuss the constructional features of synchronous machine. Also derive an expression for generated emf for an alternator.

AKTU 2016-17, Marks 10

Answer

A. **Construction of synchronous machine :** Refer Q. 1.1, Page 1–2A, Unit-1.

B. **Derivation (EMF Equation) :**

1. When the magnetic field is cut by a conductor, emf is induced in the conductor and the magnitude of this induced emf in the conductor depends upon the rate of cutting of flux.
2. Let,
   Z = Number of conductors per phase
   T = Number of turns per phase ($Z = 2T$)
   ϕ = Flux per pole
   P = Number of poles
   f = Frequency of induced emf
   N = Speed of rotor in rpm
3. Now, $f = \dfrac{PN}{120}$, $\quad \therefore \quad N = \dfrac{120 f}{P}$
4. In one revolution, each conductor is cut by flux of $P\phi$ and time to cut this flux is $\dfrac{60}{N}$ seconds.

∴ Average rate of cutting the flux

$$= \frac{\phi P}{\frac{60}{N}} = \frac{\phi PN}{60}$$

5. Average emf induced in one conductor

$$= \frac{\phi PN}{60}$$

6. Average emf induced in Z conductor

$$= \frac{\phi PN}{60} \times Z = \frac{\phi P \times 120f}{60 \times P} \times Z = 2\,\phi fZ$$

$$= 2\,\phi f \times 2\,T = 4\,\phi f T$$

$$\text{rms emf per phase} = 1.11 \times 4\,\phi f T = 4.44\,\phi f T \text{ V}$$

This is for full pitched and concentrated winding.

7. But for fractional pitch and distributed winding; coil span factor (K_c) and distribution factor (K_d) are taken into account.

$$\therefore \quad \text{rms emf per phase} = 4.44\,K_c\,K_d\,\phi f\,T \text{ V}$$

Que 1.9. Explain EMF equation of alternator. A 3ϕ, 50 Hz, 8-pole alternator has a star-connected winding with 120 slots and 8 conductors per slot. The flux per pole is 0.05 Wb, sinusoidally distributed. Determine the phase and line voltages.

AKTU 2014-15, Marks 10

Answer

EMF equation : Refer Q.1.8, Page 1–12A, Unit-1.

Numerical :

Given : $f = 50$ Hz, $P = 8$; Number of slots = 120, Conductor per slot = 8
To Find : Phase voltage, E_p and Line voltage.

1. Number of slots per pole, $n = \frac{120}{8} = 15$

2. Number of slots per pole per phase, $m = \frac{n}{3} = \frac{15}{3} = 5$

3. Angular displacement between the slots, $\beta = \frac{180}{5} = 36°$ (electrical)

4. Distribution factor, $K_d = \frac{\sin \frac{m\beta}{2}}{m \sin(\beta/2)} = \frac{\sin\left(\frac{5 \times 36}{2}\right)}{5 \sin\left(\frac{36}{2}\right)}$

$$= \frac{1}{1.54} = 0.65$$

5. For full pitched coil $K_p = 1$, then winding factor $K_w = K_p K_d = 0.65$
6. Number of conductor per phase

$$Z_p = \frac{\text{Number of conductor per slot} \times \text{Number of slots}}{\text{Number of phases}}$$

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

7. Number of turns per phase $(T) = \frac{Z_p}{2} = \frac{120}{2} = 60$
8. Then voltage generated per phase,

$$E_p = 4.44 \times K_w \times \phi \times f \times T$$
$$= 4.44 \times 0.65 \times 0.05 \times 50 \times 60$$
$$= 433 \text{ V}$$

9. Line voltage $= \sqrt{3} \times 433 = 749.9 \approx 750$ V

Que 1.10. **A 3-phase, 4 pole, star-connected synchronous generator runs at 1500 rpm. The stator has 80 slots and 18 conductors per slot. The flux in the stator yoke is 0.006 Wb. Determine generated phase and line voltages, if the winding factor is 0.96.**

AKTU 2012-13, Marks 05

Answer

Given : Number of poles, $P = 4$; Conductors per slot = 18
Stator slots = 80; Flux = 0.006 Wb; $K_w = 0.96$
To Find : Generated phase voltage, E_p and Generated line voltage, E_L.

1. Total number of conductors

$$= \text{Conductors per slot} \times \text{Number of slots}$$
$$= 18 \times 80 = 1440$$

2. Conductors per phase,

$$Z_p = \frac{1440}{3} = 480$$

3. Generated voltage per phase,

$$E_p = 2.22\, K_w f \phi Z_p = 2.22 \times 0.96 \times 50 \times 0.006 \times 480$$
$$E_p = 306.892 \text{ V}$$

4. Generated line voltage,

$$E_L = \sqrt{3}\, E_p = \sqrt{3} \times 306.892$$
$$E_L = 531.55 \text{ V}$$

PART-2

Equivalent Circuit and Phasor Diagram, Armature Reaction, Open-Circuit (O.C.) and Short Circuit (S.C.) Tests.

CONCEPT OUTLINE : PART-2

- **Open circuit characteristic (Plot of V_{oc} vs I_f) :** It is the magnetic characteristic of the machine.
- **Short circuit characteristics (Plot of I_{sc} vs I_f) :** It is linear as I_f is very small.

$$R_{a(eff)} = \frac{\text{Short circuit load loss/phase}}{(\text{Short circuit armature current})^2}$$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.11. **Define equivalent circuit of synchronous machine. Also define its phasor diagram.**

Answer

A. Equivalent circuit :

1. When alternator delivers current, voltage drop takes place, *i.e.*, $I_a Z_s$ drop. The synchronous impedance is composed of R_a and X_s.

   The synchronous reactance, $X_s = X_L + X_a$

   Thus $\qquad Z_s = \sqrt{R_a^2 + X_s^2} = \sqrt{R_a^2 + (X_L + X_a)^2}$

   where, $\qquad X_L$ = Leakage reactance

   X_a = Armature reaction reactance

   R_a = Armature resistance.

   These parameters can be represented in equivalent circuit of alternator.

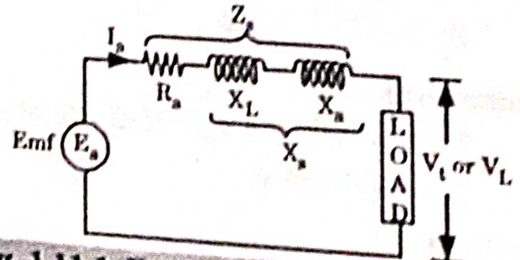

Fig. 1.11.1. Equivalent circuit of alternator.

2. From equivalent circuit as shown in Fig. 1.11.1,

$$E_a = V_t + jI_aX_a + jI_aX_L + I_aR_a$$

B. Phasor diagram of synchronous generator (alternator) at different load power factors :

a. At unity power factor :

i. Current I_a is inphase with V and I_aR_a drop is inphase with I_a.

ii. $$I_aX_s = I_a(X_a + X_L)$$

I_aX_s drop 90° lead to I_a.

iii. From Fig. 1.11.2, $E_a = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$

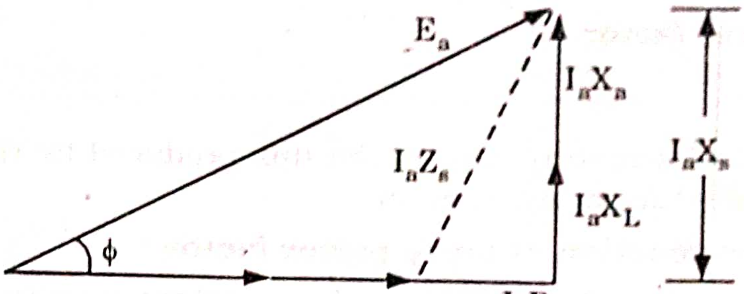

Fig. 1.11.2.

b. For lagging power factor :

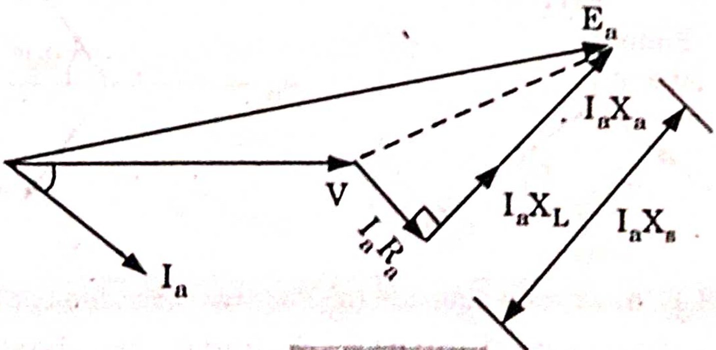

Fig. 1.11.3.

Current I_a lags V by ϕ and I_aR_a is inphase with I_a.

From Fig. 1.11.3, $E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$

c. For leading power factor :

i. I_a leads V by ϕ.

ii. From Fig. 1.11.4, $E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2}$

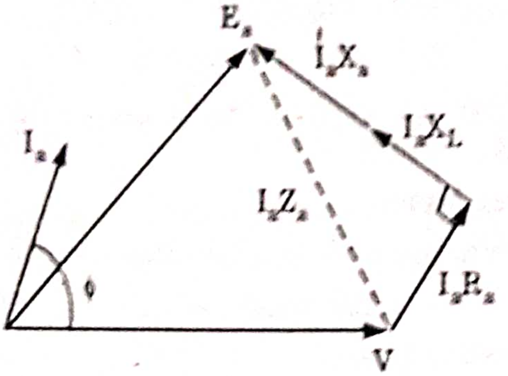

Fig. 1.11.4.

Que 1.12. **Describe in detail armature reaction and its effects under different power factor.**

Answer

The effect of armature flux on the flux produced by the rotor field poles is called armature reaction.

A. **Armature reaction at unity power factor :**

1. Suppose that the alternator is supplying current at unity power factor. The phase currents I_A, I_B and I_C will be in phase with their respective generated voltage E_A, E_B and E_C as shown in Fig. 1.12.1(*a*).

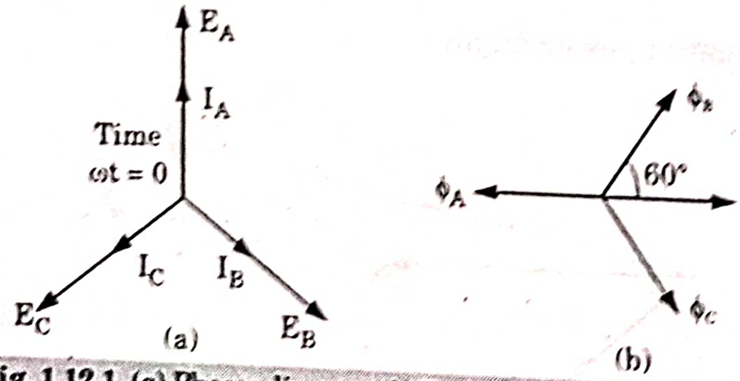

Fig. 1.12.1. (*a*) Phasor diagram (*b*) Positive directions of fluxes.

2. The positive directions of fluxes ϕ_A, ϕ_B and ϕ_C are shown in the space diagram of Fig. 1.12.1(*b*).
3. At $t = 0$, the instantaneous values of currents and fluxes are given by,

$$i_A = I_m \qquad \phi_A = \phi_m$$

$$i_B = -I_m \cos 60° = -\frac{1}{2} I_m \qquad \phi_B = -\frac{1}{2}\phi_m$$

$$i_C = -I_m \cos 60° = -\frac{1}{2} I_m \qquad \phi_C = -\frac{1}{2}\phi_m$$

4. Resolving along the horizontal direction we get

$$\phi_h = -\phi_A - \phi_B \cos 60° - \phi_C \cos 60°$$

$$= -\phi_m - \left(\frac{1}{2}\phi_m\right)\frac{1}{2} - \left(\frac{1}{2}\phi_m\right)\left(\frac{1}{2}\right)$$

$$\phi_h = -1.5\,\phi_m$$

5. Resolving along the vertical direction we get

$$\phi_v = -\phi_B \cos 30° + \phi_C \cos 60°$$

$$= -\frac{1}{2}\phi_m \cos 30° + \frac{1}{2}\phi_m \cos 30° = 0$$

6. The resultant armature reaction flux is given by

$$\phi_{AR} = \sqrt{\phi_h^2 + \phi_v^2} = \sqrt{(-1.5\phi_m)^2 + 0} = 1.5\phi_m$$

7. Also, ϕ_{AR} lags behind 90° with the main field flux.

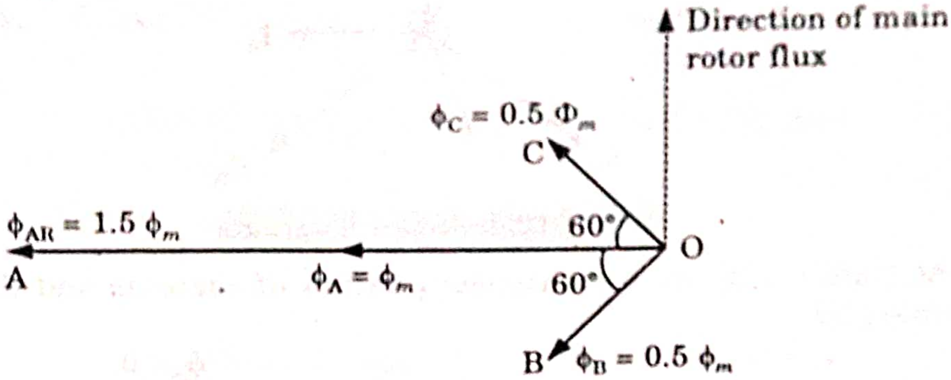

Fig. 1.12.2.

8. At the instant $\omega t = 30°$ the instantaneous values of currents and fluxes are given by

$$i_A = I_m \cos 30° = \frac{\sqrt{3}}{2} I_m \qquad \phi_A = \frac{\sqrt{3}}{2}\phi_m$$

$$i_B = 0 \qquad \phi_B = 0$$

$$i_C = -I_m \cos 30° = -\frac{\sqrt{3}}{2} I_m \qquad \phi_C = -\frac{\sqrt{3}}{2} I_m$$

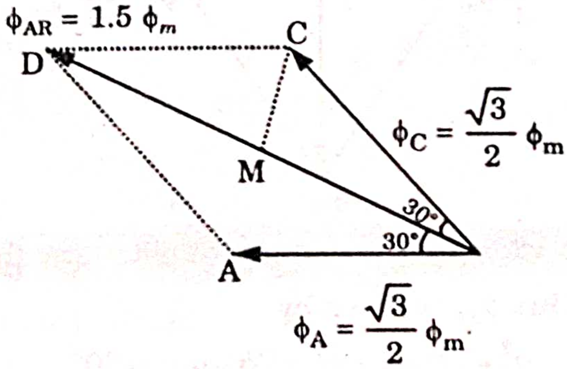

Fig. 1.12.3. Fluxes at $\omega t = 30°$.

9. Hence the resultant flux ϕ_{AR} set up by the currents in the armature remains constant in magnitude equal to 1.5 ϕ_m and it rotates at synchronous speed.

10. It is also seen that when the current is in phase with the induced voltage the armature reaction flux ϕ_{AR} lags behind the main field flux by 90°. This is called the cross-magnetizing flux.

B. Armature reaction at lagging power factor :

1. Suppose that the alternator is loaded with an inductive load of zero power factor lagging. The phase current I_A, I_B and I_C will be lagging with their respective phase voltages E_A, E_B and E_C by 90°.

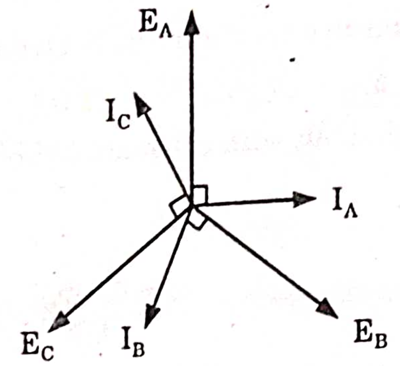

Fig. 1.12.4. Phaser diagram.

2. At time t = 0, the instantaneous values of currents and fluxes are given by

$$i_A = 0 \qquad \phi_A = 0$$

$$i_B = I_m \sin(-120°) = \frac{-\sqrt{3}}{2} I_m \qquad \phi_B = \frac{-\sqrt{3}}{2} I_m$$

$$i_C = I_m \sin(+120°) = \frac{\sqrt{3}}{2} I_m \qquad \phi_C = \frac{\sqrt{3}}{2} \phi_m$$

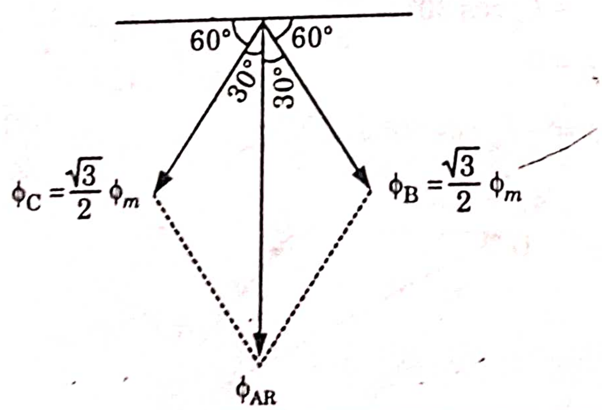

Fig. 1.12.5. Space diagram of magnetic fluxes.

3. The resultant flux ϕ_{AR} is given by

$$\phi_{AR}^2 = \phi_B^2 + \phi_C^2 + 2\phi_B\phi_C \cos 60°$$

$$= \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right) \times \frac{1}{2}$$

$$\therefore \qquad \phi_{AR} = 1.5\phi_m$$

4. It is seen that the direction of the armature reaction flux is opposite to the main field flux. Therefore, it will oppose and weaken the main field flux. It is said to be demagnetizing.

C. Armature reaction at leading power factor :

1. Suppose that the alternator is loaded with a load of zero power factor leading. The phase currents I_A, I_B and I_C will be leading their respective phase voltages E_A, E_B and E_C by 90°.
2. At time $t = 0$, the instantaneous values of currents and fluxes are given by

$$i_A = 0 \qquad \phi_A = 0$$

$$i_B = I_m \cos 30° = \frac{\sqrt{3}}{2} I_m \qquad \phi_B = \frac{\sqrt{3}}{2} I_m$$

$$i_C = -I_m \cos 30° = -\frac{\sqrt{3}}{2} I_m \qquad \phi_C = -\frac{\sqrt{3}}{2}\phi_m$$

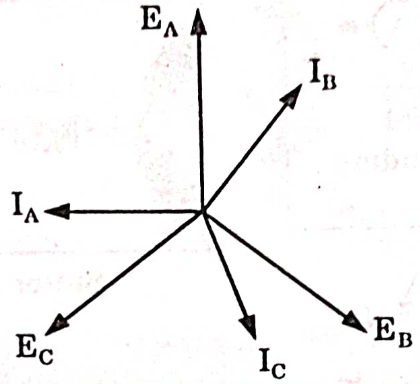

Fig. 1.12.6.

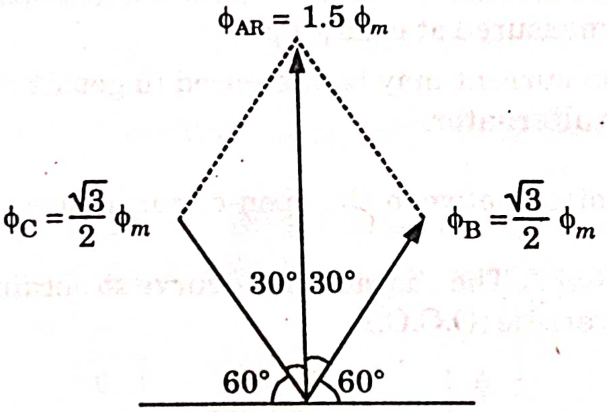

Fig. 1.12.7. Fluxes for zero leading pf.

3. The resultant flux is given by

$$\phi_{AR}^2 = \phi_B^2 + \phi_C^2 + 2\phi_B\phi_C \cos 60°$$

$$= \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right) \times \frac{1}{2}$$

$$\phi_{AR} = 1.5\ \phi_m$$

4. It is seen that direction of armature reaction flux is in the direction of main field flux. Thus, it is a magnetizing flux.

Que 1.13. **What do you mean by "O.C.C." and "S.C.C." in synchronous machines ? Determine the values of synchronous reactance and short circuit ratio from O.C.C. and S. C.C.**

AKTU 2013-14, Marks 10

Answer

A. **Open-circuit test :**

1. The alternator is run at rated synchronous speed and the load terminals kept open as shown in Fig. 1.13.1. That is, all the loads are disconnected. The field current is set to zero.

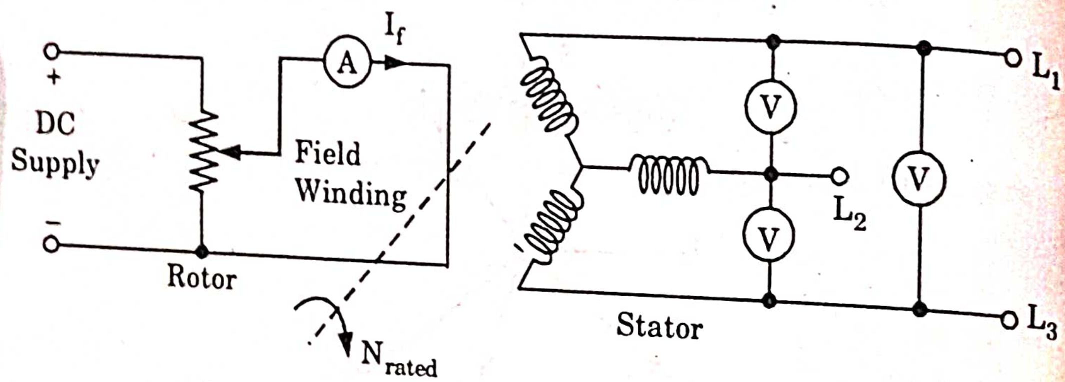

Fig. 1.13.1. Open-circuit test on an alternator.

2. Then the field current is gradually increased in steps, and the terminal voltage E_t is measured at each step.
3. The excitation current may be increased to get 25 % more than rated voltage of the alternator.
4. A graph is plotted between the open-circuit phase voltage $E_p \left(= \dfrac{E_t}{\sqrt{3}}\right)$ and field current I_f. The characteristic curve so obtained is called open-circuit characteristic (O.C.C.).

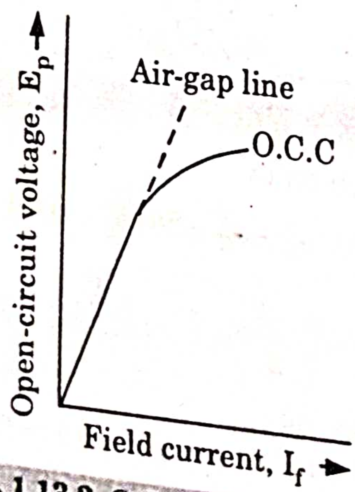

Fig. 1.13.2. O.C.C. of an alternator.

5. The extension of the linear portion of an O.C.C. is called the *air-gap line* of the characteristic. The O.C.C. and the air-gap line are shown in Fig. 1.13.2.

B. Short-circuit test :

1. The armature terminals are shorted through three ammeters Fig. 1.13.3.
2. The field current should first be decreased to zero before starting the alternator.
3. Each ammeter should have a range greater than the rated full-load value. The alternator is then run at synchronous speed.

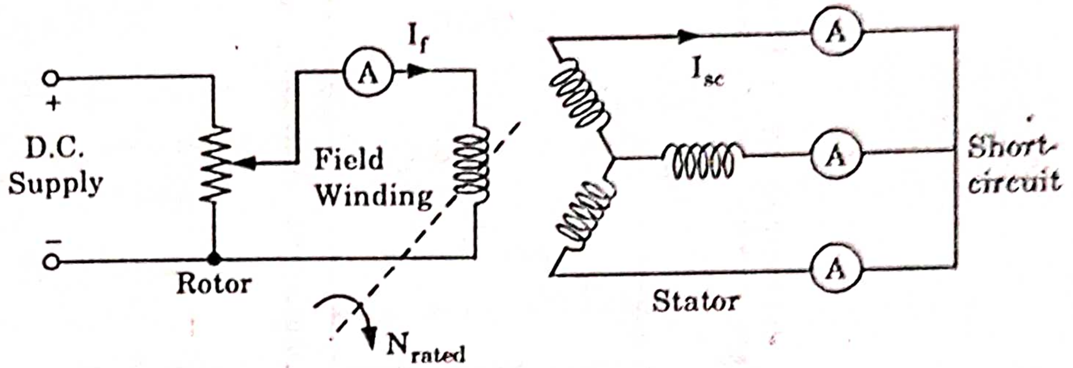

Fig. 1.13.3. Short-circuit test on an alternator.

4. Then the field current is gradually increased in steps, and the armature current is measured at each step.
5. The field current may be increased to get armature currents upto 150 % of the rated value.
6. The field current I_f and the average of three ammeter readings at each step is taken.
7. A graph is plotted between the armature current I_a and the field current I_f. The characteristic so obtained is called short-circuit characteristic (S.C.C.).

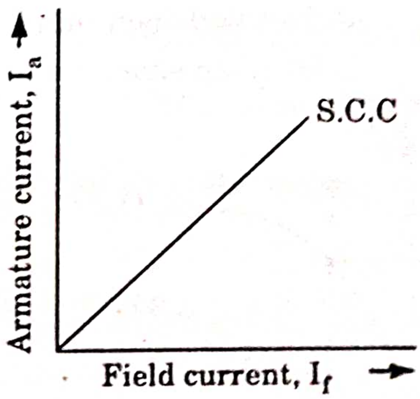

Fig. 1.13.4. The S.C.C. of an alternator.

C. Calculation of Z_s :

1. The synchronous impedance Z_s is equal to the open-circuit voltage divided by the short-circuit current at that field current which gives the rated emf per phase.

$$Z_s = \frac{\text{Open-circuit voltage per phase}}{\text{Short-circuit armature current}}$$

2. Then synchronous reactance is,

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

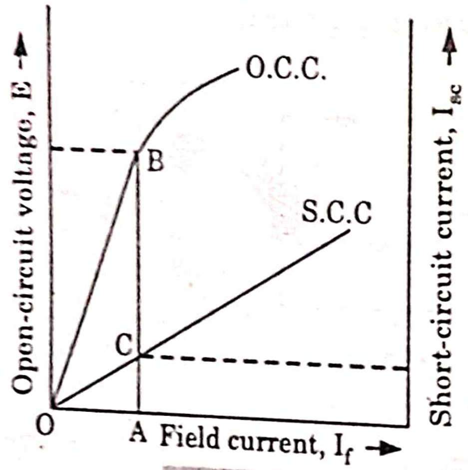

Fig. 1.13.5.

3. In Fig. 1.13.5, consider the field current I_f = OA that produces rated alternator voltage per phase. Corresponding to this current the open-circuit voltage is *AB*.

$$\therefore \qquad Z_s = \frac{AB \text{ (in voltage)}}{AC \text{ (in amperes)}}$$

D. Short circuit ratio (SCR) :

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

2. Mathematically, $\text{SCR} = \dfrac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}} = \dfrac{op}{os}$

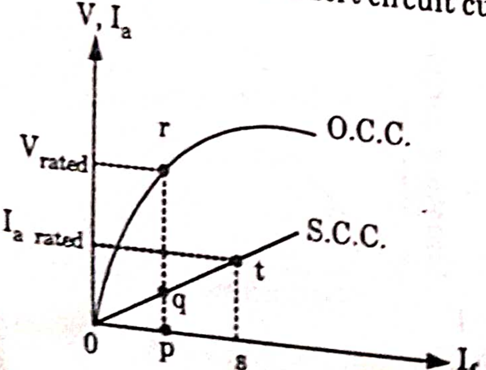

Fig. 1.13.6.

Que 1.14. A 3ϕ, hydro-electric synchronous generator is read to be 110 MW, 0.8 pf lagging, 6 kV, Y-connected, 50 Hz, 100 rpm. Determine the following :

i. The number of poles
ii. The kVA rating
iii. The prime-mover rating if the full-load generator efficiency is 97.1 % (leave out field loss). **AKTU 2013-14, Marks 10**

Answer

Given : $\cos\phi = 0.8$ (lagging), $f = 50$ Hz, $N_s = 100$ rpm, $V = 6$ kV
To Find : Number of poles, P; kVA rating and prime-mover rating, $(MW)_{rating}$.

i. Number of poles, $P = \dfrac{120 f}{N_s} = \dfrac{120 \times 50}{100} = 60$

ii. $$(MVA)_{rating} = \frac{110}{0.8} = 137.5$$

$$\therefore \quad (kVA)_{rating} = 0.137$$

iii. $$(MW)_{turbine} = \frac{110}{0.971} = 113.3$$

Que 1.15. A 500 kVA, 11 kV, 3ϕ star-connected alternator has the following data :
Friction and windage loss = 1500 W
Open-circuit core loss = 2500 W
Effective armature resistance/phase = 40 Ω
Field copper loss = 1000 W
Find the following parts in regard with above synchronous alternator :

i. Alternator efficiency of half load and at 0.85 power factor lagging.
ii. Maximum efficiency of the alternator.

Answer

Given : V_L = 11 kV, Friction and windage loss = 1500 W,
Open-circuit core loss = 2500 W, Field copper loss = 1000 W,
Effective armature resistance/phase = 40 Ω.
To Find : Efficiency, η at half load and 0.85 pf, and Maximum efficiency, η_{max}.

1. Full load armature current/phase

$$I_a = \frac{500}{\sqrt{3} \times 11} = 26.243 \text{ A}$$

2. Short circuit load loss at half load

$$= 3\left(\frac{I_a}{2}\right)^2 \times r_a + \text{Stray load loss}$$

$$= 3\left(\frac{26.243}{2}\right)^2 \times 4 + 0 = 2066.116 \text{ W}$$

3. Total loss at half load

$$= 1500 + 2500 + 2066.116 + 1000 = 7066.116 \text{ W}$$

4. $$\eta_{\text{half load}} = \left[1 - \frac{7066.116}{7066.116 + 500000 \times \frac{1}{2} \times 0.8}\right] \times 100\%$$

$$= 96.588\ \%$$

5. For maximum efficiency,

Variable losses, $3I^2_{am} r_a$ = Rotational losses + Field circuit losses

$$3I^2_{am} \times 4 = 1500 + 2500 + 1000 = 5000 \text{ W}$$

6. The current I_{am} at which maximum efficiency occurs is given by

$$I_{am} = \sqrt{\frac{5000}{12}} = 20.412 \text{ A}$$

7. Output maximum efficiency

$$= 3V_t I_{am} \cos \phi = 3 \times \frac{11000}{\sqrt{3}} \times 20.412 \times 0.8$$

$$= 311120.666 \text{ W}$$

8. Total losses at maximum efficiency

$$= 2 \times 5000 = 10{,}000 \text{ W}$$

9. Maximum efficiency, $\eta_{max} = \left[1 - \frac{\text{losses}}{\text{total input}}\right] \times 100\ \%$

$$= \left[1 - \frac{10{,}000}{311120.666 + 10{,}000}\right] = 96.886\ \%$$

PART-3

Voltage Regulation using Synchronous Impedance Method, MMF Method, Potier's Triangle Method.

CONCEPT OUTLINE : PART-3

- **Voltage regulation :**

$$V_R = \left. \frac{V_{t(\text{no load})}\Big|_{I_f \text{ same as at full load}} - V_{t(\text{rated})}}{V_{t(\text{rated})}} \right|_{\text{specified pf}}$$

- **Determination of V_R :**

A. Direct load test

B. Indirect methods

i. Synchronous impedance method or EMF method.

ii. Ampere-turn method or MMF method.

iii. Zero power factor method or Potier method.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.16. **Sketch and explain the open-circuit and short-circuit characteristics of a synchronous machine. How voltage regulation can be calculated by the use of their results ?**

AKTU 2014-15, Marks 10

Answer

A. **Open-circuit and short-circuit characteristics :** Refer Q. 1.13, Page 1–21A, Unit-1.

B. **Voltage regulation using O.C.C and S.C.C :**

1. From O.C.C. and S.C.C., Z_s can be determined for any load condition.
2. The armature resistance per phase (R_a) can be measured by different methods. One of the method is applying DC known voltage across the two terminals and measuring current. So value of R_a per phase is known.

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

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

So synchronous reactance per phase can be determined.

3. No-load induced emf per phase, E_{ph} can be determined by

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

where V_{ph} = Phase value of rated voltage

I_a = Phase value of current depending on the load condition

$\cos \phi$ = pf of load

Positive sign for lagging power factor while negative sign for leading power factor, R_a and X_s values are known from the various tests performed.

4. The regulation then can be determined by using formula,

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

Que 1.17. **Determine voltage regulation of alternator by synchronous impedance (or EMF) method ? Why this method is called pessimistic method in synchronous machine.**

Answer

1. The result obtained from the OC (open circuit) test and SC (short circuit) test are used to find the regulation by this method.
2. This method is called as EMF method because in this method armature resistance drop ($I_a R_a$ drop) and leakage reactance drop ($I_a X_L$) are actually EMF quantities hence it is known as EMF method.
3. The regulation found by this method is always more than found from the test of direct loading. Hence EMF method is therefore called as pessimistic method.

A. At lagging power factor condition :

1. Let the phase values of effective resistance and synchronous reactance of armature be R_a and X_s ohm respectively and current I_a lagging behind the terminal voltage V by phase angle ϕ.

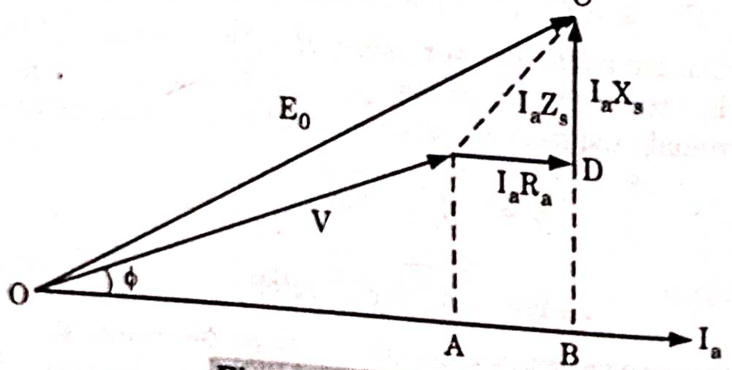

Fig. 1.17.1. Phasor diagram.

2. From phasor diagram,

$$E_0 = \sqrt{(OB)^2 + (BC)^2}$$

$$OB = OA + AB = V\cos\phi + I_aR_a$$
$$BC = BD + DC = V\sin\phi + I_aX_s$$
$$E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$$
$$\%\text{ Regulation} = \frac{E_0 - V}{V} \times 100$$

B. At unity power factor condition :

In ΔOBC, $OC^2 = OB^2 + BC^2$

$\therefore$ $E_0^2 = (OA + AB)^2 + (I_aX_s)^2$

$\therefore$ $E_0^2 = (V + I_aR_a)^2 + (I_aX_s)^2$

$\therefore$ $E_0^2 = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$.

$\therefore$ $\%\text{ Regulation} = \dfrac{E_0 - V}{V} \times 100$

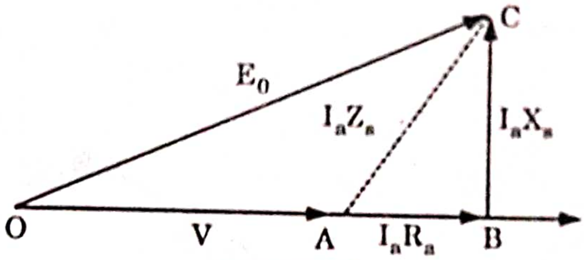

Fig. 1.17.2.

C. At leading power factor condition :

In $\Delta\,OCE$, $OC^2 = OE^2 + EC^2$

$\therefore$ $E_0^2 = (OD + DE)^2 + (BE - BC)^2$

$E_0^2 = (V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2$

$\therefore$ $E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2}$

$\therefore$ $\%\text{ Regulation} = \dfrac{E_0 - V}{V} \times 100$

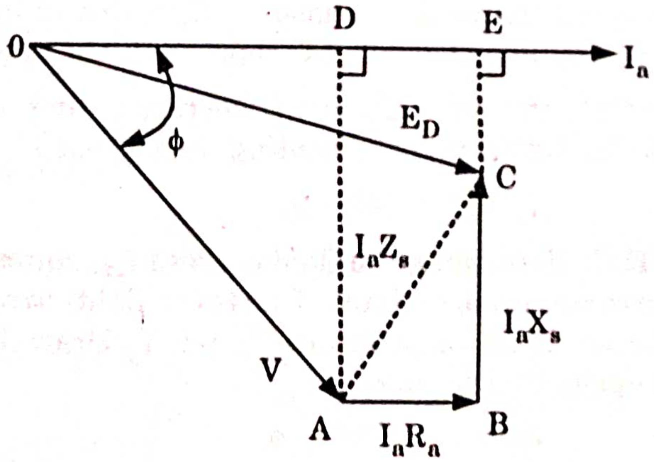

Fig. 1.17.3.

Que 1.18. State and explain the MMF method for calculation of voltage regulation of synchronous alternator.

AKTU 2015-16, Marks 10

Answer

1. This method is also known as ampere-turn method.
2. The mmf method replaces the effect of armature leakage reactance by an equivalent additional armature reaction mmf so that this mmf may be combined with the armature reaction mmf F_{ar}.
3. The following procedure is used for drawing the phasor diagram at lagging power factor cos ϕ.

a. The armature terminal voltage per phase (V) is taken as the reference phasor along OA.

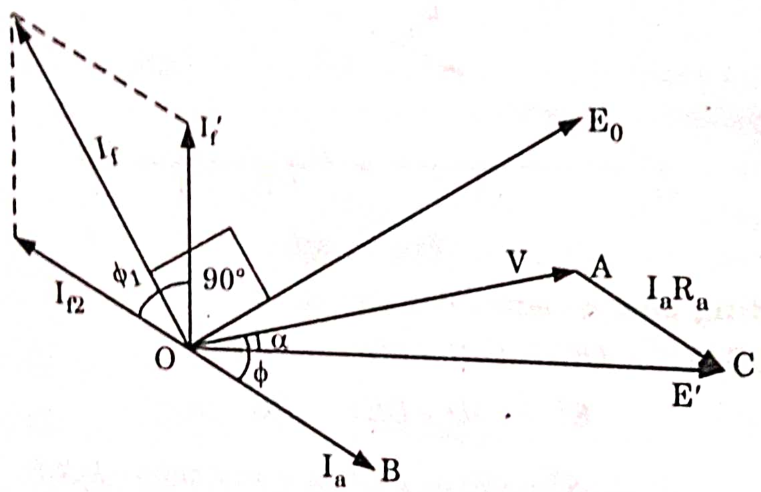

Fig. 1.18.1.

b. Armature current phasor I_a is drawn lagging the phasor V for lagging power factor angle ϕ for which the regulation is to be calculated.

c. The armature resistance drop phasor $I_a R_a$ is drawn inphase with I_a along the line AC. Join O and C. OC represents the emf E'.

d. From the O.C.C., the field current I_f' corresponding to voltage E' is noted. Draw the field current I_f' leading the voltage E' by 90°.

Thus, $$I_f' = I_f' \angle 90° - \alpha.$$

e. From the S.C.C., determine the field current I_{f2} required to calculate the rated current on short circuit. This is the field current required to overcome the synchronous reactance drop I_aX_s. Draw the field current I_{f2}, in phase opposition to current I_a.

Thus, $$I_{f2} = I_{f2} \angle 180° - \phi.$$

f. Determine the phasor sum of field currents I_f' and I_{f2}. This gives resultant field current I_f which would generate a voltage E_0 under no-load conditions of the alternator. The open-circuit emf E_0 corresponding to field current I_f is found from the open-circuit characteristic.

g. The regulation of the alternator is given from the relation,

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

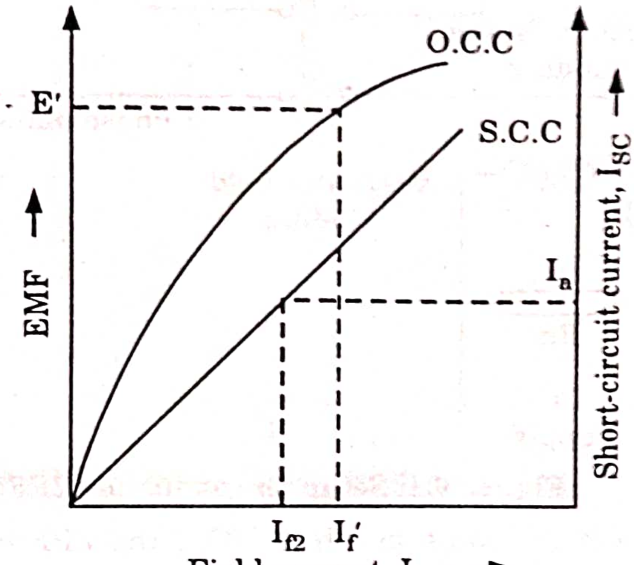

Fig. 1.18.2.

Que 1.19. **Explain clearly how stator leakage reactance and armature reactance are estimated by Potier's Triangle method ?**

AKTU 2012-13, Marks 05

OR

Explain procedure to draw Potier Triangle.

Answer

Two tests are conducted :

A. **Open circuit test :** Refer Q. 1.13, Page 1–21A, Unit-1.

B. **ZPF (Zero Power Factor) Test :** Steps in conduction of ZPF test are as follows as shown in Fig. 1.19.1.

1. The connections are made as per the circuit diagram. Initially the inductive load is kept closed (switch S is closed) and field excitation is kept minimum with rheostat (Rh).
2. The prime mover (PM) is started and speed is adjusted to rated speed.
3. The load is gradually increased till rated current is delivered by alternator at rated terminal voltage.
4. Due the inductive load the alternator operates at zero lagging pf ($\phi = 90°$ lag).

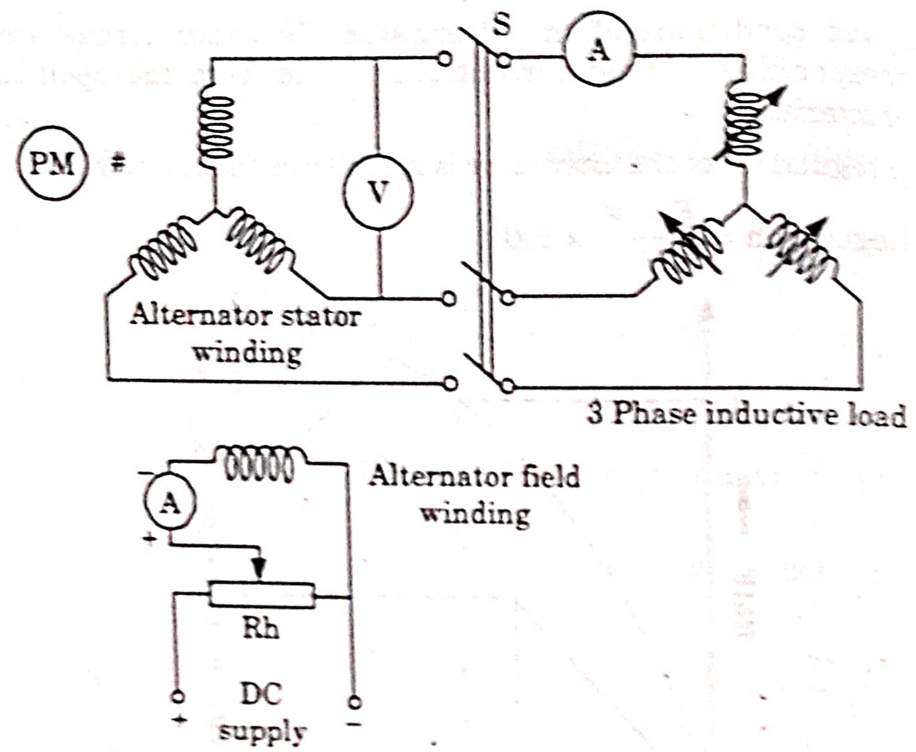

Fig. 1.19.1. Setup for conducting ZPF test.

Procedure : On the same graph of OCC, the ZPF characteristic is plotted. The procedure for plotting Potier's triangle is as follow :

1. Plot open circuit characteristic.
2. Plot the field current corresponding to zero terminal voltage *i.e.* short circuit full load zero pf current (point A). The point A lies on X-axis because alternator is shorted so voltage is zero.
3. Point P corresponds to a point when alternator delivers rated current at rated voltage with this purely inductive load. Thus point P is plotted. This point can be intermediate point also *i.e.* current less than full load current with rated voltage.
4. Line PQ is drawn parallel to OA and $l(OA) = l(PQ)$.
5. A tangent OM is drawn parallel to OCC. This tangent is known as air gap line.
6. From point Q, a line parallel to air gap line is drawn which cuts the OCC at point R. Thus P, Q, R points are obtained. These points are joined to form a ΔPQR.
7. A perpendicular RS is drawn on line PQ. The ΔPQR is known as Potier triangle.
8. This triangle is made to side downward such that PQ remains horizontal and point R slides on OCC. The locus of point P will be known as ZPF characteristics.
9. The perpendicular RS gives the voltage drop due to armature leakage reactance *i.e.*, $I_a X_L$.

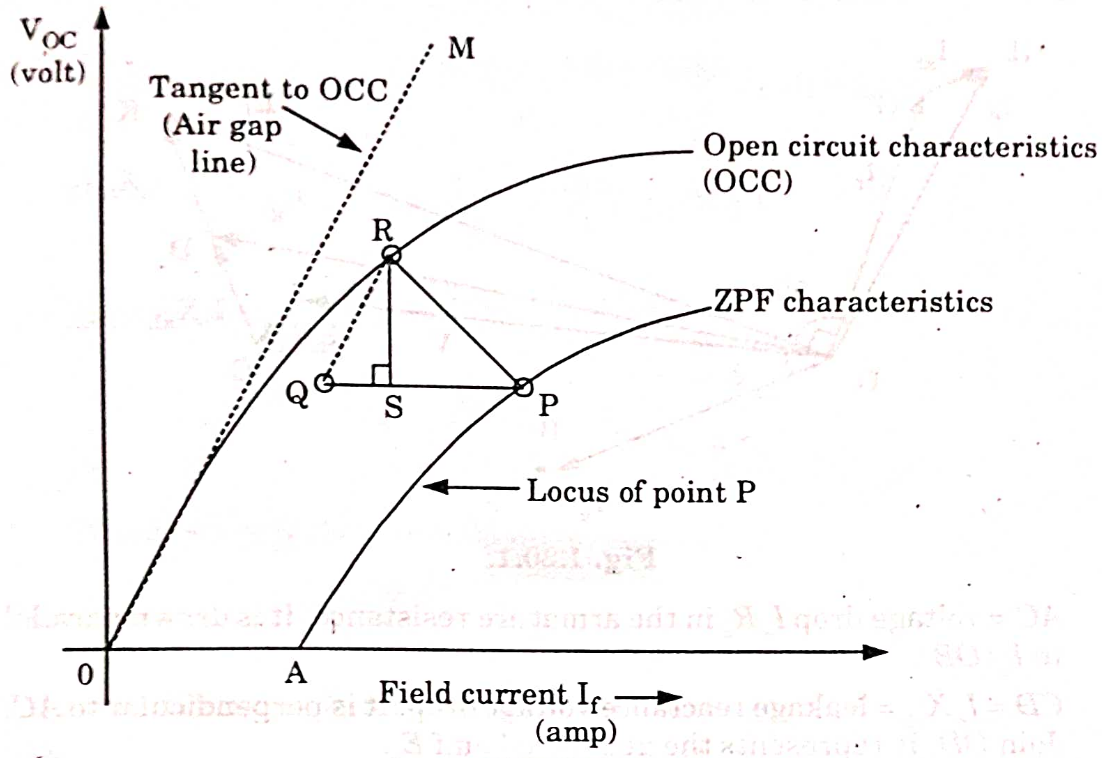

Fig. 1.19.2.

10. The length *PS* gives field current necessary to overcome demagnetising effect of armature reaction at full load.
11. The length *SQ* represents field current required to induce an emf for balancing leakage drop *RS*.
12. Armature leakage reactance, $X_L = \dfrac{RS}{(I_{aph})_{fl}}$. This is also known as Potier reactance. Potier reactance is also an approximation of stator leakage reactance.

Que 1.20. **Explain the Potier-triangle method of determining the voltage regulation of an alternator.** **AKTU 2014-15, Marks 10**

Answer

Potier triangle method (or ZPF method) :

To determine regulation using Potier triangle, the phasor diagram for lagging power factor cos ϕ is drawn as shown in Fig. 1.20.1. In the phasor diagram :

1. $OA = V$ = terminal phase voltage at full load. It is taken as reference phasor and drawn horizontally.
2. $OB = I_a$ = full-load current lagging behind V by an angle ϕ, cos ϕ is the power factor of the load.

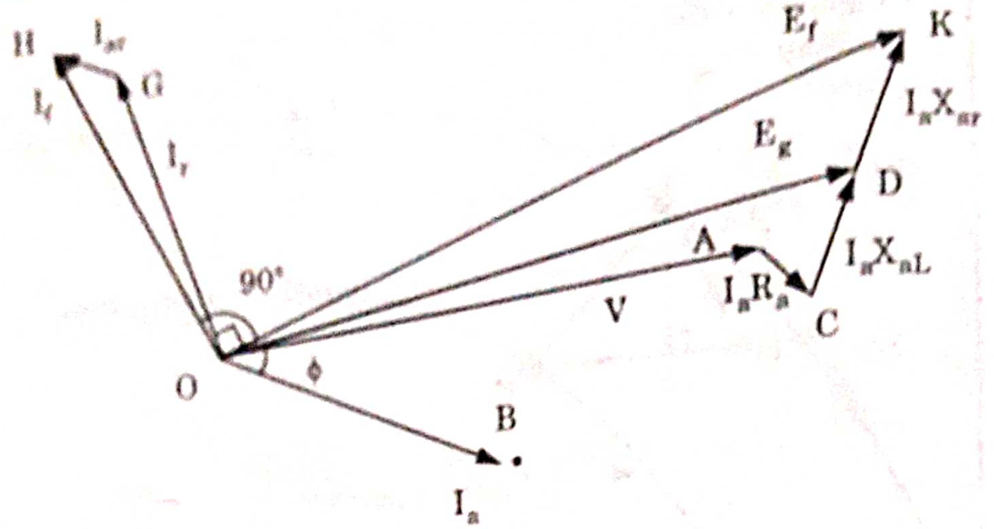

Fig. 1.20.1.

3. AC = voltage drop I_aR_a in the armature resistance. It is drawn parallel to I_a (OB).
4. $CD = I_aX_{aL}$ = leakage reactance voltage drop. It is perpendicular to AC. Join OD. It represents the generated emf E_g.
5. Find the field excitation current I_r corresponding to this generated emf E_g from the O.C.C. Draw OG (equal to I_r perpendicular to OD).
6. Draw GH parallel to load current OB $(= I_a)$ to represent excitation (field current) equivalent to full-load armature reaction I_{ar}. OH gives the total field current I_f
7. If the load is thrown off, then terminal voltage will be equal to generated emf, corresponding to field excitation OH.
8. Determine the emf $E_f (= OK)$ corresponding to field excitation OH from the O.C.C. Phasor OK will lag behind phasor OH by 90°. DK represents the voltage drop due to armature reaction.
9. Percentage voltage regulation = $\dfrac{E_f - V}{V} \times 100\ \%$.

Que 1.21. **A 3-phase, star connected alternator is rated at 1600 kVA, 13500 V. The armature effective resistance and synchronous reactance are 1.5 Ω and 30 Ω respectively per phase. Calculate the percentage regulation for a load of 1280 kW at power factor of**

i. 0.8 lagging

ii. 0.8 leading.

Answer

Given : Load = 1280 kW, V_L = 13500 V, S = 1600 kVA, R_e = 1.5 Ω, X_s = 30 Ω

To Find : Power factor at 0.8 lagging and 0.8 leading.

1. Load, $$S = \frac{\text{load in kW}}{\text{pf}} = \frac{1280}{0.8} = 1600 \text{ kVA}$$

2. Phase voltage, $$V_p = \frac{V_L}{\sqrt{3}} = \frac{13500}{\sqrt{3}} = 7794 \text{ V}$$

3. Load current, $$I = \frac{S \text{ in kVA} \times 1000}{\sqrt{3}\, V_L}$$

$$= \frac{1600 \times 1000}{\sqrt{3} V_L} = 68.4 \text{ A}$$

4. When power factor is 0.8 (lagging)

$$\cos \phi = 0.8$$

and $$\sin \phi = 0.6$$

Open circuit voltage per phase,

$$E_{op} = \sqrt{(V_p \cos \phi + IR_e)^2 + (V_p \sin \phi + IX_s)^2}$$

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

$$= 9243 \text{ V}$$

Percentage regulation

$$= \frac{E_{op} - V_p}{V_p} \times 100 = \frac{9243 - 7794}{7794} \times 100 = 18.59 \%$$

5. hen power factor is leading, $\cos \phi = 0.8$

and $$\sin \phi = -0.6$$

Open circuit voltage per phase,

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

$$= 6859.7 \text{ V}$$

$$\text{Percentage regulation} = \frac{6859.7 - 7794}{7794} \times 100 = -11.99 \%$$

PART-4

Parallel Operation of Synchronous Generators, Operation on Infinite Bus, Synchronizing Power and Torque Coefficient.

CONCEPT OUTLINE : PART-4

- **Reason for paralleling of alternators :**
1. Several alternators can supply a bigger load than a single alternator.
2. During periods of light load, one or more alternators may be shutdown, and those remaining operate at or near full load, and thus more efficiently.

- **Characteristics of an infinite bus :**
1. The terminal voltage remains constant.
2. The frequency remains constant.
3. The synchronous impedance is very small.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.22. **Explain necessity and conditions of parallel operation of alternator.**

Answer

A. Necessity :

1. **Load growth :** Load demand is now a day's increasing due to increasing use of electric power. Existing system may not be sufficient to meet with the increased demand and hence additional units of alternators to be added to satisfy the increased demand.
2. **Continuity of service :** Instead of only one unit supplying the power many smaller units shall run on the system so that if any of the unit fails the other can meet the demand and continuity can be maintained.
3. **Repairs :** The units are sometimes to be taken off from the system for repair works. In its place other unit is to be paralleled to the circuit so that faulty unit can be taken off for repair work.
4. **Maintenance :** As per the maintenance schedule the units are to be switched off and taken out electrically so the other unit shall continue the supply and one unit may be paralleled to the system.
5. **Efficiency :** The machine works to its maximum efficiency at nearly to its full load capacity. If the demand on the system decreases, then that unit may operate at a lower load condition at a lower frequency. This is not economical. Hence bigger unit is to be shut off and smaller unit may be introduced so that smaller unit can work to its full capacity at higher efficiency.

B. Conditions for satisfactory parallel operation of alternators :

1. A stationary alternator must not be connected to live bus-bars as its $E = 0$ and hence short circuit may occur.
2. The terminal voltage of the incoming alternator must be same as the bus-bar voltage (rms values).
3. The generated frequency of the incoming alternator must be same as the bus-bar frequency.
4. The phase sequence of the incoming alternator must be same as the phase sequence of bus bar.
5. The polarity of the incoming alternator terminals must be same as the bus-bar terminals. The magnitude of the voltage of the alternator can be adjusted by field regulator and frequency can be adjusted by speed variation.

Que 1.23. **Discuss different methods of synchronization.**

Answer

A. Dark lamp method of synchronization :

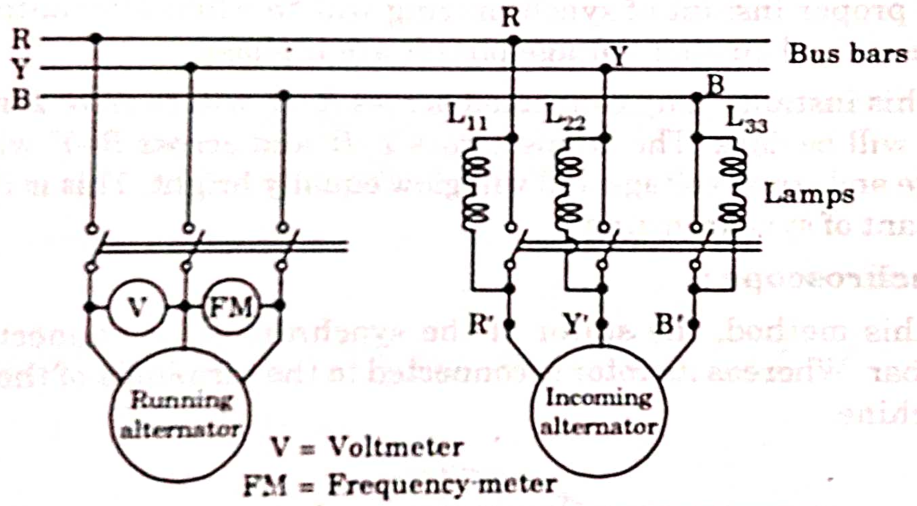

Fig. 1.23.1. Dark lamp method of synchronizing.

1. The three lamp pairs L_{11}, L_{22} and L_{33} of equal watts and voltage ratings are connected as shown in the Fig. 1.23.1 across the switch and to the bus-bar and alternator terminals.
2. If the bus-bar voltage phasor and the alternator voltage phasor are in-phase with each other, then, the polarities of bus-bar and alternator are same and at this instant, the voltage across each lamp will be zero and the lamps will be dark.
3. This is the proper instant of synchronizing. The synchronizing switch is made ON so that the incoming alternator is connected to the system satisfactorily.

B. One dark two equally bright lamp method or bright lamp method of synchronizing :

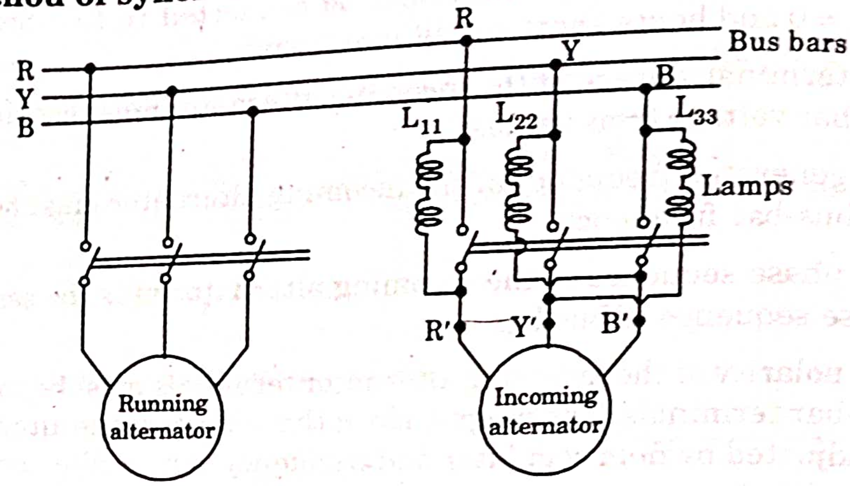

Fig. 1.23.2. One dark, two equally bright lamp method of synchronizing.

1. In this method, the lamp connections are made as shown in Fig. 1.23.2. One lamp is directly connected across $R - R'$ and the other two are cross-connected.
2. The proper instant of synchronizing will be when alternator voltage phasors and bus-bar voltage phasor are inphase.
3. At this instant, lamp connected across $R–R'$ will receive zero voltage and will be dark. The lamps across $Y–B'$ and across $B–Y'$ will receive large and equal voltage and will glow equally bright. This is the proper instant of synchronizing.

C. Synchroscope :

1. In this method, the stator of the synchroscope is connected to the busbar. Whereas its rotor is connected to the terminals of the incoming machine.

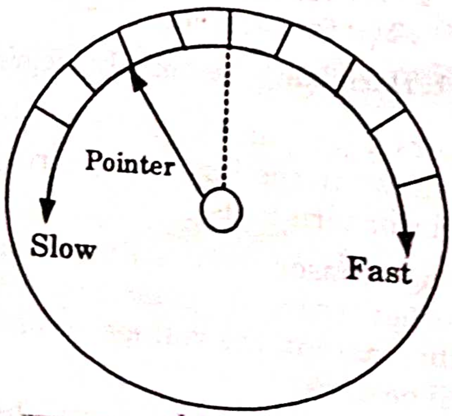

Fig. 1.23.3. Synchroscope.

2. If the incoming alternator is slow, the pointer of the synchroscope turns in anticlockwise direction and indicates 'slow' and vice-versa.

3. When the speed of the alternator is proper so that its frequency is equal to the bus bar frequency, the pointer of synchroscope is at the central portion. This is the correct instant of synchronizing.

Que 1.24. **Explain the parallel operation of alternators and also discuss the process of synchronism.** **AKTU 2016-17, Marks 7.5**

Answer

A. Parallel operation of alternators :

1. Consider two identical alternators connected in parallel as shown in Fig. 1.24.1

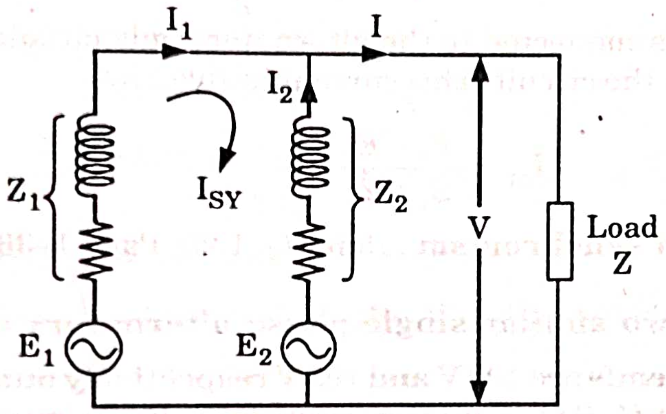

Fig. 1.24.1.

2. The terminal voltage V is given by,

$$\bar{V} = \bar{E}_1 - \bar{I}_1 \bar{Z}_1 = \bar{E}_2 - \bar{I}_2 \bar{Z}_2$$

Terminal voltage, $\bar{V} = \bar{I}\,\bar{Z}$ and Load current $\bar{I} = \bar{I}_1 + \bar{I}_2$

3. From the above expression,

$$\bar{E}_1 = \bar{V} + \bar{I}_1 \bar{Z}_1$$

$$\therefore \quad \bar{E}_1 = \bar{I}\,\bar{Z} + \bar{I}_1 \bar{Z}_1 = (\bar{I}_1 + \bar{I}_2)\bar{Z} + \bar{I}_1 \bar{Z}_1$$

$$= \bar{I}_1 (\bar{Z} + \bar{Z}_1) + \bar{I}_2 \bar{Z} \quad \text{...(1.24.1)}$$

Also
$$\bar{E}_2 = \bar{I}\,\bar{Z} + \bar{I}_2 \bar{Z}_2 = (\bar{I}_1 + \bar{I}_2)\bar{Z} + \bar{I}_2 \bar{Z}_2$$

$$= \bar{I}_2 (\bar{Z} + \bar{Z}_2) + \bar{I}_1 \bar{Z} \quad \text{...(1.24.2)}$$

4. Solving eq. (1.24.1) and (1.24.2) simultaneously,

$$\bar{I}_1 = \frac{(\bar{E}_1 - \bar{E}_2)\bar{Z} + \bar{E}_1 \bar{Z}_2}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

and
$$\bar{I}_2 = \frac{(\bar{E}_2 - \bar{E}_1)\bar{Z} + \bar{E}_2 \bar{Z}_1}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

$$\bar{I} = \bar{I}_1 + \bar{I}_2 = \frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

5.

$$= \frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{\bar{Z}\left[(\bar{Z}_1 + \bar{Z}_2) + \frac{\bar{Z}_1 \bar{Z}_2}{\bar{Z}}\right]}$$

6.

$$\bar{V} = \bar{I}\,\bar{Z} = \bar{Z}\,\frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{\bar{Z}\left[(\bar{Z}_1 + \bar{Z}_2) + \frac{\bar{Z}_1 \bar{Z}_2}{\bar{Z}}\right]}$$

$$= \frac{\bar{E}_1 \bar{Z}_2 + \bar{E}_2 \bar{Z}_1}{(\bar{Z}_1 + \bar{Z}_2) + \frac{\bar{Z}_1 \bar{Z}_2}{\bar{Z}}}$$

7. If no load is connected to the alternators only circulating current I_{SY} will flow in the circuit. This current is given by,

$$\bar{I}_{SY} = \frac{\bar{E}_1 - \bar{E}_2}{\bar{Z}_1 + \bar{Z}_2}$$

B. **Process of synchronism :** Refer Q. 1.23, Page 1–36A, Unit-1.

Que 1.25. **Two similar single-phase alternators are running in parallel. Their emfs are 100 V and 105 V respectively and the impedance of each is (0.2 + j1.0) Ω. Find the terminal voltage, current and power supplied by each machine to a load impedance of (2 + j3) Ω.**

AKTU 2012-13, Marks 05

Answer

Given : $\bar{E}_1 = 100 + j0 = 100 \angle 0°$ V, $\bar{E}_2 = 105 + j0 = 105 \angle 0$ V,

$\bar{Z}_1 = \bar{Z}_2 = 0.2 + j1\ \Omega = 1.0198 \angle 78.69°\ \Omega°$, $\bar{Z}_L = 2 + j3\ \Omega$

To Find : V, I_1, I_2, P_1, P_2.

1. Let
$$V = E_1 - I_1 Z_1$$
$\therefore$
$$V = (100 + j0) - I_1(0.2 + j1) \quad ...(1.25.1)$$
Similarly,
$$V = E_2 - I_2 Z_2 = (105 + j0) - I_2\,(0.2 + j1) \quad ...(1.25.2)$$
Also,
$$V = IZ_L = (I_1 + I_2)\,Z_L = (I_1 + I_2)\,(2 + j3) \quad ...(1.25.3)$$
2. Adding eq. (1.25.1) and eq. (1.25.2),
$$2V = (205 + j0) - (I_1 + I_2)\,(0.2 + j1)$$
$\therefore$
$$V = 102.5 - (0.1 + j0.5)\,(I_1 + I_2) \quad ...(1.25.4)$$
3. Multiplying (0.1 + j0.5) in both sides of eq. (1.25.3), we get
$$(0.1 + j0.5)V = (0.1 + j0.5)(2 + j3)\,(I_1 + I_2) \quad ...(1.25.5)$$

4. Multiplying $(2 + j3)$ in eq. (1.25.4), we get

$$(2 + j3)V = (2 + j3)(102.5) - (2 + j3)(0.1 + j0.5)(I_1 + I_2) \quad ...(1.25.6)$$

5. Adding eq. (1.25.5) and eq. (1.25.6),

$$V[2.1 + j3.5] = (102.5)(2 + j3)$$

$$\therefore \quad V = \frac{102.5 \times 3.6055 \angle 56.31^\circ}{4.0816 \angle 59.036^\circ}$$

$$= 90.5438 \angle -2.726^\circ \text{ V}$$

6. $$I_1 = \frac{E_1 - V}{Z_1} = \frac{(100 + j0) - (90.441 - j4.306)}{1.0198 \angle 78.69^\circ}$$

$$= \frac{9.559 + j4.306}{1.0198 \angle 78.69^\circ}$$

$$= \frac{10.484 \angle 42.25^\circ}{1.0198 \angle 78.69^\circ} = 10.2804 \angle -54.44^\circ \text{ A} \quad ...(1.25.7)$$

From eq. (1.25.7), $\phi_1 = -54.44^\circ$

7. $$P_1 = VI_1 \cos \phi_1 = 90.5438 \times 10.2804 \times \cos(-54.44^\circ)$$

$$= 541.327 \text{ W}$$

8. $$I_2 = \frac{E_2 - V}{Z_2} = \frac{(105 + j0) - (90.441 - j4.306)}{1.0198 \angle 78.69^\circ}$$

$$= 14.8876 \angle -62.214^\circ \text{ A}$$

9. $$P_2 = VI_2 \cos \phi_2 = 90.5438 \times 14.8876 \times \cos(-62.214^\circ)$$

$$= 628.388 \text{ W}$$

Que 1.26. **What is an infinite bus ? An alternator connected to infinite bus is operating at rated load and unity power factor, how its operation shall be affected by increasing the field current in respect of induced emf, torque angle and power factor ?**

AKTU 2012-13, Marks 05

OR

Explain the effect of varying excitation in a synchronous generator connected to the infinite busbar. **AKTU 2016-17, Marks 7.5**

Answer

A. Infinite bus :

An infinite bus is a power system so large that its voltage and frequency remains constant regardless of how much real and reactive power is drawn from or supplied to it.

B. Effect on operation :

1. Let us consider that alternator is supplying power to an infinite bus which has induced emf E, power angle δ and working at unity power factor with current I.
2. With mechanical power input to the alternator remaining constant, the power given by $\frac{EV}{X_s}$ sin δ will remain constant.
3. If by varying excitation induced emf E is increased to E_1 then the load angle will also change from δ to δ_1.
4. From the phasor diagram it can be determined as $E_1 \sin \delta_1 = E \sin \delta$ as V and X_s are constant. The drop due to synchronous reactance also increases and armature current increases from I to I_1.
5. This current has two components one real component and other quadrature component. This quadrature component is nothing but demagnetizing component. This will result in lagging power factor cos ϕ_1.
6. Similarly if the excitation is decreased so that induced emf reduces from E to E_2 with corresponding change in power angle from δ to δ_2. The armature current in this case will be I_2 which has real component and magnetizing component which results in leading power factor cos ϕ_2. This can be represented in the phasor diagram shown in Fig. 1.26.1.

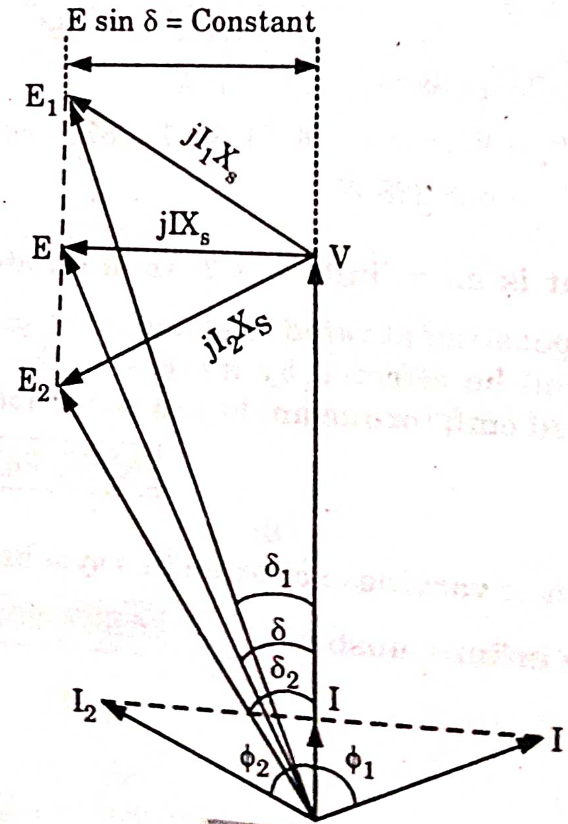

Fig. 1.26.1.

7. From the phasor diagram it can be seen that

$$I_1 \cos \phi_1 = I_2 \cos \phi_2 = I$$

Multiplying by V throughout,

$$V I_1 \cos \phi_1 = V I_2 \cos \phi_2 = VI$$

8. This indicates that power delivered to the bus will remain constant. Thus by changing the field excitation the active power is unaltered. But change in excitation results in corresponding operating power factor as shown in Fig. 1.26.1.

Que 1.27. **Discuss synchronous power and synchronous torque co-efficient for synchronous machine.**

Answer

1. Consider a synchronous generator transferring a steady power P_0 at a steady load angle δ_0.
2. Suppose that, due to a transient disturbance, the rotor of the generator accelerates, so that the load angle increases by an angle $d\delta$.
3. The operating point of the machine shifts to a new constant-power line and the load on the machine increases to $P_0 + \delta P$.
4. Since the steady power input remains unchanged, this additional load decreases the speed of the machine and brings it back to synchronism.
5. Similarly, if due to a transient disturbance, the rotor of the machine retards, so that the load angle decreases.
6. The operating point of the machine shifts to a new constant power line and the load on the machine decreases to $P_0 - \delta P$.
7. Since the steady power input remains unchanged, the reduction in load accelerates the rotor. Consequently, the machine again comes in synchronism.
8. The effectiveness of this correcting action depends on the change in power transfer for a given change in load angle. The measure of effectiveness is given by synchronizing power coefficient.
9. It is defined as the rate at which the synchronous power P varies with the load angle δ. It is also called stiffness of coupling, rigidity factor, or stability factor and is denoted by P_{syn}.

$$P_{syn} = \frac{dP}{d\delta} \quad \text{...(1.27.1)}$$

10. Power output per phase of the cylindrical rotor generator

$$P = \frac{V}{Z_s}[E_f \cos(\theta_z - \delta) - V \cos \theta_z]$$

$$\therefore \quad P_{syn} = \frac{dP}{d\delta} = \frac{VE_f}{Z_s} \sin(\theta_z - \delta). \quad \text{...(1.27.2)}$$

11. The synchronizing torque coefficient

$$\tau_{syn} = \frac{d\tau}{d\delta} = \frac{1}{2\,\pi n_s}\frac{dP}{d\delta}$$

$$\tau_{syn} = \frac{VE_f}{2\pi\, n_s\, Z_s}\sin(\theta_z - \delta) \qquad \text{...(1.27.3)}$$

12. For a cylindrical rotor machine, neglecting saturating and stator resistance eq. (1.27.2) and (1.27.3) become

$$P_{syn} = \frac{V\,E_f}{X_s}\cos\delta \qquad \text{...(1.27.4)}$$

$$\tau_{syn} = \frac{V\,E_f}{2pi\; n_s\, X_s}\cos\delta \qquad \text{...(1.27.5)}$$

13. For a salient-pole machine

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

$$\therefore \quad P_{syn} = \frac{V\,E_f}{X_s}\cos\delta + V^2\left(\frac{1}{X_d} - \frac{1}{X_q}\right)\cos 2\delta \qquad \text{...(1.27.6)}$$

Que 1.28. **A 1500 kVA, 3-phase star-connected 6.6 kV, 8-pole, 50 Hz synchronous generator has a reactance of 0.6 pu and negligible resistance. Calculate the synchronizing power per mechanical degree at full load and 0.8 power factor lagging.**

AKTU 2016-17, Marks 10

Answer

Given : $V_L = 6.6$ kV, $f = 50$ Hz, $P = 1500$ kVA, $P = 8$
To Find: Synchronizing power, P_{syn}.

1. $$V_p = \frac{6.6 \times 1000}{\sqrt{3}} = 3810.51 \text{ V}$$

2. $$I_a = \frac{(1500) \times 1000}{\sqrt{3} \times 6600} = 131.22 \text{ A}$$

3. $\therefore$ $$X_{s\,pu} = \frac{I_a X_{s\Omega}}{V_p}$$

$$X_{s\Omega} = \frac{V_p}{I_a} = 0.6 \times \frac{3810.5}{131.2} = 17.42\ \Omega$$

4. $$E_f = V_p + I_a Z_s$$
$$= V_p + (I_a \angle -\phi)(X_s \angle 90°)$$

$$= V_p + I_a X_s \angle 90° - \phi$$
$$= V_p + I_a X_s[\cos (90° - \phi) + j \sin (90° - \phi)]$$
$$= V_p + I_a X_s (\sin \phi + j \cos \phi)$$
$$= (V_p + I_a X_s \sin \phi) + j I_a X_s \cos \phi$$
$$= (3810.5 + 131.2 \times 17.42 \times 0.6) + j\, 131.2 \times 17.42 \times 0.8$$
$$= 5638.9 + j\, 1828.40 = 5928 \angle 17.96° \text{ V}$$
$$\therefore \quad E_f = 5928 \text{ V}, \delta = 17.96°$$

5. Synchronizing power per mechanical degree

$$P_{syn} = \left(\frac{dP}{d\delta}\right) p \frac{\pi}{180}$$
$$= \left(\frac{3 V_p E_f}{X_s} \cos \delta\right) p \frac{\pi}{180}$$
$$= \frac{3 \times 3810.5 \times 5928}{17.42} \cos 17.96° \times \frac{4\pi}{180}$$
$$= 258340.6 \text{ W} = 258.3406 \text{ kW.}$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Discuss the constructional details and working principles of 3ϕ synchronous machines. Also mention its applications.

Ans. Refer Q. 1.1, Unit-1.

Q. 2. Why a rotating field system preferred against a stationary field in a synchronous machine ? A 2 pole alternator rotates at 3000 rpm. What is the frequency of the generated emf ?

Ans. Refer Q. 1.4, Unit-1.

Q. 3. Explain EMF equation of alternator. A 3ϕ, 50 Hz, 8-pole alternator has a star-connected winding with 120 slots and 8 conductors per slot. The flux per pole is 0.05 Wb, sinusoidally distributed. Determine the phase and line voltages.

Ans. Refer Q. 1.9, Unit-1.

Q. 4. Define equivalent circuit of synchronous machine. Also define its phasor diagram.

Ans. Refer Q. 1.11, Unit-1.

Q. 5. Describe in detail armature reaction and its effects under different power factor.

Ans. Refer Q. 1.12, Unit-1.

Q. 6. What do you mean by "O. C. C." and "S. C. C." in synchronous machines ? Determine the value of synchronous reactance and short circuit ratio from O.C.C. and S. C.C.

Ans. Refer Q. 1.13, Unit-1.

Q. 7. Sketch and explain the open-circuit and short-circuit characteristics of a synchronous machine. How voltage regulation can be calculated by the use of their results ?

Ans. Refer Q. 1.16, Unit-1.

Q. 8. Explain the Potier-triangle method of determining the voltage regulation of an alternator.

Ans. Refer Q. 1.20, Unit-1.

Q. 9. Explain the parallel operation of alternators and also discuss the process of synchronism.

Ans. Refer Q. 1.24, Unit-1.

Q. 10. What is an infinite bus ? An alternator connected to infinite bus is operating at rated load and unity power factor, how its operation shall be affected by increasing the field current in respect of induced emf, torque angle and power factor ?

Ans. Refer Q. 1.26, Unit-1.

☺☺☺

2 UNIT

Synchronous Machine-II

PART-1

Two Reaction Theory, Power Flow Equation of Cylindrical and Salient Pole Machines, Operating Characteristics.

CONCEPT OUTLINE : PART-1

- **Two reaction theory :** The theory proposes to resolve the given armature MMF into two mutually perpendicular components, direct axis (d-axis), located along the axis of rotor of salient pole and quadrature axis (q-axis), located perpendicular to the rotor axis of salient pole.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.1. **Discuss two reaction theory applicable for salient and non-salient pole synchronous machine.**

OR

Explain the two reaction theory applicable to salient-pole synchronous machine.

AKTU 2014-15, Marks 10

Answer

A. Two reaction theory :

1. The theory proposes to resolve the given armature mmfs into two mutually perpendicular components, with one located along the axis of the rotor salient pole. It is known as the direct-axis (or d-axis) component.
2. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature-axis (or q-axis) component.
3. The d-axis component of the armature mmf F_a is denoted by F_d and the q-axis component by F_q.
4. The component F_d is either magnetizing or demagnetizing. The component F_q results in a cross-magnetizing effect.
5. If ψ is the angle between the armature current I_a and the excitation voltage E_f and F_a is the amplitude of the armature mmf, then

$$F_d = F_a \sin \psi$$

and

$$F_q = F_a \cos \psi$$

B. Salient pole synchronous machine two reaction theory :

1. In the cylindrical rotor synchronous machine, the air gap is uniform. The pole structure of the rotor of a salient pole machine makes the air gap highly non-uniform.
2. Consider a 2 pole, salient pole rotor rotating in the anticlockwise direction within a 2 pole stator as shown in the Fig. 2.1.1.

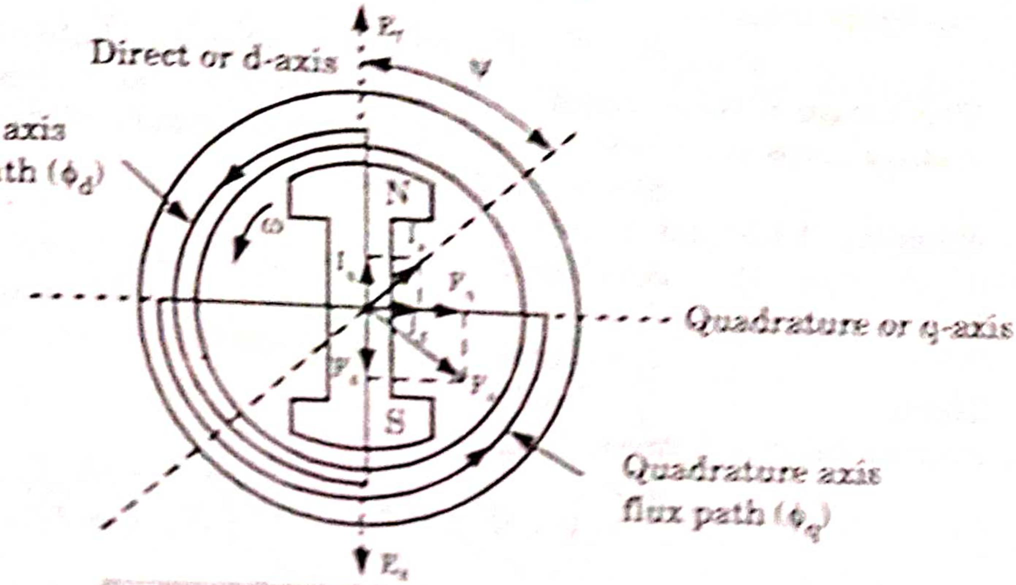

Fig. 2.1.1. Salient pole alternator.

3. The axis along the axis of the rotor is called the *d*-axis. The axis perpendicular to *d*-axis is known as the *q*-axis. The direct axis flux path involves two small air gaps and is the path of the minimum reluctance. The path shown in Fig. 2.1.1 by ϕ_q has two large air gaps and is the path of the maximum reluctance.
4. The rotor flux induces a voltage E_f in the stator. The stator armature current I_a will flow through the synchronous motor when a lagging power factor load is connected to it. This stator armature current I_a lags behind the generated voltage E_f by an angle ψ.
5. The armature current produces stator magnetomotive force (MMF) F_a. This MMF lags behind I_a 90°. The MMF F_a produces stator magnetic field along the direction of F_a. The stator MMF is resolved into two components, namely the direct axis component F_d and the quadrature axis component F_q.
6. If,

$$\phi_d = \text{Direct axis flux}$$
$$\phi_q = \text{Quadrature axis flux}$$
$$R_d = \text{Reluctance of the direct axis flux path}$$

Then,
$$\phi_d = \frac{F_d}{R_d}, \phi_q = \frac{F_q}{R_q}$$

7. The fluxes of the direct and quadrature axis produce a voltage in the windings of the stator by armature reaction.

$$E_{ad} = -jX_{ad}I_d \quad ...(2.1.1)$$
$$E_{aq} = -jX_{aq}I_q \quad ...(2.1.2)$$

Where,
E_{ad} = Direct axis component armature reaction voltage
E_{aq} = Quadrature axis component armature reaction voltage
X_{ad} = Direct axis armature reaction reactance
X_{aq} = Quadrature axis armature reaction reactance

8. The total voltage E' induced in the stator is the sum of EMF induced by the field excitation.

$$E' = E_f + E_{ad} + E_{aq} = E_f - jX_{ad}I_d - jX_{aq}I_q \quad ...(2.1.3)$$

9. The voltage E' is also equal to the sum of the terminal voltage V and the voltage drops in the resistance and leakage reactance of the armature.

$$E' = V + R_aI_a + jX_1I_a \quad ...(2.1.4)$$

10. From eq. (2.1.3) and (2.1.4)

$$E_f = V + R_aI_a + jX_1I_a + jX_{ad}I_d + jX_{aq}I_q \quad ...(2.1.5)$$

11. If
I_q = q-axis component of I_a in phase with E_f
I_d = d-axis I_a lagging E_f by 90°

Then,
$$I_a = I_d + I_q \quad ...(2.1.6)$$

12. Putting value of I_a in eq. (2.1.5), we get

$$\begin{aligned} E_f &= V + R_a(I_d + I_q) + jX_1(I_d + I_q) + jX_{ad}I_d + jX_{aq}I_q \\ &= V + R_a(I_d + I_q) + j(X_1 + X_{ad})I_d + j(X_1 + X_{aq})I_q \\ &= V + R_aI_a + jX_dI_d + jX_qI_q \end{aligned} \quad ...(2.1.7)$$

Where,
X_d = Direct axis synchronous reactance
X_q = Quadrature axis synchronous reactance

Eq. (2.1.7) is the final voltage equation for a salient pole synchronous generator.

Que 2.2. **State and explain two reaction theories applicable to cylindrical synchronous machine. Also give the real power and reactive power flow equations of the cylindrical machine.**

AKTU 2015-16, Marks 15

Answer

A. **Two reaction theory :** Refer Q. 2.1, Page 2–2A, Unit-2.

B. **Derivation :**

1. Let,
V = Terminal voltage per phase
E_f = Excitation voltage per phase
I_a = Armature current
δ = Phase angle between E_f and V.

2. For a synchronous generator, $\vec{E}_f$ leads $\vec{V}$ by angle δ.

$$\vec{V} = V\angle 0°, \quad \vec{E}_f = E_f\angle\delta$$

$$\vec{Z}_s = R_a + jX_s = Z_s\angle\theta_z \; [Z_s = \text{Synchronous impedance}]$$

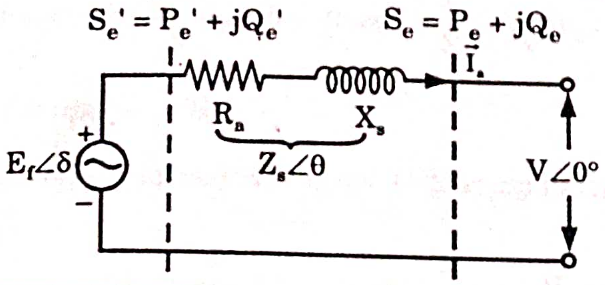

Fig. 2.2.1. Circuit model of cylindrical rotor synchronous generator.

3. From impedance triangle shown in Fig. 2.2.3,

$$\theta_z = \tan^{-1}\frac{X_s}{R_a} \text{ and } \alpha_z = 90 - \theta_z = \tan^{-1}\frac{R_a}{X_s}$$

4. Let subscripts i, o, g and m denote input, output, generator and motor respectively. From Fig. 2.2.1, $\vec{E}_f = \vec{V} + \vec{Z}_s\,\vec{I}_a$ ...(2.2.1)

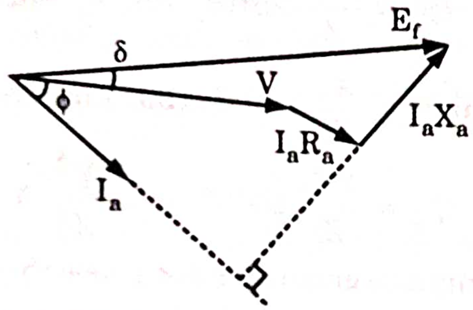

Fig. 2.2.2. Phasor diagram at lagging pf.

$$\vec{I}_a = \frac{\vec{E}_f - \vec{V}}{\vec{Z}_s} \quad \text{...(2.2.2)}$$

5. Complex power output of the generator per phase (S_{og})

$$S_{og} = P_{og} + jQ_{og} = \vec{V}\,\vec{I}_a^{\,*} \quad \text{...(2.2.3)}$$

$$= \vec{V}\left(\frac{\vec{E}_f - \vec{V}}{\vec{Z}_s}\right)^* = V\angle 0°\left(\frac{E_f\angle\delta - V\angle 0}{Z_s\angle\theta_z}\right)^*$$

$$= V\angle 0°\left(\frac{E_f}{Z_s}\angle(\delta-\theta_z) - \frac{V\angle-\theta_z}{Z_s}\right)^* = \frac{VE_f}{Z_s}\angle(\theta_z - \delta) - \frac{V^2}{Z_s}\angle\theta_z$$

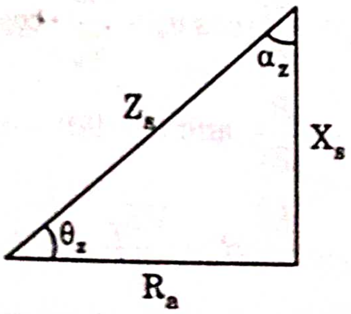

Fig. 2.2.3. Impedance triangle.

$$\therefore \quad P_{og} + jQ_{og} = \frac{VE_f}{Z_s}\cos(\theta_z - \delta) + j\frac{VE_f}{Z_s}\sin(\theta_z - \delta) - \frac{V^2}{Z_s}(\cos\theta_z + j\sin\theta_z) \quad ...(2.2.4)$$

6. Equating real part of eq. (2.2.4), we get real output (also called electrical power)

$$P_{og} = \frac{VE_f}{Z_s}\cos(\theta_z - \delta) - \frac{V^2}{Z_s}\cos\theta_z$$

Since $\cos\theta_z = \frac{R_a}{Z_s}$ and $\theta_z = 90° - \alpha_z$

we get $$P_{og} = \frac{VE_f}{Z_s}\sin(\delta + \alpha_z) - \frac{V^2}{Z_s^2}R_a \quad ...(2.2.5)$$

7. Equating imaginary parts of eq. (2.2.4), we get reactive output power

$$Q_{og} = \frac{VE_f}{Z_s}\sin(\theta_z - \delta) - \frac{V^2}{Z_s}\sin\theta_z$$

Since $\sin\theta_z = \frac{X_s}{Z_s}$ and $\theta_z = 90° - \alpha_z$

we get $$Q_{og} = \frac{VE_f}{Z_s}\cos(\delta + \alpha_z) - \frac{V^2}{Z_s^2}X_s \quad ...(2.2.6)$$

8. Complex power input to generator per phase (S_{ig})

$$S_{ig} = P_{ig} + jQ_{ig} = \bar{E}_f \bar{I}_a^*$$

$$= E_f\angle\delta\left(\frac{E_f}{Z_s}\angle(\theta_z - \delta) - \frac{V}{Z_s}\angle\theta_z\right)$$

$$= \frac{E_f^2}{Z_s}\angle\theta_z - \frac{VE_f}{Z_s}\angle(\theta_z + \delta)$$

$$\therefore \quad P_{ig} + jQ_{ig} = \frac{E_f^2}{Z_s}\cos\theta_z + j\frac{E_f^2}{Z_s}\sin\theta_z - \left[\frac{VE_f}{Z_s}\cos(\theta_z + \delta) + j\frac{VE_f}{Z_s}\sin(\theta_z + \delta)\right] \quad ...(2.2.7)$$

9. Equating real part of eq. (2.2.7), we get real power input

$$P_{ig} = \frac{E_f^2}{Z_s}\cos\theta_z - \frac{VE_f}{Z_s}\cos(\theta_z + \delta)$$

Since $\cos\theta_z = \frac{R_a}{Z_s}$ and $\theta_z = 90° - \alpha_z$

we get $$P_{ig} = \frac{E_f^2}{Z_s^2}R_a + \frac{VE_f}{Z_s}\sin(\delta - \theta_z) \quad ...(2.2.8)$$

10. Equating imaginary part of eq. (2.2.7), we get reactive power input

$$Q_{ig} = \frac{E_f^2}{Z_s}\sin\theta_z - \frac{VE_f}{Z_s}\sin(\theta_z + \delta)$$

Since $\sin\theta_z = \dfrac{X_s}{Z_s}$ and $\theta_z = 90° - \alpha_z$

we get $$Q_{ig} = \frac{E_f^2}{Z_s^2}X_s - \frac{VE_f}{Z_s}\cos(\delta - \alpha_z) \quad ...(2.2.9)$$

Que 2.3. **Discuss two reaction theory. Derive expression of developed power (P_d) for a salient pole synchronous machine ignoring armature resistance and draw power vs power angle characteristic. Why a salient pole machine is more stable as compared to a cylindrical rotor machine ?**

AKTU 2012-13, Marks 10

OR

Derive an expression for the active power for a salient pole synchronous machine. Also compare the salient and non-salient pole synchronous machines.

AKTU 2016-17, Marks 10

Answer

A. **Two reaction theory :** Refer Q. 2.1, Page 2–2A, Unit-2.

B. **Derivation :**

1. The resistance R_a of armature has negligible effect on relationship between power output of a synchronous machine and its torque angles. It may, therefore, be neglected. The phasor diagram at lagging pf for a salient pole synchronous generator, neglecting R_a is shown in Fig. 2.3.1.
2. The complex power output per phase, $S_{1\phi} = VI_a^*$ ...(2.3.1)
3. Taking $\vec{E_f}$ as the reference phasor

$$\vec{V} = V\angle -\delta = V\cos\delta - jV\sin\delta$$
$$I_a = I_q - jI_d$$
$$I_a^* = I_q + jI_d$$

$$\therefore \quad S_{1\phi} = \vec{V}I_a^* = (V\cos\delta - jV\sin\delta)(I_q + jI_d) \quad ...(2.3.2)$$

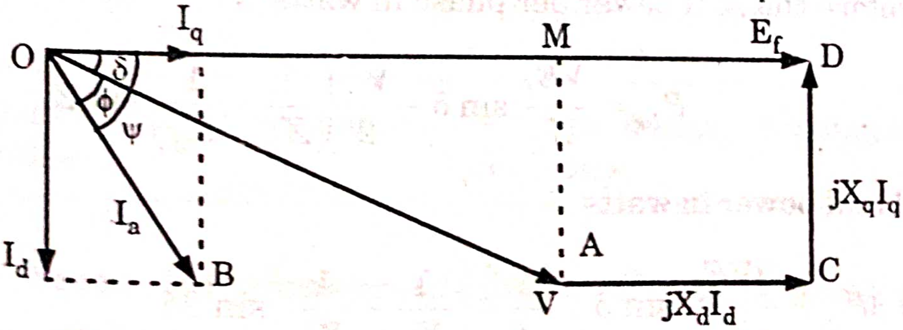

Fig. 2.3.1. Phasor diagram at lagging pf of a salient-pole generator, neglecting R_a.

4. From the phasor diagram of Fig. 2.3.1, we get

$$X_q I_q = CD = AM = V \sin \delta$$

$$I_q = \frac{V \sin \delta}{X_q} \quad ...(2.3.3)$$

$$X_d I_d = AC = MD = OD - OM = E_f - V \cos \delta$$

$$I_d = \frac{E_f - V \cos \delta}{X_d} \quad ...(2.3.4)$$

5. Substituting the values of I_q and I_d in eq. (2.3.2), we get

$$S_{1\phi} = (V \cos \delta - jV \sin \delta)\left(\frac{V \sin \delta}{X_q} + j\frac{E_f - V \cos \delta}{X_d}\right)$$

$$= \left(\frac{V^2}{X_q} \sin \delta \cos \delta + \frac{VE_f}{X_d} \sin \delta - \frac{V^2}{X_d} \sin \delta \cos \delta\right)$$

$$+ j\left(\frac{VE_f}{X_d} \cos \delta - \frac{V^2}{X_d} \cos^2 \delta - \frac{V^2}{X_q} \sin^2 \delta\right)$$

$$= \left[\frac{VE_f}{X_d} \sin \delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta\right]$$

$$+ j\left[\frac{VE_f}{X_d} \cos \delta - \frac{V^2}{2X_d}(1 + \cos 2\delta) - \frac{V^2}{2X_q}(1 - \cos 2\delta)\right]$$

$$= \left[\frac{VE_f}{X_d} \sin \delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta\right]$$

$$+ j\left[\frac{VE_f}{X_d} \cos \delta - \frac{V^2}{2X_d X_q}\{(X_q + X_d) - (X_d - X_q) \cos 2\delta\}\right] \quad ...(2.3.5)$$

6. Also, $S_{1\phi} = P_{1\phi} + jQ_{1\phi}$ ...(2.3.6)

7. Therefore the real power per phase in watts is

$$P_{1\phi} = \frac{VE_f}{X_d} \sin \delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta$$

Total real power in watts

$$P_{3\phi} = 3P_{1\phi} = \frac{3VE_f}{X_d} \sin \delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta \quad ...(2.3.7)$$

C. **Power vs Angle Characteristics :**

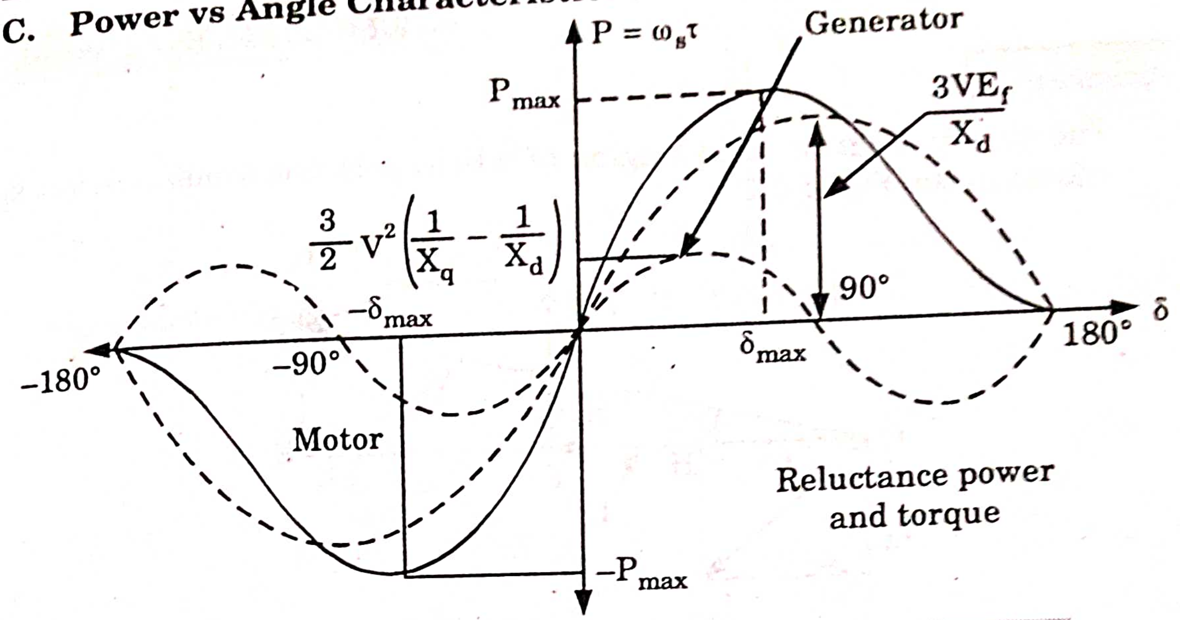

Fig. 2.3.2. Power-angle curve of a salient-pole machine.

D. **Reason :**

1. Saliency describes the effect of differing sizes of air gap around the circumference of the rotor.
2. This is important with salient pole rotors and the effect varies with the apparent internal reactance of the machine depending upon the relative position of rotor and stator.
3. Saliency tends to make the machine 'stiffer'. That is, for a given load, the load angle is smaller with salient pole machine.
4. Salient pole machines are therefore, more stable as compared to cylindrical rotor machine.

E. **Comparison :**

S. No.	Salient pole	Non-salient pole
1.	Air gap is non-uniform.	Air gap is uniform due to smooth cylindrical periphery.
2.	Mechanically weak.	Mechanically robust.
3.	Preferred for low speed alternators.	Preferred for high speed alternators *i.e.*, for turboalternators.
4.	Separate damper winding is provided.	Separate damper winding is not necessary.

Que 2.4. **From the phasor diagram of the salient pole synchronous machine, show that :**

$$\tan \delta = \frac{I_a X_q \cos \phi - I_a R_a \sin \phi}{V_t - I_a X_q \sin \phi - I_a R_a \cos \phi}$$

where the symbols having their usual meanings.

AKTU 2013-14, Marks 10

Answer

1. The phasor diagram for a lagging pf salient pole synchronous motor is shown in the Fig. 2.4.1.

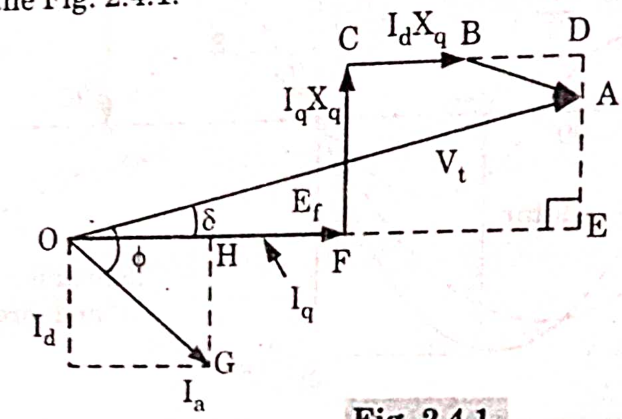

Fig. 2.4.1.

2. From phasor diagram,

$$\sin \delta = \frac{AE}{OA} = \frac{AE}{V_t}$$

$$AE = DE - AD$$

$$\therefore \quad AE = FC - AD = I_qX_q - I_dR_a$$

$$\therefore \quad \sin \delta = \frac{I_qX_q - I_dR_a}{V_t}$$

$$V_t \sin \delta = I_qX_q - I_dR_a \quad \ldots(2.4.1)$$

3. From triangle OGH,

$$\cos(\phi - \delta) = \frac{I_q}{I_a} \text{ and } \sin(\phi - \delta) = \frac{I_d}{I_a}$$

$$\therefore \quad I_q = I_a \cos(\phi - \delta) \text{ and } I_d = I_a \sin(\phi - \delta)$$

4. Putting value of I_d and I_q in eq. 2.4.1, we get

$$V_t \sin \delta = I_a \cos(\phi - \delta)X_q - I_a \sin(\phi - \delta)R_a$$

$$\therefore \quad V_t \sin \delta = I_aX_q [\cos \phi \cos \delta + \sin \phi \sin \delta]$$
$$- I_aR_a [\sin \phi \cos \delta - \cos \phi \sin \delta]$$

$$\sin \delta [V_t - I_aX_q \sin \phi - I_aR_a \cos \phi] = [I_aX_q \cos \phi - I_aR_a \sin \phi] \cos \delta$$

$$\therefore \quad \tan \delta = \frac{\sin \delta}{\cos \delta} = \frac{I_aX_q \cos \phi - I_aR_a \sin \phi}{V_t - I_aX_q \sin \phi - I_aR_a \cos \phi}$$

Que 2.5. **Explain the operation of synchronous machine on constant excitation variable load.**

Answer

1. Fig. 2.5.1 shows the circuit diagrams and phasor diagrams of a synchronous machine in generating mode (Fig. 2.5.1(*a*) and Fig. 2.5.1(*c*)) and motoring mode (Fig. 2.5.1(*b*) and Fig. 2.5.1(*d*)).

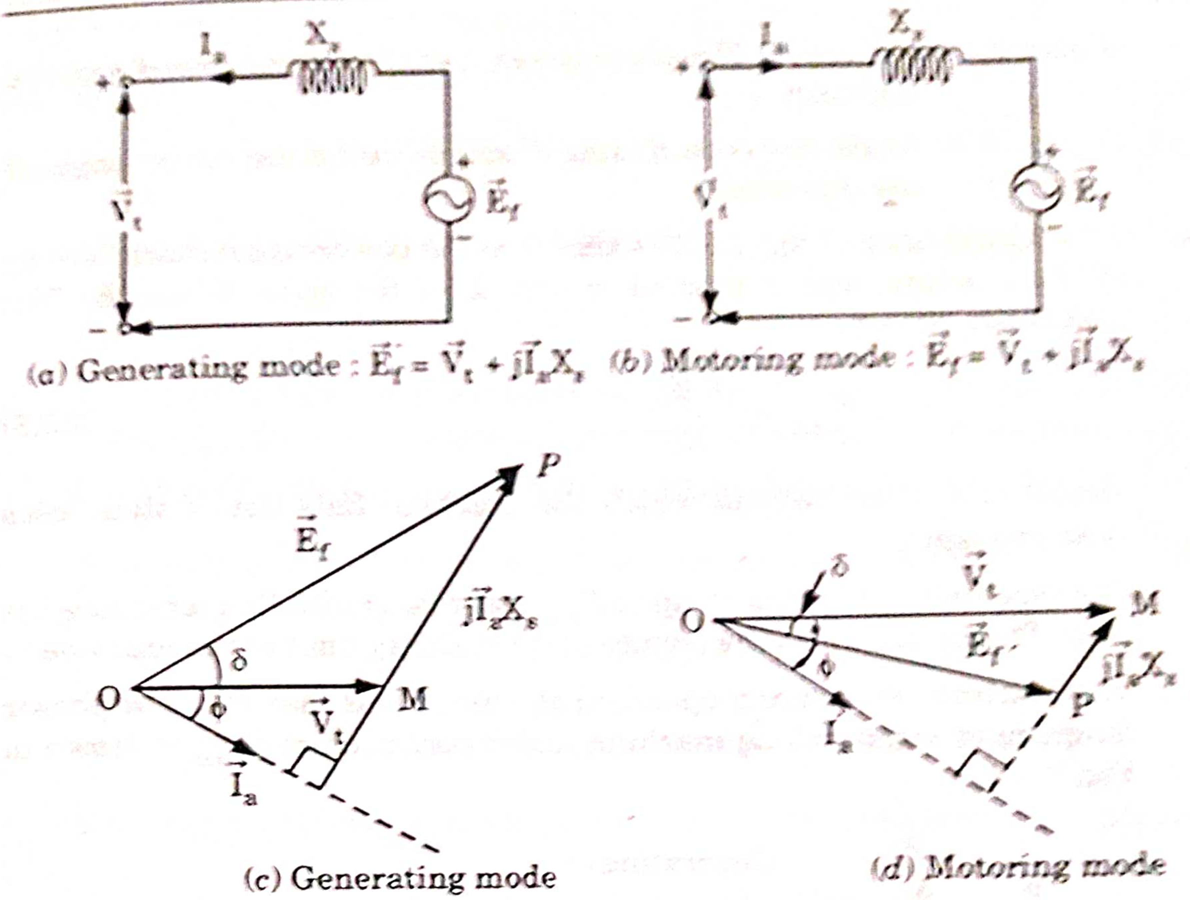

Fig. 2.5.1. Synchronous machine operation (generating/motoring mode).

2. The machine is assumed to be connected to infinite bus-bars of voltage V_t.
3. It is observed from the phasor diagrams that in generating mode, the excitation emf E_f leads V_t by angle δ, while it lags V_t in the motoring mode.
4. It follows from the phasor triangle OMP (Fig. 2.5.1(*c*) and Fig. 2.5.1(*d*)) that

$$\frac{E_f}{\sin(90 \pm \phi)} = \frac{I_a X_s}{\sin \delta};$$

(90° + ϕ), generating; (90° − ϕ), motoring

$$I_a \cos\phi = \frac{E_f}{X_s}\sin\delta \quad ...(2.5.1)$$

where ϕ is the power factor angle.

5. Multiplying both sides of eq. (2.5.1) by V_t

$$V_t I_a \cos\phi = \frac{V_t E_f}{X_s}\sin\delta$$

$$P_e = \frac{V_t E_f}{X_s}\sin\delta \quad ...(2.5.2)$$

where $P_e = V_t I_a \cos\phi$ = Electrical power (per phase) exchanged with the bus-bars

δ = Angle between E_f and V_t and is called the power angle of the machine.

6. This relationship of eq. (2.5.2) is known as the power-angle characteristic of the machine and is plotted in Fig. 2.5.2 for given V_t and E_f. The maximum power

$$P_{e\,max} = \frac{V_t E_f}{X_s} \qquad ...(2.5.3)$$

occurs at $\delta = 90°$ beyond which the machine falls out of step (loses synchronism).

7. The machine can be taken up to $P_{e\,max}$ only be gradually increasing the load. This is known as the steady-state stability limit of the machine.

8. The machine is normally operated at δ much less than 90°. The phasor diagram of a generating machine under condition of $P_{e\,max}$ is drawn in Fig. 2.5.3.

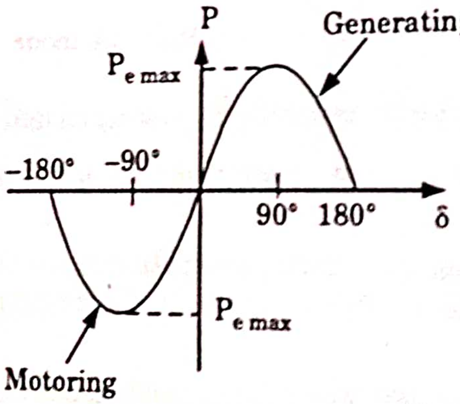

Fig. 2.5.2. Power-angle characteristic

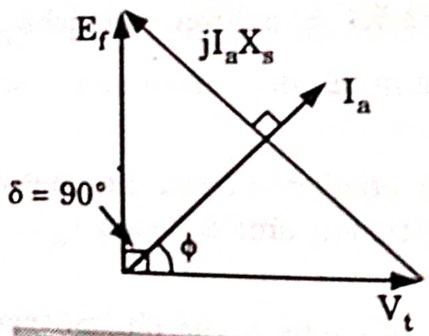

Fig. 2.5.3. Phasor diagram of generating machine at steady-state stability limit.

Que 2.6. **Explain operation of synchronous machine at constant load with variable excitation.**

Answer

1. Power, $$P_e = \frac{V_t E_f}{X_s} \sin\delta \qquad ...(2.6.1)$$

where,

P_e = Electrical power exchanged with bus bar

δ = Angle between E_f and V_t

E_f = Excitation emf

V_t = Terminal voltage.

2. At constant load, from eq. (2.6.1)

$$E_f \sin \delta = \frac{P_e X_s}{V_t} = \text{Constant.} \quad ...(2.6.2)$$

Also $V_t I_a \cos \phi = P_e = \text{Constant.}$

$$I_a \cos \phi = \frac{P_e}{V_t} = \text{Constant.}$$

3. At constant load, as the excitation emf E_f is varied (by varying field current I_f), the power angle δ varies such that $E_f \sin \delta$ remains constant.
4. The phasor diagrams of machine are shown in Fig. 2.6.1(*a*) and 2.6.1(*b*).

   As E_f varies, the tip of phasor $\vec{E}_f$ moves on a line parallel to $\vec{V}_t$ and at distance $E_f \sin \delta = P_e X_s / V_t$ from it.
5. Since $I_a \cos \phi$ = constant, the projection of the current phasor on V_t must remain constant, *i.e.*, the tip of the current phasor traces a line perpendicular to V_t at distance $I_a \cos \phi = P_e / V_t$ from the origin.
6. The current phasor $\vec{I}_a$ is always located at 90° to phasor $\vec{I}_a X_s$ (phasor joining tips to $\vec{E}_f$ and $\vec{V}_t$ in the direction of $\vec{E}_f$).
7. The effect of varying excitation (E_f) on machine operating characteristic is brought out by Fig. 2.6.1(*a*) and Fig. 2.6.1(*b*).
8. **Normal excitation :** At this excitation the machine operation meets the condition $E_f \cos \delta = V_t$ at which machine power factor is unity.

   Over excitation : $E_f \cos \delta > V_t$

   Under excitation: $E_f \cos < V_t$
9. The following conclusions are drawn from the phasor diagrams of Fig. 2.6.1(*a*) and Fig. 2.6.1(*b*).

i. **Generating Machine :**

a. The machine supplies a lagging power factor current when over-excited.

b. The machine supplies a leading power factor current when under-excited.

ii. **Motoring machine :**

a. The machine draws a leading power factor current when over-excited.

b. The machine draws a lagging power factor current when under-excited.

iii. **Minimum excitation :**

From Fig. 2.6.1(*a*) and Fig. 2.6.1(*b*) it is seen that as excitation is reduced, the angle δ continuously increases. The minimum permissible excitation, E_f(min), corresponds to the stability limit, *i.e.*, $\delta = 90°$.

$$E_f(\text{min}) = \frac{P_e X_s}{V_t}$$

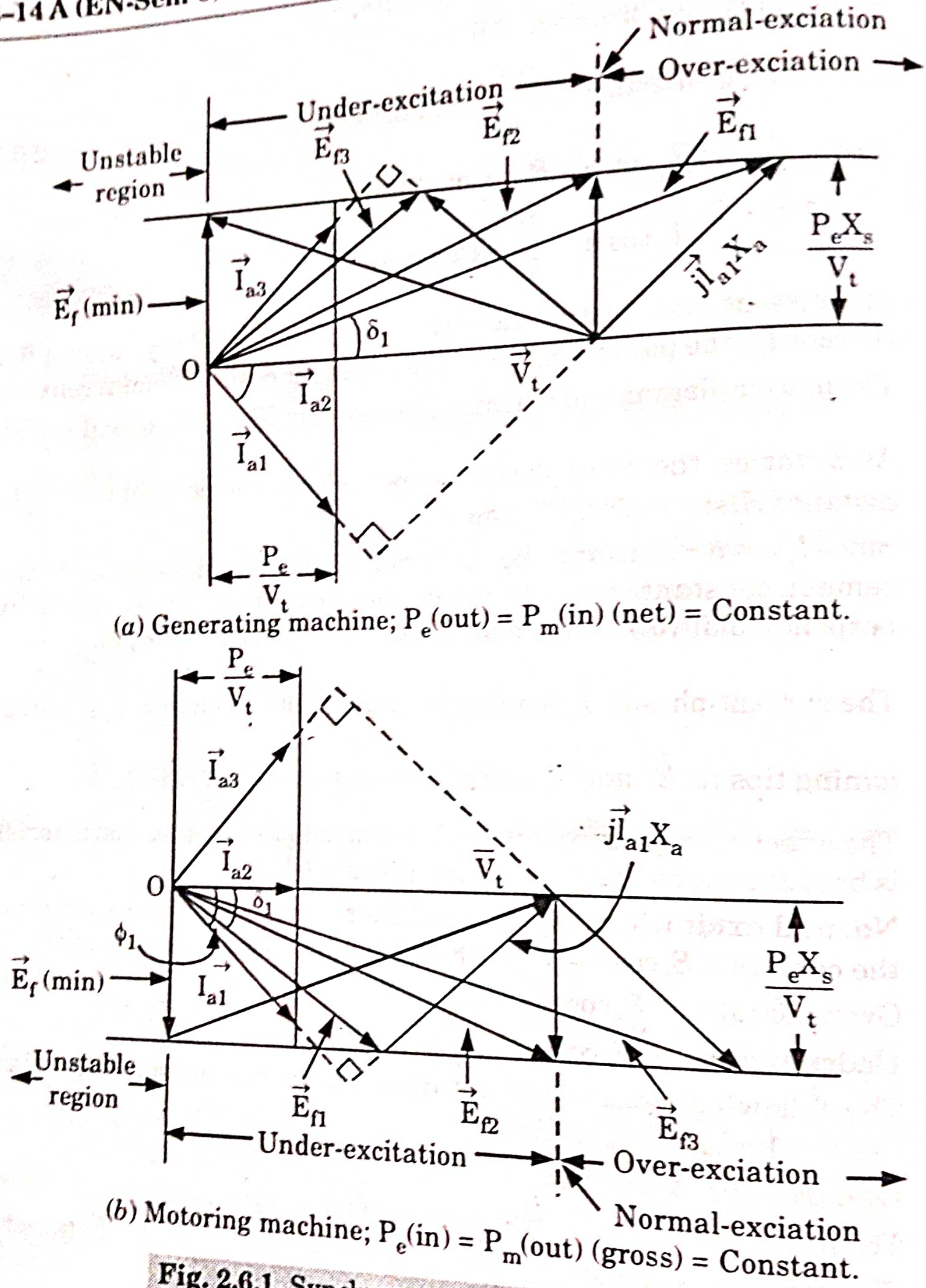

Fig. 2.6.1. Synchronous machine operation at constant load and variable excitation.

PART-2

Synchronous Motor-Starting Methods, Effect of varying field Current at Different Loads, V-curves, Hunting and Damping, Synchronous Condenser.

CONCEPT OUTLINE : PART-2

- Synchronous motor is not self starting motor, it is started by an auxiliary motor and then synchronized to mains. Before loading, it is floating on the mains; drawing or delivering almost zero current.
- **Excitation emf :**

$$E_f = V_t \cos \delta + I_d R_a + I_d X_d \text{ (generating)}$$
$$E_f = V_t \cos \delta - I_d R_a + I_d X_d \text{ (motoring)}$$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.7. **Explain the constructional features and working principle of the synchronous motor and develop the torque expression of synchronous motor.** **AKTU 2015-16, Marks 10**

Answer

A. **Construction :**
It consists of two parts :

1. **Stator :** Consisting of a three-phase star or delta connected winding. This is excited by a three-phase AC supply.
2. **Rotor :** Rotor is a field winding, the construction of which can be salient (projected pole) or non-salient (cylindrical) type. Practically most of the synchronous motors use salient *i.e.*, projected pole type construction. The field winding is excited by a separated DC supply through slip rings.

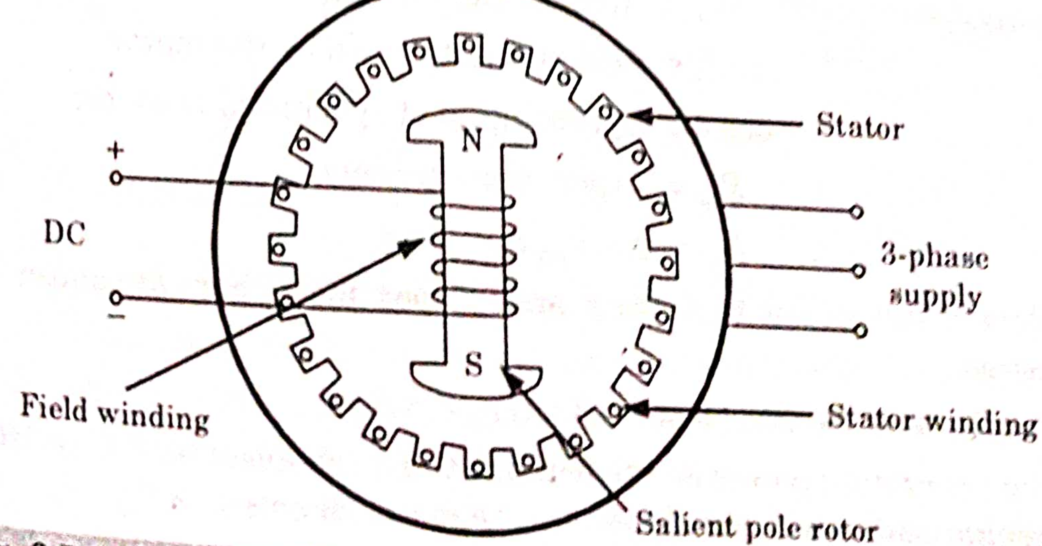

Fig. 2.7.1. Schematic representation of three-phase synchronous motor.

B. Working principle :

1. Consider the 2-pole synchronous motor. When a 3-phase AC voltage is applied to the stator winding, a rotating magnetic field is produced in the air gap.
2. The stator field rotates at synchronous speed.

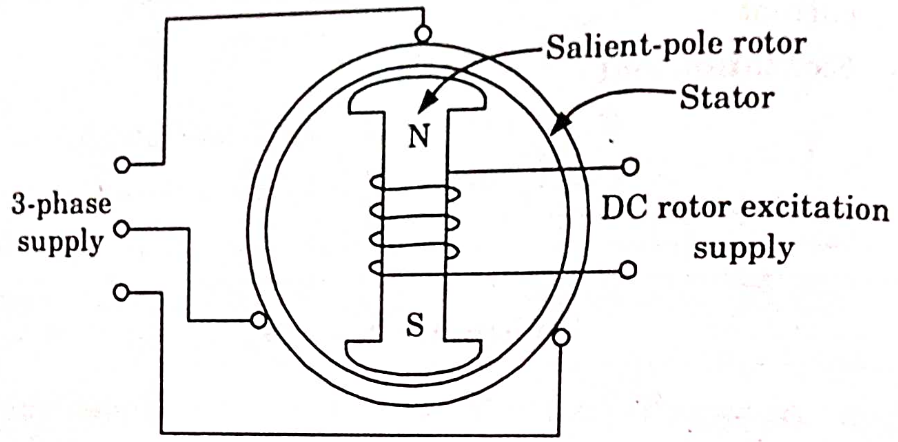

Fig. 2.7.2. A 2-pole synchronous motor.

3. The field current of the motor produces a steady-state magnetic field. Therefore, there are two magnetic fields present in the machine.
4. The rotor will tend to align with the stator field. Since, the stator magnetic field is rotating, the rotor magnetic field and the rotor will tend to rotate with the rotating field of the stator.
5. In order to develop a continuous torque, the two fields must be stationary with respect to each other. This is possible only when the rotor also rotates at synchronous speed. Hence rotor rotates at synchronous speed.

C. Torque Expression :

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

$\therefore$
$$P_{in} = \sqrt{3}\, V_L\, I_L \cos \phi$$

where

V_L = Applied line voltage

I_L = Line current drawn by the motor

$\cos \phi$ = Operating pf of synchronous motor

2. $$P_{in} = 3 \text{ (per phase power)}$$
$$P_{in} = 3 \times V_{ph}\, I_{aph} \cos \phi$$
3. Now in stator, due to its resistance R_a per phase there are stator copper losses.

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

4. The remaining power is converted to the mechanical power, called gross mechanical power developed by the motor denoted as P_m.
$$P_m = P_{in} - \text{Stator copper losses}$$

5. Now,
$$P = T \times \omega$$
$$\therefore \quad P_m = T_g \times \frac{2\pi N_s}{60}$$
$$\therefore \quad T_g = \frac{P_m \times 60}{2\pi N_s}$$

This is the gross mechanical torque developed.

6. Net output of the motor can be obtained by subtracting friction and winding *i.e.*, mechanical losses from gross mechanical power developed.
$$\therefore \quad P_{out} = P_m - \text{Mechanical losses}$$

7. $$\therefore \quad T_{shaft} = \frac{P_{out} \times 60}{2\pi N_s} \text{ N-m}$$

where T_{shaft} = Shaft torque available to load
P_{out} = Power available to load.

Que 2.8. **Explain why 3ϕ synchronous machines are not self-starting ? What are the methods for starting of the 3ϕ synchronous machines ?**

Answer

A. Reason :

1. Consider a 2-pole synchronous motor. When a 3-phase AC voltage is applied to the stator winding, a rotating magnetic field is produced in the air gap. The stator field rotates at synchronous speed.

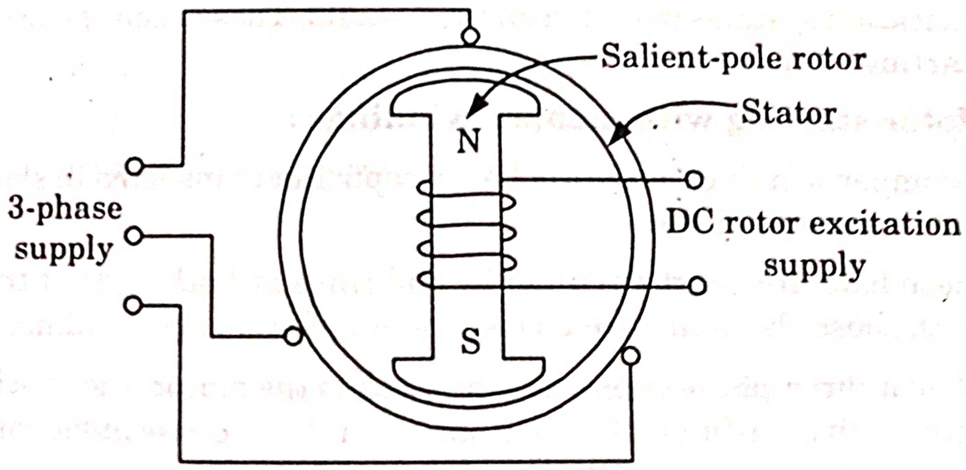

Fig. 2.8.1. A 2-pole synchronous motor.

2. The field current of the motor produces a steady-state magnetic field.
3. Therefore, there are two magnetic fields present in the machine. The rotor will tend to align with the stator field.
4. Since, the stator magnetic field is rotating, the rotor magnetic field and the rotor will tend to rotate with the rotating field of the stator.

5. In order to develop a continuous torque, the two fields must be stationary with respect to each other.
6. This is possible only when the rotor also rotates at synchronous speed.
7. Let us assume that the rotor is stationary. When a pair of rotating stator poles sweeps across the stationary rotor poles at synchronous speed, the stator poles will tend to rotate the rotor in one direction and then in the other direction.
8. However, because of the rotor inertia, the stator field slides by so fast that the rotor cannot follow it.
9. Consequently, the rotor does not move and we can say that the starting torque is zero. Hence, a synchronous motor is not self-starting.

B. **Starting methods :**

i. **Motor starting with an external prime mover :**

1. In this method an external motor drives the synchronous motor and brings it to synchronous speed.
2. The synchronous machine is then synchronised with the bus-bar as a synchronous generator. The prime mover is then disconnected.
3. Once in parallel, the synchronous machine will work as a motor.
4. Now the load can be connected to the synchronous motor. Since load is not connected to the synchronous motor before synchronising, the starting motor has to overcome the inertia of the synchronous motor at no load.
5. Therefore the rating of the starting motor is much smaller than the rating of the synchronous motor.
6. At present most of large synchronous motors are provided with brushless excitation systems mounted on their shafts. These exciters are used as starting motors.

ii. **Motor starting with damper windings :**

1. A damper winding consists of heavy copper bars inserted in slots of the pole faces of the rotor.
2. These bars are short-circuited by end rings at both ends of the rotor. Thus, these short-circuited bars form a squirrel-cage winding.
3. When a three-phase supply is connected to the stator, the synchronous motor with damper winding will start as a three-phase induction motor.
4. As the motor approaches synchronous speed, the DC excitation is applied to the field windings.
5. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed. As rotor rotates at synchronous speed, the relative motion between damper winding and rotating magnetic field is zero.

Que 2.9. **Define the V-curves and inverted V-curves at different loading conditions of synchronous motors.**

Answer

1. Let us assume that the motor is operating at no load.
2. If the field current is increased from this small value, the armature current I_a decreases until the armature current becomes minimum and the motor is operating at unity power factor. Upto this point the motor was operating at a lagging power factor.
3. If the field current is increased further, the armature current increases again and the motor starts to operate at a leading power factor.
4. If a graph is plotted between armature current I_a and field current I_f at no load, the lowest curve in Fig. 2.9.1 is obtained.
5. If this procedure is repeated for various increased loads, a family of curves is obtained as shown in Fig. 2.9.1.
6. Since the shape of these curves resembles the letter "V", these curves are commonly known as V-curves of a synchronous motor.
7. The V-curves are useful in adjusting the field current. Increasing the field current I_f beyond the level for minimum armature current I_a results in leading power factor and vice-versa.

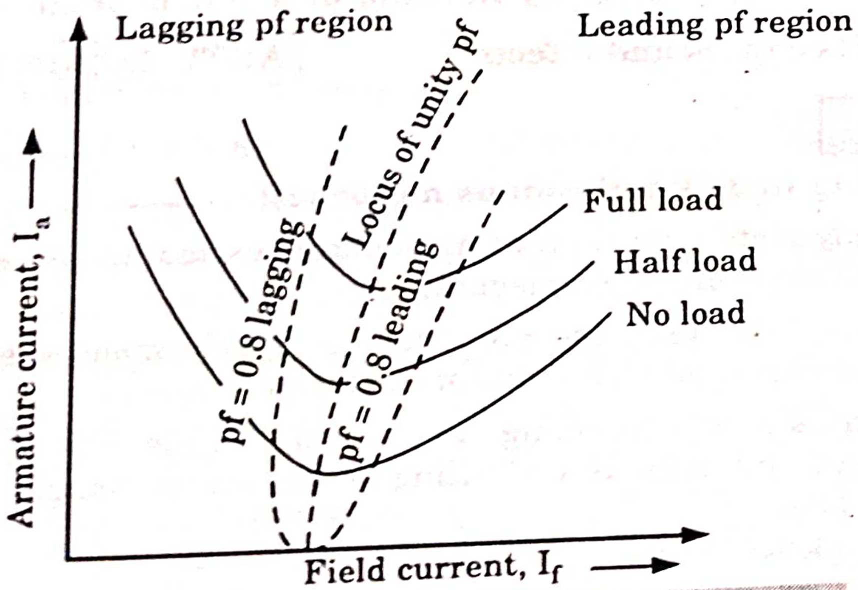

Fig. 2.9.1. V-curves of a synchronous motor.

8. Therefore, by controlling the field current of a synchronous motor, the reactive power supplied to or consumed from the power system can be controlled.
9. A family of curves is also obtained by plotting the power factor versus field current. These are inverted V-curves as shown in Fig. 2.9.2.

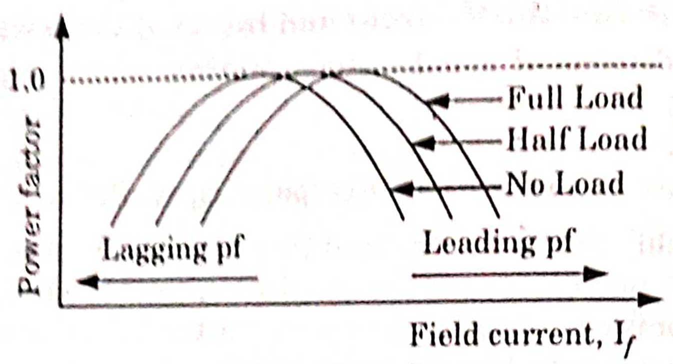

Fig. 2.9.2. Power factor versus field current at different loads (Inverted V-curve).

Que 2.10. **What are the causes of "HUNTING" in synchronous machines ? How is it minimised ? What are the advantages and disadvantages of "HUNTING" in synchronous machines ?**

AKTU 2013-14, Marks 10

OR

Explain hunting of a synchronous machine. What are V-curves of a synchronous motor ? **AKTU 2014-15, Marks 10**

OR

What do you understand by hunting of a synchronous machine ? What are its causes and effects ? **AKTU 2016-17, Marks 7.5**

Answer

A. Hunting in 3ϕ synchronous motors :

1. A steady-state operation of a synchronous motor is a condition of equilibrium from electromagnetic.
2. In the steady state, the rotor runs at synchronous speed, thereby maintaining a constant value of the torque angle δ.
3. If there is a sudden change in the load torque, the equilibrium is disturbed, and there is a resulting torque which changes the speed of the motor.
4. It is given by

$$\tau_e - \tau_{load} = J\frac{d\omega_m}{dt} \qquad ...(2.10.1)$$

where, J = Moment of inertia

ω_m = Angular velocity

5. The electromagnetic torque is given by

$$\tau_e = \frac{3VE_f}{\omega_s X}\sin\delta \qquad ...(2.10.2)$$

6. Since δ is increased, the electromagnetic torque increases.
7. The torque angle δ is larger than the required value δ_1 for the new state of equilibrium. Hence, the rotor speed continues to increase beyond the synchronous speed.
8. As a result of rotor acceleration above synchronous speed, the torque angle δ decreases.
9. At the point where motor torque becomes equal to the load torque, the equilibrium is not restored, because now the speed of the motor is greater than the synchronous speed. Therefore the motor continues to swing backwards. The torque angle goes on decreasing.
10. When the load angle δ becomes less than the required value δ_1, the mechanical load becomes greater than the developed power. Therefore, the motor starts to slow down. The load angle is increased again. Thus, the rotor swings or oscillates around synchronous.
11. This phenomenon of oscillation of the rotor about its final equilibrium position is called hunting.
12. Since during rotor oscillations, the phase of the phasor E_f changes relative to phasor V, hunting is also known as phase swinging.

B. Causes of hunting :

1. Sudden changes of load.
2. Faults occurring in the system.
3. Sudden changes in the field current.
4. Cyclic variations of load torque.

C. Reduction of hunting :

1. **Damper winding or damping :**
   a. When rotor starts oscillating *i.e.*, when hunting starts a relative motion between damper winding and the rotating magnetic field is created.
   b. Due to this relative motion, emf gets induced in the damper winding.
   c. According to Lenz's law, the direction of induced emf is always so as to oppose the cause producing it. The cause is the hunting.
   d. So such induced emf opposes the hunting. The induced emf tries to damp the oscillations as quickly as possible. Thus hunting is minimised due to damper winding.
2. **Use of flywheels :** The prime mover is provided with a large and heavy flywheel. This increases the inertia of the prime mover and helps in maintaining the rotor speed constant.
3. By designing synchronous machines with suitable synchronizing power coefficients.

D. **Disadvantages of hunting :**

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

E. **V-curve :** Refer Q. 2.9, Page 2–19A, Unit-2.

Que 2.11. **Write short notes on any two of the following :**
i. Mode of operations of synchronous motors.
ii. Hunting phenomena in 3ϕ synchronous motors.
iii. Power flow equations of cylindrical and salient pole machines.

Answer

i. **Mode of operations of synchronous motors :**

Normal Excitation :

1. At start, consider normal behaviour of the synchronous motor, when excitation is adjusted to get $E_b = V$ *i.e.*, induced emf is equal to applied voltage. Such an excitation is called normal excitation of the motor.
2. Motor is drawing certain current I_a from the supply. The power factor of the motor is lagging in nature as shown in the Fig. 2.11.1(*a*).

Under Excitation :

1. When the excitation is adjusted in such a way that the magnitude of induced emf is less than the applied voltage ($E_b < V$) the excitation is called under excitation.
2. Due to this, E_R increases in magnitude. This means for constant Z_s, current drawn by the motor increases.
3. But E_R phase shift in such a way that, phasor I_a also shifts ($E_R \wedge I_a = \theta$) to keep $I_a \cos \phi$ component constant.
4. So, in under excitated condition, current drawn by motor increases. The power factor decreases and becomes more and more lagging in nature.

Over Excitation :

1. The excitation to the field winding for which the induced emf becomes greater than applied voltage ($E_b > V$), is called over excitation.
2. Due to increased magnitude of E_b, E_R also increases in magnitude. But the phase of E_R also changes. Now $E_R \wedge I_a = \theta$ is constant, hence I_a also changes its phase. So ϕ changes. The I_a increases to keep $\cos \phi$ constant.

3. The phase of I_a changes so that I_a becomes leading with respect to V_{ph} in over excited condition. So power factor of motor becomes leading in nature.

Critical Excitation :

1. When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity ($\cos \phi = 1$) is called critical excitation. Then I_a is in phase with V_{ph}.
2. Now $I_a \cos \phi$ must be constant, $\cos \phi = 1$ is at its maximum hence motor has to draw minimum current from supply for unity power factor condition.

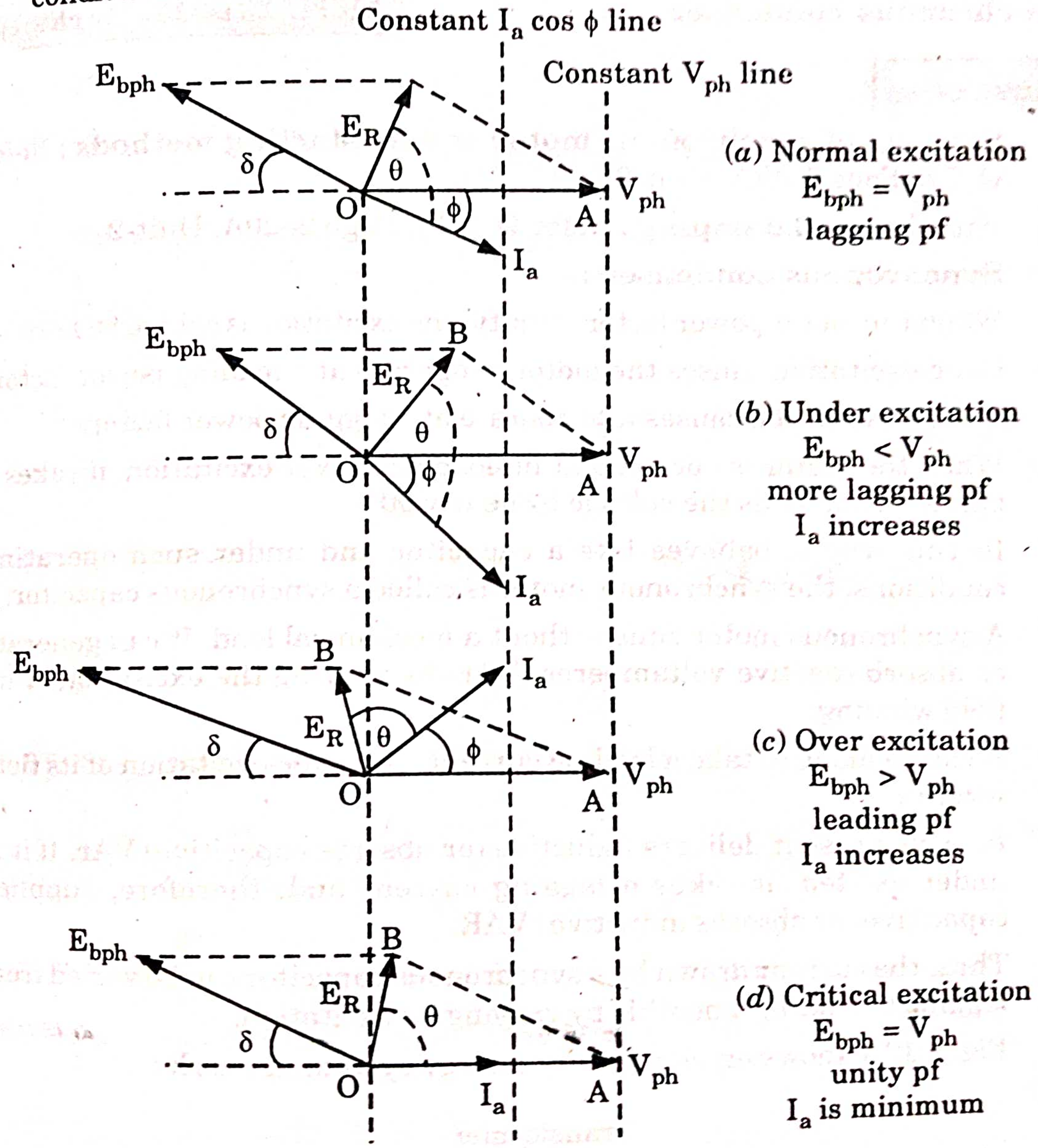

Fig. 2.11.1. Constant load variable excitation operation.

ii. **Hunting :** Refer Q. 2.10, Page 2–20A, Unit-2.

iii. **Power flow equation in cylindrical machine :** Refer Q. 2.2, Page 2–4A, Unit-2.

Power flow equation in salient pole machine : Refer Q. 2.3, Page 2–7A, Unit-2.

Que 2.12. **Discuss the following :**

i. **Starting of synchronous motor.**
ii. **Hunting and Damping.**
iii. **Synchronous condenser.** **AKTU 2012-13, Marks 10**

OR

Explain starting method of synchronous motor and its working as synchronous condenser. **AKTU 2014-15, Marks 10**

Answer

A. **Starting of synchronous motor and its starting methods :** Refer Q. 2.8, Page 2–17A, Unit-2.

B. **Hunting and damping :** Refer Q. 2.10, Page 2–20A, Unit-2.

C. **Synchronous condenser :**

1. When the motor power factor is unity, the excitation is said to be normal.
2. Over-excitation causes the motor to operate at a leading power factor.
3. Under-excitation causes it to operate at a lagging power factor.
4. When the motor is operated at no-load with over excitation, it takes a current that leads the voltage by nearly 90°.
5. In this way it behaves like a capacitor and under such operating conditions, the synchronous motor is called a synchronous capacitor.
6. A synchronous motor runs without a mechanical load. It can generate or absorb reactive voltamperes (VAr) by varying the excitation of its field winding.
7. It can be made to take a leading current with over-excitation of its field winding.
8. In such a case it delivers inductive (or absorbs capacitive) VAr. If it is under-excited, it takes a lagging current and, therefore, supplies capacitive (or absorbs inductive) VAR.
9. Thus, the current drawn by a synchronous capacitor can be varied from lagging to leading smoothly by varying its excitation.

Fig. 2.12.1 shows an elementary energy system network :

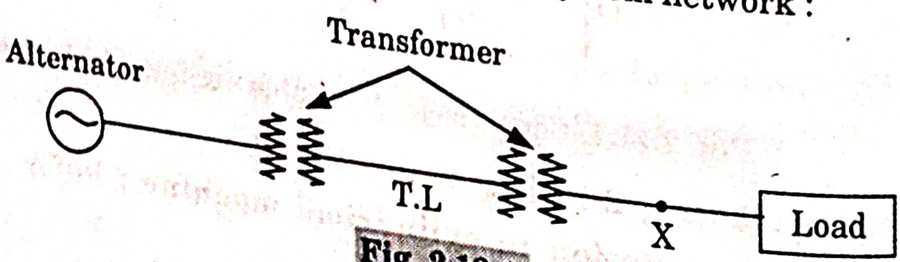

Fig. 2.12.1.

10. Let V_t is the terminal voltage at point A and E_f is the alternator excitation voltage. I is the load current of power factor cos θ and X is the total reactance between E_f and V_t, then phasor diagram for this system is as shown in Fig. 2.12.2.

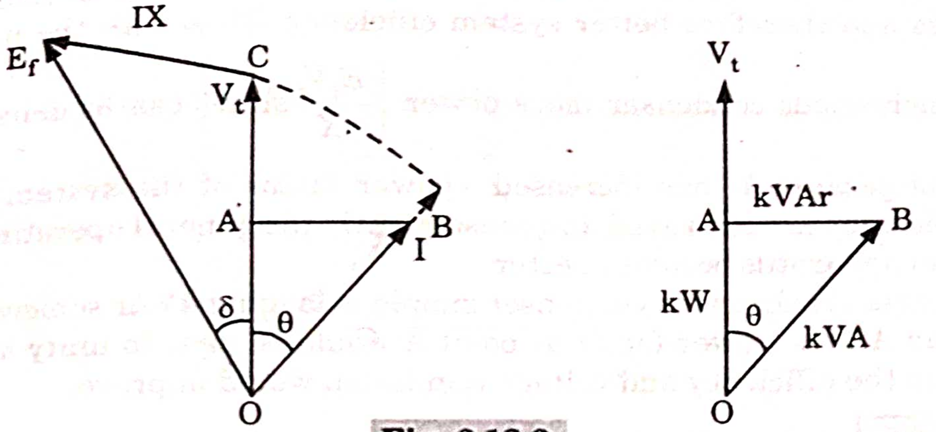

Fig. 2.12.2.

11. At the point X, the load is OA kW proportional to I cos θ. The apparent power is OB kVA proportional to I and load kVAr is AB proportional to I sin θ.

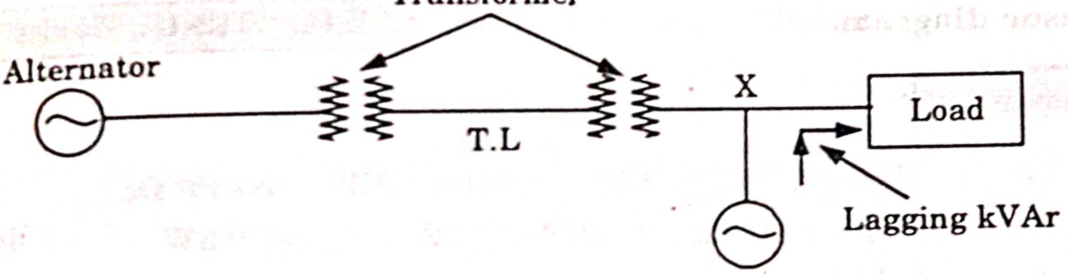

Fig. 2.12.3.

12. With the installation of synchronous condenser at X, Fig. 2.12.3 suppose that the load power factor at X is improved to unity then lagging kVAr required by the load and equal to AB are locally supplied by the synchronous condenser as $OG = AB$ as shown in Fig 2.12.4..

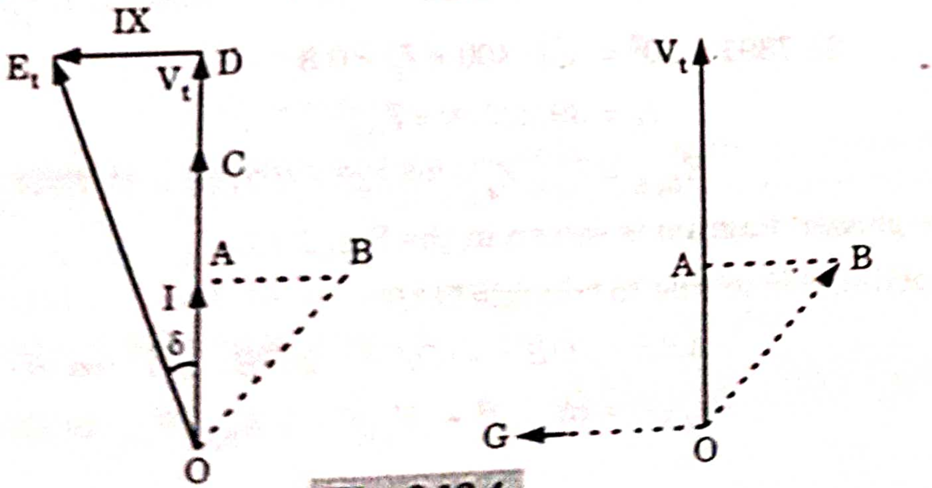

Fig. 2.12.4.

13. In this manner, the energy system network between alternator and point A is relieved of lagging kVAr. The current is reduced from OB to OA and the voltage at point A rises from OC to OD function the same E_f.
14. Since the system current has reduced it would result in decreased I^2R loss and therefore better system efficiency. Thus with the help of a synchronous condenser more power $\left[\frac{E_f V_t}{X}\sin\delta\right]$ can be delivered to load because V_t has increased ; power factor of the system and its efficiency are improved and consequently the general operation of the load apparatus becomes better.
15. In case synchronous condenser supply is lagging kVAr somewhat less than AB th. power factor at point A would be near to unity and even then the efficiency and voltage regulation would improve.

Que 2.13. **A 20 kW, 400 V, 3-phase, star-connected synchronous motor has per phase impedance of (0.15 + j0.90) Ω. Determine the induced emf, torque angle and mechanical power developed for full load at 0.8 pf lagging. Assume 92 % efficiency of the motor. Draw phasor diagram.**

AKTU 2012-13, Marks 10

Answer

Given : $V_L = 400$ V, $Z_s = 0.15 + j0.9\ \Omega = 0.9124 \angle 80.53°\ \Omega$,
$\theta = 80.53°$, $\phi = \cos^{-1} 0.8 = 36.869°$, $\eta = 92\ \%$, $P_{out} = 20$ kW
To Find : Induced emf, E_{bph}; Torque angle, δ; Power, P_m.
To Draw : Phasor diagram.

1.
$$P_{in} = \frac{P_{out}}{\eta} = \frac{20}{0.92} = 21.7391 \text{ kW}$$
$$P_{in} = \sqrt{3}\ V_L I_L \cos\phi$$
$$21.7391 \times 10^3 = \sqrt{3}\ 400 \times I_L \times 0.8$$
$$\therefore \quad I_L = 39.222 \text{ A} = I_{aph}$$
2.
$$E_{Rph} = I_{aph} Z_s = 39.222 \times 0.9124 = 35.7863 \text{ V}$$
The phasor diagram is shown in the Fig. 2.13.1.
3. Applying cosine rule to triangle OAB,
$$(AB)^2 = (OB)^2 + (OA)^2 - 2(OB)(OA)\cos(\theta - \phi)$$
$$\therefore (E_{bph})^2 = (E_{Rph})^2 + (V_{ph})^2 - 2\, E_{Rph} V_{ph} \cos(\theta - \phi)$$

$$\therefore \quad (E_{bph})^2 = (35.7863)^2 + \left(\frac{400}{\sqrt{3}}\right)^2 - 2 \times 35.7863 \times \frac{400}{\sqrt{3}} \times \cos(80.53° - 36.869°)$$

$$\therefore \quad E_{bph} = 206.534 \text{ V}$$

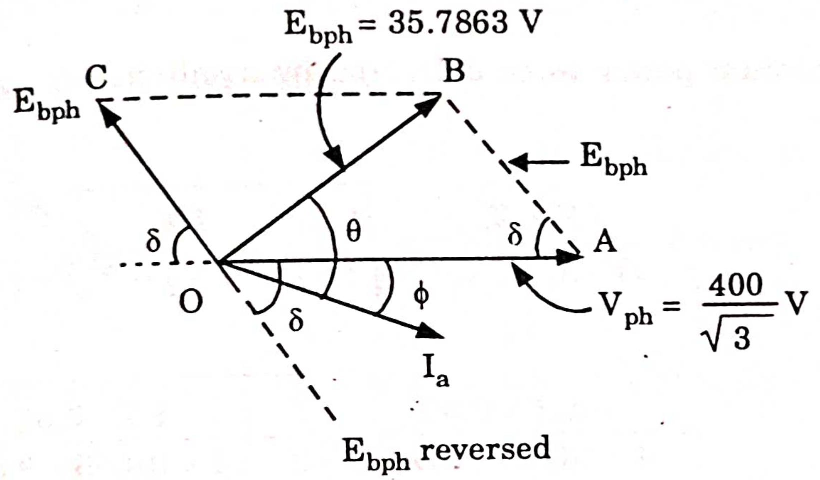

Fig. 2.13.1.

4. To find torque angle δ, use sine rule to triangle OAB.

$$\therefore \quad \frac{OB}{\sin\delta} = \frac{AB}{\sin(\theta - \phi)}$$

$$\frac{35.7863}{\sin\delta} = \frac{230.9401}{\sin(80.53° - 36.869°)}$$

$$\therefore \quad \delta = \sin^{-1} 0.1069 = 6.1414°$$

5. P_m = Mechanical power developed

$$= P_{in} - 3I^2_{aph} R_a$$

$$= 21.7391 \times 10^3 - 3 \times (39.222)^2 \times 0.15 = 21.04 \text{ kW}$$

Que 2.14. **A salient-pole synchronous motor has**

$$X_d = 0.85 \text{ p. u.}$$

and $$X_q = 0.55 \text{ p. u.}$$

It is connected to bus-bars of 1.0 p.u. voltage, while its excitation is adjusted to 1.2 p.u. Calculate the maximum power output, the motor can supply without loss of synchronism. Compute the minimum p.u. excitation that is necessary for the machine to stay in synchronism while supplying the full-load torque (*i.e.*, 1.0 p. u. power).

AKTU 2013-14, Marks 10

Answer

Given : X_d = 0.85 p.u., V = 1 p.u., X_q = 0.55 p.u., E = 1.2 p.u.

To Find : i. Maximum power output, P_{max}

ii. Minimum excitation, E_b, when P_m = 1.0 p.u.

1. For maximum power to be delivered by a salient pole synchronous motor,

$$\cos\delta = \frac{-E \times X_q}{4V(X_d - X_q)} + \sqrt{\frac{1}{2} + \left[\frac{EX_q}{4V(X_d - X_q)}\right]^2}$$

$$= \frac{-1.2 \times 0.55}{4 \times 1(0.85 - 0.55)} + \sqrt{\frac{1}{2} + \left[\frac{1.2 \times 0.55}{4 \times 1(0.85 - 0.55)}\right]^2}$$

$$= -0.55 + 0.896 = 0.346$$

load angle $\delta(\max) = \cos^{-1} 0.346 = 69.8°$

2. Maximum power is given by

$$P_{max} = \frac{EV}{X_d}\sin\delta + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta$$

$$= \frac{1.2 \times 1}{0.85}\sin 69.8° + \frac{1}{2}\left[\frac{1}{0.55} - \frac{1}{0.85}\right] \sin(2 \times 69.8°)$$

$$= 1.533 \text{ p.u.}$$

3. When excitation is variable, E_b is variable,

$$P_m = \frac{E_b \times 1}{0.85}\sin\delta + \frac{1}{2}\left[\frac{1}{0.55} - \frac{1}{0.85}\right]\sin 2\delta$$

$\therefore$
$$1 = 1.176\,E_b \sin\delta + 0.3208 \sin 2\delta \quad ...(2.14.1)$$

4. For maximum power output, differentiate eq. (2.14.1).

$\therefore$
$$0 = 1.176\,E_b \cos\delta + 0.3208 \times 2\cos 2\delta \quad ...(2.14.2)$$

5. Solving eq. (2.14.1) and (2.14.2),

$$\delta = 63° \text{ and } E_b = 0.706 \text{ p.u.}$$

Que 2.15. **A 5 MVA, 11 kV, 50 Hz, 4 pole, star-connected synchronous generator with synchronous reactance of 0.7 p.u. is connected to an infinite bus. Find synchronising power and the corresponding torque per unit of mechanical angle displacement :**

i. **At no load**

ii. **At full load of 0.8 p.f. lagging.**

Answer

Given : $V_L = 11$ kV, $X_s' = 0.7$ p.u., $P = 4$
To Find : Synchronising power, P_{SY} and
Synchronising torque, T_{SY} at no-load and full load of 0.8 pf.

1.
$$I_a\ (fl) = \frac{VA}{\sqrt{3}\ V_L} = \frac{5 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 262.432\ \text{A} = I_{aph}$$

$\therefore$
$$X_s = 0.7\ \text{p.u.} = 70\ \%\ \ i.e.,\ I_a X_s = 70\ \%\ \text{of}\ V_{ph}$$
$$I_a X_s = 0.7 \times 6350.85$$
$$X_s = \frac{4445.595}{262.432}$$

2.
$$\delta'_{mech} = 1°,\ \delta'_{electrical} = \text{pair of poles} \times \delta'_{mech}$$

$\therefore$
$$\delta'_{electrical} = 2 \times 1° = \frac{\pi}{90}\ \text{rad}$$
$$\text{Pair of poles} = \frac{4}{2} = 2$$

3. On no-load,
$$E = \frac{V_L}{\sqrt{3}} = 6350.85\ \text{V}$$

$\therefore$
$$P_{SY} = \frac{\delta' E^2}{X_s} = \frac{\pi}{90} \times \frac{(6350.85)^2}{16.94} = 83.11\ \text{kW per phase}$$

$\therefore$ Total synchronizing power $= 3\ P_{SY} = 249.332$ kW

4. Synchronizing torque, $T_{SY} = \dfrac{P_{SY}}{2\pi n_s}$ where $n_s = \dfrac{N_s}{60}$

$$\therefore \qquad T_{SY} = \frac{249.332 \times 10^3}{2\pi \times \dfrac{1500}{60}} = 1587.3 \text{ N-m}$$

5. Full load 0.8 p.f. lagging

$$I_a = 262.432 \angle 0° \text{ A}, \cos \phi = 0.8$$

$$\therefore \qquad \phi = 36.869°$$

$$X_s = 16.94 \angle 90\ \Omega$$

6. $$V = 6350.85 \angle 36.869° \text{ V} = 5080.739 + j\, 3810.43 \text{ V}$$

$$\vec{E} = \vec{V} + I_a \vec{X}_s = [6350.85 \angle 36.869°]$$

$$+ \{262.432 \angle 0° \times 16.94 \angle 90°\}$$

$$= 5080.739 + j\, 3810.43 + 0 + 4445.598 j$$

$$= 5080.739 + j\, 8256.028 \text{ V} = 9694.117 \angle 58.392° \text{ V}$$

Thus E leads I by 58.392° and V leads I by 36.869°

7. $\therefore$ Power angle $\delta = E \wedge V = 58.392° - 36.869° = 21.523° = 0.3756$ rad

8. $$\therefore \qquad P_{SY} \text{ per phase} = \frac{EV}{X_s} \cos \delta \sin \delta'$$

$$= \frac{9694.117 \times 6350.85}{16.94} \times \cos 0.3756 \sin \frac{\pi}{90}$$

$$= 117.992 \text{ kW}$$

$$\therefore \qquad \text{Total } P_{SY} = 3 \times 117.992 = 353.978 \text{ kW}$$

$$\therefore \qquad T_{SY} = \frac{P_{SY}}{2\pi n_s} = \frac{353.978 \times 10^3}{2\pi \times \left(\dfrac{1500}{60}\right)} = 2253.494 \text{ N-m}$$

Que 2.16. **Discuss the merits and demerits of 3ϕ synchronous motor.**

Answer

A. Merits :

1. Power factor can be controlled very easily.

2. An over-excited synchronous motor having a leading power factor can be operated in parallel with induction motors.
3. The speed is constant and independent of load.
4. Electromagnetic power varies linearly with the voltage.
5. These motors can be constructed with wider air gaps than induction motors.
6. These motors usually operate at higher efficiencies, especially in the low speed unity power factor ranges.

B. Demerits :

1. The cost per kW output is generally high.
2. It requires DC excitation which must be supplied from external source.
3. The synchronous motor is inherently not self-starting motor and needs some arrangement for its starting and synchronizing.
4. It cannot be used for variable speed jobs as there is no possibility of speed adjustment.
5. It cannot be started under load.
6. Its starting torque is zero.
7. When overloaded it may fall out of synchronism and stop.

Que 2.17. **What are the applications of synchronous motor ?**

Answer

1. Power factor correction
2. Voltage regulation and
3. Constant speed, constant-load drives.
4. They are used in power houses and substations in parallel to the bus-bars to improve the power factor.
5. Where power apparatus operating at lagging power, they are employed to improve the power factor.
6. Such motors are also used to regulate the voltage at the end of transmission lines.
7. Because of the higher efficiency possible with synchronous motors, they can be employed advantageously for the loads where constant speed is required.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. State and explain two reaction theories applicable to cylindrical synchronous machine. Also give the real power and reactive power flow equations of the cylindrical machine.

Ans. Refer Q. 2.2, Unit-2.

Q. 2. Discuss two reaction theory. Derive expression of developed power (P_d) for a salient pole synchronous machine ignoring armature resistance and draw power vs power angle characteristic. Why a salient pole machine is more stable as compared to a cylindrical rotor machine ?

Ans. Refer Q. 2.3, Unit-2.

Q. 3. Explain the operation of synchronous machine on constant excitation variable load.

Ans. Refer Q. 2.5, Unit-2.

Q. 4. Explain the constructional features and working principle of the synchronous motor and develop the torque expression of synchronous motor.

Ans. Refer Q. 2.7, Unit-2.

Q. 5. What are the causes of "HUNTING" in synchronous machines ? How is it minimised ? What are the advantages and disadvantages of "HUNTING" in synchronous machines ?

Ans. Refer Q. 2.10, Unit-2.

Q. 6. A 20 kW, 400 V, 3-phase, star-connected synchronous motor has per phase impedance of (0.15 + j0.90) Ω. Determine the induced emf, torque angle and mechanical power developed for full load at 0.8 pf lagging. Assume 92 % efficiency of the motor. Draw phasor diagram.

Ans. Refer Q. 2.13, Unit-2.

Q. 7. A 5 MVA, 11 kV, 50 Hz, 4 pole, star-connected synchronous generator with synchronous reactance of 0.7 p.u. is connected to an infinite bus. Find synchronising power and the corresponding torque per unit of mechanical angle displacement :

i. At no load

ii. At full load of 0.8 p.f. lagging.

Ans. Refer Q. 2.15, Unit-2.

Q. 8. Explain why 3ϕ synchronous machines are not self-starting ? What are the methods for starting of the 3ϕ synchronous machines ?

Ans. Refer Q. 2.8, Unit-2.

Q. 9. Define the V-curves and inverted V-curves at different loading conditions of synchronous motors.

Ans. Refer Q. 2.9, Unit-2.

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3 UNIT

Three Phase Induction Machine-I

PART-1

Constructional Features, Rotating Magnetic Field, Principle of Operation, Phasor Diagram, Equivalent Circuit.

CONCEPT OUTLINE : PART-1

- **3-ϕ Induction motors are of two types :**
  i. Squirrel-cage induction motor
  ii. Wound-rotor or slip-ring induction motor
- **Slip :**

$$s = \frac{N_s - N_r}{N_s}$$

and $$f_r = sf_s$$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. Give the constructional details about three phase induction motor. Which types of rotor are used in 3ϕ induction motor ?

Answer

Construction of 3ϕ induction motor : There are two main parts of induction motor :

A. **Stator :**

1. It is a stationary part of the motor. This part is made of silicon steel stampings (*i.e.*, thin sheets). The stampings are slotted.
2. When complete stator is assembled, the slots are formed on the inner side of the stator.
3. The slots may be open type, semi-open type or closed type. In these slots, a 3ϕ winding is accommodated. This winding may be star or delta connected.
4. The three ends of this winding are brought out into the terminal box where 3ϕ AC supply can be connected.
5. The stator windings, stator and the AC supply connected to the stator winding is shown in Fig. 3.1.1.

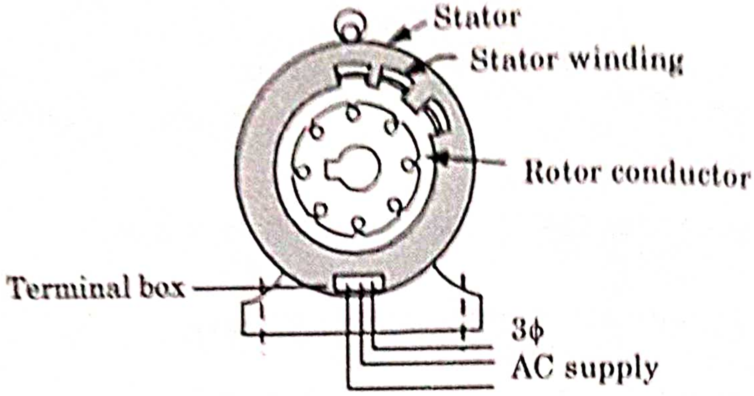


Fig. 3.1.1. Diagram of 3-phase induction motor.

B. Rotor : There are two types of induction motors depending upon the construction of the rotor :

a. Squirrel cage type rotor :

1. This is the simplest and most rugged construction. The rotor consists of a cylindrical laminated core with skewed rotor slots.
2. The rotor conductors which are thick copper bars, are placed in these slots and are brazed or welded to end rings. Thus, the rotor conductors are permanently short-circuited. Therefore it is not possible to add any external resistance in the rotor circuit.
3. The rotor body is made of silicon steel stampings. The construction of the rotor looks like a cage of "squirrel" and hence called as "squirrel cage type motor".

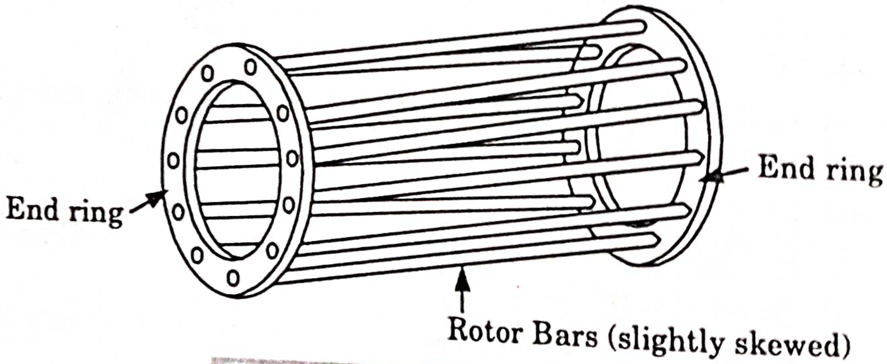


Fig. 3.1.2. Squirrel cage rotor.

b. Wound type rotor with slip rings :

1. In this type of induction motor, the rotor is wound for the same number of poles as that on the stator.
2. The rotor is made up of laminations with slots on the outer periphery in which a 3ϕ rotor winding is placed.
3. The three phase are starred internally, the remaining three terminals are brought out and connected to the slip-rings mounted on the shaft.

4. The slip-rings are made up of copper or phosphor bronze and there are three brushes resting on them. External connections to additional resistances are done at the brushes.
5. When running under normal conditions, the slip-rings are short-circuited by a metal collar which is pushed along the shaft and the brushes are lifted from the slip-rings to reduce the frictional losses and wear.
6. As a regular 3ϕ winding is used for rotor, this type is called as "phase wound rotor type". It is also called as "slip-ring type" because slip-rings are used.

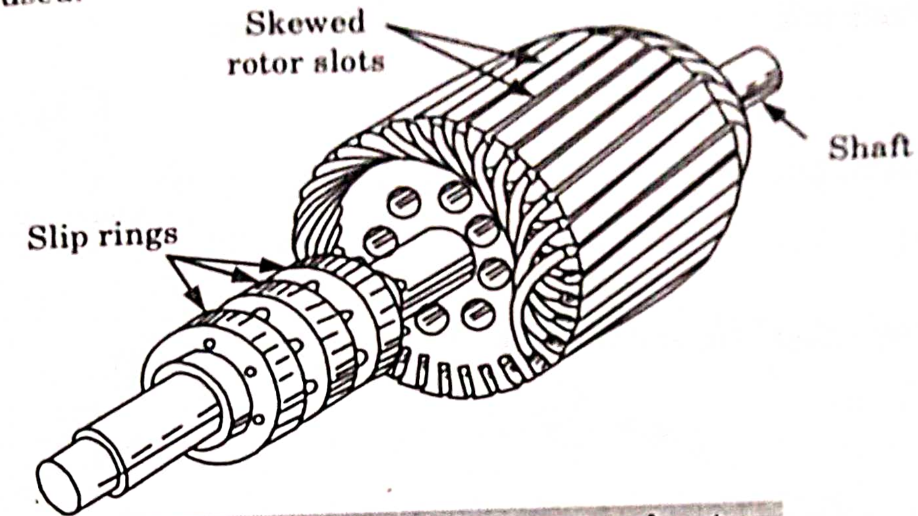


Fig. 3.1.3. Slip-ring type motor's rotor.

Que 3.2. **Explain how a Rotating Magnetic Field (RMF) is produced in a 3-phase induction motor ? Develop suitable expression.**

AKTU 2012-13, Marks 10

Answer

1. When a 3ϕ windings displaced in space by 120° are supplied by 3ϕ balanced current, a magnetic flux is produced which rotates in space.

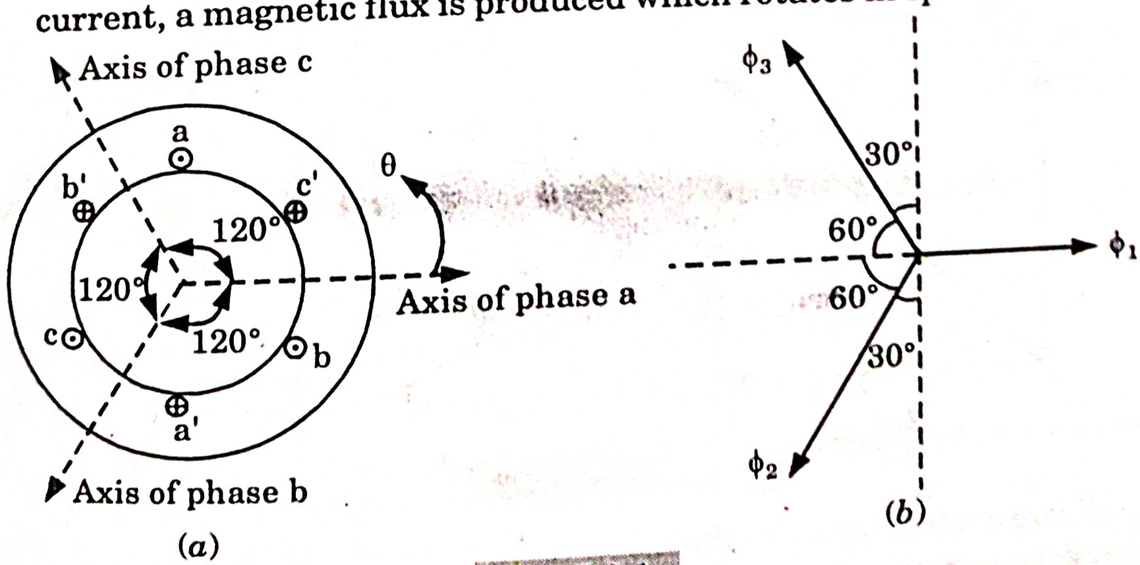


Fig. 3.2.1.

2. Let us consider a three identical coil displaced 120° in space mechanically and supplied by a balanced 3ϕ supply, then instantaneous flux :

$$\phi_1 = \phi_m \sin \omega t$$
$$\phi_2 = \phi_m \sin (\omega t - 120°)$$
$$\phi_3 = \phi_m \sin (\omega t + 120°)$$

3. From Fig. 3.2.1(*b*) the resultant horizontal component of flux

$$\phi_h = \phi_1 - \phi_2 \cos 60° - \phi_3 \cos 60° = \phi_1 - (\phi_1 + \phi_3) \cos 60° \quad ...(3.2.1)$$

4. Put the value of ϕ_1, ϕ_2 and ϕ_3 in eq. (3.2.1), we get

$$\phi_h = \frac{3}{2}\phi_m \sin \omega t$$

5. The resultant vertical component of flux

$$\phi_v = 0 - \phi_2 \cos 30° + \phi_3 \cos 30° \quad ...(3.2.2)$$
$$= \cos 30° (\phi_3 - \phi_2)$$

6. Put the value of ϕ_2 and ϕ_3 in eq. (3.2.2), we get

$$\phi_v = \frac{3}{2}\phi_m \cos \omega t$$

7. Resultant flux, $\phi_r = \sqrt{\phi_h^2 + \phi_v^2} = \frac{3}{2}\phi_m$

8. Also $\tan \theta = \frac{\phi_v}{\phi_h} = \tan\left(\frac{\pi}{2} - \omega t\right)$

$\therefore$ $$\theta = \frac{\pi}{2} - \omega t \quad ...(3.2.3)$$

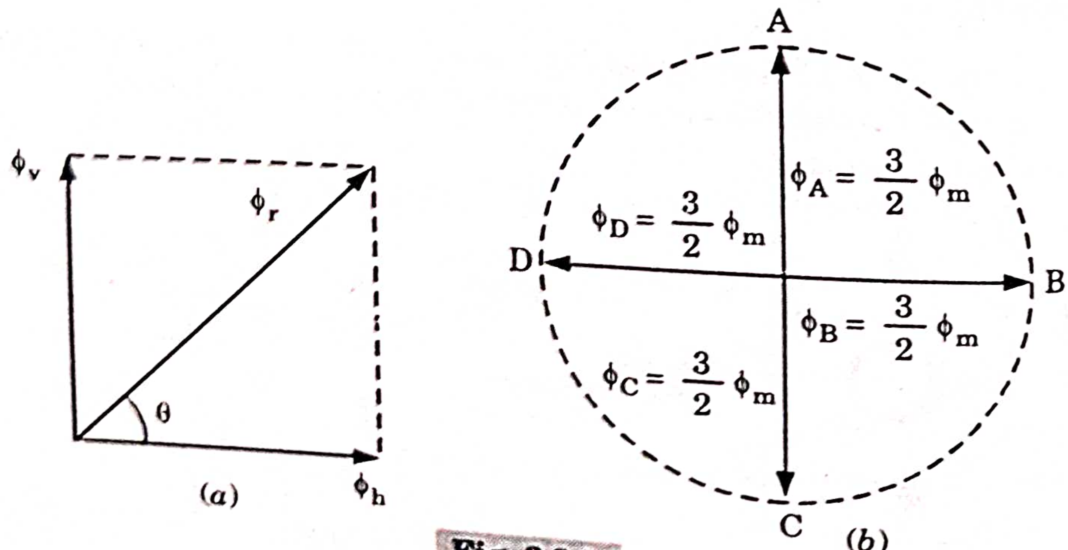


Fig. 3.2.2.

9. From eq. (3.2.3),

i. at $\omega t = 0°$, $\theta = 90°$, at position *A*

ii. at $\omega t = 90°$, $\theta = 0°$, at position B

iii. at $\omega t = 180°$, $\theta = -90°$, at position C

iv. at $\omega t = 270°$, $\theta = -180°$, at position D

10. So it is seen that the resultant flux ϕ_r is independent of time and rotates in space in clockwise direction.

Que 3.3. **Explain the principle of operation of a 3-phase induction motor.**

AKTU 2014-15, Marks 05

Answer

1. Let us consider that the rotor is stationary and one conductor is on the rotor as shown in Fig. 3.3.1.

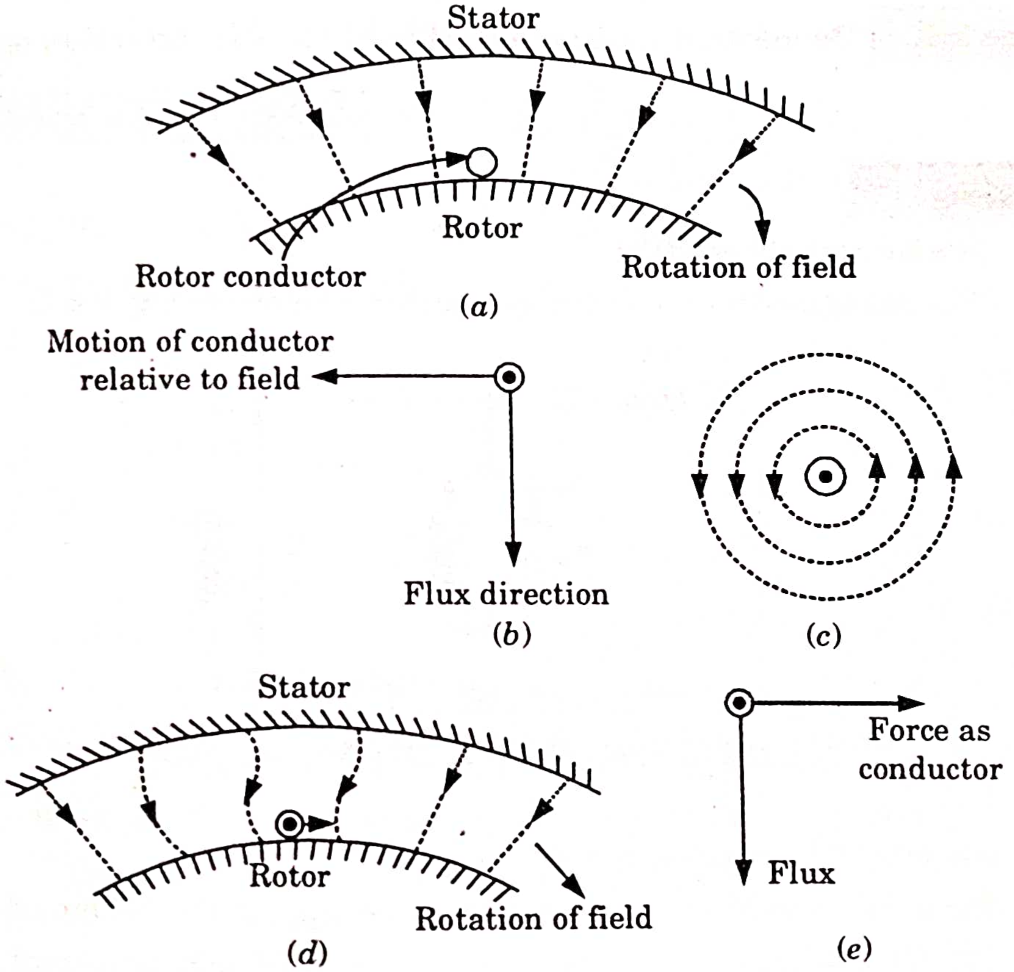


Fig. 3.3.1. Production of torque.

2. Let the rotation of the magnetic field be clockwise.
3. A magnetic field moving clockwise has the same effect as a conductor moving anti-clockwise in a stationary field.
4. By Faraday's law of electromagnetic induction, a voltage will be induced in the conductor. Due to this induced voltage, a current starts to flow in rotor conductor.

5. By right-hand rule the direction of induced current is downward as shown in Fig. 3.3.1(b).
6. Now the current in the rotor conductor produces its own magnetic field as shown in Fig. 3.3.1(c) due to this a force is produced on the rotor conductor.
7. By the left-hand rule the direction of force can be determined.
8. It is seen that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field.
9. Since the rotor conductor is in a slot on the rotor, and the force acts in a tangential direction to the rotor and torque is developed. Similar torque is produced on all conductors in same direction.
10. Since the rotor is free to move, it starts rotating in the same direction. Thus it is noted that a 3ϕ induction motor is a self-starting motor.

Que 3.4. **Develop the equivalent circuit for a 3ϕ induction motor.**

AKTU 2014-15, Marks 05

Answer

A. Stator circuit model :

1. The stator model of the induction motor is shown in Fig. 3.4.1.

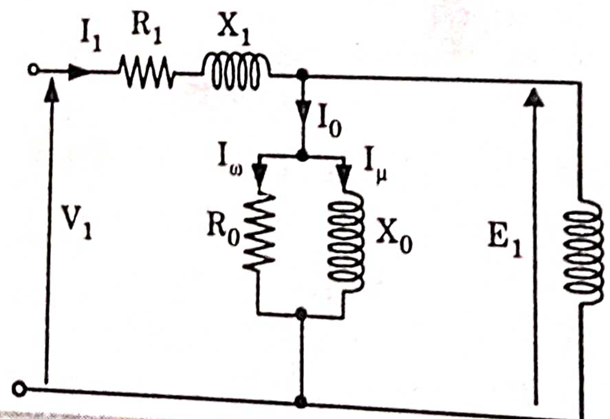


Fig. 3.4.1. Stator model of an induction motor.

2. It consists of a stator phase winding resistance R_1, a stator phase winding leakage reactance X_1.
3. These two components appear right at the input to the machine model.
4. The no-load current I_0 is simulated by a pure inductive reactor X_0 taking the magnetizing component I_μ and a non-inductive resistor R_0 carrying the core loss current I_ω.
5. Thus,
$$I_0 = I_\mu + I_\omega \quad \text{....(3.4.1)}$$

B. Rotor circuit model :

1. In an induction motor, when a 3ϕ supply is applied to the stator windings, a voltage is induced in the rotor windings of the machine.

2. In general, the greater the relative motion of the rotor and the stator magnetic fields, the greater the resulting rotor voltage.
3. The largest relative motion occurs when the rotor is stationary. This condition is called the standstil condition.
4. This is also known as the locked-rotor or blocked-rotor condition. If the induced rotor voltage at this condition is E_{20} then the induced voltage at any slip is given by

$$E_{2s} = sE_{20}$$

5. The rotor resistance R_2 is a constant (except for the skin effect). It is independent of slip.
6. The reactance of the induction motor rotor depends upon the inductance of the rotor and the frequency of the voltage and current in the rotor.
7. If L_2 = Inductance of rotor, the rotor reactance is given by

$$X_2 = 2\pi f_2 L_2$$

8. But $f_2 = sf_1$

$\therefore$ $X_2 = 2\pi sf_1 L_2 = s(2\pi f_1 L_2)$

or $X_2 = sX_{20}$

where X_{20} is the standstill reactance of the rotor.

The rotor circuit is shown in Fig. 3.4.2.

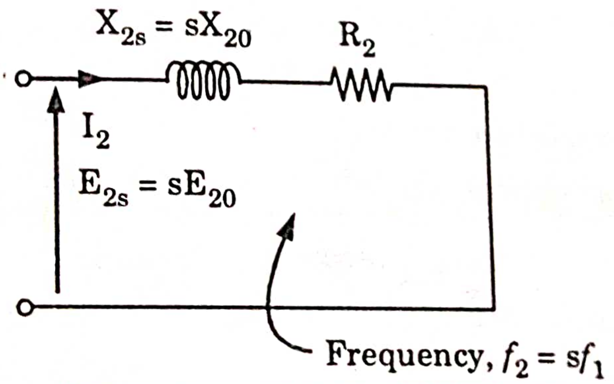


Fig. 3.4.2. Rotor circuit model.

9. The complete equivalent circuit of the induction motor is shown in Fig. 3.4.3.

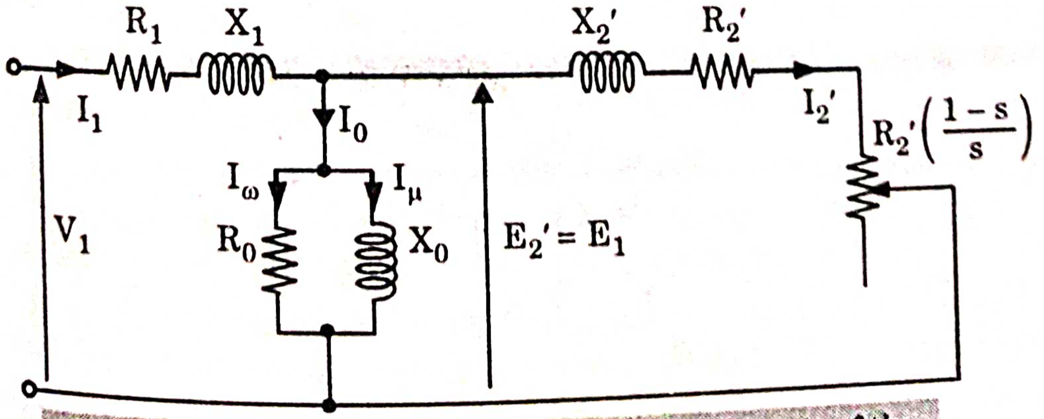


Fig. 3.4.3. Per phase complete equivalent circuit of the induction motor referred to the stator.

Que 3.5. **Draw Phasor diagram of induction motor.**

Answer

1. Equivalent circuit of three phase induction motor is shown Fig. 3.5.1.

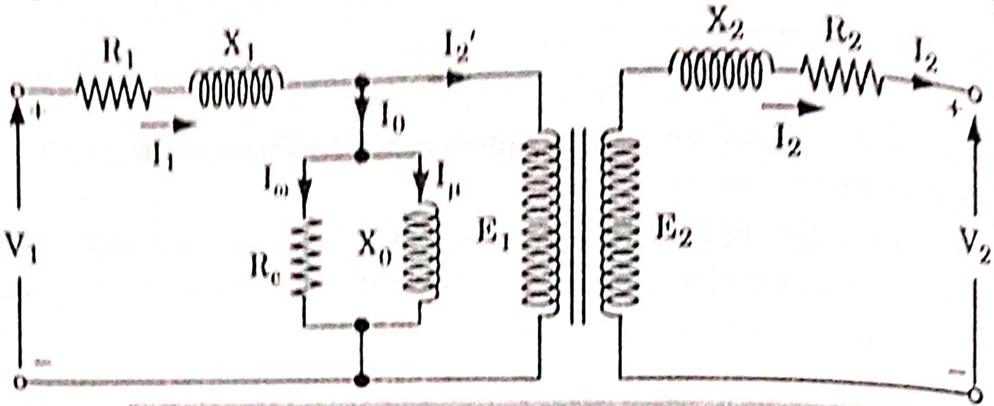


Fig. 3.5.1. Equivalent circuit of 3ϕ induction motor.

2. From approximate equivalent circuit of induction motor shown in Fig. 3.5.1, the equations for primary and secondary sides are

$$V_1 = I_1R_1 + jI_1X_1 + (-E_1)$$

$$I_1 = I_0 + I_2'$$

$$I_0 = I_\mu + I_\omega$$

$$E_2 = I_2R_2 + jI_2X_2 + V_2$$

E_1, E_2 lags behind flux ϕ by 90°.

I_2' is equal and opposite to I_2.

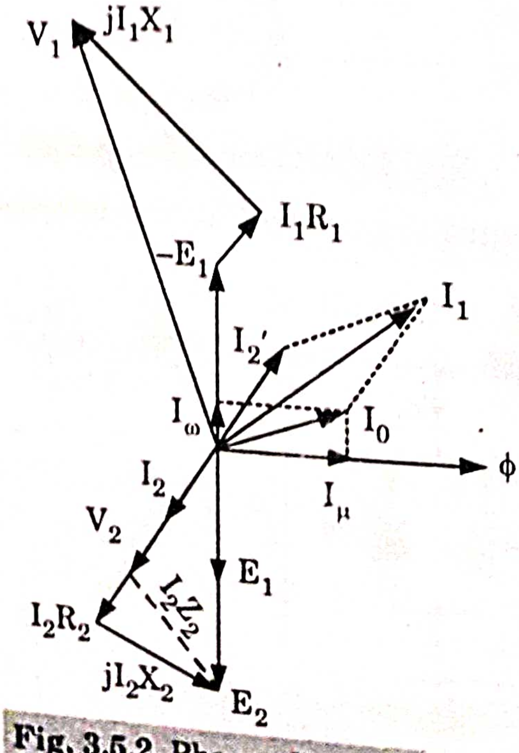


Fig. 3.5.2. Phasor diagram.

Que 3.6. **What are the similarities and dissimilarities between "three-phase transformers" and "three-phase induction machines"? Explain why a 3ϕ IM can't run at synchronous speed $\left(N_s = \frac{120f}{P}\right)$, symbols having their usual meanings ?**

Answer

A. Similarities :

1. In both of them, the induced voltage is $E \propto f\phi N$.
2. Both have similar emf or voltage ratio *i.e.*,
$$\frac{E_1}{E_2} = \frac{N_1 K_{w1}}{N_2 K_{w2}} = \frac{N_1'}{N_2'}$$
N_1' and N_2' being effective number of series turns per phase.
Thus, wound rotor induction motor is similar to transformer at no load.
3. Resultant mutual flux in a transformer is due to combined action of primary and secondary mmfs; similarly in induction machines, synchronously rotating air gap flux (or mutual flux) is due to combined action of both stator and rotor mmfs.
4. In induction machines, rotating air gap flux generates counter emf (E) in stator winding, similar to counter emf induced (by mutual flux) in primary winding of transformer.
5. With increase in shaft load (secondary), rotor mmf (secondary mmf) reacts on stator winding (primary) in order to extract more power from the AC source in induction machine (transformer).
6. 3ϕ induction motor with blocked rotor behaves similar to short circuited transformer.
7. Primary and secondary windings of transformers, similar to the stator and rotor windings of 3ϕ induction machines possess resistance and leakage reactance.
8. Phasor diagrams and equivalent circuits of 3ϕ transformer and 3ϕ induction machines are almost similar.

B. Dissimilarities :

1. Voltage ratio of induction machine includes winding factors K_{w1} and K_{w2} (because the windings are distributed along the air gap) unlike transformer's voltage ratio that requires none.
2. In emf equation of transformers, maximum value of flux is used, while in that of induction machines, average value of flux is employed.
3. No load current of induction motor varies from 30 to 50 % of full load current, whereas in transformers no load current varies from 2 to 6 % of full load current.

C. **Reason :**

1. The rotor of 3ϕ induction motor, if it is supposed to rotate at synchronous speed, N_s, in the direction of rotating field, then there would not be any flux cutting action as the rotor and flux would be stationary with respect to each other.
2. Thus, no emf will be generated in rotor conductors hence no current flows in rotor bars, thus there will not be any torque developed.
3. And without torque, the speed of the rotor reduces.
4. Thus, the rotor of 3ϕ induction motor can never attain synchronous speed.

Que 3.7. **Derive expression of slip speed, slip, percentage slip and frequency of rotor voltage and current.**

Answer

A. **Slip speed :** The slip speed expresses the speed of the rotor relative to the field.

If N_s = Synchronous speed in rpm

N_r = Actual rotor speed in rpm

Slip speed = $N_s - N_r$ rpm

B. **Slip :** The slip speed expressed as a fraction of the synchronous speed is called the per-unit slip or fractional slip. The per-unit slip is usually called the slip. It is denoted by s.

$$s = \frac{N_s - N_r}{N_s} \text{ per unit (p.u.)}$$

C. **Percentage slip :**

1. Let n_s = Synchronous speed in rps

n_r = Actual rotor speed in rps

then
$$s = \frac{n_s - n_r}{n_s} \text{ p.u.}$$

and percentage slip = $\dfrac{n_s - n_r}{n_s} \times 100$

Also,
$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

2. The slip at full load varies from about 5 percent for small motors to about 2 percent for large motors.

D. **Frequency of rotor voltage and current :**

1. The frequency of current and voltage in the stator must be the same as the supply frequency given by

$$f = \frac{PN_s}{120} \quad ...(3.7.1)$$

2. The frequency in the rotor windings is variable and depends on the difference between the synchronous speed and the rotor speed. Hence the rotor frequency depends upon the slip. The rotor frequency is given by

$$f_r = \frac{P(N_s - N_r)}{120} \quad ...(3.7.2)$$

3. Division of eq. (3.7.2) by eq. (3.7.1) gives

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s}$$

$$\therefore \quad f_r = sf$$

That is, Rotor current frequency = Per unit slip × Supply frequency

4. When the rotor is stationary (stand-still)

$$N_r = 0, \quad s = \frac{N_s - N_r}{N_s} = 1 \quad \text{and} \quad f_r = f.$$

5. When the rotor is driven by a mechanical prime mover at synchronous speed N_s, then $s = 0$ and $f_r = 0$. Therefore, frequency of rotor current varies from $f_r = f$ at stand-still ($s = 1$) to $f_r = 0$ at synchronous speed ($s = 0$).

Que 3.8. **A 4-pole, 50 Hz induction motor runs with 4 % slip at full load.**
What will be the frequency of current induced in the rotor :
i. At starting,
ii. At full-load ?

AKTU 2014-15, Marks 05

Answer

Given : $P = 4$, $f = 50$ Hz, $s = 0.04$
To Find : i. Frequency, f_r at starting
ii. Frequency, f_r at full load

1. At starting, $s = 1$
$f_r = sf = 1 \times 50 = 50$ Hz
2. At full load, $s = 0.04$
$f_r = 0.04 \times 50 = 2$ Hz

Que 3.9. **A 6-pole, 50 Hz induction motor runs with 5 % slip. What is its speed ? What is the frequency of the rotor current ?**

AKTU 2014-15, Marks 05

Answer

Given : $f = 50$ Hz, $P = 6$, $s = 0.05$
To Find : i. Rotor speed, N_r
ii. Rotor frequency, f_r.

1. Synchronous speed, $N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000$ rpm
2. Rotor speed, $N_r = (1 - s)N_s$
$= (1 - 0.05) \times 1000 = 950$ rpm
3. Rotor frequency, $f_r = sf = 0.05 \times 50 = 2.5$ Hz

Que 3.10. **A 3-phase, 4-pole, 60 Hz induction motor has a slip of 5 % at no-load, and 7 % at full load. Determine the following :**
i. The relative speed between stator surface and rotor field.
ii. The relative speed between stator field and rotor field.
iii. The relative speed between stator surface and rotor surface.

AKTU 2015-16, Marks 10

Answer

Given : $P = 4$, $f = 60$ Hz, slip at no-load = 0.05, slip at full load = 0.07
To Find : i. Relative speed between stator surface and rotor field
ii. Relative speed between stator field and rotor field
iii. Relative speed between stator surface and rotor surface.

1. $N_s = \frac{120f}{P} = \frac{120 \times 60}{4} = 1800$ rpm
2. Speed at no-load = (1 – slip at no-load) × N_s
$= (1 - 0.05) \times 1800 = 1710$ rpm
3. Speed at full load = (1 – slip at full load) × N_s
$= (1 - 0.07) \times 1800 = 1674$ rpm
4. Rotor frequency, f_2 (at no-load) $= sf_1 = 0.05 \times 60 = 3$ Hz
Rotor frequency, f_2 (at full load) $= sf_1 = 0.07 \times 60 = 4.2$ Hz
5. Relative speed between stator surface and rotor field
= (Mechanical speed of rotor) + (Speed of rotor field with respect to rotor structure)
Speed of rotor field with respect to rotor structure (at no-load)
$= \frac{120 \times 3}{4} = 90$ rpm
$\therefore$ Relative speed = 1710 + 90 = 1800 rpm

Speed of rotor field with respect to rotor structure (at full load)

$$= \frac{120 \times 4.2}{4} = 126 \text{ rpm}$$

$\therefore$ Relative speed = 1674 + 126 = 1800 rpm

6. Since both the stator and rotor fields are rotating at synchronous speed of 1800 rpm, speed of rotor field with respect to stator field is zero.
7. Relative speed between stator surface and rotor surface at no-load = 1710 rpm. At full load relative speed is 1674 rpm.

PART-2

Torque and Power Equations, Torque-Slip Characteristics, Efficiency.

CONCEPT OUTLINE : PART-2

- **Relation between P_g, P_{cu} and P_m :**
  $P_g : P_{cu} : P_m = 1 : s : (1 - s)$
- **Developed torque :**

$$\tau_d = \frac{P_g}{\omega_s}$$

$$\tau_d = \frac{Ks\, E_{20}^2\, R_2}{R_2^2 + s^2 X_{20}^2} \qquad \left[\text{where } K = \frac{3}{2\pi\, n_s}\right]$$

- **Relation between τ_{fl}, τ_{max} and τ_{st} :**

1. $\dfrac{\tau_{fl}}{\tau_{max}} = \dfrac{2s_m s_{fl}}{s_m^2 + s_{fl}^2}$
2. $\dfrac{\tau_{st}}{\tau_{max}} = \dfrac{2s_m}{1 + s_m^2}$
3. $\dfrac{\tau_{st}}{\tau_{fl}} = \dfrac{s_{fl}^2 + s_m^2}{s_{fl}(1 + s_m^2)}$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.11. **Derive the expression for developed torque for a 3ϕ induction motor and obtain the condition for maximum torque. Obtain the ratio of full load torque to maximum torque. Also draw torque-slip curves and discuss the effect of rotor resistance.**

AKTU 2012-13, Marks 10

OR

Sketch the torque-slip characteristics of a 3ϕ induction motor indicating there in the starting torque, maximum torque and the operating region.

AKTU 2014-15, Marks 10

Answer

A. Torque of an induction motor :

1. Electrical power generated in rotor

$$= 3E_{2s}I_{2s}\cos\phi_{2s}$$

$$= 3E_{2s}\frac{E_{2s}}{Z_{2s}}\frac{R_2}{Z_{2s}} = \frac{3E_{2s}^2R_2}{Z_{2s}^2} = \frac{3s^2E_{20}^2R_2}{R_2^2+(sX_{20})^2}$$

2. All this power is dissipated as I^2R loss (copper loss) in the rotor circuit.
3. Input power to rotor = $2\pi n_s\tau_d$
4. $s \times$ Rotor input = Rotor copper loss

$$s\times 2\pi n_s\tau_d = \frac{3s^2E_{20}^2R_2}{R_2^2+s^2X_{20}^2}$$

$$\tau_d = \frac{3E_{20}^2}{2\pi n_s}\frac{sR_2}{R_2^2+s^2X_{20}^2}$$

$$\tau_d = \frac{KsE_{20}^2R_2}{R_2^2+s^2X_{20}^2} \quad ...(3.11.1)$$

where, $K = \frac{3}{2\pi n_s} = \frac{3}{\omega_s}$ = Constant

B. Condition for maximum torque :

1. Let $KE_{20}^2 = K_1$ (Constant)

$$\therefore \quad \tau_d = \frac{K_1sR_2}{R_2^2+s^2X_{20}^2}$$

$$\tau_d = \frac{K_1R_2}{\frac{R_2^2}{s}+sX_{20}^2} = \frac{K_1R_2}{\left(\frac{R_2}{\sqrt{s}}-X_{20}\sqrt{s}\right)^2+2R_2X_{20}} \quad ...(3.11.2)$$

2. The developed torque τ_d will be maximum when the right-hand side of eq. (3.11.2) is maximum, which is possible only when

$$\frac{R_2}{\sqrt{s}} - X_{20}\sqrt{s} = 0$$

$$R_2 = sX_{20}$$
$$R_2 = X_{2s}$$

3. Maximum torque is obtained by putting $sX_{20} = R_0$ in eq. (3.11.1).

$$\therefore \quad \tau_{d\max} = \frac{KsR_2E_{20}^2}{R_2^2 + R_2^2} = \frac{KsE_{20}^2}{2R_2} = \frac{KsE_{20}^2}{2sX_{20}} = \frac{KE_{20}^2}{2X_{20}}$$

C. Ratio :

1. $$\tau_{fl} = \frac{KsR_2E_{20}^2}{R_2^2 + (sX_{20})^2}$$

2. $$\frac{\tau_{fl}}{\tau_{d\max}} = \frac{Ks\,R_2\,E_{20}^2}{R_2^2 + (sX_{20})^2} \div \frac{KE_{20}^2}{2X_{20}} = \frac{2s\,R_2X_{20}}{R_2^2 + (sX_{20})^2}$$

3. But $R_2 = s_mX_{20}$

Then $$\frac{\tau_{fl}}{\tau_{d\max}} = \frac{2ss_mX_{20}^2}{s_m^2X_{20}^2 + s^2X_{20}^2}$$

4. $$\therefore \quad \frac{\tau_{fl}}{\tau_{d\max}} = \frac{2ss_m}{s^2 + s_m^2}$$

D. Torque-slip characteristics : The torque-slip characteristics are divided into three regions :

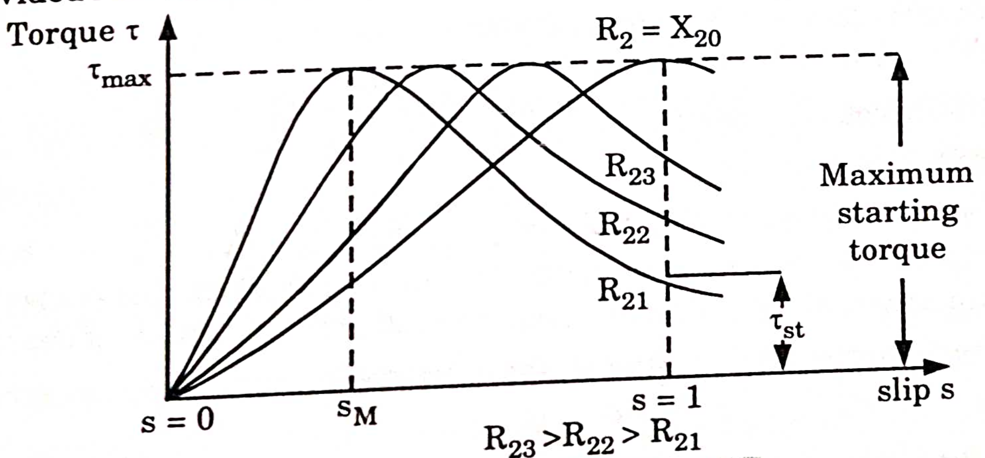


Fig. 3.11.1. Torque-slip curves.

a. **Low-slip region :** At synchronous speed $s = 0$, therefore, the torque is zero. When speed is near to synchronous speed, the slip is very low and $(sX_{20})^2$ is negligible in comparison with R_2. Therefore,

$$\tau = \frac{K_1s}{R_2}$$

If R_2 is constant, $\tau = K_2s \left(\text{where, } K_2 = \frac{K_1}{R_2}\right)$

Relation shows that torque is proportional to slip. Hence, when slip is small, the torque-slip curve is straight line.

b. **Medium-slip region :** As slip increases, $(sX_{20})^2$ becomes large, so that R_2^2 may be neglected in comparison with $(sX_{20})^2$ and

$$\tau = \frac{K_1 R_2}{sX_{20}^2}$$

$$\therefore \qquad \tau \propto \frac{1}{s}$$

The torque-slip characteristic is represented by a rectangular hyperbola.

c. **High-slip region :** The torque decreases beyond the point of maximum torque. The result is that the motor slows down and eventually stops. At this stage, the overload protection must immediately disconnect the motor from the supply to prevent damage due to overheating.

Que 3.12. **By means of power-flow diagram, show the flow of power in a 3-phase induction motor from the electrical source to mechanical load at the motor shaft. Based on above, show that**

$$P_g : P_{cu} : P_m = 1 : s : (1 - s)$$

where, all terms used have their usual meanings.

Answer

The input power to an induction motor is in the form of 3-phase voltage and currents. It is given by :

$$P_{in} = \sqrt{3}\, V_L I_L \cos\phi_i = 3V_{sp} I_{sp} \cos\phi_i$$

where, $\cos\phi_i$ = input power factor

A. **The losses in the stator are :**

1. Stator-copper loss, $P_{scl} = 3I_{sp}^2 R_{sp}$
2. Stator-core losses, $P_{s(h+e)}$

The output power of the stator, $P_{os} = P_{is} - P_{sc} - P_{s(h+e)}$

3. This power P_{os} is transferred to the rotor of the machine across the air-gap between the stator and rotor. It is called the air-gap P_g of the machine.
4. Thus, Power output of the stator = Air-gap power = Input power to rotor

or, $$P_{os} = P_g = P_{ir}$$

B. **The losses in the rotor are :**

1. Rotor-copper losses, $P_{rcu} = 3I_2^2 R_2$
2. Rotor-core losses, $P_{r(h+e)}$
3. Friction and windage losses, P_{fw}
4. Stray load losses, P_{misc}, consisting of all other losses not covered above.

C. **Mechanical power developed, P_m :**

1. If rotor copper losses are subtracted from rotor input power P_g, the remaining power is converted from electrical to mechanical form. This is called developed mechanical power, P_m.

2. Developed mechanical power = rotor input – rotor copper loss

$$P_m = P_{ir} - P_{cu}$$

$$P_m = P_g - P_{cu}$$

$$P_m = P_g - 3I_2^2 R_2$$

D. The output of the motor is given by :

$$P_0 = P_m - P_{fw} - P_{misc}$$

P_0 is also called shaft power or output mechanical power of an induction motor. The power flow diagram is shown in Fig. 3.12.1.

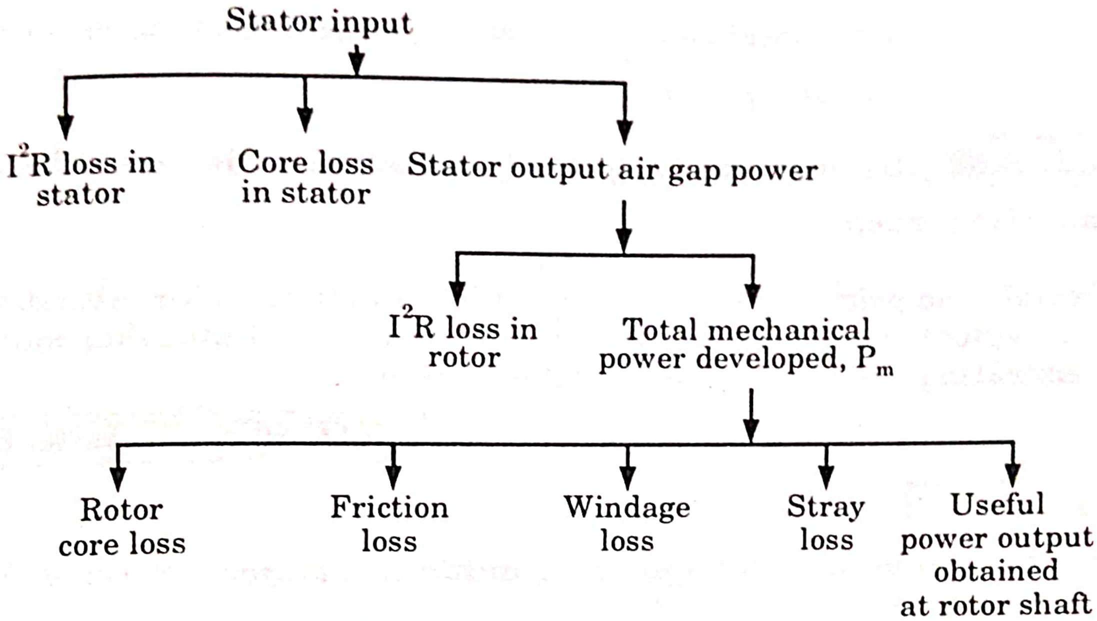


Fig. 3.12.1. The power-flow diagram of an induction motor.

E. Proof :

1. Let τ_d = Developed torque = Torque exerted on the rotor by rotating flux

   n_s = Synchronous speed

   n_r = Rotor speed.

2. Power transferred from stator to rotor = Air-gap power P_g

$$P_g = \omega_s \tau_d = 2\pi n_s \tau_d = \text{Input power to rotor}$$

3. Total mechanical power developed by the rotor :

$$P_m = \omega_s \tau_d = 2\pi n_s \tau_d$$

4. Total I^2R loss in rotor = (Power transferred from stator to rotor) – (Total mechanical power developed by rotor)

$$P_{cu} = P_g - P_m = 2\pi(n_s - n_r)\tau_d$$

5. $$\frac{\text{Total } I^2R \text{ loss in rotor}}{\text{Input power to rotor}} = \frac{2\pi(n_s - n_r)\tau_d}{2\pi n_s \tau_d}$$

Rotor copper loss = s × Rotor input

$$P_{cu} = sP_g = sP_0$$

6. Also, rotor input = mechanical power developed + rotor copper loss

$$P_0 = P_m + P_{cu}$$

$$P_{cu} = s(P_m + P_{cu})$$

$$P_{cu}(1-s) = sP_m$$

$$P_{cu} = \frac{s}{1-s}P_m$$

7. That is, rotor copper loss = $\frac{s}{1-s}$ × mechanical power developed by rotor

$$P_g : P_{cu} : P_m = 1 : s : (1-s)$$

Que 3.13. **Discuss the torque-slip characteristic curve for 3ϕ induction machine.**

OR

Explain the principle of operation of 3ϕ induction motor. Also draw the typical torque-speed characteristic of a 3ϕ induction motor illustrating the stable and unstable regions.

AKTU 2016-17, Marks 10

Answer

A. **Principle of operation of 3ϕ induction motor :** Refer Q. 3.3, Page 3–6A, Unit-3.

B. **Torque-speed characteristics of inductor motor with stable and unstable region :**

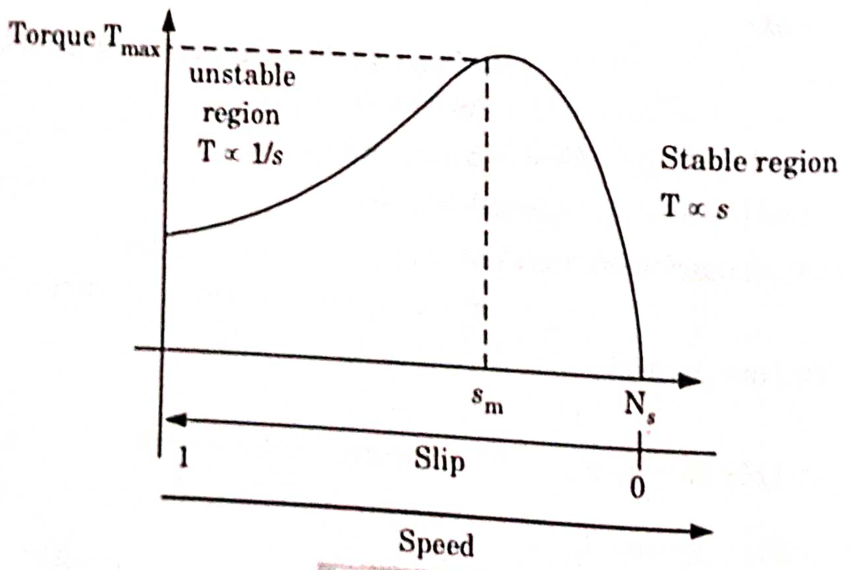


Fig. 3.13.1.

1. For higher slip, $s \approx 1$

$$\left[R_1 + \frac{R_2'}{s}\right]^2 + X^2 = (R_1 + R_2')^2 + X^2$$

$$T = \frac{3}{\omega_s}\left[\frac{V^2 R_2'/s}{(R_1 + R_2')^2 + X^2}\right]$$

$$T \propto \frac{1}{s} \qquad \text{(Rectangular hyperbola)}$$

2. For lower slip,

$$s \approx 0$$

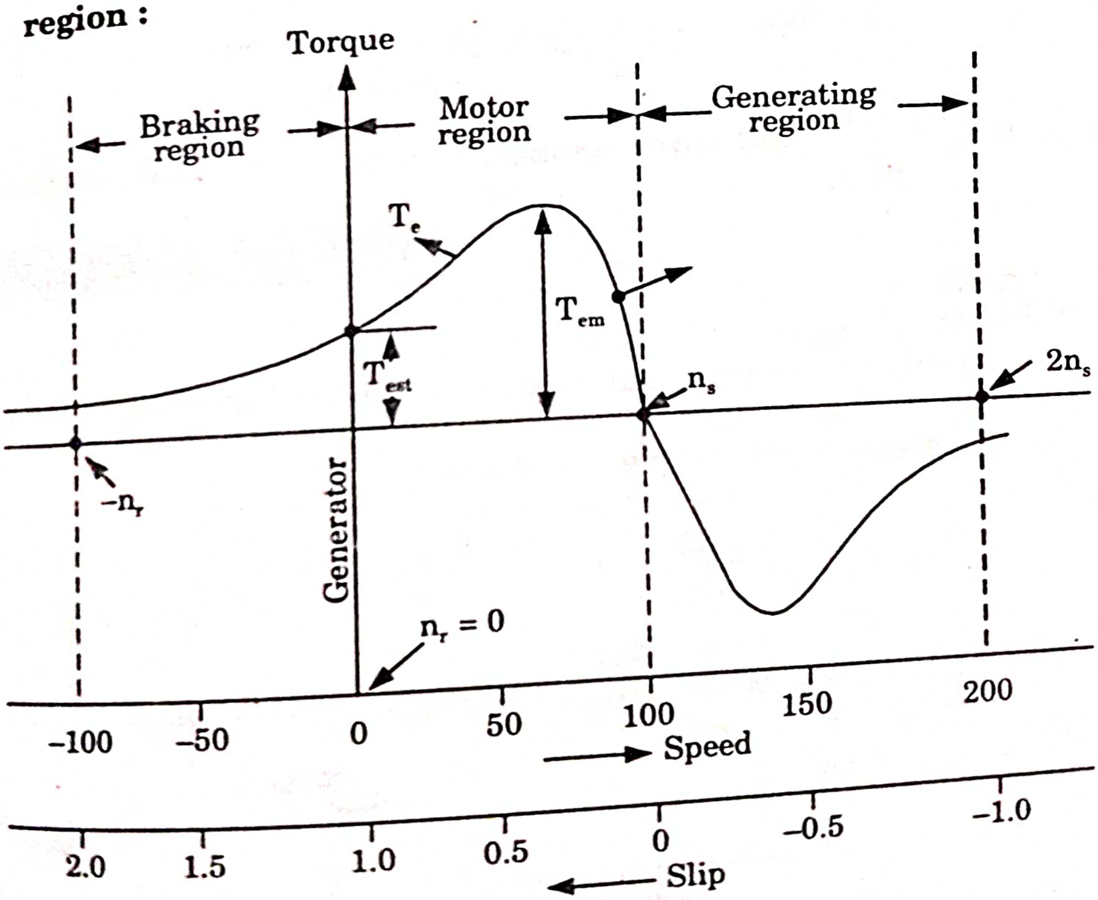
$$\left[R_1 + \frac{R_2'}{s}\right]^2 + X^2 = \left(\frac{R_2'}{s}\right)^2$$

$$T = \frac{3}{\omega_s}\left[\frac{V^2 R_2'/s}{(R_2'/s)^2}\right]$$

$$T = \frac{3}{\omega_s} \times \frac{V^2}{(R_2'/s)} = \frac{3}{\omega_s}\frac{V^2}{R_2'} s$$

$$T \uparrow \propto s \uparrow$$

C. Torque-slip characteristics of induction machine with different region :



n_r = Rotor speed
n_s = Synchronous speed

Fig. 3.13.2.

1. **Motoring mode ($0 < s \le 1$) :** For normal operating condition, rotor rotates in the direction of rotating field produced by the stator currents and slip varies from 1 at standstill to zero at synchronous speed *i.e.*, ($1 \le s \ge 0$).

2. **Generating mode ($s < 0$) :**
   i. In this mode slip is negative *i.e.*, $s < 0$. An induction motor will operate in this region only when its stator terminal are connected to constant frequency voltage source and its rotor is driven above synchronous speed, by prime mover.
   ii. If stator is disconnected from voltage source and rotor is driven above synchronous speed by prime mover no generating action would take place.
3. **Braking mode ($s > 1$) :** In this mode slip is more than 1. Slip more than one can be obtained by driving the rotor by prime mover, opposite to the direction of rotating field, braking action also called plugging. For plugging any two stator leads are interchanged.

Que 3.14. **For a 3ϕ IMs, show that :**

$$\frac{T}{T_{max}} = \frac{\sqrt{K^2+1}}{1+\frac{1}{2}\sqrt{K^2+1}\left[\frac{s}{s_{max,\,T}}+\frac{s_{max,\,T}}{s}\right]}$$

where $K = \dfrac{X_1 + X_2'}{R_1}$ and other symbols having their usual meaning.

AKTU 2013-14, Marks 10

Answer

1. Consider the Thevenin's equivalent network for induction motor as shown in the Fig. 3.14.1.
2. The expression for the torque at slip s is,

$$T = \frac{3}{\frac{2\pi N_s}{60}} \times \frac{R_2'}{s} \times (I_{2r}')^2$$

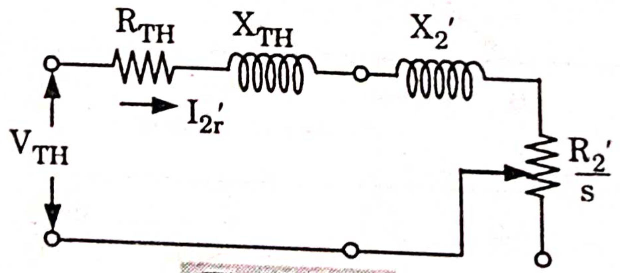


Fig. 3.14.1.

$$I_{2r}' = \frac{V_{TH}}{\sqrt{\left(R_{TH}+\frac{R_2'}{s}\right)^2+(X_{TH}+X_2')^2}}$$

$$\therefore \quad T = \frac{3}{\omega_s} \times \frac{R_2'}{s} \frac{V_{TH}^2}{\left(R_{TH}+\frac{R_2'}{s}\right)^2+(X_{TH}+X_2')^2} \quad \ldots(3.14.1)$$

3. While the expression for maximum torque is,

$$T_{max} = \frac{3}{\omega_s} \frac{0.5\, V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}} \qquad ...(3.14.2)$$

and $$s_{max,T} = \frac{R_2'}{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}}$$

4. Dividing equation (3.14.1) and (3.14.2),

$$\frac{T}{T_{max}} = \frac{[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}\,]\left(\frac{R_2'}{s}\right)}{0.5\left[\left(R_{TH} + \frac{R_2'}{s}\right)^2 + (X_{TH} + X_2')^2\right]}$$

$$= \frac{R_{TH}\left[1 + \sqrt{1 + \left(\frac{X_{TH} + X_2'}{R_{TH}}\right)^2}\,\right]\frac{R_2'}{s}}{0.5\left[R_{TH}^2 + 2R_{TH}\frac{R_2'}{s} + \left(\frac{R_2'}{s}\right)^2 + (X_{TH} + X_2')^2\right]}$$

$$= \frac{R_{TH}\left[1 + \sqrt{1 + \left(\frac{X_{TH} + X_2'}{R_{TH}}\right)}\,\right]\frac{R_2'}{s}}{\frac{R_{TH}\, R_2'}{s}\left[1 + \frac{1}{2}\left(\frac{R_{TH}^2 + (X_{TH} + X_2')^2 + \left(\frac{R_2'}{s}\right)^2}{R_{TH}\frac{R_2'}{s}}\right)\right]}$$

$$= \frac{1 + \sqrt{1 + K^2}}{1 + \frac{1}{2}\left[\frac{R_{TH}^2 + (X_{TH} + X_2')^2 + \left(\frac{R_2'}{s}\right)^2}{R_{TH}\frac{R_2'}{s}}\right]}$$

$$= \frac{1 + \sqrt{1 + K^2}}{1 + \frac{1}{2R_{TH}}\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}\left[\frac{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2} + \frac{(R_2'/s)^2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}}}{\left(\frac{R_2'}{s}\right)}\right]}$$

$$= \frac{1 + \sqrt{1 + K^2}}{1 + \frac{1}{2}\sqrt{1 + \left(\frac{X_{TH} + X_2'}{R_{TH}^2}\right)^2}\left[\frac{s}{\left(\frac{R_2'}{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}}\right)} + \left(\frac{\frac{R_2'}{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}}}{s}\right)\right]}$$

But $\dfrac{R_2'}{\sqrt{R_{TH}^2 + (X_{TH} + X_2')^2}} = s_{max,\,T}$

$$\therefore \quad \frac{T}{T_{max}} = \frac{1+\sqrt{1+K^2}}{1+\frac{1}{2}\sqrt{K^2+1}\left[\dfrac{s}{s_{max,\,T}} + \dfrac{s_{max,T}}{s}\right]}$$

Que 3.15. **Explain efficiency characteristic for 3ϕ induction motor?**

Answer

1. In 3ϕ IM, there are certain fixed losses (such as core loss, friction and windage loss) in addition to variable losses that include stator and rotor copper losses varying nearly as the square of the load.
2. At light loads, the efficiency is quite low because the fixed losses are a relatively large part of the input, with the increase in load.
3. The efficiency at first increases rapidly and attains a maximum value. The fixed and variable losses being equal at this point.
4. Beyond this point the copper losses (I^2R losses) become relatively large, causing the efficiency to decrease.
5. The maximum efficiency occurs at about 80 to 95% of rated output. The higher values being applicable to large motors.

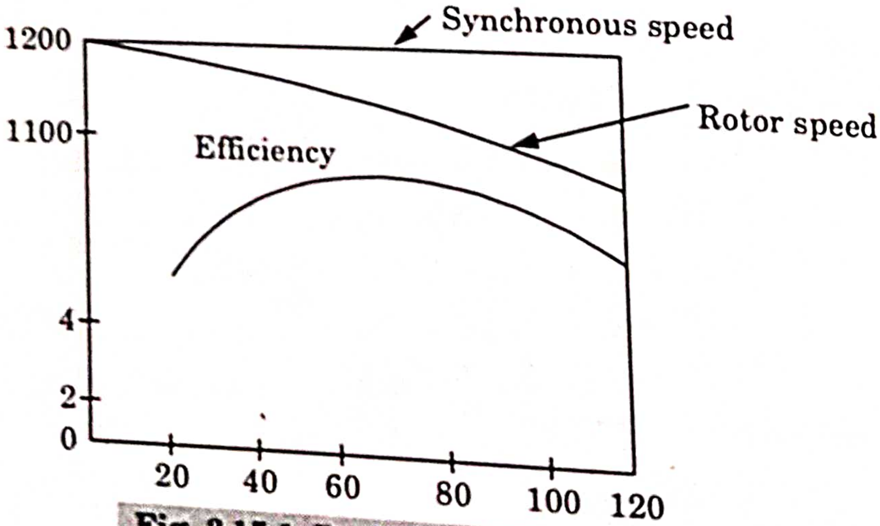


Fig. 3.15.1. Performance curve.

Que 3.16. **A 3ϕ, 400 V, 6-pole, 50 Hz, induction motor develops mechanical power of 20 kW at 985 rpm. Calculate :**
i. The rotor copper loss,
ii. The total input power, and
iii. Rotor frequency (f_r).
The stator losses are equal to 1800 W. Neglect mechanical loss.

AKTU 2013-14, Marks 10

Answer

Given : $f = 50$ Hz, $P = 6$, $N_r = 985$ rpm, $P_{sc} = 1.8$ kW

To Find :
i. Rotor copper loss
ii. Total input power, P_i
iii. Rotor frequency, f_r.

1. $$N_s = \frac{120 f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

$\therefore$ $$s = \frac{N_s - N_r}{N_s} = \frac{1000 - 985}{1000} = 0.015$$

2. Rotor copper loss, $$P_{rc} = \frac{s}{1-s} \times P_{mech}$$

$$= \frac{0.015}{1 - 0.015} \times 20 = 0.304 \text{ kW}$$

3. The total input power, $$P_i = P_{mech} + P_{rc} + P_{sc}$$
$$= 20 + 0.304 + 1.8 = 22.104 \text{ kW}$$

4. Rotor frequency, $$f_r = sf$$
$$= 0.015 \times 50 = 0.75 \text{ Hz}$$

Que 3.17. **A 4 pole, 50 Hz, 3ϕ IM has a rotor resistance of 4.5 Ω/phase and standstill reactance of 8.5 Ω/phase. With no external resistance in the rotor circuit, the starting torque of the motor is 85 N-m.**

i. What is the rotor voltage at standstill ?

ii. What would be the starting torque if 3 Ω resistance were added in each rotor phase ?

iii. Neglecting stator voltage drop, what would be the induced rotor voltage and the torque at a slip of 0.03 ?

AKTU 2013-14, Marks 10

Answer

Given : $P = 4$; $f = 50$ Hz; At start, $s = 1$, $R_2 = 4.5$ Ω/phase; $X_2 = 8.5$ Ω/phase; $T_{st} = 85$ N-m

To Find :
i. Rotor voltage at $s = 1$, E_2.
ii. Starting torque, T_{st}' if 3 Ω resistance is added in each rotor phase.
iii. Induced rotor voltage, E_{2r} and torque, T at $s = 0.03$.

1. The torque at slip s is,

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

$$N_s = \frac{120f}{60P} = 25 \text{ rpm}$$

$$85 = \frac{3}{2\pi \times 25} \times \frac{E_2^2 \times 4.5}{4.5^2 + 8.5^2}$$

$$E_2 = 302.46 \text{ V/ph}$$

2. $$R_2' = R_2 + 3 = 4.5 + 3 = 7.5 \ \Omega$$

$$\therefore \quad T_{st}' = \frac{3}{2\pi \times 25} \times \frac{(302.46)^2 \times 7.5}{7.5^2 + 8.5^2} = 101.975 \text{ N-m}$$

3. $$E_{2r} = sE_2 = 0.03 \times 302.46 = 9.0738 \text{ V}$$

$$\therefore \quad T = \frac{3}{2\pi \times 25} \times \frac{(302.46)^2 \times 0.03 \times 4.5}{(4.5)^2 + (0.03 \times 8.5)^2}$$

$$= 11.61 \text{ N-m}$$

Que 3.18. **A 746 kW, 3-phase, 50 Hz, 16-pole induction motor has a rotor impedance of (0.02 + *j*0.15) ohm at standstill. Full-load torque is obtained at 360 rpm. Calculate :**

i. The speed at which maximum torque occurs.

ii. The ratio of full-load to maximum torque.

iii. The external resistance per phase to be inserted in the rotor circuit to get maximum torque at starting.

AKTU 2016-17, Marks 10

Answer

Given : $P = 16, f = 50$ Hz, $N_r = 360$ rpm, $R_2 + jX_2 = (0.02 + j0.15)\ \Omega$

To Find : N_m, $\frac{\tau_{fl}}{\tau_{max}}$ and external resistance, r.

1. $$N_s = \frac{120f}{P} = \frac{120 \times 50}{16} = 375 \text{ rpm}$$

2. Slip at full load, $$s_{fl} = \frac{N_s - N_r}{N_r} = \frac{375 - 360}{375} = 0.04$$

3. Slip at maximum torque,

$$s_m = \frac{R_2}{X_{20}} = \frac{0.02}{0.15} = \frac{2}{15} = 0.133$$

4. Speed at maximum torque,

$$N_m = (1 - s_m) N_s = (1 - 0.133) \times 375 = 325 \text{ rpm}$$

5. $$\frac{\tau_{fl}}{\tau_{max}} = \frac{2\, s_m\, s_{fl}}{s_m^2 + s_{fl}^2} = \frac{2 \times 0.133 \times 0.04}{(0.133)^2 + (0.04)^2} = 0.552$$

6. Let the external resistance per phase added to the rotor circuit be r ohms.
   $\therefore$ Rotor resistance per phase, $R_2 = (0.02 + r)\,\Omega$

7. The starting torque will be maximum when

$$R_2 = X_{20}$$
$$0.02 + r = 0.15$$
$$\therefore \quad r = 0.13\,\Omega$$

Que 3.19. **A 400 V, 6-pole, 50 Hz, 3-phase induction motor develops shaft torque of 120 N-m at a rotor frequency of 1.5 Hz. Calculate**

i. Shaft power and mechanical power developed if the mechanical torque lost in friction and windage is 8 N-m.
ii. Rotor ohmic loss.
iii. Power input to motor.
iv. The motor efficiency in case total stator loss is 500 W.

AKTU 2016-17, Marks 7.5

Answer

Given : $V_L = 300$ V, $f_s = 50$ Hz, $f_r = 1.5$ Hz, $P = 6$,
$\tau_{sh} = 120$ N-m, $\tau_{lost} = 8$ N-m
To Find : Shaft power, P_{out}; Mechanical power, P_m;
Rotor ohmic loss, P_c; Input power, P_{in} and efficiency, % η.

1. $$f_r = sf_s$$
$$\therefore \quad s = \frac{f_r}{f_s} = \frac{1.5}{50} = 0.03$$

2. $$N_s = \frac{120 f_s}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$
$$N_r = (1 - s)N_s = (1 - 0.03) \times 1000 = 970 \text{ rpm}$$

3. **Shaft power :** $$P_{out} = \tau_{sh} \times \frac{2\pi N_r}{60}$$
$$= 120 \times 2\pi \times \frac{970}{60}$$
$$= 12189.38 \text{ W}$$

4. Rotational loss, $$= \tau_{lost} \times \frac{2\pi \times N_r}{60}$$
$$= 8 \times 2\pi \times \frac{970}{60} = 812.6 \text{ W}$$

5. **Mechanical power :** $P_m = P_{out}$ + Rotational loss

$$= 12189.38 + 812.2$$
$$P_{mech} = 13002 \text{ W}$$

6. **Rotor ohmic loss P_c :**

$\therefore \quad P_g : P_c : P_m = 1 : s : (1 - s)$

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

$$P_c = P_m \left(\frac{0.03}{1-0.03}\right) = 402.12 \text{ W}$$

7. **Power input to motor P_{in} :**

$$\frac{P_g}{P_c} = \frac{1}{s}$$

$$P_g = \frac{P_c}{s} = 13404 \text{ W}$$

8. $$P_{in} = P_g + \text{Total stator loss}$$
$$= 13404 + 500$$
$$= 13904 \text{ W}$$

9. **Motor efficiency, η :**

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{12189.38}{13904} \times 100 = 87.67 \%$$

PART-3

No-Load Test and Blocked Rotor Tests, Induction Generator and its Applications.

CONCEPT OUTLINE : PART-3

- **Determination of circuit model parameters :**

1. **No-load test :**

   Conducted at rated voltage

   Determines core loss, R_m and X_m.

2. **Blocked rotor test :**

   Conducted at reduced voltage, full-load current

   Determines full load copper loss, R_2' and X_2'.

- **Induction Generator :**

1. Also called asynchronous generator.
2. Output depends upon the magnitude of the negative slip.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.20. **Explain briefly no-load test in 3ϕ induction motor.**

Answer

1. This test is used to determine the circuit parameters of the equivalent circuit of the three-phase induction motors.
2. In this method the motor is uncoupled from its load and the rated voltage at the rated frequency is applied to the stator to run the motor without the load.
3. With the help of the two wattmeters the input power of the motor is measured. The circuit diagram of the no-load test is shown in Fig. 3.20.1.

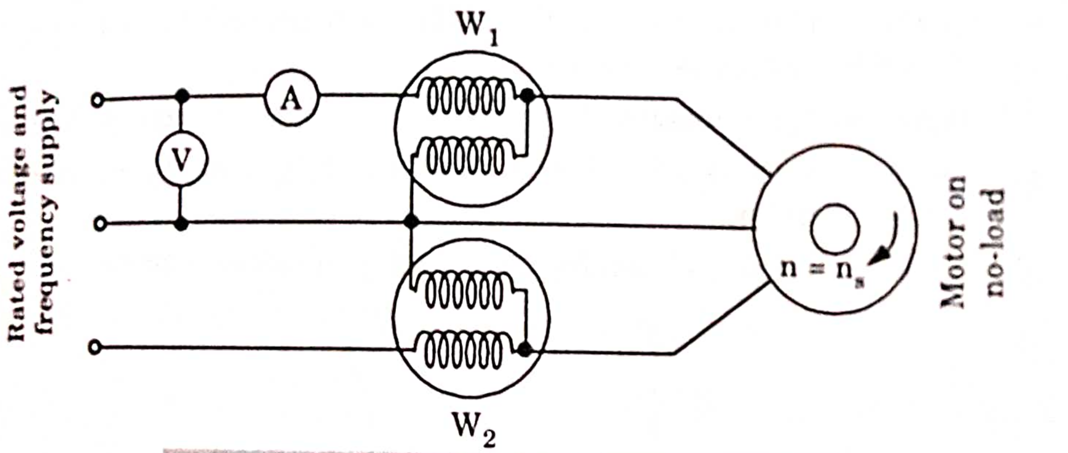


Fig. 3.20.1. Connection diagram for conducting no-load test on induction motor.

4. An ammeter measures the no-load current, and a voltmeter gives the normal rated supply voltage. The I^2R losses on the primary side is neglected as they vary with the square of the load current and the no-load current is also 20-30 % of the full load current.
5. As the motor is running at no-load, the total input power is equal to the constant iron loss, friction and windage losses of the motor.

$P_{constant} = P_0 = W_1 + W_2$ = sum of the two wattmeter readings

6. From test

V_0 = Input line voltage

P_0 = Total three phase input power at the no-load

I_0 = Input line current

$$Z_0 = \frac{V_0 / \sqrt{3}}{I_0}$$

$$R_0 = \frac{P_0/3}{I_0^2}$$

$$X_0 = (Z_0^2 - R_0^2)^{1/2}$$

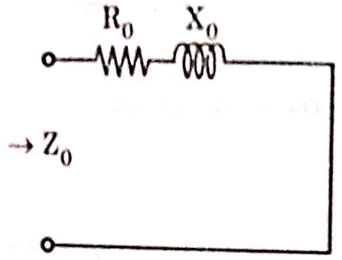


Fig. 3.20.2. Circuit model at no-load.

Separating out core-loss from windage and friction loss :

1. Friction and windage loss can be separated from the no-load loss P_0. At no-load various readings of the no-load loss are taken at the different stator applied voltages. The readings are taken from rated to the breakdown value at rated frequency.
2. As the iron losses are proportional to the square of the flux density and therefore, the applied voltage.
3. The curve is extended to the left to cut the vertical axis at the point A.
4. At the vertical axis $V = 0$ and hence the intercept OA represents the independent loss.
5. A curve plotted between P_0 and V is shown in Fig. 3.20.3.

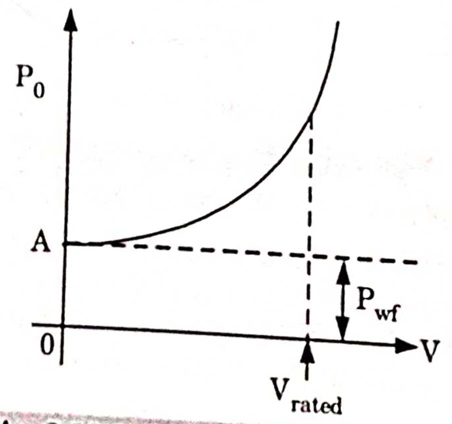


Fig. 3.20.3. Separation of P_{wf} and P_c

Que 3.21. **Define blocked rotor test for 3ϕ induction motor.**

Answer

1. This test is performed the short circuit current I_{sc} with normal applied voltage to stator.
2. Power factor on short-circuit, total equivalent resistance and reactance of the motor as referred to stator (R_{01} and X_{01}).

3. In this test of rotor is held firmly and stator is connected across supply of variable voltage.

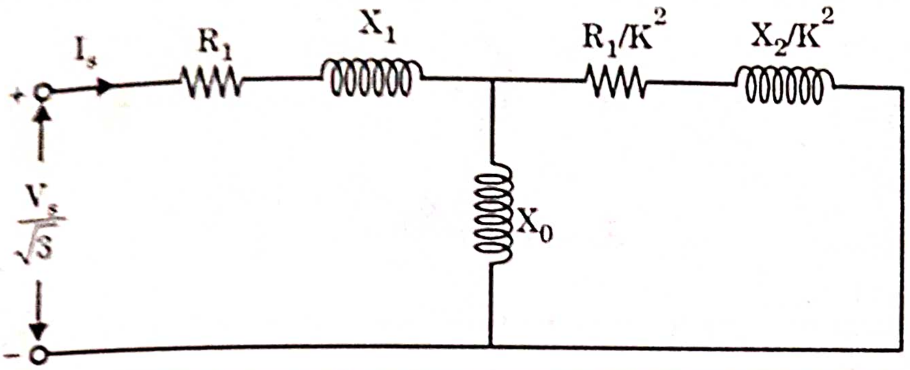


Fig. 3.21.1. Equivalent circuit of a polyphase induction motor under blocked rotor condition.

4. If V_s is the applied voltage (line to line value) and causes current I_s in the stator winding and P_s is the total input power at short circuit then short circuit current I_{sc} with normal voltage V (line to line) applied across the motor is given by

$$I_{sc} = I_s \frac{V}{V_s} \quad ...(3.21.1)$$

and power factor, $$\cos \phi_s = \frac{P_s}{\sqrt{3} V_s I_s} \quad ...(3.21.2)$$

5. Input on short circuit, $P_s = 3 I_s^2 R_{01}$

motor equivalent resistance per phase as referred to stator,

$$R_{01} = \frac{P_s}{3 I_s^2} \quad ...(3.21.3)$$

6. Motor equivalent impedance per phase, as referred to stator

$$Z_{01} = \frac{V_s / \sqrt{3}}{I_s} \quad ...(3.21.4)$$

7. Motor equivalent reactance per phase, as referred to stator,

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} \quad ...(3.21.5)$$

These values constitute the series equivalent of the blocked rotor test.

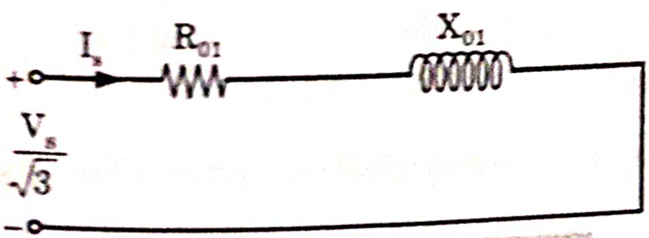


Fig. 3.21.2. Salient pole rotor.

8. Usually the stator resistance per phase X_1 is assumed to be equal to rotor reactance per phase, as referred to stator,

$$X_2' = \left(\frac{X_2}{K_2}\right)$$

so,
$$X_1 = X_2' = \frac{X_{01}}{2}$$

9. In case of wound rotor motors the stator and rotor resistance are separated by dividing R_{01} in the ratio of DC resistance of the stator and rotor winding.

10. In case of squirrel cage induction motors, the rotor resistance per phase, as referred to stator can be determined by subtracting R_1 from R_{01}.

Thus,
$$R_2' = R_{01} - R_1$$

Que 3.22. **A 10 kW, 400 V, 50 Hz, 4 pole, Y-connected squirrel cage IM gave the following test results :**

No-load test : 400 V, 8 A, 250 Watts

Blocked rotor test : 90 V, 35 A, 1350 Watts

The DC resistance of the stator winding per phase measured immediately after the blocked rotor test is 0.6 Ω.

Calculate the following :

i. Equivalent circuit parameters of 3ϕ IM

ii. Rotational losses.

Answer

Given : $P_{out} = 10$ kW, $V_L = 400$ V, $f = 50$ Hz, Pole, $P = 4$
No-load test, $W_0 = 250$ W, $I_{0\,(line)} = 8$ A, $V_0 = 400$ V
Block rotor test, $V_{SC} = 90$ V, $I_{SC} = 35$ A, $W_{SC} = 1350$ W
DC resistance = 0.6 Ω

To Find : i. Equivalent circuit parameter
ii. Rotational loss, P_R.

1. The effective stator resistance per phase is taken as 1.2 times its DC values.

$$\therefore \quad R_1 = R_{stator} = 1.2 \times 0.6 = 0.72\ \Omega$$

2. $$P_R = \text{Rotational losses} = W_0 - 3\,I_0^2\,R_1$$

$$= 250 - 3 \times \left(\frac{8}{\sqrt{3}}\right)^2 \times 0.72 = 203.92 \text{ W}$$

3. For delta connection,

$$I_0(ph) = \frac{I_{0(\text{line})}}{\sqrt{3}} = \frac{8}{\sqrt{3}} \text{ A}$$

$$Z_{nl} = \frac{V_0}{I_0} = \frac{400}{\left(\frac{8}{\sqrt{3}}\right)} = 86.6025 \, \Omega$$

$$R_{nl} = \frac{W_0}{3I_0^2} = \frac{250}{3 \times \left(\frac{8}{\sqrt{3}}\right)^2} = 39062 \text{ W}$$

$$X_{nl} = \sqrt{Z_{nl}^2 - R_{nl}^2} = 86.5143 \, \Omega$$

4. From blocked rotor test,

$$R_{1e} = \frac{W_{sc}}{3I_{sc}^2} = \frac{1350}{3 \times \left(\frac{35}{\sqrt{3}}\right)^2} = 1.102 \, \Omega$$

$$Z_{1e} = \frac{V_{sc}}{I_{sc}} = \frac{90}{\left(\frac{35}{\sqrt{3}}\right)} = 4.4538 \, \Omega$$

$\therefore$ $$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2} = 4.3153 \, \Omega$$

5. Now $X_{1e} = X_1 + X_2$ and $X_1 = X_2$

6. $\therefore$ $$X_1 = X_2 = \frac{X_{1e}}{2} = \frac{4.3153}{2} = 2.1576 \, \Omega$$

$$X_0 = X_{nl} - X_1 = 86.5143 - 2.1579 = 84.3566 \, \Omega$$

$$X_R = X_2 - X_0 = 2.1576 + 57.3566 = 56.5143 \, \Omega$$

7. $$R_2 = [R_{1e} - R_1]\left[\frac{X_R}{X_0}\right]^2 = [1.102 - 0.72]\left[\frac{835146}{84.3566}\right]^2$$

$$= 0.4018 \, \Omega$$

Que 3.23. **A 5 kW, 220 V, 50 Hz, 6 pole, 3-phase, star-connected induction motor gave the following test data :**
No-Load Test : 220 V, 6 A, 475 W (Line Values)
Blocked Rotor Test : 110 V, 27 A, 1930 W.
Determine from circle diagram for full load condition the line current, power factor, torque, slip and efficiency. Also determine maximum output, maximum torque and slip for maximum torque. Take stator copper loss at stand-still twice the rotor copper loss.

AKTU 2012-13, Marks 10

Answer

Given : $V = 220$ V, $I_o = 6$ A, $W_o = 475$ W, $V_s = 110$ V, $I_s = 27$ A, $W_s = 1930$ W

To Find : Line current, Power factor, Torque, Slip, Efficiency, Maximum output power, Maximum torque, Slip for maximum torque.

1. Short-circuit current with normal voltage of 220 V applied to the stator,

$$I_{sc} = I_s \left(\frac{V}{V_s}\right) = 27 \left(\frac{220}{110}\right) = 54 \text{ A}$$

2. No-load power factor,

$$\cos \phi_o = \frac{W_o}{\sqrt{3} V I_o} = \frac{475}{\sqrt{3} \times 220 \times 6} = 0.2077$$

No-load phase angle,

$$\phi_o = 78.008°$$

3. Short-circuit power input with normal voltage,

$$P_{sc} = \left(\frac{I_{sc}}{I_s}\right)^2 W_s = \left(\frac{54}{27}\right)^2 \times 1930 = 7720 \text{ W}$$

4. Short-circuit power factor,

$$\cos \phi_s = \frac{P_{sc}}{\sqrt{3} V I_{sc}} = \frac{7720}{\sqrt{3} \times 220 \times 54} = 0.375$$

5. Short-circuit phase angle,

$$\phi_s = \cos^{-1}(0.375) = 67.96°$$

6. Let current scale be 3 A/cm

The circle diagram is shown in Fig. 3.23.1.

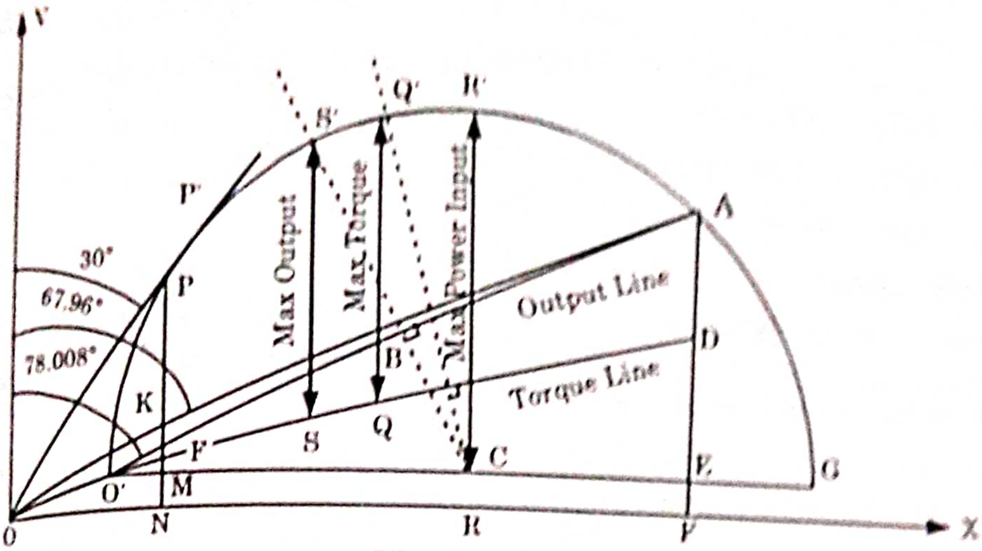


Fig. 3.23.1.

Step I : No-load current phasor OO'. It represents 6 A and measures $\frac{6}{3} = 2$ cm.

It is drawn at an angle of 78.008° with V-axis.

Step II : Phasor OA represents 54 A and measures $\frac{54}{3} = 18$ cm. It is drawn at an angle of 67.96° with V-axis.

Step III : Join O' and A. $O'G$ is drawn parallel to OX (X-axis). BC is bisector of $O'A$.

Step IV : With C as centre and $O'C$ as radius, a semicircle is drawn.

Step V : AF represents power input on short-circuit with normal voltage applied. It measures 8.5 cm and represents 7720 W.

Hence, power scale becomes

$$1 \text{ cm} = \frac{7720}{8.5} \text{ W} = 908.235 \text{ W}$$

Step VI : Full-load current is $\frac{5000}{220} = 22.72$ A. It is represented by length $= \frac{22.72}{3} = 7.57$ cm. With O' as centre and 7.57 cm as radius, an arc is drawn intersecting the semi-circle at P. This is representing full load condition. Join points O and P. Draw perpendicular PN from point P on the X-axis. This line intersects the lines $O'A$ (output line), $O'D$ (torque line), $O'E$ and OX at points K, L, M and N respectively.

Since, Stator copper loss = 2 × Rotor copper loss + Rotor copper loss = 3 × Rotor copper loss

∴ Rotor copper loss = 4 cm = AD

∴ Stator copper loss = 2 × 4 = 8 cm

Total copper loss = 3 × 4 = 12 cm

Point D separates stator and rotor copper loss. The AD (= 4 cm) represents rotor copper loss and DE (= 8 cm) represents stator copper loss. The line $O'D$ represents torque line.

i. ∴ $$\text{Line current} = \frac{5000}{220} = 22.72\text{ A}$$

ii. $$\text{Power factor} = \frac{PN}{PO} = \frac{7}{8} = 0.875$$

iii. Torque at full load, $\tau_{fl} = LP = 6\text{ cm} = 6 \times 908.235 = 5449.41$ synchronous watts

iv. $$\text{Slip} = \frac{KL}{PL} = \frac{0.4}{6} = 0.067\text{ pu} = 6.7\ \%$$

v. $$\text{Efficiency} = \frac{PK}{PN} = \frac{5.8}{7} = 0.8285\text{ pu} = 82.85\ \%$$

vi. Maximum power output = SS' = 9 cm = 9 × 908.235 = 8174.115 syn watts

vii. Maximum torque = QQ' = 9.2 cm = 9.2 × 908.235 = 8355.762 syn watts

viii. $$\text{Slip for maximum torque} = \frac{QQ''}{QQ'} = \frac{2}{9.2} = 0.2173\text{ pu} = 21.73\ \%$$

Que 3.24. **Define induction generator with the help of neat diagram. Also give its applications.**

Answer

1. An induction generator is asynchronous in nature because of which it is commonly used as "windmill generator" as a windmill runs at non-fixed speed.
2. These are used in remote areas to supplement power received from weak transmission links.

3. A transmission line connected to an induction generator feeding a local load is drawn in Fig. 3.24.1.

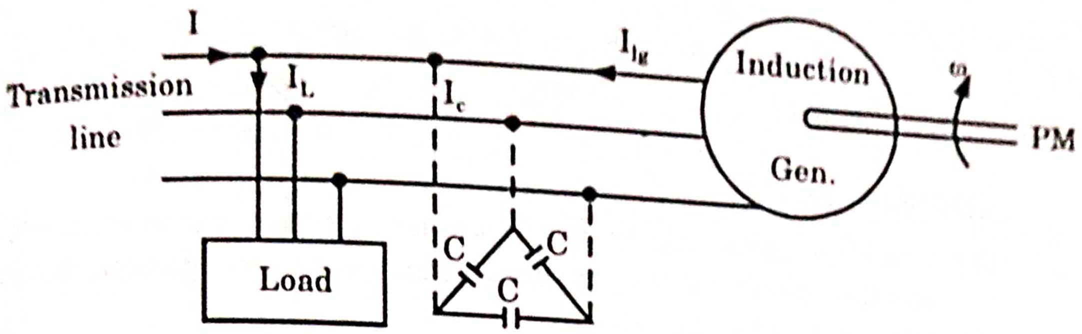


Fig. 3.24.1.

4. The prime mover must be provided with automatic control to increase the generator speed when it is required to meet increased load.

Isolated induction generator :

1. An isolated induction generator feeding a load is shown in Fig. 3.24.2.

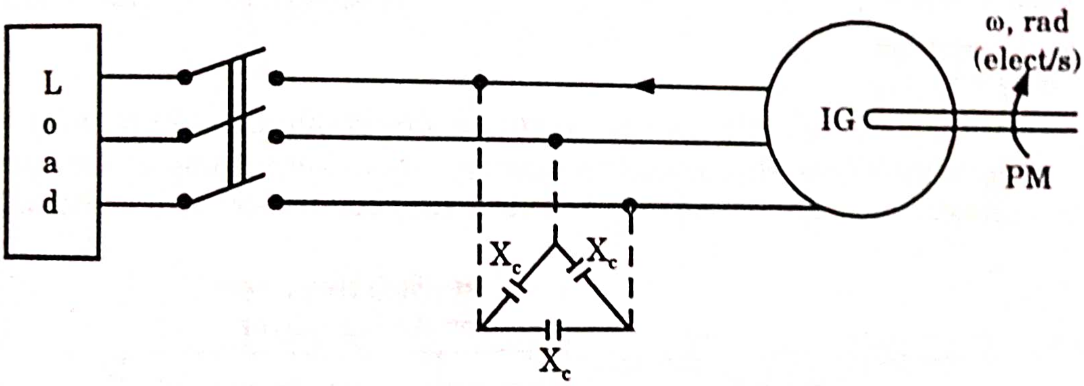


Fig. 3.24.2.

2. The delta connected capacitor across the generator terminals provides the magnetizing currents necessary to excite the isolated generator.
3. As the generator is loaded, the operating frequency depends primarily upon rotor speed but is affected by the load, while the voltage is mainly decided by capacitor reactance (X_c) at the opening frequency.
4. Let,

ω_0 = Rated frequency
ω_s = Operating frequency (stator)
ω = Stator frequency corresponding to rotor speed

$$a = \frac{\omega_s}{\omega_0}$$

and

$$b = \frac{\omega}{\omega_0}$$

5. The machine slip (which should be negative) can be expressed as

$$s = \frac{(\omega_s - \omega_r)}{a\omega_s}$$

$$= \frac{(a\omega_s - b\omega_s)}{a\omega_s} = \frac{(a-b)}{a}$$

$b < a.$

Applications :

1. The induction generator is useful when the prime mover does not run at constant speed such as in hydro-electric power stations having variable low head water supply.
2. The induction generator is very useful for installation in small power stations where it can be operated in parallel and feeding into a common main without attendant.
3. The synchronous generator is useful for braking purpose in railway work.

Que 3.25. **Explain the voltage build-up of an isolated induction generator.**

AKTU 2014-15, Marks 05

Answer

1. If the bank of delta connected capacitors is operated in parallel with induction generator then the reactive power requirement of induction generator is met by capacitors. This arrangement is shown in Fig. 3.25.1.

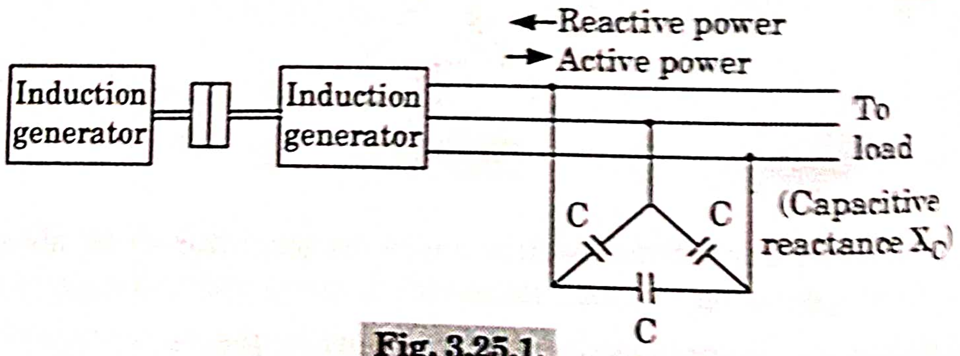


Fig. 3.25.1.

2. The induction generator in this case is said to be isolated induction generator supplying a load. The external voltage source is not required in this case.
3. Unlike in synchronous generators, induction generators are not rotated at a definite speed at a given frequency.
4. The speed varies with load as the load is proportional to slip. The frequency of the induction generator is same as the frequency of the line to which it is connected.

5. In case of self excited induction generators, the bank of delta connected capacitors supply the necessary magnetizing current for exciting the generator.
6. With the load put on the generator, the operating frequency of the stator changes. It depends on rotor speed and is affected by the load.
7. The voltage is primarily decided by the capacitive reactance at that operating frequency.
8. The equivalent circuit on per phase basis is as shown in the Fig. 3.25.2.

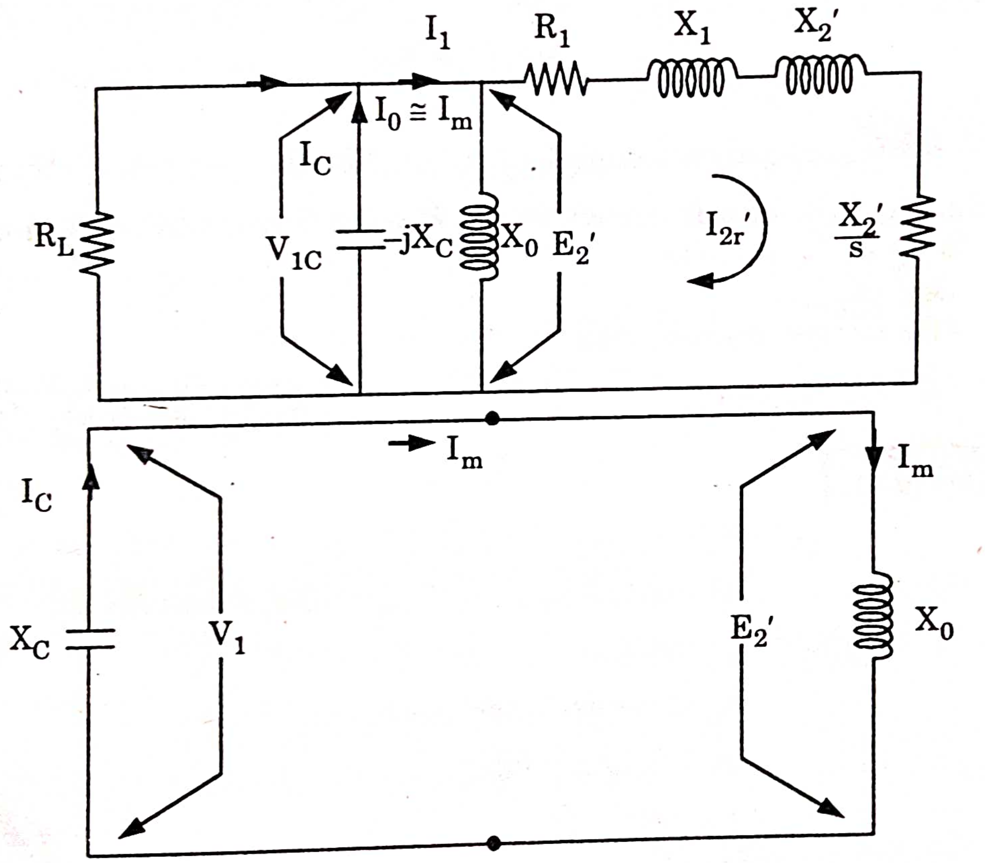


Fig. 3.25.2.

9. Initially the induction generator is running at synchronous speed. I_m is the magnetizing current in motoring mode.
10. If voltage drop in R_1 and X_1 is neglected then $V_1 \approx E_2'$. But I_m is the magnetising current supplied by capacitors, so it flows through the capacitors.

$\therefore$ $$V_1 = I_m X_c$$

11. The magnetization characteristics is shown in the Fig. 3.25.3.

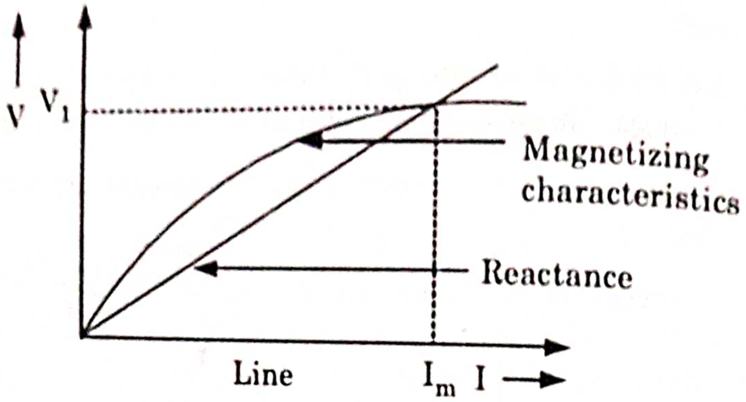


Fig. 3.25.3.

Que 3.26. **A squirrel-cage Induction Motor is rated 25 kW, 440 V, 3ϕ, 50 Hz. On full-load it draws 28.7 kW with line current 50 A and runs at 720 rpm. Calculate :**

i. The slip (*s*)

ii. The power factor, and

iii. The efficiency (η).

AKTU 2013-14, Marks 10

Answer

Given : P_{in} = 28.7 kW, P_0 = 25 kW, I_L = 50 A, f = 50 Hz, N_r = 720 rpm

To Find : i. Slip, *s*.

ii. Power factor, cos ϕ.

iii. Efficiency, η.

Let us assume $P = 8$

$$\therefore \quad N_s = \frac{120 f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

$$N_r = 720 \text{ rpm}$$

i. Slip,

$$s = \frac{N_s - N_r}{N_s} = \frac{750 - 720}{750} = 0.04$$

ii.

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

$$28.7 \times 10^3 = \sqrt{3} \times 400 \times 50 \times \cos\phi$$

$$\therefore \quad \cos\phi = 0.75$$

iii. Efficiency,

$$\eta = \frac{P_0}{P_{in}} = \frac{25}{28.7} = 0.8710 = 87.10\ \%$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Give the constructional details about three phase induction motor. Which types of rotor are used in 3ϕ induction motor ?

Ans. Refer Q. 3.1, Unit-3.

Q. 2. Explain the principle of operation of a 3-phase induction motor.

Ans. Refer Q. 3.3, Unit-3.

Q. 3. Draw Phasor diagram of induction motor.

Ans. Refer Q. 3.5, Unit-3.

Q. 4. Derive expression of slip speed, slip, percentage slip and frequency of rotor voltage and current.

Ans. Refer Q. 3.7, Unit-3.

Q. 5. Derive the expression for developed torque for a 3ϕ induction motor and obtain the condition for maximum torque. Obtain the ratio of full load torque to maximum torque. Also draw torque-slip curves and discuss the effect of rotor resistance.

Ans. Refer Q. 3.11, Unit-3.

Q. 6. Discuss the torque-slip characteristic curve for 3ϕ induction machine.

Ans. Refer Q. 3.13, Unit-3.

Q. 7. Define blocked rotor test for 3ϕ induction motor.

Ans. Refer Q. 3.21, Unit-3.

Q. 8. Explain how a Rotating Magnetic Field (RMF) is produced in a 3-phase induction motor ? Develop suitable expression.

Ans. Refer Q. 3.2, Unit-3.

Q. 9. A 5 kW, 220 V, 50 Hz, 6 pole, 3-phase, star-connected induction motor gave the following test data :
No-Load Test : 220 V, 6 A, 475 W (Line Values)
Blocked Rotor Test : 110 V, 27 A, 1930 W.
Determine from circle diagram for full load condition the line current, power factor, torque, slip and efficiency. Also determine maximum output, maximum torque and slip for maximum torque. Take stator copper loss at stand-still twice the rotor copper loss.

Ans. Refer Q. 3.23, Unit-3.

Q. 10. Define induction generator with the help of neat diagram. Also give its applications.

Ans. Refer Q. 3.24, Unit-3.

☺☺☺

4 UNIT

Three Phase Induction Machine-II

PART-1

Starting of Three Phase Induction Motor.

CONCEPT OUTLINE : PART-1

- **Method of starting :**

1. **Direct on-line starter :** The motor is connected by means of a starter across the full load supply voltage.
2. **Star/delta starting :** Start in star, run in delta. Starting current and torque both reduced by a factor of 1/3.
3. **Autotransformer starting :** Used for very large motor. Both starting current and torque reduce by a factor of x^2, x = Voltage reduction factor.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. **Why "Starter" is required to start a 3ϕ induction motor ? Name different starting methods and describe star-delta method of starting a squirrel cage induction motor. Determine the ratio of starting to full load torque.**

AKTU 2012-13, Marks 10

Answer

A. **Starter :**

1. When the supply is connected to the stator of a three-phase induction motor, a rotating magnetic field is produced and the rotor starts rotating. Thus, a three-phase induction motor is self-starting.
2. At the time of starting the motor slip is unity and the starting current is very large.
3. The purpose of a starter is not to start the motor. The purpose of starter is :

i. To reduce the heavy starting current.

ii. To provide over-load and under-voltage protection.

B. **Commonly used starters for 3ϕ induction motor are :**

i. Direct on-line starter

ii. Star-delta starter
iii. Auto-transformer starter

C. Star-delta starting :

1. Fig. 4.1.1 shows the connection of a three-phase induction motor with a star-delta starter.

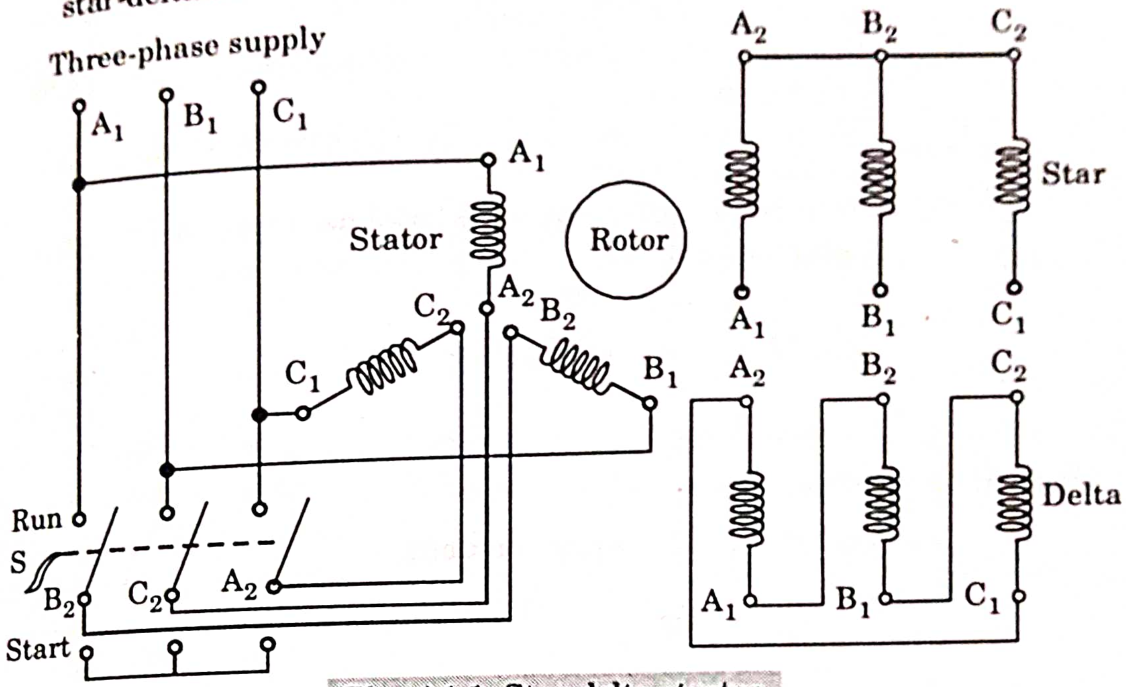


Fig. 4.1.1. Star-delta starter.

2. When the switch S is in start position, the stator windings are connected in star.
3. When the motor picks up speed, say 80 percent of its rated value, the changeover switch S is thrown quickly to the run position which connects the stator windings in delta.
4. By connecting the stator windings, first in star and then in delta, the line current drawn by the motor at starting is reduced to one-third as compared to starting current in the windings connected in delta.
5. At the time of starting when stator winding are star connected, each stator phase gets a voltage $V_L/\sqrt{3}$. Since, the torque developed by an induction motor is proportional to the square of the applied voltage, star-delta starting reduces the starting torque to one-third of that obtainable level by direct-delta starting.

D. Expression for torque ratio :

1. At starting, the stator windings are connected in star and therefore voltage across each phase winding is equal to $1/\sqrt{3}$ times the line voltage.
2. Let V_L = Line voltage
   I_{styp} = Starting current per phase with stator windings connected in star
   I_{styl} = Starting line current with stator winding in star

3. For star connection, Line current = Phase current

$\therefore \quad I_{st\gamma l} = I_{st\gamma p}$

4. If V_1 = Phase voltage

V_L = Line voltage

$I_{st\Delta p}$ = Starting current per phase by direct switching with stator winding connected in delta.

$I_{st\Delta l}$ = Starting line current by direct switching with stator winding in delta.

$I_{sc\Delta p}$ = Short-circuit phase current by direct switching with stator windings in delta.

Z_{e10} = Standstill equivalent impedance per phase of the motor referred to stator.

$$I_{st\gamma p} = \frac{V_1}{Z_{e10}} = \frac{V_L}{\sqrt{3}Z_{e10}}$$

$$I_{st\Delta p} = \frac{V_L}{Z_{e10}}$$

5. For delta connection,

$$\text{Line current} = \sqrt{3} \times \text{Phase current}$$

$$I_{st\Delta l} = \sqrt{3}I_{st\Delta p} = \frac{\sqrt{3}V_L}{Z_{e10}}$$

6. $\dfrac{\text{Starting line current with star-delta starting}}{\text{Starting line current with direct switching in delta}}$

$$= \frac{I_{st\gamma p}}{I_{st\Delta l}} = \frac{(V_L / \sqrt{3}Z_{e10})}{\sqrt{3}(V_L / Z_{e10})} = \frac{1}{3} \quad ...(4.1.1)$$

7. Also, $\dfrac{\text{Starting torque with star-delta starting}}{\text{Starting torque with direct switching in delta}}$

$$= \frac{(V_L / \sqrt{3})^2}{V_L^2} = \frac{1}{3} \quad ...(4.1.2)$$

8. And, $\dfrac{\text{Starting torque with star-delta starting}}{\text{Full load torque with direct windning in delta}}$

$$= \left[\frac{(I_{st\gamma p})^2 \dfrac{R_2}{1}}{2\pi\, n_s}\right] \div \left[\frac{I_{fl\Delta p}^2}{2\pi n_s}\frac{R_2}{s_{fl}}\right] = \left(\frac{I_{st\gamma p}}{I_{fl\Delta p}}\right)^2 s_{fl} \quad ...(4.1.3)$$

where $I_{fl\Delta p}$ = Full-load phase current with winding in delta.

9. But $\quad I_{st\gamma p} = \dfrac{V_L / \sqrt{3}}{Z_{e10}}$

$$I_{st\Delta p} = \frac{V_L}{Z_{e10}}$$

$$\therefore \quad I_{st\gamma p} = \frac{1}{\sqrt{3}} I_{st\Delta p}$$

and

$$I^2_{st\gamma p} = \frac{1}{3} I^2_{st\Delta p}$$

10. $\therefore \dfrac{\text{Starting torque with star-delta starting}}{\text{Full load torque with stator winding in delta}}$

$$= \left(\frac{I_{st\gamma p}}{I_{fl\Delta p}}\right)^2 s_{fl} = \frac{1}{3}\left(\frac{I_{st\Delta p}}{I_{fl\Delta p}}\right)^2 s_{fl}$$

Que 4.2. **Discuss auto-transformer starting method of 3ϕ induction motor.**

Answer

1. Auto-transformer starter is suitable for both star and delta connected motors. In this method, by using a 3ϕ auto-transformer tapping, the starting current is limited.
2. Auto-transformer starter connection diagram is shown in Fig. 4.2.1.

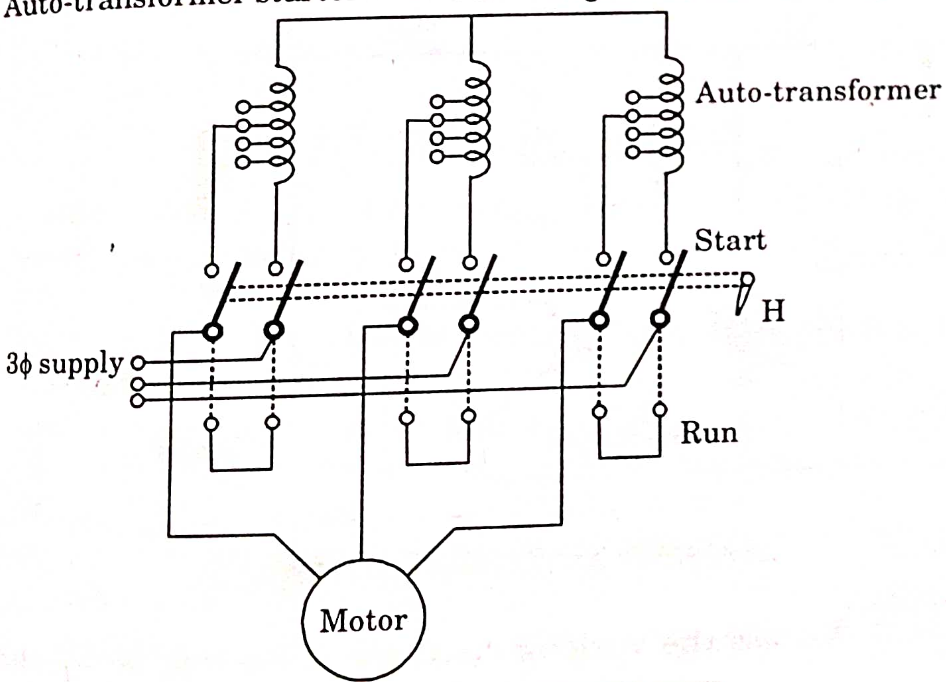


Fig. 4.2.1. Auto-transformer starter.

3. With auto-transformer, per phase starting current in motor winding

$$= \frac{xV_1}{Z_{sc}} = xI_{sc} \qquad ...(4.2.1)$$

Where, x = Transformation ratio

4. If no load current = 0 A

then per phase input VA = per phase output VA

$$I_{st} V_1 = xV_1(xI_{sc})$$

$$I_{st} = x^2 I_{sc} \quad \text{...(4.2.2)}$$

5. $\dfrac{\tau_{est}}{\tau_{fl}} = \dfrac{(\text{per phase starting current in motor winding})^2}{(\text{per phase motor full-load current})^2} s_{fl}$

6. From eq. (4.2.1),

$$\frac{\tau_{est}}{\tau_{fl}} = \frac{(xI_{sc})^2}{I_{fl}^2} s_{fl}$$

$$= x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \quad \text{...(4.2.3)}$$

8. From eq. (4.2.2) and (4.2.3),

$$\frac{\tau_{est}}{\tau_{fl}} = x^2 \left(\frac{1}{x^2}\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} = \frac{1}{x^2}\left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} \quad \text{...(4.2.4)}$$

9. From eq. (4.2.3),

$$\frac{\tau_{est}}{\tau_{fl}} = \frac{(x^2 I_{sc}) I_{sc}}{I_{fl}^2} s_{fl} = \frac{I_{st} I_{sc}}{I_{fl}^2} s_{fl}$$

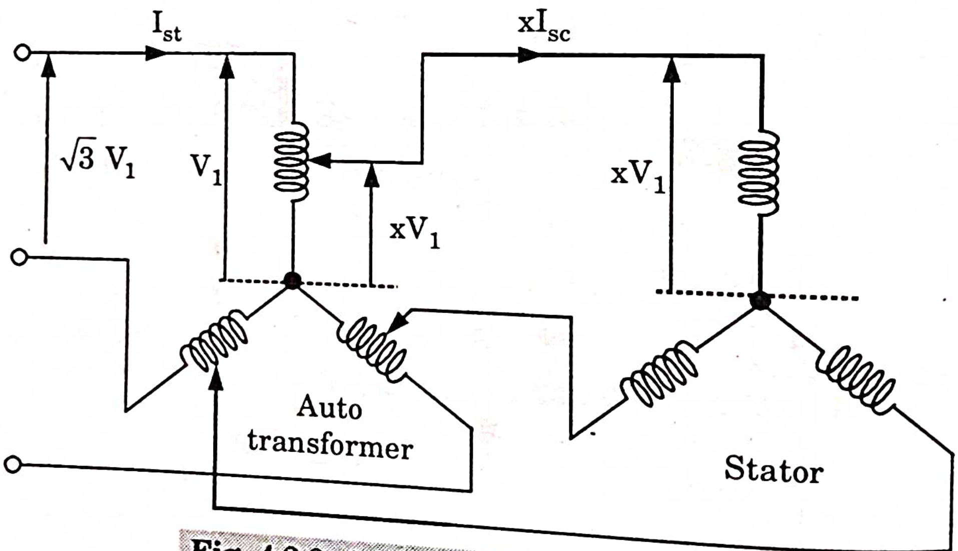


Fig. 4.2.2. Auto-transformer starting.

Que 4.3. **Discuss the various methods of starting of a 3-phase induction motor.**

AKTU 2015-16, Marks 10

Answer

A. Direct on-line starter :

1. In the direct on-line method of starting, induction motor is connected by means of a starter across the full supply voltage. Connection diagram is shown in Fig. 4.3.1.

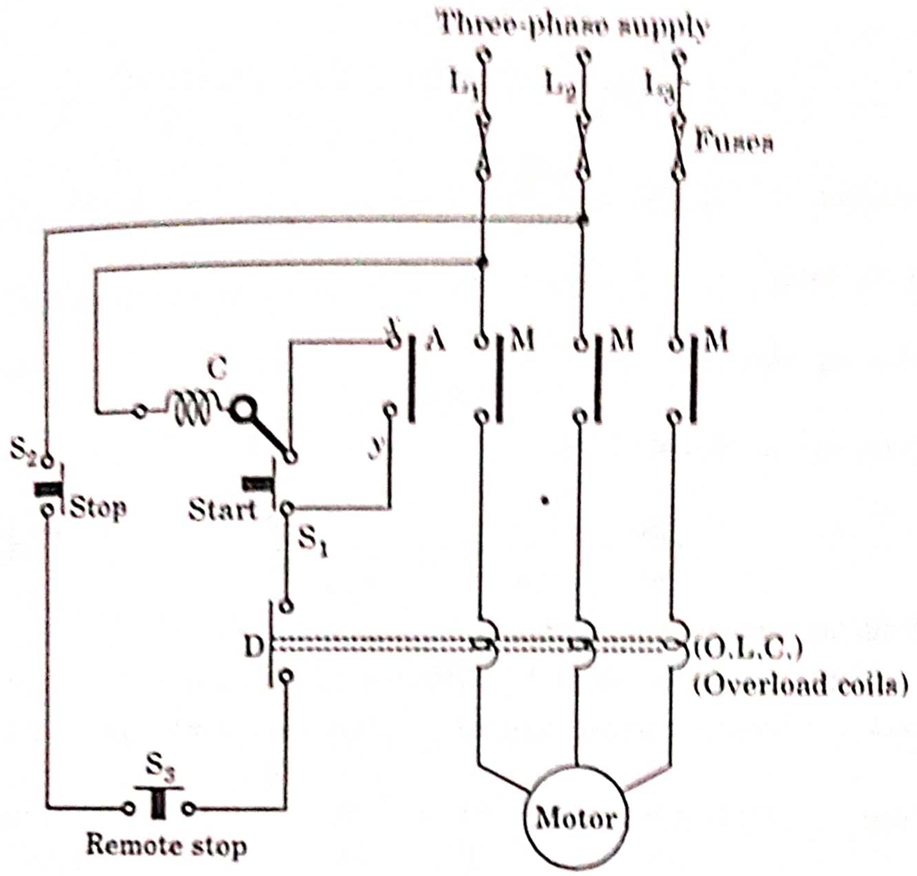


Fig. 4.3.1. Direct on-line starter.

2. It consists of a coil-operated contactor C controlled by 'START' and 'STOP' buttons. On pressing S_1 (start) coil C is energised from L_1 and L_2 (conductors).
3. The three main contacts M and auxiliary contact A close and the terminal x and y are short-circuited.
4. When S_1 is released, it moves back under spring action. Even then the C remains energised through xy. Thus, the main contacts M remain closed and motor continues to get supply.
5. When the STOP push button S_2 is pressed, the supply through the contactor coil C is disconnected. Since the coil C is de-energised, the main contacts M and auxiliary contact A are opened. The supply to motor is disconnected and the motor stops.
6. **Undervoltage protection :** When the voltage falls below a certain value or in the event of failure of supply during motor operation, the coil C is de-energised. The motor is then disconnected from the supply.
7. **Overload protection :** In case of an overload on the motor, one or all the overload coils (O.L.C.) are energised. The normally closed contact D is opened and the contactor coil C is de-energised to disconnect the supply to the motor.
8. For a 3ϕ induction motor,

Torque $\tau_e = \dfrac{3I_2^2 R_2}{2\pi n_s s}$ ...(4.3.1)

9. At starting $s = 1, I_2 = I_{2st}, \tau_e = \tau_{est}$

From eq. (4.3.1), $\tau_{est} = \dfrac{3I_{2st}^2 R_2}{2\pi n_s \times 1}$ ...(4.3.2)

At full load $s = s_{fl}, I_2 = I_{2fl}, \tau_e = \tau_{efl}$

From eq. (4.3.1), $\tau_{efl} = \dfrac{3I_{2st}^2 R_2}{2\pi n_s \times s_{fl}}$ ...(4.3.3)

10. From eq. (4.3.2) and (4.3.3),

$$\therefore \quad \frac{\tau_{est}}{\tau_{efl}} = \left(\frac{I_{2st}}{I_{2fl}}\right)^2 \times s_{fl} \qquad ...(4.3.4)$$

11. If the no-load current neglected,
I_{st} × Effective stator turn = I_{2st} × Effective rotor turn ...(4.3.5)
Also I_{fl} × Effective stator turn = I_{2fl} × Effective rotor turns ...(4.3.6)

12. From eq. (4.3.5) and (4.3.6), $\dfrac{I_{st}}{I_{fl}} = \left(\dfrac{I_{2st}}{I_{2fl}}\right)$ ...(4.3.7)

13. From eq. (4.3.4) and (4.3.7), $\dfrac{\tau_{est}}{\tau_{efl}} = \left(\dfrac{I_{st}}{I_{fl}}\right)^2 s_{fl}$ ...(4.3.8)

14. $\because$ Starting current is equal to the short circuit current then

$$I_{st} = I_{sc} \qquad ...(4.3.9)$$

From eq. (4.3.8) and (4.3.9), we get

$$\frac{\tau_{est}}{\tau_{efl}} = \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}$$

B. **Auto-transformer starter :** Refer Q. 4.2, Page 4–5A, Unit-4.

C. **Star-Delta Starting :** Refer Q. 4.1, Page 4–2A, Unit-4.

Que 4.4. **A 3ϕ squirrel cage IM (SCIM) has maximum torque equal to twice the full-load torque. Determine the ratio of motor torque to its full load torque, if it is started by :**

i. D.O.L. starter

ii. Auto-transformer starter with 70 % tapping

iii. Star-delta starter.

The per phase rotor resistance and per phase standstill reactance referred to stator are 0.2 Ω and 2 Ω respectively. Neglect stator impedance.

Answer

Given : $\tau_{max} = 2\tau_{fl}$, $r_2 = 0.2\ \Omega$, $x_2 = 2\ \Omega$, $\tau_{em} = 2\ \tau_{efl}$

To Find : Ratio, $\dfrac{\tau_{est}}{\tau_{efl}}$.

1. With negligible stator impedance, slip at which maximum torque occurs is

$$s_{mr} = \frac{r_2}{x_2} = \frac{0.2}{2} = 0.1$$

Now
$$\frac{\tau_{est}}{\tau_{em}} = \frac{2}{\dfrac{s_{mt}}{1} + \dfrac{1}{s_{mt}}} = \frac{2}{\dfrac{0.1}{1} + \dfrac{1}{0.1}} = \frac{2}{10.1}$$

$$\tau_{est} = \frac{2}{10.1}(2\tau_{efl}) = 0.396\ \tau_{efl}$$

$$\frac{\tau_{est}}{\tau_{efl}} = \frac{0.396}{1}$$

2. With auto-transformer starter with 70% tapping :

$$\frac{\tau_{est\ \text{with auto-transformer}}}{\tau_{est\ \text{with direct switching}}} = x^2$$

$$\tau_{est\ \text{with auto-transformer}} = (0.70)^2 \times 0.396\ \tau_{efl} = 0.194\ \tau_{efl}$$

$$\frac{\tau_{est}}{\tau_{efl}} = 0.194$$

3. Star-delta starter :

$$\tau_{est} = \frac{1}{3}(\tau_{est}\ \text{by direct on-line starting})$$

$$= \frac{1}{3}(0.396\ \tau_{efl}) = 0.132\ \tau_{efl}$$

$$\frac{T_{est}}{T_{efl}} = 0.132$$

PART-2

Deep-Bar and Double-Cage Rotors, Cogging and Crawling.

CONCEPT OUTLINE : PART-2

- **High-Torque cage motors :**
  i. Deep-bar rotor
  ii. Double-cage rotor.
- **Crawling :** The tendency of the motor to run at a stable speed as low as one-seventh of the normal speed N_s and being unable to pick up its normal speed is known as crawling of motor.
- **Cogging :** The phenomenon of magnetic locking between stator and rotor teeth is called cogging.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.5. **Write short notes on the following :**

i. Deep-bar rotor in 3ϕ IMs

ii. Double-cage rotor in 3ϕ IMs. **AKTU 2013-14, Marks 10**

OR

Explain the working of deep-bar and double-cage rotor induction motors. **AKTU 2016-17, Marks 7.5**

Answer

A. Deep-bar rotor :

1. Fig. 4.5.1 shows a cage rotor with deep and narrow bars.
2. A bar may be assumed to be made up of number of narrow layers connected in parallel.
3. Fig. 4.5.1 shows three such layers A, B and C. It is seen that the top most layer element A is linked with minimum leakage flux and, therefore, its leakage inductance is minimum.

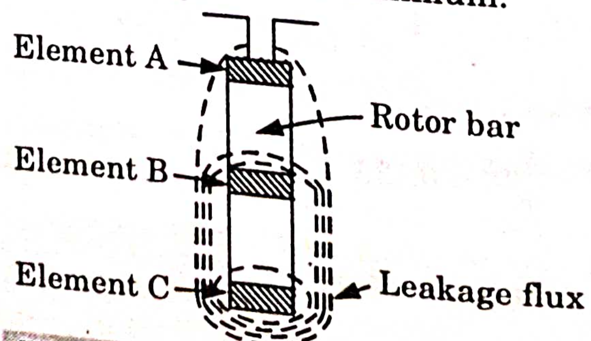


Fig. 4.5.1. Deep-bar cage rotor bar.

4. On the other hand, the bottom layer C links with maximum leakage flux. Therefore its leakage inductance is maximum.
5. At starting the rotor-frequency is equal to the supply frequency.
6. The bottom layer element C offers more impedance to the flow of current than the top layer element A.
7. Therefore maximum current flows through the top layer and minimum through the bottom layer.
8. Because of the unequal current distribution of current, the effective rotor resistance increases and the leakage reactance decreases.
9. With a high rotor resistance at starting conditions, the starting torque is relatively higher and the starting current is relatively lower.
10. Under normal operating conditions, the slip and the rotor frequency are very small. The reactances of all the layers of the bar are small compared to their resistances.

B. **Double-cage rotor :**

1. An induction motor with two rotor windings or cages is used for obtaining high starting torque at low starting current.
2. The stator of a double-cage rotor induction motor is similar to that of an ordinary induction motor. In the double-cage rotor there are two layers of bars as shown in Fig. 4.5.2.

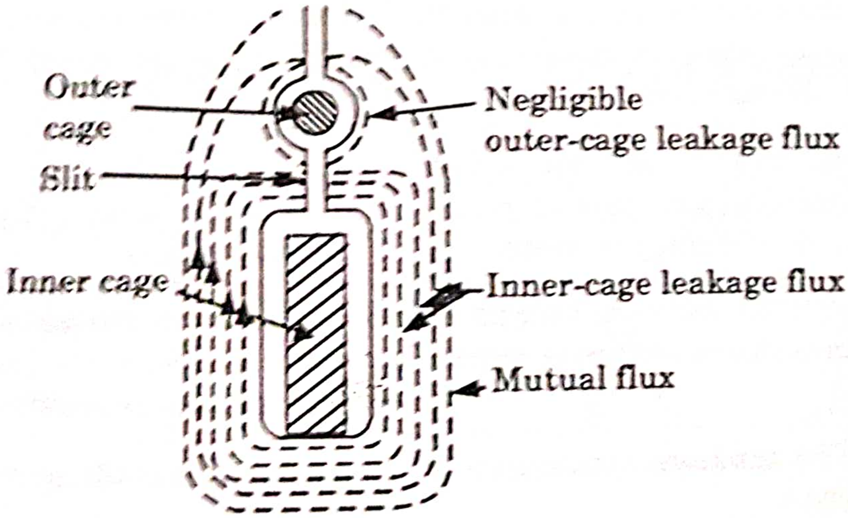


Fig. 4.5.2. Double-cage rotor slot.

3. Each layer is short circuited by end rings.
4. The outer-cage bars have a smaller cross-sectional area than the inner bars and are made of high resistivity materials like brass, aluminium bronze etc.
5. The inner-cage bars are made of low-resistance copper. Thus, the resistance of the outer cage is greater than the resistance of the inner-cage.
6. There is a slit between the top and bottom slots. The slit increases permeance for leakage flux around the inner-cage bars.

7. Thus, the leakage flux linking the inner-cage winding is much larger than that of the outer-cage winding, and the inner winding, therefore, has a greater self inductance.
8. At starting, the voltage induced in the rotor is same as the supply frequency. Hence, the leakage reactance of the inner-cage winding is much larger than that of the outer-cage winding.
9. As the rotor speed increases, the frequency of the rotor emf decreases. At normal operating speed, the leakage reactance of both the windings becomes negligibly small.

Que 4.6. **Compare deep-bar induction motor with a double-cage induction motor.**

AKTU 2012-13, Marks 05

Answer

S. No.	Deep-bar	Double-cage
1.	Starting current is high hence, not suitable for direct on-line starting.	Starting current is low hence, suitable for direct on-line starting.
2.	Starting torque is low.	Starting torque is high.
3.	Effective rotor resistance is low hence at start rotor heating is not severe.	Effective rotor resistance is high hence at start rotor heating is large.
4.	As rotor resistance is low rotor copper losses are less and efficiency is more.	The rotor copper losses are high due to high rotor resistance and efficiency is less.
5.	The breakdown torque or maximum torque is more.	The breakdown torque or maximum torque is smaller as two cages produce maximum torques at different speeds.
6.	The leakage reactance is low.	The effective leakage reactance is high.
7.	The power factor is high.	The power factor is low.
8.	The torque-slip characteristics are fixed and constant.	With proper choice of resistances and reactances of inner and outer cages, wide range of torque-slip characteristics can be obtained.
9.	For same rating, cost is low.	For same rating, cost is high due to double cages.

Que 4.7. **Derive equivalent circuit of a double-cage induction motor.**

Answer

1. Let

R_1 = Resistance per phase of stator

X_1 = Reactance per phase of stator

R_{2o}' = Resistance per phase of outer cage referred to stator

X_{2o}' = Standstill leakage reactance per phase of outer cage referred to stator

R_{2i}' = Resistance per phase of the inner cage referred to stator

X_{2i}' = Standstill leakage reactance per phase of the inner cage referred to stator

s = Fractional slip

2. If it is assumed that the main flux completely link both the cages, the impedances of the two cages can be considered in parallel.

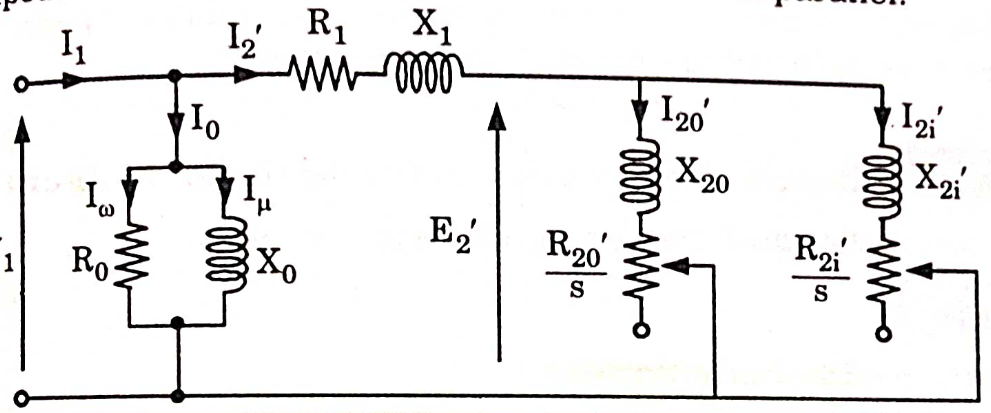


Fig. 4.7.1. Equivalent circuit of a double-cage induction motor.

3. The equivalent circuit of the double-cage induction motor at slip s is shown in Fig. 4.7.1. If the shunt branches containing R_o and X_o are neglected, the equivalent circuit is simplified to that shown in Fig. 4.7.2.

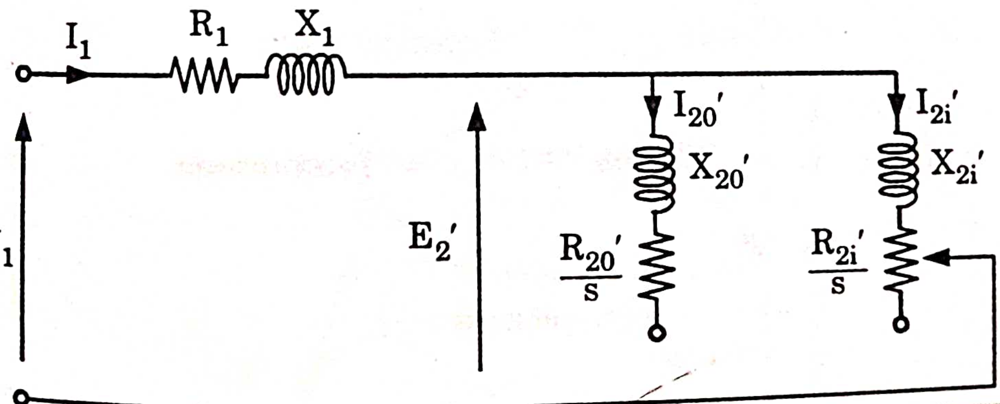


Fig. 4.7.2. Approximate equivalent circuit of a double-cage induction motor with magnetising current neglected.

4. At slip s, the outer-cage impedance, $Z_{2o}' = \dfrac{R_{2o}'}{s} + jX_{2o}'$

At slip s, the inner-cage impedance, $Z_{2i} = \dfrac{R_{2i}'}{s} + jX_{2i}'$

5. The impedance of the stator, $Z_1 = R_1 + jX_1$

Equivalent impedance per phase of the motor referred to stator

$$Z_{e_1} = jX_1 + (Z_{2o}' \,||\, Z_{2i}')$$

$$Z_{e_1} = R_1 + jX_1 + \frac{1}{\dfrac{1}{Z_{2o}'} + \dfrac{1}{Z_{2i}'}} = R_1 + jX_1 + \frac{Z_{2o}'Z_{2i}'}{Z_{2o}' + Z_{2i}'}$$

6. Current through the outer-cage

$$I_{2o}' = \frac{E_2}{Z_{2o}'}$$

Current through the inner-cage

$$I_{2i}' = \frac{E_2}{Z_{2i}'}$$

7. The rotor current (referred to the stator) is equal to the phasor sum of the currents through the outer and inner cages.

$$I_2' = I_{2o}' + I_{2i}$$

Que 4.8. **Sketch torque-slip characteristic of double cage induction motor and also compare cage torques.**

Answer

A. Torque-slip characteristic :

1. It is assumed that the two cages develop two separate torque. The total torque of the motor is equal to the sum of the two cage torques.
2. The torque-slip characteristics of the two cages and total torque of the motor is shown in Fig. 4.8.1.

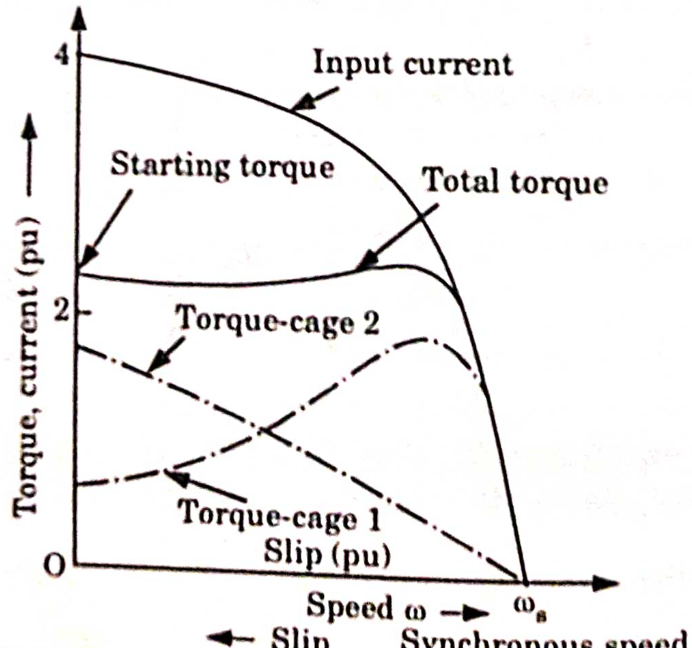


Fig. 4.8.1. Torque and slip characteristics of a double-cage induction motor.

B. **Comparison of cage torques :**

1. Power developed per phase by the outer cage

$$P_{do} = (I_{2o}')^2 \frac{R_{2o}'}{s}$$

2. Power developed per phase by the inner cage

$$P_{di} = (I_{2i}')^2 \frac{R_{2i}'}{s}$$

3. Power developed per phase by both the cages

$$P_d = P_{do} + P_{di} = (I_{2o}')^2 \frac{R_{2o}'}{s} + (I_{2i}')^2 \frac{R_{2i}'}{s}$$

4. From the equivalent circuit of the double-cage motor

$$I_{2o}' = \frac{E_2'}{Z_{2o}'}$$

$$I_{2i}' = \frac{E_2'}{Z_{2i}'}$$

$$Z_{2o}' = \sqrt{\left(\frac{R_{2o}'}{s}\right)^2 + (X_{2o}')^2}$$

$$Z_{2i}' = \sqrt{\left(\frac{R_{2i}'}{s}\right)^2 + (X_{2i}')^2}$$

5. If

τ_{do} = Torque developed by the outer-cage

τ_{di} = Torque developed by the inner-cage

τ_d = Total torque developed by the two cages

$$P_d = (2\pi n_s)\, \tau_d$$

$$\tau_d = \frac{P_d}{2\pi n_s} = \frac{1}{2\pi n_s}\left[(I_{2o}')^2 \frac{R_{2o}'}{s} + (I_{2i}')^2 \frac{R_{2i}'}{s}\right]$$

$$\frac{\tau_{do}}{\tau_{di}} = \frac{\left(\frac{R_{2o}'}{s}\right)^2 + (X_{2o}')^2}{\left(\frac{R_{2i}'}{s}\right)^2 + (X_{2i}')^2} \quad ...(4.8.1)$$

Que 4.9. **The two-cages of a 3ϕ, 50 Hz, 4-pole delta connected induction motor have respective standstill leakage impedances of (2 + j8) and (9 + j2) Ω /phase. Estimate the gross-torque developed :**

i. **At standstill, the effective rotor voltage being 230 V/phase, and**

ii. **At 1450 rpm when the effective rotor voltage is 400 V/phase. What is the gross-starting torque if a Y-Δ starter is used ? Rotor quantities given are all referred to the stator; the stator impedance is negligible.**

AKTU 2013-14, Marks 10

Answer

Given : $P = 4, f = 50$ Hz
At standstill, $s = 1, Z_{20} = (2 + j8)\ \Omega, Z_{2i} = (9 + j2)\ \Omega, E_2 = 230$ V/phase
At 1450 rpm, $N = 1450$ rpm, $E_2 = 400$ V/phase

To Find :
i. Starting torque, T_s
ii. Torque developed at $s = 1, T_d$
iii. Torque developed at 1450 rpm, T_d.

1.
$$T_d = \frac{3}{2\pi\eta_s}\left[\left(\frac{E_{20}}{Z_{20}}\right)^2 \times \frac{R_{20}}{s} + \left(\frac{E_{20}}{Z_{2i}}\right)^2 \times \frac{R_{2i}}{s}\right] \quad ...(4.9.1)$$

Putting values in eq. (4.9.1),

$$= \frac{3 \times 4 \times 60}{2\pi \times 120 \times 50}\left[\frac{(230)^2 \times 2}{(\sqrt{2^2 + 8^2})^2} + \frac{(230)^2 \times 9}{(\sqrt{9^2 + 2^2})^2}\right]$$

$$= 136.69 \text{ N-m}$$

2.
$$s = \frac{N_s - N_r}{N_s} = 1 - \frac{N_r}{N_s} = 1 - \frac{N_r P}{120 f}$$

$$= 1 - \frac{1450 \times 4}{120 \times 50} = 0.0333$$

3.
$$Z_{20} = \frac{R_{20}}{s} + jX_{20} = \left(\frac{2}{0.033} + j8\right)\Omega$$

$$|Z_{20}| = 61.13\ \Omega$$

4.
$$Z_{2i} = \frac{R_{2i}}{s} + jX_{21} = \left(\frac{9}{0.033} + j2\right)\Omega$$

$$|Z_{2i}| = 272.73\ \Omega$$

5.
$$T_d = \frac{3}{2\pi\eta_s}\left[\left(\frac{E_{20}}{Z_{20}}\right)^2 \times \frac{R_{20}}{s} + \left(\frac{E_{2i}}{Z_{2i}}\right)^2 \times \frac{R_{2i}}{s}\right] \quad ...(4.9.2)$$

Putting values in eq. (4.9.2), we get

$$T_d = \frac{3 \times 4 \times 60}{2\pi \times 120 \times 50}\left[\left(\frac{(400)^2}{(61.13)^2} \times \frac{2}{0.0333} + \frac{(400)^2}{(272.73)^2} \times \frac{9}{0.033}\right)\right]$$

$$= 60.76 \text{ N-m}$$

6. In star-delta starter,

$$E_2 = \frac{400}{\sqrt{3}}\ \Omega$$

$$s = 1$$

7. Putting in eq. (4.9.1),

$$T_s = \frac{3 \times 4 \times 60}{2\pi \times 120 \times 50}\left[\frac{(400/\sqrt{3})^2}{(2^2 + 8^2)} \times \frac{2}{1} + \frac{(400/\sqrt{3})^2}{(9^2 + 2^2)} \times \frac{9}{1}\right]$$

$$T_s = 137.8 \text{ N-m}$$

Que 4.10. **If the outer-cage has an equivalent impedance of (0.6 + *j*0.6) ohm and the inner-cage an equivalent impedance of (0.1 + *j*0.8) ohm both at supply frequency, calculate the current and torque in synchronous watts for the two cages at standstill and at 10 % slip. The effective standstill e.m.f. of each cage is 200 V.**

AKTU 2014-15, Marks 10

Answer

Given : $R_{20}' = 0.6\ \Omega$, $X_{20}' = 0.6\ \Omega$, $R_{2i}' = 0.1\ \Omega$, $X_{2i}' = 0.8\ \Omega$, $E_2' = 200$ V
To Find : Current and torque for two cages at standstill and at 10 % slip.

Assume synchronous speed $(N) = 1500$ rpm, $n_s = \frac{N}{60}$

A. At standstill, $s = 1$

1. Outer-cage impedance,

$$Z_{2o}' = \frac{R_{2o}'}{s} + jX_{2o}' = \left(\frac{0.6}{1} + j0.6\right)\ \Omega = 0.848 \angle 45°\ \Omega$$

2. Outer-cage current,

$$I_{2o}' = \frac{E_2'}{Z_{2o}'} = \frac{200}{0.848} = 235.85 \text{ A}$$

3. Outer-cage torque

$$= \frac{1}{2\pi n_s}(I_{2o}')^2 \frac{R_{2o}'}{s}$$

$$= \frac{1 \times 60}{2\pi \times 1500} \times (235.85)^2 \times \frac{0.6}{1}$$

$$= 212.47 \text{ N-m}$$

4. Inner-cage impedance,

$$Z_{2i}' = \frac{R_{2i}'}{s} + jX_{2i}' = \left(\frac{0.1}{1} + j0.8\right)\ \Omega$$

$$= (0.1 + j0.8)\ \Omega$$

$$= 0.806 \angle 82.87°\ \Omega$$

5. Inner-cage current,

$$I_{2i}' = \frac{E_2'}{Z_{2i}'} = \frac{200}{0.806} = 248.14 \text{ A}$$

6. Inner-cage torque $= \frac{1}{2\pi n_s}(I_{2i}')^2 \frac{R_{2i}'}{s} = \frac{1 \times 60}{2\pi \times 1500} \times (248.14)^2 \times \frac{0.1}{1}$

$= 39.19$ N-m

7. Net torque developed by two cages

$= (212.47 + 39.19)$

$= 251.66$ N-m

B. At slip $s = 10\ \% = 0.1$

1. Outer-cage impedance,

$$Z_{2o}' = \frac{R_{2o}'}{s} + jX_{2o}' = \left(\frac{0.6}{0.1} + j0.6\right)\ \Omega = (6 + j0.6)\ \Omega$$

$= 6.02 \angle 5.71°\ \Omega$

$$I_{2o}' = \frac{E_2'}{Z_{2o}'} = \frac{200}{6.02} = 33.22 \text{ A}$$

2. Outer-cage torque,

$$= \frac{1}{2\pi n_s}(I_{2o}')^2 \cdot R_{2o}'$$

$$= \frac{1 \times 60}{2\pi \times 1500} \times (33.22)^2 \times 6$$

$= 42.15$ N-m

3. Inner-cage impedance,

$$Z_{2i}' = \frac{R_{2i}'}{s} + jX_{2i}' = \left(\frac{0.1}{0.1} + j0.8\right)$$

$= (1 + j0.8) = 1.28 \angle 38.66°\ \Omega$

4. Inner-cage current,

$$I_{2i}' = \frac{E_2'}{Z_{2i}'} = \frac{200}{1.28} = 156.25 \text{ A}$$

5. Inner-cage torque $= \frac{1}{2\pi n_s}(I_{2i}')^2 R_{2i}' = \frac{1 \times 60}{2\pi \times 1500} \times (156.25)^2 \times 1.28$

$= 198.94$ N-m

6. Net torque developed by two cages

$= 42.15 + 198.94$

$= 241.09$ N-m

Que 4.11. **The impedances at standstill of the inner and outer cages of a double cage rotor are $(0.01 + j0.5)\ \Omega$ and $(0.05 + j0.1)\ \Omega$ respectively. The stator impedance may be assumed to be negligible. Calculate the ratio of the torques due to the two cages :**

i. At starting, and
ii. When running with a slip of 5 %.

Answer

Given : $Z_{inner} = (0.01 + j0.5)\ \Omega$, $Z_{outer} = (0.05 + j0.1)$
Stator impedance = 0

To Find : i. Ratio, $\dfrac{\tau_o}{\tau_i}$ at starting.

ii. Ratio, $\dfrac{\tau_o}{\tau_i}$ at $s = 0.05$.

i.

1. $$\tau_s = \frac{3}{\omega_s}\frac{V'^2 R_2}{R_2^2 + X_2^2}$$

2. Torque due to outer-cage $= \tau_{so} = \dfrac{3}{\omega_s}\dfrac{V'^2(0.05)}{(0.05)^2 + (0.1)^2}$

3. Similarly, torque due to inner-cage
$$= \tau_{si} = \frac{3}{\omega_s}\frac{V'^2 R_2}{R_2^2 + X_2^2} = \frac{3V'^2}{\omega_s}\frac{(0.01)}{(0.01)^2 + (0.5)^2}$$

4. $$\frac{\tau_{so}}{\tau_{si}} = \frac{0.05}{0.01} \times \frac{(0.01)^2 + (0.5)^2}{(0.05)^2 + (0.1)^2} = 100.04$$

$$\frac{\tau_{so}}{\tau_{si}} \cong 100$$

ii.

1. $$\tau = \frac{3}{\omega_s}\frac{V'^2(R_2 / s)}{(R_2 / s)^2 + X_2^2}$$

Slip, $s = 0.05$

2. $$\tau = \frac{3}{\omega_s}\frac{V'^2(R_2 / 0.05)}{(R_2 / 0.05)^2 + X_2^2}$$

3. $$\tau_o = \frac{3}{\omega_s}V'^2\frac{(0.05/0.05)}{(0.05/0.05)^2 + (0.1)^2} = \frac{3V'^2}{\omega_s}\frac{1}{(1 + 0.1^2)}$$

4. $$\tau_i = \frac{3}{\omega_s}V'^2\frac{(0.01/0.05)}{(0.01/0.05)^2 + (0.5)^2} = \frac{3V'^2}{\omega_s}\frac{0.2}{(0.2^2 + 0.5^2)}$$

5. $$\frac{\tau_o}{\tau_i} = \frac{(0.2^2 + 0.5^2)1}{(1 + 0.1^2)0.2} = 1.4356$$

Que 4.12. **What are the effects of space harmonics on 3-phase induction motor performance ?**

AKTU 2016-17, Marks 7.5

OR

Discuss briefly crawling phenomenon in 3ϕ IM.

Answer

1. A 3-phase winding carrying sinusoidal currents produces space harmonics of the order

$$h = 6k \pm 1$$

where k is a positive integer (1, 2, 3, ...).

2. The synchronous speed of the h^{th} harmonic is $(1/h)$ times the speed of the fundamental wave. The space harmonic waves rotate in the same direction as the fundamental wave if $h = 6k + 1$, and in the opposite direction if $h = 6k - 1$.
3. A space harmonic wave of order h is equivalent to a machine with number of poles equal to (h × number of poles of the stator). Therefore, the synchronous speed of the h^{th} space harmonic wave is

$$n_{s(h)} = \frac{n_s}{h} = \frac{120\,f}{h \times P}$$

where

f = Supply frequency

P = Number of poles of the stator

4. Thus, for $k = 1$, a 3-phase winding will produce predominant backward rotating fifth harmonic rotating at a speed of (1/5) of synchronous speed and forward rotating seventh harmonic rotating at a speed of (1/7) of synchronous speed.
5. Since fifth harmonic flux rotates in the direction opposite to the rotation of the rotor, the fifth harmonic torque opposes the fundamental component torque and produces a braking torque.
6. The seventh harmonic flux rotates in the same direction as the fundamental flux and aids the fundamental component torque.
7. The resultant torque-speed characteristic will be the combination of the fundamental, fifth and seventh harmonic characteristics as shown in Fig. 4.12.1.
8. Fig. 4.12.1 also shows load torque-speed characteristic. If the motor torque is developed due to the fundamental flux alone, the motor will accelerate to the point L which is the intersection of the load torque characteristic and the motor torque-speed curve.
9. Due to the presence of seventh harmonic flux torque, the load torque curve intersects the motor torque-speed characteristic at point A.
10. Since the seventh harmonic flux torque curve has a negative slope at point A stable running condition over the torque range between the maximum and minimum points results. The motor torque falls below the load torque.

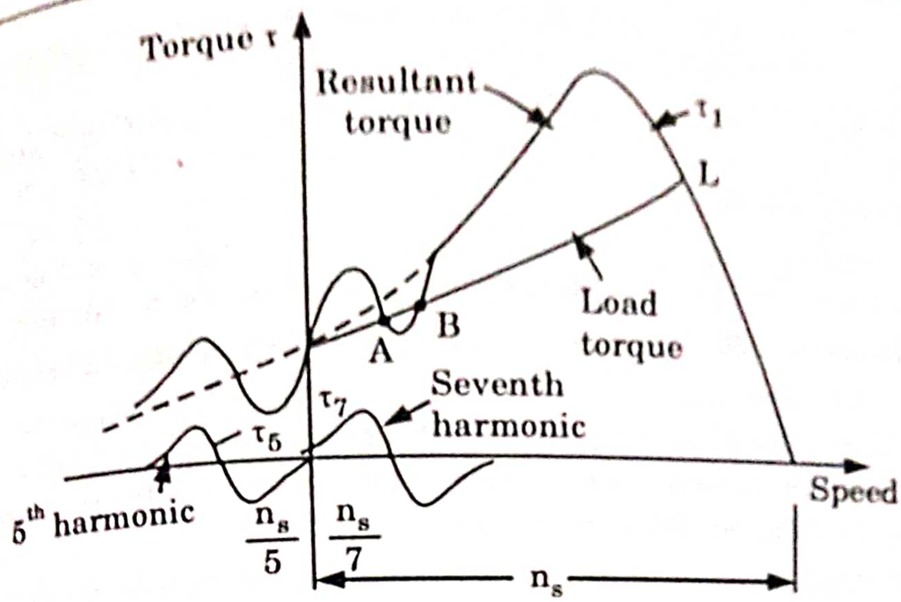


Fig. 4.12.1. Torque-speed characteristics of 3-phase induction motor showing the effect of space harmonic asynchronous (harmonic) torques.

11. At this stage the motor will not accelerate upto its normal speed, but will remain running at a speed which is nearly (1/7) of its normal speed and the operating point would be A.
12. This tendency of the motor to run at a stable speed low as one-seventh of the normal speed n_s and being unable to pick up its normal speed is known as crawling of the motor.
13. Crawling can be reduced by reducing fifth and seventh harmonics. This can be done by using a chorded (or short pitched) winding.

    Effect of space harmonics : Space harmonic fluxes are produced by windings, slotting, magnetic saturation, inequalities in the air gap length etc. These harmonic fluxes induce voltages and circulate harmonic currents in the rotor windings. These harmonic currents in the rotor interact with the harmonic fluxes to produce harmonic torques, vibrations and noise.

Que 4.13. **Define the following :**

i. **Cogging phenomena in 3ϕ IMs**

ii. **Crawling phenomena in 3ϕ IMs.** **AKTU 2013-14, Marks 10**

OR

Explain the phenomenon of crawling and cogging in a 3ϕ induction motor. **AKTU 2014-15, Marks 10**

Answer

A. **Cogging :**

1. Sometimes, even when full voltage is applied to the stator winding, the rotor of a 3-phase cage induction motor fails to start.

2. This happens when the numbers of stator and rotor slots are either equal or have an integral ratio.
3. With the number of stator slots equal to or an integral multiple of rotor slots, strong alignment forces are produced between stator and rotor at the instant of starting.
4. These forces may create an alignment torque greater than the accelerating torque with consequent failure of the motor to start.
5. This phenomenon of magnetic locking between stator and rotor teeth is called cogging or teeth locking.
6. The reluctance of the magnetic path is minimum when the stator and rotor teeth face each other. Under this condition there is a magnetic locking between stator and rotor teeth.
7. In order to reduce or eliminate cogging the number of stator slots are never made equal to or have an integral ratio with rotor slot. Cogging can also be reduced by using skewed rotor.

B. Crawling : Refer Q. 4.12, Page 4–19A, Unit-4.

Que 4.14. **Explain crawling and cogging. A 3-phase, 430 V, 50 Hz, 4-pole squirrel cage induction motor has 24 stator slots and 28 rotor slots. What are possible crawling speeds ?** **AKTU 2012-13, Marks 10**

Answer

Crawling : Refer Q. 4.12, Page 4–19A, Unit-4.
Cogging : Refer Q. 4.13, Page 4–21A, Unit-4.
Numerical :

Given : $f = 50$ Hz, $P = 4$, $V = 430$ V
To Find : Crawling speed.

1. The harmonics is given by the equation

$$n = 6N \pm 1$$

2. Put

$$N = 1,$$

$$\therefore \quad n = 5 \text{ and } 7$$

3. For 5[th] harmonic

$$\text{Crawling speed} = \frac{n_s}{5} = \frac{120f}{P \times 5} = \frac{120 \times 50}{4 \times 5} = 300 \text{ rpm}$$

4. For 7[th] harmonic,

$$\text{Crawling speed} = \frac{n_s}{7} = \frac{120f}{P \times 7} = \frac{120 \times 50}{4 \times 7} = 214.28 \text{ rpm}$$

5. Similarly, for all other harmonics we can find the speed.

PART-3

Speed Control with and without Emf Injection in Rotor Circuit.

CONCEPT OUTLINE : PART-3

- **Speed control of Induction motors :**

1. Pole changing
2. Stator voltage control
3. Supply frequency control
4. Rotor resistance control
5. Slip energy recovery.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.15. **Write short note on the following :**

i. **DOL starter for 3ϕ induction motor.**

ii. **Pole changing method of speed control of 3ϕ induction motors.**

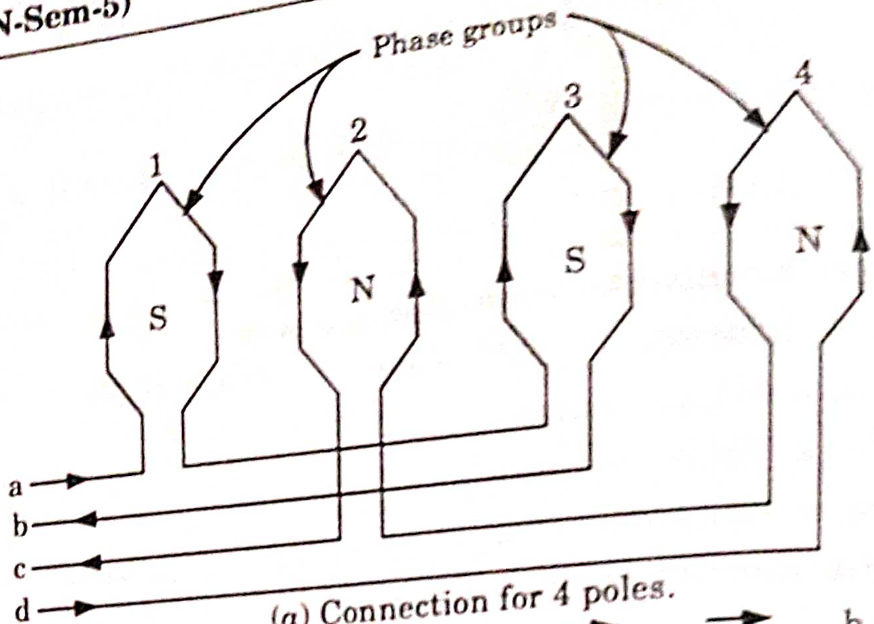
AKTU 2016-17, Marks 10

Answer

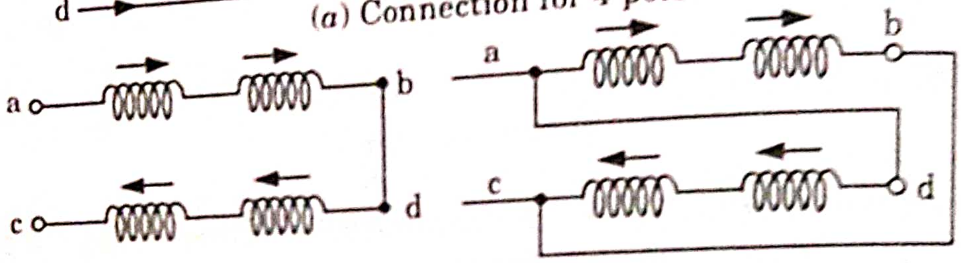
A. **DOL starter :** Refer Q. 4.3, Page 4–6A, Unit-4.

B. **Pole-changing methods :**

1. In this method a single stator winding is divided into few coil groups. The terminals of all these groups are brought out. The number of poles can be changed with only simple changes in coil connections.
2. Fig. 4.15.1 shows one phase of a stator winding consisting of 4 coils divided into two groups $a-b$ and $c-d$.
3. Group $a-b$ consists of odd-numbered coils (1, 3) and connected in series. Group $c-d$ has even numbered coils (2, 4) connected in series.
4. The terminals a, b, c, d are taken out as shown in Fig. 4.15.1. The coils can be made to carry current in the given direction by connecting coil groups either in series or parallel shown in Fig. 4.15.1(b) and Fig. 4.15.1(c) respectively.
5. By choosing a suitable combination of series or parallel connections between coil group of each phase, speed change can be obtained.



(a) Connection for 4 poles.



(b) Series connection.

(c) Parallel connection.

Fig. 4.15.1.

Que 4.16. **Discuss different method of speed control of squirrel cage IM.**

Answer

A. **Pole changing :** Refer Q. 4.15, Page 4–23A, Unit-4.

B. **Stator voltage control :**

1. The speed of a 3-phase induction motor can be varied by varying the supply voltage.
2. The torque developed is proportional to the square of the supply voltage, and the slip at maximum torque is independent of supply voltage.
3. Variation of supply voltage does not alter the synchronous speed also. The torque-speed characteristics of three-phase induction motor for varying supply voltage are shown in Fig. 4.16.1.
4. Speed control is obtained by varying the supplying voltage until the torque required by the load is developed at the desired speed.
5. The torque developed is proportional to the square of the supply voltage and current is proportional to the voltage. Therefore, as voltage is reduced to reduce speed for the same current, the torque developed by the motor is reduced.
6. Consequently, this method is suitable for applications where load torque decreases with speed, as in the case of a fan load.

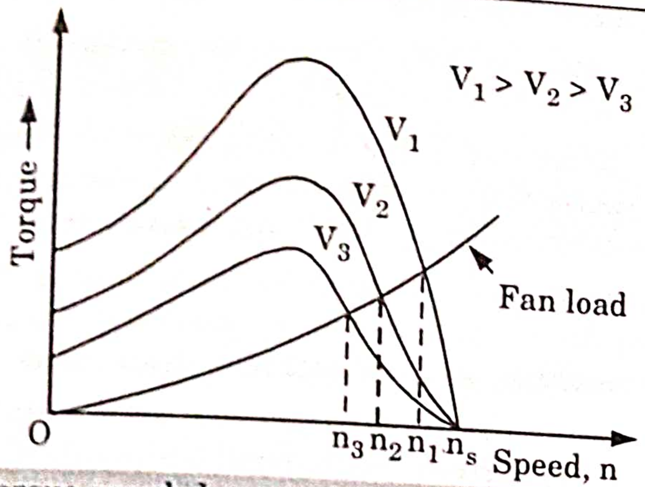


Fig. 4.16.1. Torque-speed characteristics for various terminal voltages.

C. Variable-frequency control :

1. The synchronous speed of an induction motor is given by

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

2. The synchronous speed and, therefore, the speed of the motor can be controlled by varying the supply frequency.
3. The emf induced in the stator of the induction motor is given by

$$E_1 = 4.44\, k_{w1} f \phi T_1$$

4. Therefore, if the supply frequency is changed, E_1 will also change to maintain the same air gap flux.
5. In order to avoid saturation and to minimize losses, motor is operated at rated air gap flux by varying terminal voltage with frequency so to maintain (V/f) ratio constant at the rate value. This type of control is known as constant volts per hertz.
6. The variable frequency supply is generally obtained by the following converters :
   a. Voltage source inverter
   b. Current source inverter
   c. Cycloconverter.

Que 4.17. **Discuss briefly the various methods of speed control of 3ϕ induction motors.**

AKTU 2014-15, Marks 10

Answer

For squirrel cage : Refer Q. 4.16, Page 4–24A, Unit-4.

For wound type rotor IM : The method used for squirrel cage IM can also be used for this type.

A. **Rotor resistance control :**

1. The speed of wound induction motor can be controlled by connecting external resistance in the rotor circuit through slip rings.
2. Although the maximum torque is independent of rotor resistance, yet the exact location of τ_{max} is dependent on it. Greater the value of R_2 greater is the value of slip at which maximum torque occurs.
3. As the rotor resistance is increased, the pull-out speed of the motor decreases, but the maximum torque remains constant. Therefore, by this method, control is provided from the rated speed to lower speeds.
4. This method of speed control is very simple. It is possible to have a large starting torque, low starting current and large pull-out torques at small values of slip.

B. **Slip-energy recovery :**

1. The principle of slip power recovery is to connect an external source of emf of slip frequency to the rotor circuit.
2. A method for recovering the slip power is shown Fig. 4.17.1. This method is known as static Scherbius drive. It provides the speed control of a slip ring induction motor below synchronous speed.
3. A portion of rotor AC power (slip power) is converted into DC by a diode bridge.
4. The rectified current is smoothed by the smoothing reactor.
5. The output of the rectifier is then connected to the DC terminals of the inverter, which inverts this DC power to AC power and feeds it back to the AC source. The inverter is a controlled rectifier operated in the inversion mode.
6. This method of speed control is used in large power applications where variation of speed over a wide range involves a large amount of slip power.

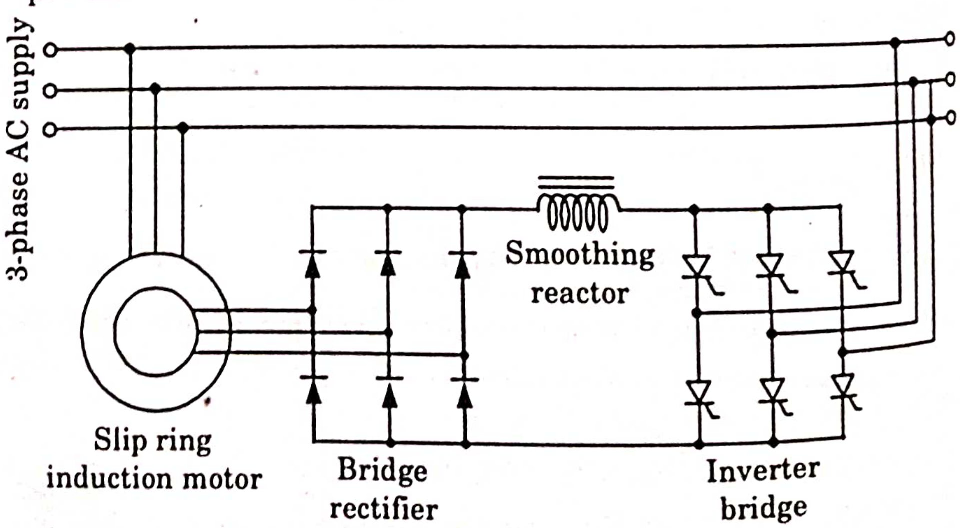


Fig. 4.17.1. Static Scherbius drive for speed control of slip ring induction motor.

Applications : Large power fans and pump drives which require speed control in narrow range.

Que 4.18. Describe how speed and power factor of a slip-ring induction motor be controlled by injecting voltage in the rotor circuit ?

AKTU 2012-13, Marks 05

Answer

1. In this method, a voltage is injected in the rotor circuit. The frequency of rotor circuit is a slip frequency and hence the voltage to be injected must be at a slip frequency.
2. It is possible that the injected voltage may oppose the rotor induced emf or may assist the rotor induced emf.
3. If it is in the phase opposition, effective rotor resistance increases.
4. If it is in the phase of rotor induced emf, effective rotor resistance decreases.
5. Thus, by controlling the magnitude of the injected emf, rotor resistance and effectively speed can be controlled.
6. Practically two methods are available which use this principle. These methods are

A. Kramer system :

1. Fig. 4.18.1 shows the scheme of a Kramer system.

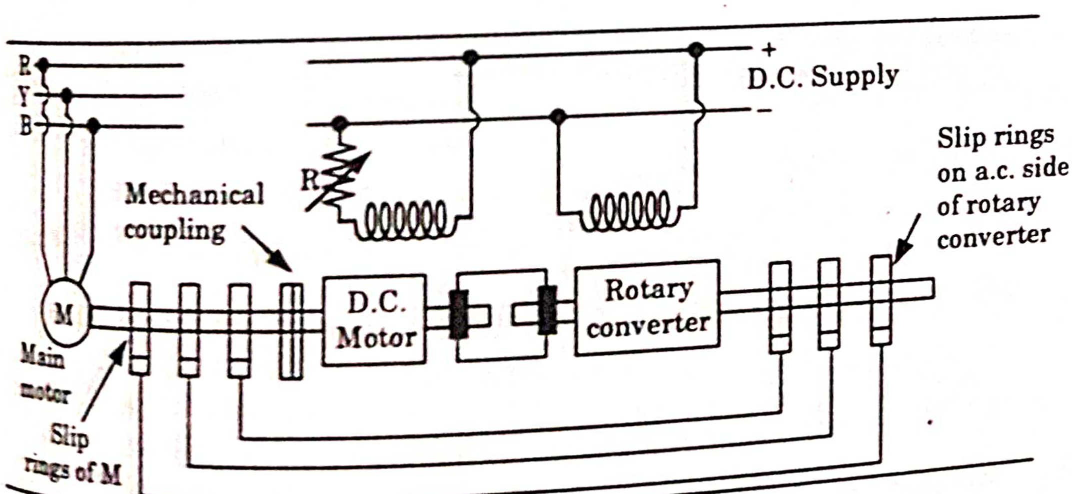


Fig. 4.18.1. Kramer system.

2. It consists of main induction motor M, the speed of which is to be controlled. The two additional equipments are DC motor and a rotary converter.
3. The slip rings of the main motor are connected to the ac side of a rotary converter. The DC side of rotary converter feeds a DC shunt motor commutator, which is directly connected to the shaft of the main motor.

4. A separate DC supply is required to excite the field winding of DC motor and exciting winding of a rotary converter. The variable resistance is introduced in the field circuit of a DC motor which acts as a field regulator.
5. The speed of the set is controlled by varying the field of the DC motor with the rheostat R.
6. When the field resistance is changed, the back emf of motor changes, thus the DC voltage at the commutator changes.
7. This changes the DC voltage on the DC side of a rotary converter. Now rotary converter has a fixed ratio between its AC side and DC side voltages.
8. Thus voltage on its AC side also changes. This AC voltage is given to the slip rings of the main motor. So the voltage injected in the rotor of main motor changes which produces the required speed control.
9. Very large motors above 4000 kW such as steel rolling mills use such type of speed control.

B. Scherbius system : Refer Q. 4.17, Page 4–25A, Unit-4.

Que 4.19. **A 4-pole induction motor and 6-pole induction motor are connected in cumulative cascade at 50 Hz supply. The frequency in the secondary circuit of the 6-pole motor is observed to be 1.0 Hz. Determine the slip in each machine and the combined speed of the set ?**

Answer

Given : $P_1 = 4, P_2 = 6, f = 50$ Hz, $f' = 1$ Hz
To Find : Slip, s.

1. Combined speed of the set,

$$N_{sc} = \frac{120f}{P_1 + P_2} = \frac{120 \times 50}{4+6} = 600 \text{ rpm}$$

2. The frequency in the secondary circuit of the 6 pole motor

$$f' = s'f = 1.0 \text{ Hz}$$

so, slip
$$s' = \frac{f'}{f} = \frac{1.0}{50} = 0.02$$

3. Actual speed of the set,

$$N_1 = N_{sc}(1 - s')$$
$$= 600(1 - 0.02) = 588 \text{ rpm}$$

4. Synchronous speed of 4-pole induction motor,

$$N_s = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

5. Slip for 4-pole induction motor,

$$s = \frac{N_s - N_1}{N_s} = \frac{1500 - 588}{1500} = 0.608 \text{ or } 60.8\ \%$$

6. The impressed frequency on the second motor

$$f' = sf = 0.608 \times 50 = 30.4 \text{ Hz}$$

7. Synchronous speed of 6-pole induction motor with frequency f'

$$N_s' = \frac{120 \times f'}{P_2} = \frac{120 \times 30.4}{6} = 608 \text{ rpm}$$

8. Slip for 6-pole induction motor,

$$s = \frac{N_s' - N}{N_s'} = \frac{608 - 588}{608} = 0.033 \text{ or } 3.3\ \%$$

Que 4.20. **The rotor of a 4-pole, 50 Hz, slip ring induction motor has a resistance of 0.25 Ω per phase and runs at 1440 rpm at full load. Calculate the external resistance per phase which must be added to lower the speed to 1200 rpm, the torque being the same as before.**

Answer

Given : $P = 4$, $f = 50$ Hz, $R = 0.25\ \Omega$ per phase
$N_1 = 1440$ rpm, $N_2 = 1200$ rpm
To Find : R_{ext} (per phase).

1. Synchronous speed of motor,

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

2. Full load speed, $N = 1440$ rpm

3. Full load slip, $$s_1 = \frac{N_s - N_1}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

4. After inserting resistance in the rotor circuit

5. Motor speed, $N_2 = 1200$ rpm

Slip, $$s_2 = \frac{1500 - 1200}{1500} = 0.2$$

Since slip, $$s = \frac{\text{Rotor copper loss}}{\text{Input power to rotor}} = \frac{3I_2^2 R_2}{\text{Input power to rotor}}$$

∵ For constant power input to rotor and rotor current

$$s \propto R_2$$

6. For constant load torque power input to rotor and rotor current remains the same.

So,
$$\frac{s_2}{s_1} = \frac{R_2 + R_{ext}}{R_2}$$

$$\frac{0.20}{0.04} = \frac{0.25 + R_{ext}}{0.25}$$

or,
$$R_{ext} = 1\,\Omega$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Why "Starter" is required to start a 3ϕ induction motor? Name different starting methods and describe star-delta method of starting a squirrel cage induction motor. Determine the ratio of starting to full load torque.

Ans. Refer Q. 4.1, Unit-4.

Q. 2. Discuss the various methods of starting of a 3-phase induction motor.

Ans. Refer Q. 4.3, Unit-4.

Q. 3. Explain the working of deep-bar and double-cage rotor induction motors.

Ans. Refer Q. 4.5, Unit-4.

Q. 4. Compare deep-bar induction motor with a double-cage induction motor.

Ans. Refer Q. 4.6, Unit-4.

Q. 5. Sketch torque slip characteristic of double-cage induction motor and also compare cage torques.

Ans. Refer Q. 4.8, Unit-4.

Q. 6. If the outer cage has an equivalent impedance of (0.6 + j0.6) ohm and the inner cage an equivalent impedance of (0.1 + j0.8) ohm both at supply frequency, calculate the current and torque in synchronous watts for the two cages at standstill and at 10 % slip. The effective standstill emf of each cage is 200 V.

Ans. Refer Q. 4.10, Unit-4.

Q. 7. Explain the phenomenon of crawling and cogging in a 3ϕ induction motor.

Ans. Refer Q. 4.13, Unit-4.

Q. 8. Discuss briefly the various methods of speed control of 3ϕ induction motors.

Ans. Refer Q. 4.17, Unit-4.

☺☺☺

5

UNIT

Single Phase Induction Motor

PART-1

Double Revolving Field Theory, Equivalent Circuit

CONCEPT OUTLINE : PART-1

- **Single-phase induction motor :**

1. A 1ϕ motor consists of a single-phase winding mounted on the stator and a cage winding on the rotor.
2. When a 1ϕ supply is connected to the stator winding a pulsating magnetic field is produced. By pulsating field we mean that the field builds up in one direction, falls to zero, and then builds up in the opposite direction.
3. Under these conditions, the rotor does not rotate due to inertia. Therefore, a 1ϕ induction motor is inherently not self-starting.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.1. Explain why 1ϕ IM are not self starting ? What do you understand by 'forward field' and 'backward field' in conjunction with 1ϕ IM ?

OR

Why the 1ϕ induction motor is not self-starting ? Explain double revolving field theory.

AKTU 2014-15, Marks 10

Answer

A. **Reason :**

1. A 1ϕ motor consists of a single-phase winding mounted on the stator and a cage winding on the rotor.
2. When a 1ϕ supply is connected to the stator winding a pulsating magnetic field is produced. By pulsating field we mean that the field builds up in one direction, falls to zero, and then builds up in the opposite direction.
3. Under these conditions, the rotor does not rotate due to inertia. Therefore, a 1ϕ induction motor is inherently not self-starting.

B. **Double-revolving field theory :**

1. It states that a stationary pulsating magnetic field can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions.

2. The induction motor responds to each magnetic field separately, and the net torque in the motor is equal to the sum of the torques due to each of the two magnetic fields.
3. The equation for an alternating magnetic field whose axis is fixed in space is given by

$$b(\alpha) = \beta_{max} \sin \omega t \cos \alpha \quad \text{...(5.1.1)}$$

where β_{max} is the maximum value of the sinusoidally distributed air-gap flux density produced by a properly distributed stator winding carrying an alternating current of frequency ω and α is space-displacement angle measured from the axis of the stator winding.

4. Since $\sin A \cos B = \frac{1}{2} \sin (A - B) + \frac{1}{2} \sin (A + B)$,

Eq. (5.1.1) can be written as

$$b(\alpha) = \frac{1}{2} \beta_{max} \sin (\omega t - \alpha) + \frac{1}{2} \beta_{max} \sin (\omega t + \alpha) \quad \text{...(5.1.2)}$$

5. The first term on the right-hand side of eq. (5.1.2) represents the equation of a revolving field moving in the positive α direction. It has a maximum value equal to $\frac{1}{2} \beta_{max}$.
6. The second term on the right-hand side of eq. (5.1.2) represents the equation of a revolving field moving in the negative α direction. Its amplitude is also equal to $\frac{1}{2} \beta_{max}$.
7. The field moving in the positive α direction is called the forward rotating field. The field moving in the negative α direction is called the backward rotating field.
8. It is to be noted that both the fields rotate at synchronous speed $\omega_s (= 2\pi f)$ in opposite directions.
9. Thus, $\frac{1}{2} \beta_{max} \sin (\omega t - \alpha)$ is the forward field

and $\frac{1}{2} \beta_{max} \sin (\omega t - \alpha)$ is the backward field.

Que 5.2. **What do you mean by forward slip and backward slip in single-phase induction motor ?**

Answer

1. We know that the slip

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

where
n_s = Stator speed
n_r = Rotor speed.

2. By definition, the direction in which the rotor is started initially will be called the forward field.

then forward slip, $s_f = \frac{n_s - n_r}{n_s} = 1 - \frac{n_r}{n_s}$ ...(5.2.1)

3. Since the backward rotating flux rotates opposite to the stator, the sign of n_r must be changed to obtain backward slip thus,

$$s_b = \frac{n_s - (-n_r)}{n_s} = 1 + \frac{n_r}{n_s} \quad ...(5.2.2)$$

4. Adding eq. (5.2.1) and (5.2.2)

$$s_f + s_b = \left(1 - \frac{n_r}{n_s}\right) + \left(1 + \frac{n_r}{n_s}\right)$$

$$s_f + s_b = 2$$

$$s_b = 2 - s_f$$

Que 5.3. **Draw the equivalent circuit of a single-phase induction motor. Also draw torque-speed characteristic of single-phase induction motor.**

OR

State and explain forward and backward revolving field theory associated with single-phase induction motors. Also draw & explain its torque-speed characteristics. **AKTU 2015-16, Marks 15**

Answer

A. **Forward and backward revolving field theory :** Refer Q. 5.1, Page 5–2A, Unit-5.

B. **Equivalent circuit :**

1. Fig. 5.3.1 shows the equivalent circuit at standstill with effect of forward and backward rotating fluxes separated.
2. Let

R_{1m} = Resistance of the main stator winding
X_{1m} = Leakage reactance of the main stator winding
X_M = Magnetizing reactance
R_2' = Standstill rotor resistance referred to the main stator winding.

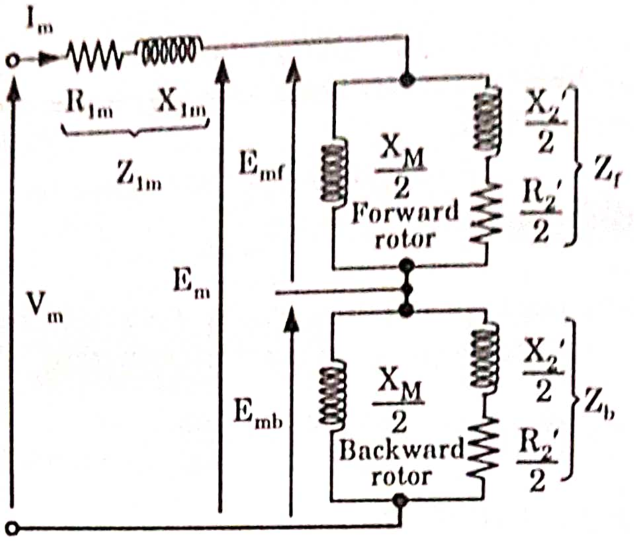


Fig. 5.3.1. Equivalent circuit at standstill.

3. Fig. 5.3.2 shows an equivalent circuit under running condition.

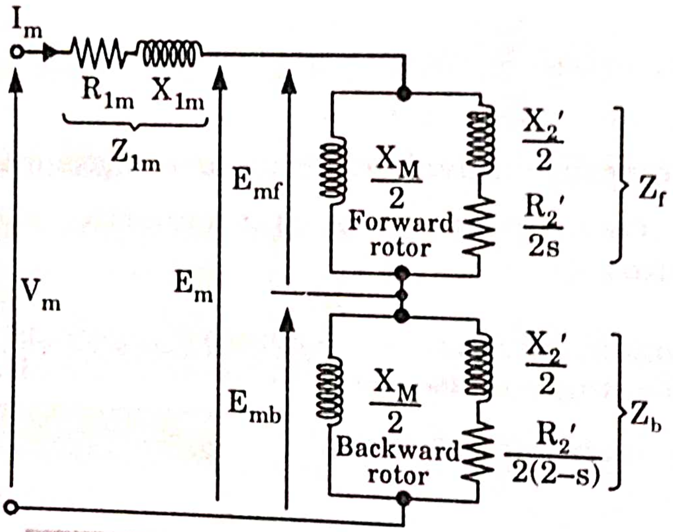


Fig. 5.3.2. Equivalent circuit at running.

4. At stand-still the air-gap flux can be resolved into two equal and opposite magnetic fields within the motor. R_2' and X_2' can be split into two parts, also the voltages E_{mf} and E_{mb} are equal at stand still.
5. Now, under running condition, at the slip s the terms are changed like resistive term in forward field group $= \frac{R_2'/2}{2s}$. The slip for the backward field is $(2 - s)$ so resistance in backward field group is $= \frac{R_2'/2}{(2-s)}$.

C. Torque-speed characteristics :

1. Fig. 5.3.3 shows torque-speed characteristic of a single-phase induction motor based on constant forward and backward flux waves.

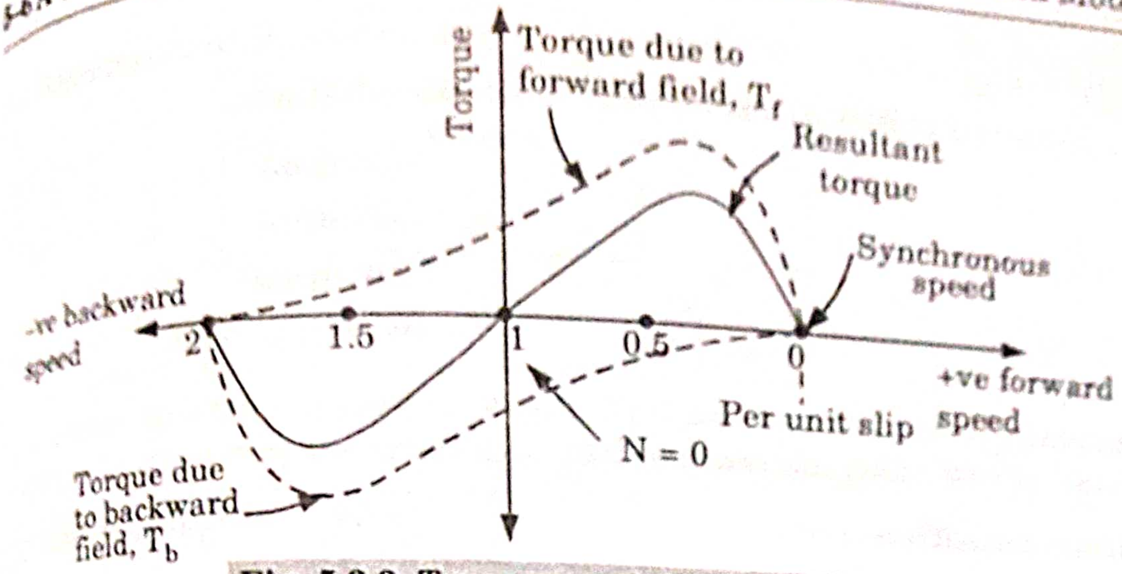


Fig. 5.3.3. Torque-speed characteristic.

2. At standstill, the impedances are equal and, therefore, the current I_{2f} and I_{2b} are equal. These currents produce mmfs which oppose the stator mmfs equally.
3. Therefore, the rotating forward and backward fluxes in the air gap are equal in magnitude, and no torque is developed.
4. However, when the rotor rotates, the impedances of the rotor circuits shown in Fig. 5.3.4 are unequal and the rotor current I_{2b} is greater than the rotor current I_{2f}.

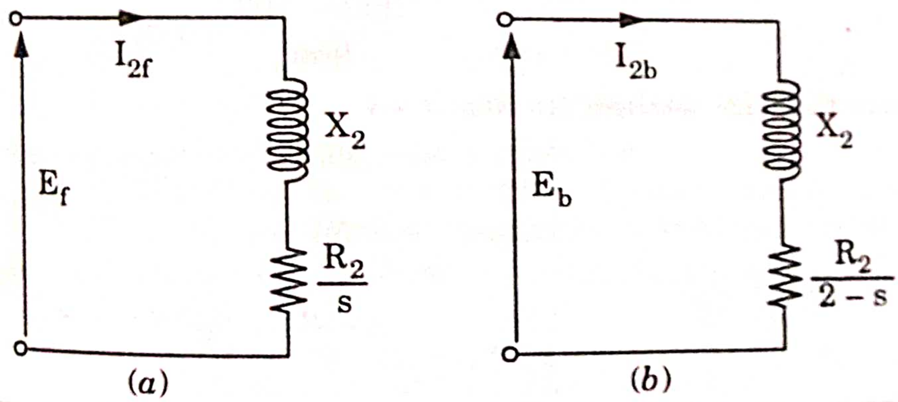


Fig. 5.3.4. Rotor equivalent circuits (*a*) For forward rotating flux wave and (*b*) For backward rotating flux wave.

4. Their mmfs, which oppose the stator mmfs, will result in the reduction of the backward rotating flux. Consequently, as the speed increases, the forward flux increases while the backward flux decreases.
5. However, the resultant flux remains essentially constant. This resultant flux induces voltage in the stator winding.
6. Both flux waves induce voltages in the rotor and produce torques in the rotor. These two torques are in opposite directions.
7. The net induced torque in the motor is equal to the difference between these torques.

Que 5.4. A 220 V, 50 Hz, 6 pole, single-phase induction motor has the following circuit model parameters as follows :

r_{1m}	3.6 ohms
r_2	6.8 ohms
$x_{1m} + x_2$	15.6 ohms
x_c	96 ohms

The rotational losses of the motor are estimated to be 75 watts. At a motor of 940 rpm, determine the line current, power factor, shaft power and efficiency.

AKTU 2015-16, Marks 15

Answer

Given : $V = 220$ volt, $P = 6, f = 50$ Hz, $N = 940$ rpm, $r_{1m} = 3.6\ \Omega$, $r_2 = 6.8\ \Omega$, $x_{1m} + x_2 = 15.6\ \Omega$, $x_c = 96\ \Omega$, rotational loss = 75 W

To Find : Line current, I_L; Power factor, $\cos\phi$; Shaft power, P_{out}; Efficiency, η.

1.
$$N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$
$$s = \frac{N_s - N}{N_s} = \frac{1000 - 940}{1000} = 0.06$$

2. The circuit model is drawn in Fig. 5.4.1.

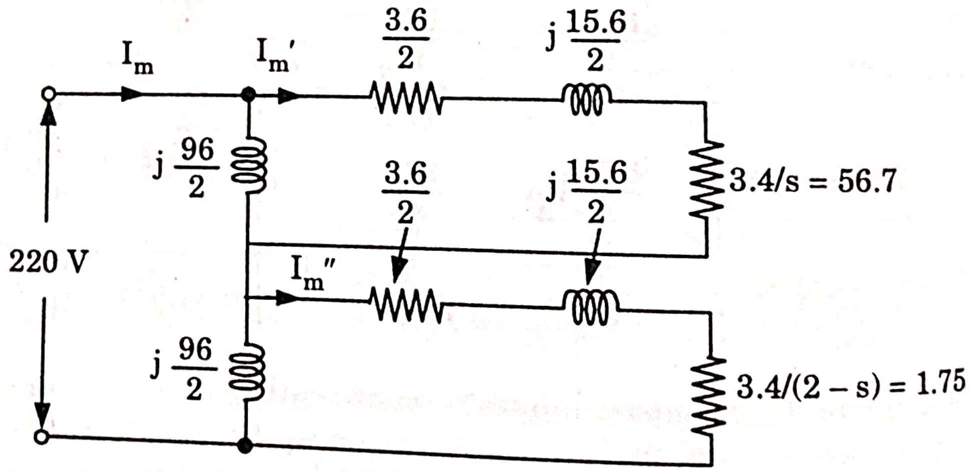


Fig. 5.4.1.

3.
$$\vec{Z}_f(\text{total}) = j\,48 \,||\, (1.8 + 56.7 + j\,7.8)$$
$$= j\,48 \,||\, (58.5 + j\,7.8)$$
$$= 35 \angle 54° = (20.6 + j\,28.3)\ \Omega$$

4.
$$\vec{Z}_b(\text{total}) = j\,48 \,||\, (1.8 + 1.75 + j7.8)$$
$$= j\,48 \,||\, (3.55 + j\,7.8)$$
$$= 7.36 \angle 69.1° = (2.63 + j\,6.88)\ \Omega$$

$$\vec{Z}\,(\text{total}) = (20.6 + j\,28.3) + (2.63 + j\,6.88)$$
$$= 23.23 + j\,35.18 = 42.16\angle 56.6°\ \Omega$$

5. $$\vec{I} = \frac{220\angle 0°}{42.16\angle 56.6°} = 5.22\ \angle -56.6°\ \text{A}$$
$$I_L = I_m = 5.22\ \angle -56.6°\ \text{A}$$
$$\text{Power factor} = \cos 56.6° = 0.55\ (\text{lagging})$$

6. $$I_m' = 5.22\ \angle -56.6° \times \frac{j\,48}{(58.5 + j\,55.8)}$$
7. $$= 3.1\angle -10°\ \text{A}$$

$$I_m'' = 5.22\ \angle -56.6° \times \frac{j\,48}{(3.55 + j\,55.8)}$$
8. $$= 4.48\ \angle -53°\ \text{A}$$

9. $$\omega_s = \frac{2\pi\,N_s}{60} = 104.7\ \text{rad/sec}$$

10. $$T = \frac{1}{104.7}\,[(3.1)^2 \times 56.7 - (4.48)^2 \times 1.75] = 4.87\ \text{N-m}$$

11. $$P_m = 104.7\,(1 - 0.06) \times 4.48 = 479.3\ \text{W}$$
$$P_{out} = 479.3 - 75 = 404.3\ \text{W}$$
$$P_{in} = 220 \times 5.22 \times 0.55 = 631.6\ \text{W}$$

12. $\therefore$ $$\%\,\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{404.3}{631.6} \times 100 = 64\ \%$$

PART-2

No-Load and Blocked Rotor Test, Starting Methods.

CONCEPT OUTLINE : PART-2

- **Starting methods of 1ϕ induction motor (or types of motor)**

1. Split-phase motor
2. Capacitor-start motor
3. Capacitor-start capacitor-run motor (two-value capacitor motor)
4. Permanent split capacitor (PSC) motor
5. Shaded-pole motor.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.5. Draw and explain the equivalent circuit diagram of 1ϕ IM for no-load and blocked-rotor tests.

Answer

A. Blocked-rotor test :

1. In this test the rotor is at rest (blocked). A low voltage is applied to the stator so that rated current flows in the main winding.
2. The voltage, current and power input are measured. Let V_{sc}, I_{sc} and P_{sc} denote the voltage, current and power respectively under these conditions.
3. With the rotor blocked, $s = 1$ the impedance $\frac{X_M}{2}$ is so large compared with $\left(\frac{R_2'}{2} + j\frac{X_2'}{2}\right)$ that it may be neglected.

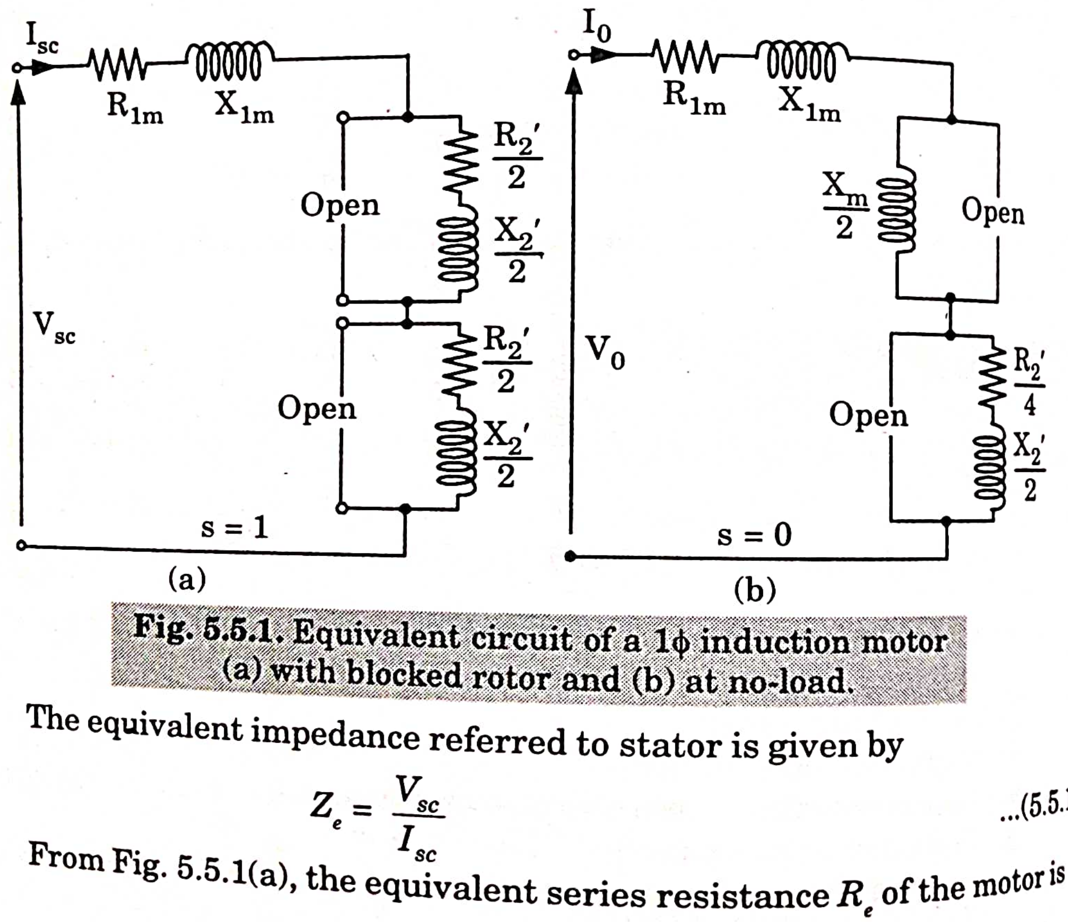


Fig. 5.5.1. Equivalent circuit of a 1ϕ induction motor (a) with blocked rotor and (b) at no-load.

4. The equivalent impedance referred to stator is given by

$$Z_e = \frac{V_{sc}}{I_{sc}} \quad \text{...(5.5.1)}$$

5. From Fig. 5.5.1(a), the equivalent series resistance R_e of the motor is

$$R_e = R_{1m} + \frac{R_2'}{2} + \frac{R_2'}{2} = R_{1m} + R_2' = \frac{P_{sc}}{I_{sc}^2} \quad \text{...(5.5.2)}$$

6. Since the resistance of the main stator winding R_{1m} is already measured (by other method e.g., DC stator resistance test) the effective rotor resistance at line frequency is given by

$$R_2' = R_e - R_{1m} = \frac{P_{sc}}{I_{sc}^2} - R_{1m} \quad ...(5.5.3)$$

7. The equivalent reactance X_e is given by

$$X_e = X_{1m} + \frac{X_2'}{2} + \frac{X_2'}{2} = X_{1m} + X_2' \quad ...(5.5.4)$$

8. Since the leakage reactances X_{1m} and X_2' cannot be separated out we make a simplifying assumption that $X_{1m} = X_2'$.

$$\therefore \quad X_{1m} = X_2' = \frac{1}{2} X_e = \frac{1}{2} \times \sqrt{Z_e^2 - R_e^2} \quad ...(5.5.5)$$

9. Thus, from blocked-rotor test, the parameters R_2', X_{1m} and X_2' can be found if, R_{1m} is known.

B. **No-load test :**

1. The motor is run without load at rated voltage and rated frequency. The voltage, current and input power are measured.

2. At no-load, the slip s is very small close to zero and $\frac{R_2'}{2s}$ is very large as compared to $\frac{X_M}{2}$.

3. The resistance $\frac{R_2'}{2(2-s)}$ associated with the backward rotating field is so small as compared to $\frac{X_M}{2}$, that the backward magnetizing current is negligible.

4. From Fig. 5.5.1(b), the equivalent reactance at no-load is given by

$$X_0 = \frac{X_M}{2} + \frac{X_2'}{2} \quad ...(5.5.6)$$

5. Since X_{1m} and X_2' are already known from the blocked-rotor test, the magnetizing reactance X_M can be calculated from eq. (5.5.6).

6. Let V_0, I_0 and P_0 denote the voltage, current and power respectively in the no-load test. Then the no-load power factor is

$$\cos \phi_0 = \frac{P_0}{V_0 I_0} \quad ...(5.5.7)$$

7. The no-load equivalent impedance is

$$Z_0 = \frac{V_0}{I_0}$$

8. The no-load equivalent reactance is

$$X_0 = Z_0 \sin \phi_0 = Z_0 \times \sqrt{1 - \cos^2 \phi_0}$$

Que 5.6. **Explain the following tests performed on 1ϕ IMs :**

i. **Stator resistance DC test**

ii. **No-load test**

iii. **Blocked-rotor test**

Also mention their utility. **AKTU 2013-14, Marks 10**

Answer

A. **Stator resistance DC test :**

1. A variable DC voltage source is connected between stator terminals.
2. The DC source is adjusted to provide approximately rated stator current, and the resistance between the two stator leads is determined from the voltmeter and ammeter readings.

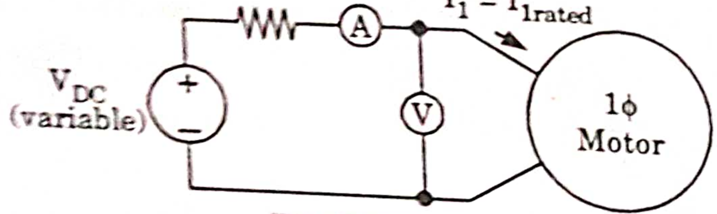


Fig. 5.6.1.

3. $$R = V/I$$

Where, R = Stator resistance

V = Voltmeter reading

I = Current reading

Utility : This test is used to determine stator DC resistance.

B. **No-load test :** Refer Q. 5.5, Page 5–9A, Unit-5.

Utility : This test is used to determine the rotational losses and magnetization current of single phase induction motor.

C. **Blocked rotor test :** Refer Q. 5.5, Page 5–9A, Unit-5.

Utility : This test is used to determine the rotor and stator impedances of single phase induction motor.

Que 5.7. **A 220 V, 1ϕ induction motor gave the following test results :**

Blocked-rotor test : 120 V, 9.6 A, 460 W

No-load test : 220 V, 4.6 A, 125 W

The stator winding resistance is 1.5 Ω and during the blocked-rotor test, the starting winding is open. Determine the equivalent circuit parameters and core, friction and windage losses.

AKTU 2012-13, Marks 10

Answer

Given : Blocked-rotor test : $V_{sc} = 120$ V, $I_{sc} = 9.6$ A, $P_{sc} = 460$ W, $R_{1m} = 1.5\ \Omega$, No-load test : $V_0 = 220$ V, $I_0 = 4.6$ A, $P_0 = 125$ W, $R_{1m} = 1.5\ \Omega$

To Find : Equivalent parameters, Core, friction and windage losses.

$$Z_e = \frac{V_{sc}}{I_{sc}} = \frac{120}{9.6} = 12.5\ \Omega$$

$$R_e = \frac{P_{sc}}{I_{sc}^2} = \frac{460}{(9.6)^2} = 4.99\ \Omega$$

$$X_e = \sqrt{Z_e^2 - R_e^2} = \sqrt{(12.5)^2 - (4.99)^2} = 11.46\ \Omega$$

$$X_{1m} = X_2' = \frac{1}{2} X_e = \frac{1}{2} \times 11.46 = 5.73\ \Omega$$

$$R_e = R_{1m} + R_2'$$

$$R_2' = R_e - R_{1m} = 4.99 - 1.5 = 3.49\ \Omega$$

No-load power factor,

$$\cos \phi_0 = \frac{P_0}{V_0 I_0} = \frac{125}{220 \times 4.6} = 0.1235$$

$$\sin \phi_0 = 0.9923$$

$$\therefore \quad Z_0 = \frac{V_0}{I_0} = \frac{220}{4.6} = 47.82\ \Omega$$

$$X_0 = Z_0 \sin \phi_0 = 47.82 \times 0.9923 = 47.45\ \Omega$$

Core, friction and windage losses

= Power input to motor at no-load – No-load copper loss

$$= P_0 - I_0^2 \left(R_{1m} + \frac{R_2'}{4} \right) = 125 - (4.6)^2 \left(1.5 + \frac{3.49}{4} \right)$$

$$= 74.8 \text{ W}$$

Que 5.8. **A 230 V, single-phase induction motor gave the following results :**

Blocked-rotor test : 120 V, 9.6 A, 460 W

No-load test : 230 V, 4.6 A, 125 W

Stator winding resistance is 1.5 Ω and during the blocked-rotor test, auxiliary winding is open. Determine the equivalent circuit parameters.

AKTU 2016-17, Marks 10

Answer

Given : $V_L = 230$ V

Blocked-rotor test : $V_{sc} = 120$ V, $I_{sc} = 9.6$ A, $P_{sc} = 460$ W

No-load test : $V_0 = 230$ V, $I_0 = 4.6$ A, $P_0 = 125$ A, $R_{1m} = 1.5\ \Omega$

To Find : X_2', R_2', R_0 and X_0.

1. **Blocked-rotor test :**

$$Z_e = \frac{V_{sc}}{I_{sc}} = \frac{120}{9.6} = 12.5\ \Omega$$

$$R_e = \frac{P_{sc}}{I_{sc}^2} = \frac{460}{(9.6)^2} = 4.99\ \Omega$$

$$X_e = \sqrt{Z_e^2 - R_e^2} = \sqrt{(12.5)^2 - (4.99)^2} = 11.46\ \Omega$$

$$X_{1m} = X_2' = \frac{1}{2} X_e = \frac{1}{2} \times 11.46 = 5.73\ \Omega$$

$$R_{1m} = 1.5\ \Omega$$

$$R_e = R_{1m} + R_2'$$

$$R_2' = R_e - R_{1m} = 4.99 - 1.5 = 3.49\ \Omega$$

2. **No-load test :**

$$\cos \phi_0 = \frac{P_0}{V_0 I_0} = \frac{125W}{230 \times 4.6}\ \Omega = 0.118$$

$$\therefore \quad \sin \phi_0 = 0.9930$$

$$Z_0 = \frac{V_0}{I_0} = \frac{230}{4.6} = 50\ \Omega$$

$$X_0 = Z_0 \sin \phi_0 = 50 \times 0.9930 = 49.65\ \Omega$$

$$R_0 = Z_0 \cos \phi_0 = 5.9\ \Omega$$

Que 5.9. **What do you mean by "FORWARD" and "BACKWARD" fields in 1ϕ IMs ? Explain why in case of 1ϕ IMs, the flux is pulsating in nature ? Explain why, 1ϕ IMs are not self starting ? Enlist the methods of starting of 1ϕ IMs. Also, mention its domestic applications.**

AKTU 2013-14, Marks 10

OR

Using double-revolving field theory, explain why a single-phase induction motor is not self starting ? Name the methods to make a single-phase induction motor self starting.

AKTU 2016-17, Marks 10

Answer

A. **Forward and backward fields :** Refer Q. 5.1, Page 5–2A, Unit-5.

B. **Reason (1ϕ IM is not self starting) :** Refer Q. 5.1, Page 5–2A, Unit-5.

C. **Pulsating nature of flux :** Refer Q. 5.1, Page 5–2A, Unit-5.

D. **Methods of starting :**

1. Split-phase motor
2. Capacitor-start motor
3. Capacitor-start capacitor-run motor (or two-value capacitor motor)
4. Permanent-split capacitor (PSC) motor (or single-value capacitor motor)
5. Shaded-pole motor.

E. **Domestic applications :**

1. Washing machines
2. Fans
3. Grinders
4. Refrigerators
5. Hair driers.

Que 5.10. **Discuss why single-phase induction motors do not develop a starting torque ? Explain with the help of Double-Revolving Field Theory. Describe construction and working of a shaded-pole motor.**

AKTU 2012-13, Marks 10

Answer

A. **Reason :** Refer Q. 5.1, Page 5–2A, Unit-5.

B. **Double-revolving field theory :** Refer Q. 5.1, Page 5–2A, Unit-5.

C. **Shaded-pole motor :**

1. A shaded-pole motor is a simple type of self-starting 1ϕ induction motor. It consists of a stator and a cage-type rotor.
2. The stator is made up of salient poles. Each pole is slotted on side and a copper ring is fitted on the smaller part '*a*'. This part is called shaded pole. The ring is usually a single-turn coil and is known as shading coil.
3. When alternating current flows in the field winding, an alternating flux is produced in the field core. A portion of this flux links with shading coil, which behaves as a short-circuited secondary of transformer.
4. A voltage is induced in the shading coil and this voltage circulates a current in it. The induced current produces a flux which opposes the main core flux.
5. The shading coil, thus, causes the flux in the shaded portion to lag behind the flux in the unshaded portion of the pole.
6. At the same time, the main flux and the shaded pole flux are displaced in space. This space displacement is less than 90°.

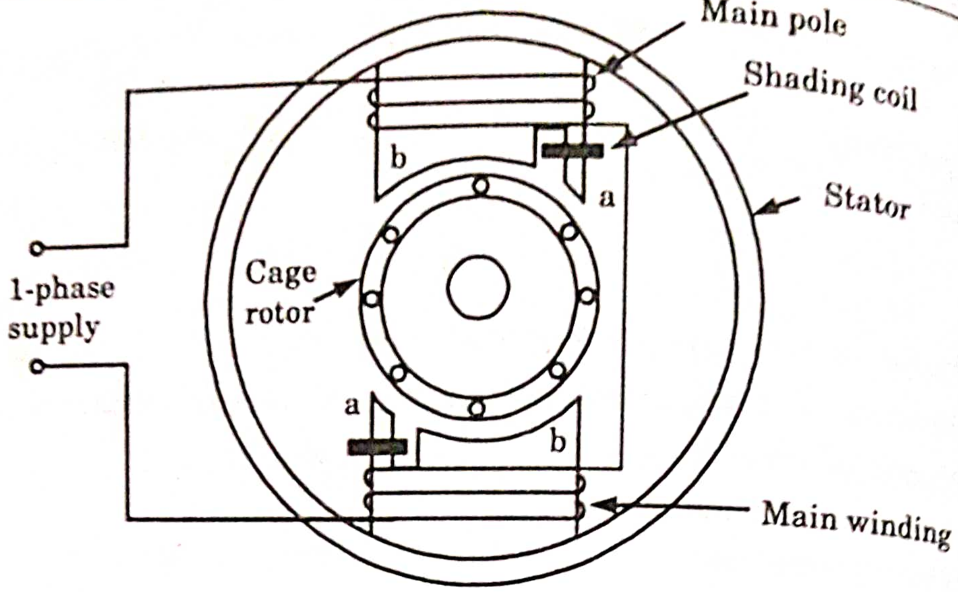


Fig. 5.10.1. Shaded-pole motor with two stator poles.

7. Since, there is time and space displacement between the two fluxes, conditions for setting up a rotating magnetic field are produced.
8. Under the action of the rotating flux a starting torque is developed on cage rotor. The direction of this rotating field (flux) is from the unshaded to shaded portion of the pole.
9. In a shaded-pole motor the reversal of direction of rotation is not possible.

Applications :

1. The most common applications are table fans, exhaust fans, hair driers, fans for refrigeration and air-conditioning equipments, electronic equipment, cooling fans etc.
2. They are also used in record players, tape recorders, slide projectors, photo copying machines, in starting electric clocks and other single-phase synchronous timing motors.

Que 5.11. **Discuss the working principle of capacitor start capacitor run motor and also explain its equivalent circuit.**

AKTU 2015-16, Marks 10

Answer

1. Fig. 5.11.1 shows the schematic diagram of a two-value capacitor motor.
2. It has a cage rotor and its stator has two windings namely the main winding and the auxiliary winding.
3. The two windings are displaced 90° in space. The motor uses two capacitors C_S and C_R. The two capacitors are connected in parallel at starting.
4. The capacitor C_S is called the starting capacitor.

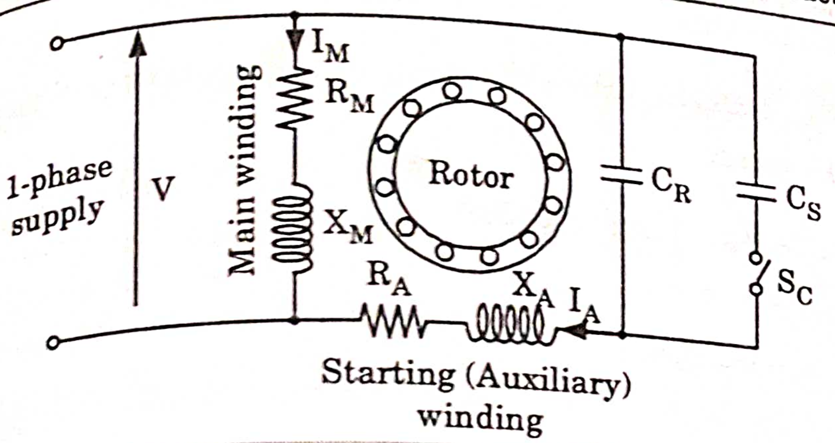


Fig. 5.11.1. Two-value capacitor motor (capacitor start capacitor run motor).

5. In order to obtain a high starting torque, a large current is required. For this purpose, the capacitive reactance X_A in the starting winding should be low.
6. During normal operation, the rated line current is smaller than the starting current. Hence the capacitive reactance should be large.

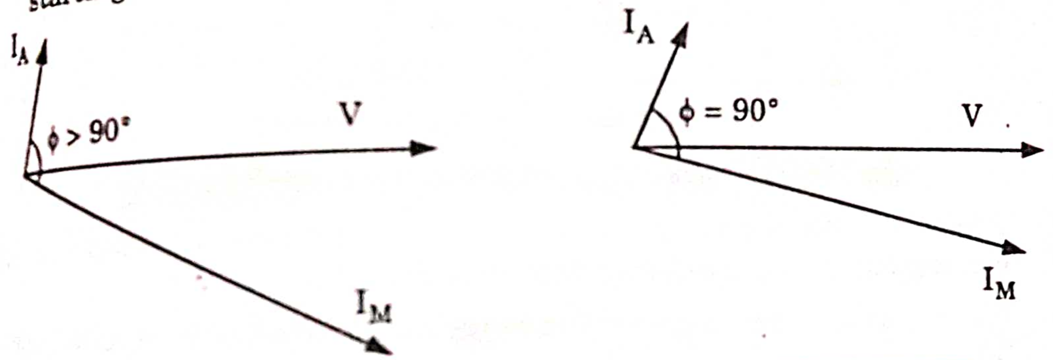


Fig. 5.11.2. Phasor diagrams of a 2-value capacitor motor.

7. The torque-speed characteristic of a 2-value capacitor motor is shown in Fig. 5.11.3.

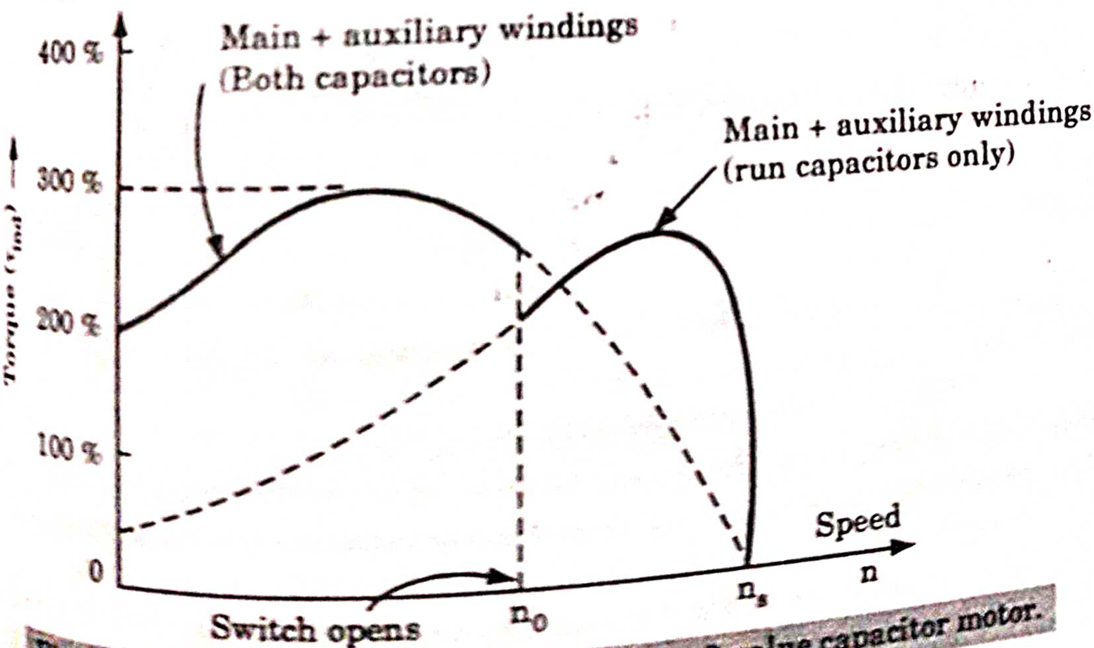


Fig. 5.11.3. Torque-speed characteristic of a 2-value capacitor motor.

Que 5.12. **Discuss different methods of starting of single phase induction motor.**

OR

Explain different types of 1ϕ IM.

Answer

A. Split-phase motor :

1. Fig. 5.12.1 shows a split-phase induction motor. It is also called a resistance-start motor.

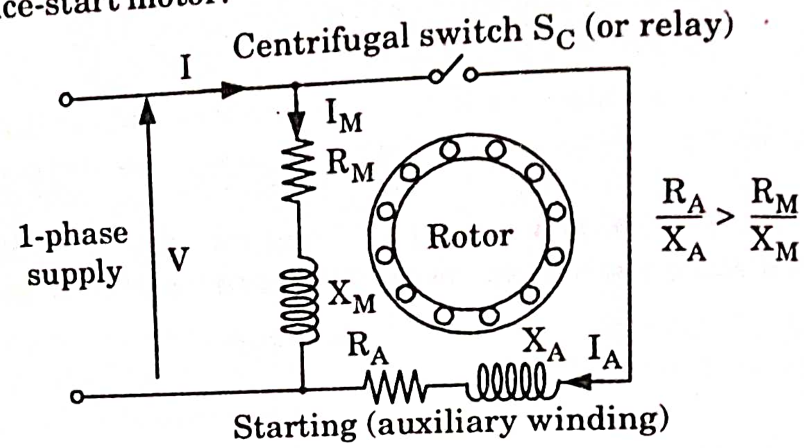


Fig. 5.12.1. Split-phase induction motor connections.

2. It has a single-cage rotor and its stator has two windings - a main winding and a starting (auxiliary) winding.
3. The main field winding and the starting winding are displaced 90° in space. The main winding has very low resistance and high inductive reactance.

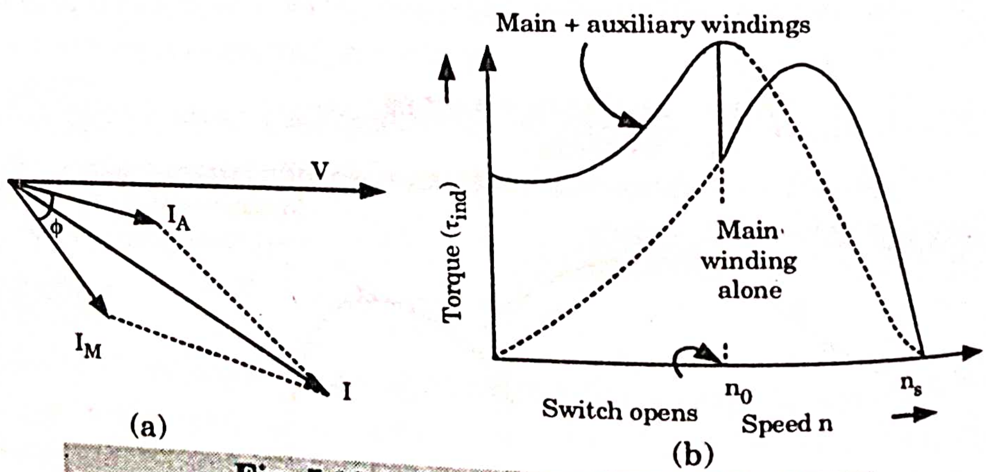


Fig. 5.12.2. Split-phase motor
(a) Phasor diagram (b) Torque-speed characteristic.

4. Thus, the current I_M in the main winding lags behind the supply voltage V by nearly 90°.
5. The auxiliary winding has a resistor connected in series with it. It has a high resistance and low inductive reactance so that the current I_A in the auxiliary winding is nearly in phase with the line voltage.

Thus, there is time phase difference between the currents in the two windings. This phase difference is enough to produce a rotating magnetic field.

Capacitor start motor :

1. Fig. 5.12.3(a) shows the connections of a capacitor-start motor. It has a cage rotor and its stator has two windings namely, the main winding and the auxiliary winding (starting winding).
2. The two windings are displaced 90° in space. A capacitor C_S is connected in series with the starting winding. A centrifugal switch S_C is also connected as shown in Fig. 5.12.3(a).

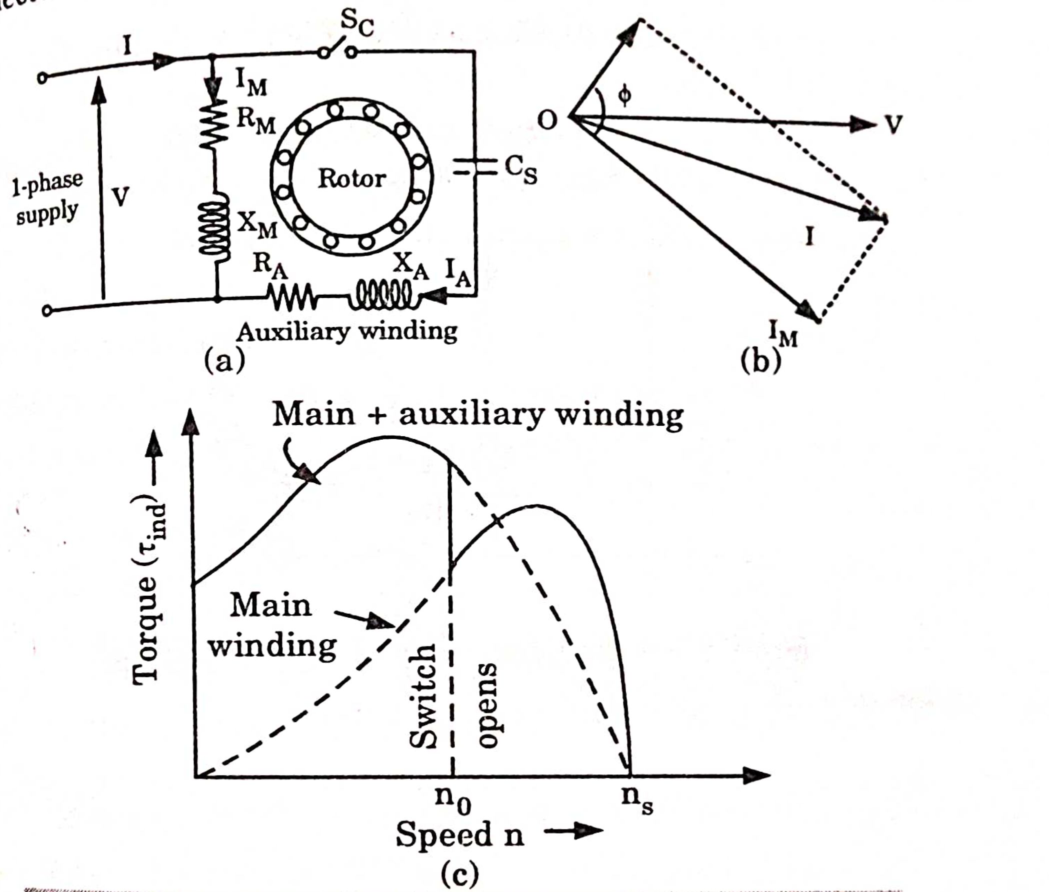


Fig. 5.12.3. Capacitor start motor (a) Circuit diagram (b) Phasor diagram (c) Torque-speed characteristics.

3. By choosing a capacitor of the proper rating the current I_M in the main winding may be made to lag the current I_A in the auxiliary winding by 90°.
4. Thus, a single-phase supply current is split into two phases to be applied to the stator windings. Thus the windings are displaced 90° apart in time phase.
5. Therefore the motor acts like a balanced two-phase motor. As the motor approaches its rated speed, the auxiliary winding and the starting capacitor C_S are disconnected automatically by the centrifugal switch S_C mounted on the shaft.

C. **Two value capacitor motor :** Refer Q. 5.11, Page 5–15A, Unit-5.

D. Permanent capacitor run motor :

1. A permanent-split capacitor (PSC) motor is shown in Fig. 5.12.4.
2. It has a cage rotor and its stator has two windings, namely, the main winding and the auxiliary winding.
3. This single-phase induction motor has only one capacitor C which is connected in series with the starting winding.
4. The capacitor C is permanently connected in the circuit both at starting and running conditions.
5. A permanent-split capacitor motor is also called the single-value capacitor motor.
6. Since the capacitor C is always in the circuit, this type of motor has no starting switch.
7. The auxiliary winding is always in the circuit, and therefore this motor operates in the same way as a balanced two-phase motor.

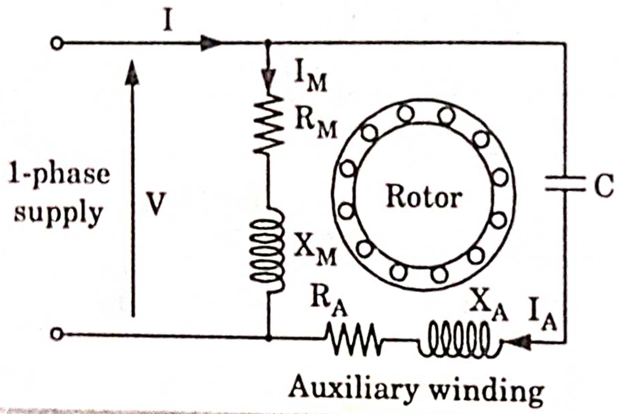


Fig. 5.12.4. Permanent-split capacitor motor.

E. Shaded pole motor : Refer Q. 5.10, Page 5–14A, Unit-5.

PART-3

Repulsion Motor, Universal Motor, Brushless Motor.

CONCEPT OUTLINE : PART-3

- **AC commutator motor :**

1. Universal motor
2. Single phase AC series motor
3. Stepper motor

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.13. **Explain the constructional details and working principle of 1ϕ reluctance motor. Also mention its domestic applications. What are the advantages and disadvantages of this motor ?**

Answer

A. **Construction :**

1. Construction of 1ϕ reluctance motor is similar to the 3ϕ salient pole synchronous motor.
2. Reluctance motor has a stator carrying the armature winding that produces rotating field, as in case of synchronous salient pole motor.
3. It has salient pole rotor that houses copper bars as in case of 3ϕ synchronous salient pole rotor, with only the difference that, here the copper bars provide the induction torque unlike the synchronous salient pole rotor.

B. **Working principle :**

1. It is based on electromechanical energy conversion.
2. When stator produces a revolving magnetic field at synchronous speed, the rotor starts to rotate in the direction of field rotation due to induction motor effect.
3. As the rotor is non-cylindrical, the reluctance of magnetic path, offered by the rotor to the rotating field, is a function of the space angle.
4. The origin of the reluctance torque is due to tendency of rotor to align itself in minimum reluctance position with respect to synchronously rotating flux.
5. Thus, when the rotor reaches near about the synchronous speed by induction action, the rotor is pulled in synchronism during positive half cycle of the sinusoidal varying synchronous torque.

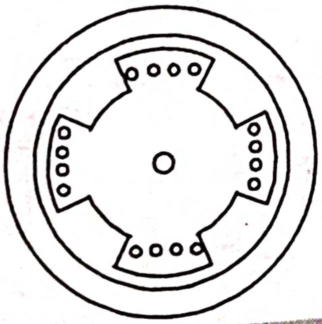


Fig. 5.13.1. **Constructional feature of 4-pole reluctance motor.**

C. **Domestic applications :** Washing machine, bladeless fan, vacuum cleaner, fan heater.

D. **Advantages :**

1. Simple and low cost due to absence of rotor windings or permanent magnets and can be easily cooled as losses appear in stator only.

2. It provides high starting torque.
3. Temperature specification of rotor is higher.
4. It can provide very high speeds of rotation.

E. Disadvantages :

1. Less efficiency.
2. Poor power factor.
3. Need of very low inertia rotor.
4. Less capacity to drive the loads.

Que 5.14. **Explain the operation of stepper motor and state some important applications of stepper motor.**

AKTU 2014-15, Marks 10

Answer

1. The stepper motor is a special type of synchronous motor which is designed to rotate through a specific angle called a step angle for each step electrical pulse received by its control unit.
2. The step sizes are 7.5°, 15° or larger.
3. The stepper motor is used in digitally controlled position control system in open loop mode. The input command is in the form of train of pulses to turn a shaft through a specified angle.

Types of stepper motor :

A. Single-stack variable reluctance motor :

1. It has a salient pole (or tooth) stator. The stator has concentrated windings placed over the stator pole.

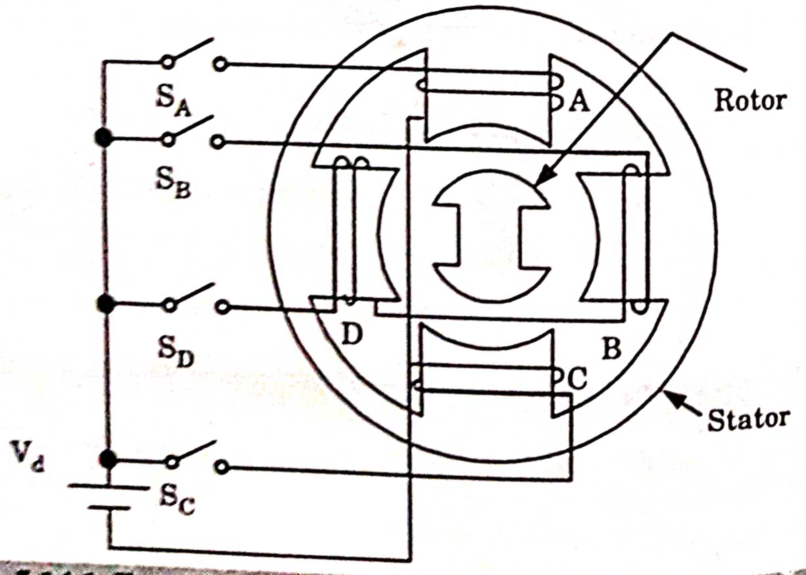


Fig. 5.14.1. Four-phase 4/2-pole variable reluctance stepper motor.

2. The number of phases of the stator depends upon the connection of stator coils.
3. Usually three or four phase windings are used.
4. The rotor is slotted structure made from ferromagnetic material and carries no winding.
5. Both the stator and rotor are made up of high quality magnetic materials having very high permeability so that the excitation current required is very small.
6. When the stator phases are excited in a proper sequence from DC source with the help of semiconductor switches, a magnetic field is produced.
7. The ferromagnetic rotor occupies the position which presents minimum reluctance to the stator field. That is, the rotor axis aligns itself to stator field axis.

B. Permanent magnet stepper motor :

1. It has 4 stator poles and 6 rotor poles producing a full step angle of 30°.
2. The end terminals of all windings are brought out to the terminal box for DC excitation.
3. The rotor of such a motor has even number of poles made of high retentivity steel alloy.
4. Both rotor and stator may employ salient or non-salient pole construction.
5. The stator pole windings are wrapped in such a way that closure of any winding's control switch causes that winding's pole to become magnetically north.

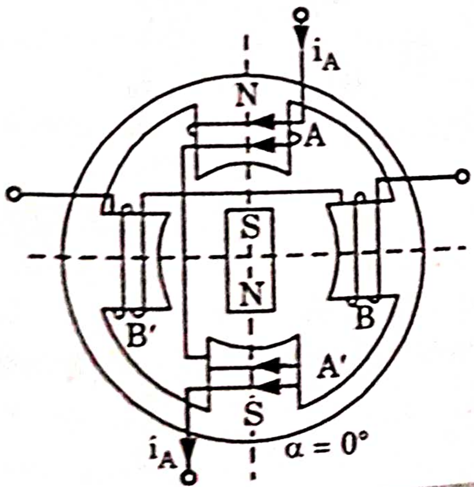


Fig. 5.14.2. 2-phase 4/2-pole PM stepper motor.

C. Advantages :

1. Compatible with digital systems.
2. No sensors are needed for position and speed sensing as these are directly obtained by counting input pulses, periodic counting input pulses and periodic counting if speed information is needed.

D. **Applications :**

As paper feed motor in typewriters and printers positioning of print heads, pens in XY-plotters, recording heads in computer disk drives and in positioning of work tables and tools in numerically controlled machine equipment.

Que 5.15. **Explain principle of operation of universal motor. Draw and explain its operation characteristics.**

AKTU 2015-16, Marks 10

Answer

A. **Construction :**

1. There are small capacity series motors which can be operated on DC supply or single phase alternating supply of same voltage with similar characteristics called universal motors.
2. It is manufactured in two types :
   a. Non-compensated, low h.p.
   b. Compensated type, high h.p.
3. Non-compensated type pole has 2 poles, having entire magnetic path as laminated.
4. Armature is wound type similar to the normal DC motor. Such non-compensated construction is shown in the Fig. 5.15.1.

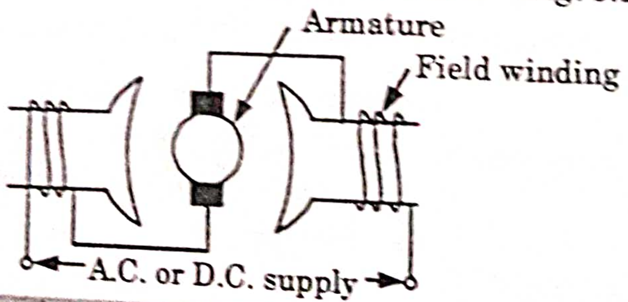
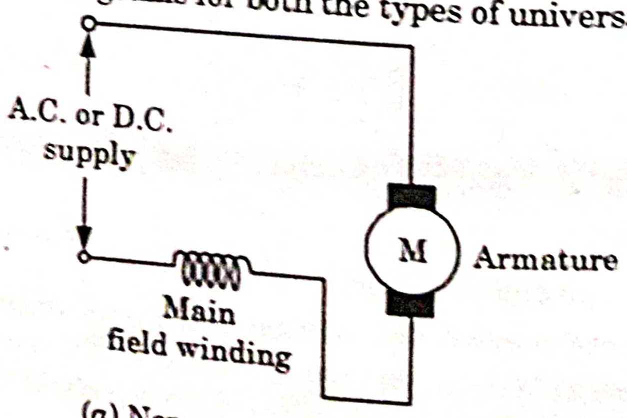
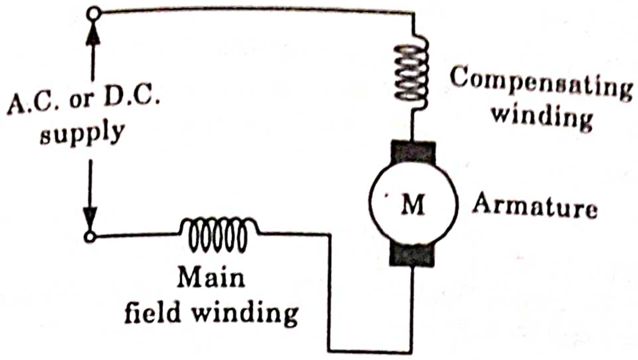


Fig. 5.15.1. Cross-section of non-compensated universal motor.

5. While in compensated type, the motor has distributed field winding consisting of main field and compensating winding. Fig. 5.15.2 shows the connection diagrams for both the types of universal motor.



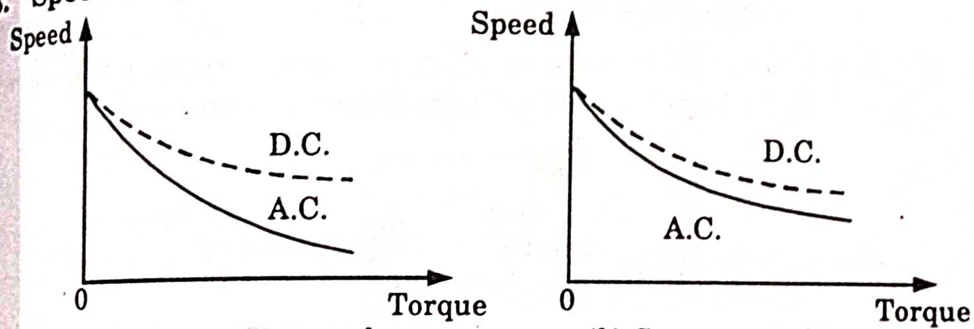
(a) Non-compensated type



(*b*) Compensated type

Fig. 5.15.2. Connection diagrams for a universal motor.

B. Speed-torque characteristics :



(*a*) Non-compensated type (*b*) Compensated type

Fig. 5.15.3. Speed-torque characteristics of universal motor.

C. Applications of universal motor :

1. Portable Drills
2. Hair Dryers
3. Grinders
4. Table fans
5. Blowers
6. Speed control.

Que 5.16. Write a short note on single-phase AC series compensated motor.

Answer

1. The single-phase series motor is a commutator type motor.
2. If the polarity of the line terminals of a DC series motor is reversed the motor will continue to run in the same direction.
3. The following modifications are made in a DC series motor so that it operates satisfactorily on alternating current :

a. The field core is constructed of a material having low hysteresis loss and is laminated.

b. The field winding is provided with small number of turns.

c. The number of armature conductors is increased.

d. In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used. This winding is put in the stator slots as shown in Fig. 5.16.1. The axis of the compensating winding is 90° (electrical) with the main field axis.

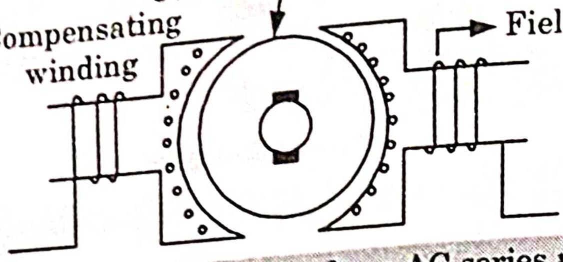


Fig. 5.16.1. Single-phase AC series motor.

4. It may be connected in series with both the armature and field as shown in Fig. 5.16.2. In this case motor is conductively compensated.

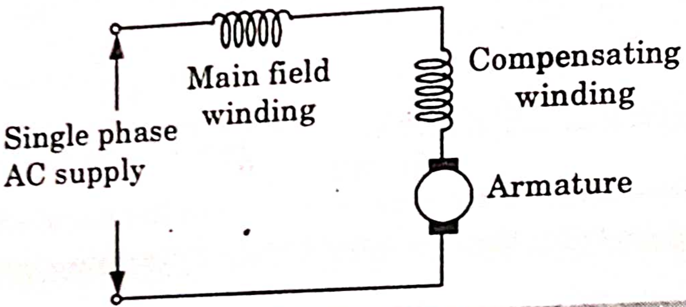


Fig. 5.16.2. Conductively compensated AC series motor.

5. The compensating winding may be short circuited on itself, in this case the motor is said to be inductively compensated.

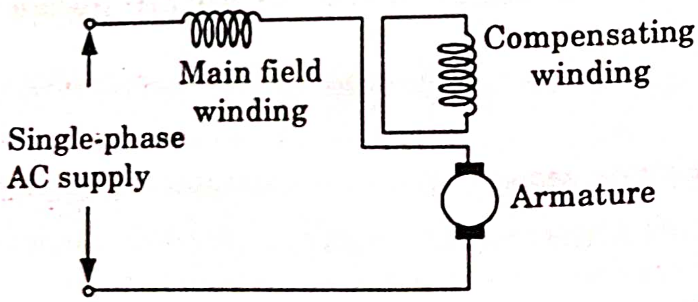


Fig. 5.16.3. Inductively compensated AC series motor.

Application : In railway traction system.

Que 5.17. **Discuss the working principle of AC series motor. Also explain its characteristics and applications in a 3ϕ induction motor. Show that rotor current frequency = Slip × Supply frequency.**

AKTU 2015-16, Marks 10

Answer

A. **Working of AC series motor :** Refer Q. 5.16, Page 5–24A, Unit-5.

B. **Torque-Speed Characteristics :**

1. For given value of torque T and applied voltage V, the armature current is same but voltage drop in case of AC series motor is much more than that in case of a DC series motor so speed of an AC series motor for a given developed torque is less than that of a DC series motor.

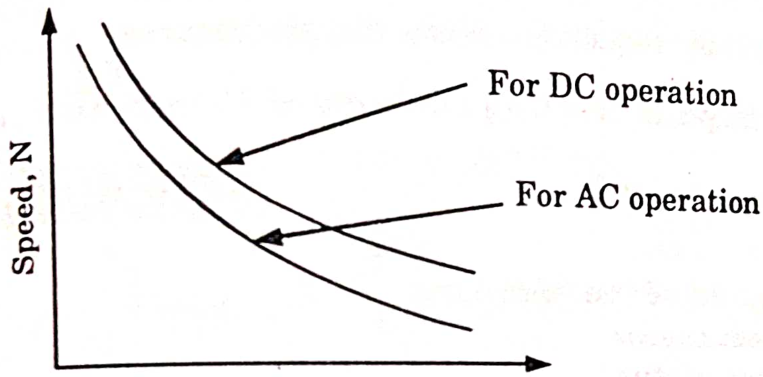


Fig. 5.17.1.

2. The single-phase AC series motor has practically the same operating characteristics as the speed varies inversely as the current.

C. **Applications :**

1. For traction services
2. Electric train engine
3. Chimney at power plants
4. Rolling machines
5. Cooling fans used to cool large machines like alternator etc.

D. **Derivation :**

1. The frequency of current and voltage in the stator must be the same as the supply frequency given by

$$f = \frac{PN_s}{120} \quad ...(5.17.1)$$

2. The frequency in the rotor winding is variable and depends on the difference between the synchronous speed and the rotor speed. Hence the rotor frequency depends upon the slip.

3. The rotor frequency is given by

$$f_r = \frac{P(N_s - N_r)N_s}{120N_s} \quad ...(5.17.2)$$

4. Division of eq. (5.17.2) by (5.17.1) gives

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s}$$

5. But $\frac{N_s - N_r}{N_s} = s$

$\therefore$ $f_r = sf$

6. That is,

Rotor current frequency = Slip × Supply frequency.

Que 5.18. **Explain starting methods of 1ϕ induction motor. What is repulsion motor ?**

AKTU 2014-15, Marks 10

OR

Discuss any two of the following :

i. **Repulsion motor**

ii. **Universal motor**

iii. **Stepper motor.**

AKTU 2012-13, Marks 10

Answer

A. **Repulsion of motor :** It is a special kind of single-phase AC motor which works due to the repulsion of similar poles.

Construction :

1. The stator of this motor carries a single-phase exciting winding. The rotor carries an ordinary distributed DC type winding, connected to the commutator at one end.
2. The brushes are short circuited on themselves and are not connected directly to the supply circuit Fig. 5.18.1.

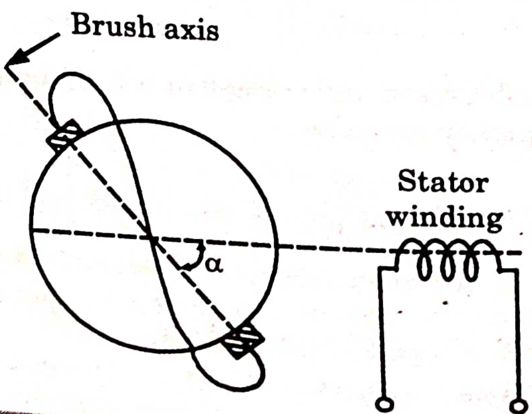


Fig. 5.18.1. Schematic diagram of a repulsion motor.

3. When $\alpha = 90°$, no mutual inductance between stator and rotor windings. Consequently, the voltage across the brushes is zero, rotor-induced currents are zero hence electromagnetic torque developed is zero.
4. When $\alpha = 0°$, the mutual inductance between two windings is maximum, so the large rotor currents produce rotor mmf opposite to the stator mmf since two mmfs are along the same axis, the torque developed is zero.
5. Thus when $\alpha = 0°$ or $90°$ motor not in run position but when $\alpha \neq 0$ (or $\alpha \neq 90°$), due to net induced voltage, electromagnetic torque is produced and rotor runs.
6. If the stator mmf at any instant is directed from A to B, then the rotor-induced mmf must have a component opposite to the stator mmf at the same instant, *i.e.*, the rotor induced mmf must be directed from C to D in Fig. 5.18.2(*c*).

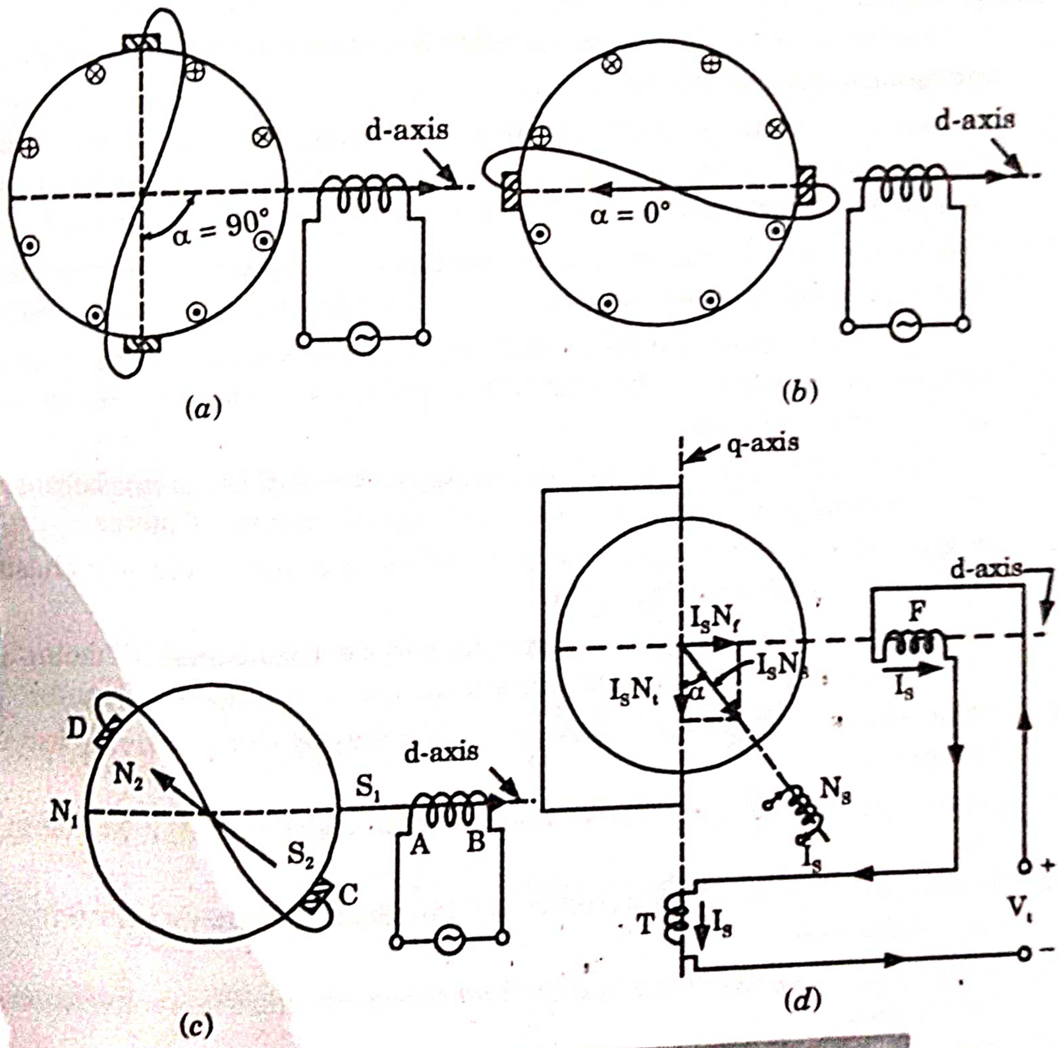


Fig. 5.18.2. Production or torque in repulsion motor.

7. The stator polarity at A is S_1 and at the same instant, rotor-induced polarity at C is S_2. Repulsion between like poles S_1, S_2 and N_1, N_2 results in the clockwise direction of rotation.

8. Now, electromagnetic torque ∝ (stator d-axis mmf) × (rotor q-axis mmf)

$$T \propto (I_s N_s \sin \alpha)(I_s N_s \cos \alpha)$$

$$T \propto I_s^2 N_s^2 \sin 2\alpha$$

$$T_e = K I_s^2 N_s^2 \sin 2\alpha$$

B. Universal motor : Refer Q. 5.15, Page 5–23A, Unit-5.

C. Stepper motor : Refer Q. 5.14, Page 5–21A, Unit-5.

D. Starting methods of induction motor : Refer Q. 5.12, Page 5–17A, Unit-5.

Que 5.19. **Explain brushless DC motor. Also give its advantages.**

Answer

1. A brushless DC motor is a polyphase synchronous motor with a permanent-magnet rotor.
2. This motor cannot operate without its electronic controller. Therefore, a brushless DC motor is a motor drive system that combines into one unit an AC motor, solid state inverter and a rotor position sensor.
3. The solid state inverter uses transistors of low-power drives and thyristor for high-power drives.
4. Rotor position sensor monitors the shaft position and sends the control signals for turning on the controlled switches of the inverter in an appropriate sequence.
5. A brushless DC motor is also viewed as 'inside-out' DC motor because its construction is opposite to that of a conventional DC motor.
6. It has permanent-magnet field poles on the rotor and polyphase armature winding on the stator.
7. The function of mechanical commutator in a conventional DC motor is now performed by electronic commutator in a brushless DC motor.
8. **This motor possesses following advantages over conventional DC motor :**

i. As no mechanical commutator and brushes are required, it has longer life.

ii. Problems relating to radio frequency and electromagnetic interference are minimized.

iii. It can run at speeds much higher than those obtained in a conventional DC motor.

iv. Brushless DC motor is more efficient.

Que 5.20. **Explain construction and working principle of brushless DC motors.**

Answer

A. **Construction :**

1. Fig. 5.20.1 shows an elementary form of 3-phase, 3-pulse brushless DC motor along with its electronic controller.
2. The stator has three-phase winding which is star-connected. The neutral, or star, point of the winding is connected to positive terminal of the DC supply. Full bridge diode converts AC to DC and capacitor C serves as a filter circuit.
3. The three transistors $TR1$, $TR2$ and $TR3$ are turned on in appropriate sequence so that unidirectional torque is developed.
4. When $TR1$ is turned on, phase A is energized; when $TR2$ is on, phase B is energized and so on.
5. When phase windings are energized in sequence ABC, the rotor rotation is clockwise. With sequence ACB, the rotor revolves anticlockwise.
6. The rotor-position sensor mounted on the motor shaft provides a position feedback. It monitors the shaft position and sends signals to the drive circuitry of the inverter circuit.
7. In response to these signals, the inverter allows the flow of current to stator phase windings in a controlled sequence so that motor produces the desired torque and speed.

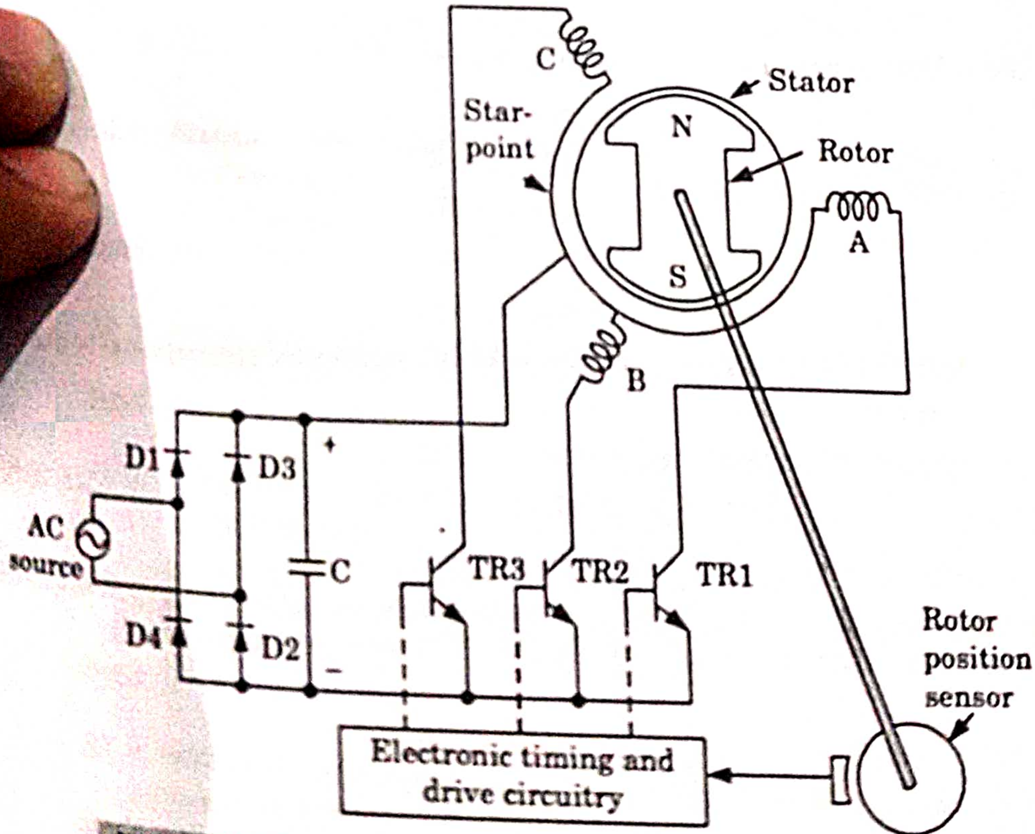


Fig. 5.20.1. Three-phase three-pulse brushless DC motor.

B. Operating principle :

1. Fig. 5.20.2 shows an elementary form of three-phase stator winding and the permanent-magnet rotor with two poles.

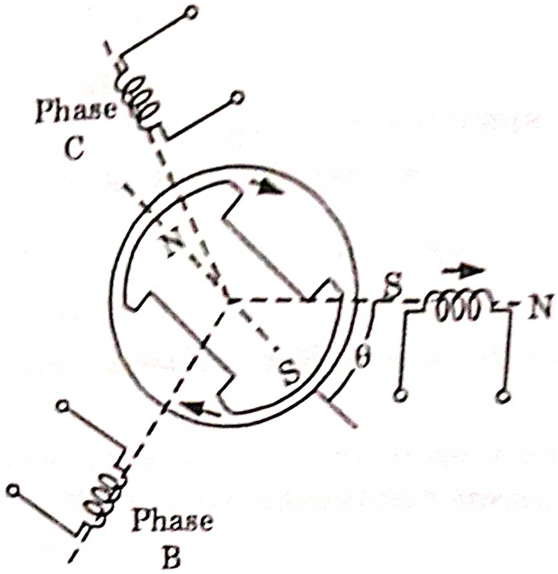


Fig. 5.20.2. An elementary form of brushless DC motor.

2. When phase *A* is energized, stator *S* and *N* poles are created as shown in Fig. 5.20.2. Stator *S* pole repels rotor *S* pole and attracts rotor *N* pole, thus producing clockwise torque.
3. The magnitudes of this torque is given by

$$T_e = K_1 \phi_s \phi_r \sin\theta \quad ...(5.20.1)$$

where ϕ_s = Stator field flux

ϕ_r = Rotor field flux

θ = Torque angle

K_1 = Torque constant.

Here, ϕ_r is constant and stator field flux is directly proportional to stator current.

4. Hence, the torque can be expressed as

$$T_e = KI \sin\theta \quad ...(5.20.2)$$

where I = Stator current.

5. In case phase windings carry instantaneous currents i_a, i_b and i_c, the instantaneous torque, from eq. (5.20.2), can be expressed as

$$T_{ea} = Ki_a \sin\theta$$
$$T_{eb} = Ki_b \sin(\theta - 120°)$$
$$T_{ec} = Ki_c \sin(\theta - 240°)$$

6. If phase currents are assumed to vary sinusoidally with θ, then

$$i_a = I_m \sin\theta,\ i_b = I_m \sin(\theta - 120°)$$

and $i_c = I_m \sin(\theta - 240°)$

7. With these currents, the torque expressions for the three-phases become,

$$T_{ea} = KI_m \sin^2\theta, T_{eb} = KI_m \sin^2(\theta - 120°)$$

and $$T_{ec} = KI_m \sin^2(\theta - 240°)$$

8. Resultant torque,

$$T_{eR} = T_{ea} + T_{eb} + T_{ec}$$

$$= KI_m [\sin^2\theta + \sin^2(\theta - 120°) + \sin^2(\theta - 240°)]$$

$$= KI_m \left[\frac{1-\cos 2\theta}{2} + \frac{1-\cos 2(\theta - 120°)}{2} + \frac{1-\cos 2(\theta-240°)}{2}\right]$$

$$= \frac{3}{2} KI_m \quad ...(5.20.3)$$

9. Eq. 5.20.3 shows that the shaft torque is independent of rotor position θ and has linear relationship with current amplitude as in a conventional DC motor.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Explain why 1ϕ IM are not self starting ? What do you understand by 'forward field' and 'backward field' in conjunction with 1ϕ IM ?

Ans. Refer Q. 5.1, Unit-5.

Q. 2. Draw and explain the equivalent circuit diagram of 1ϕ IM for no-load and blocked-rotor tests.

Ans. Refer Q. 5.5, Unit-5.

Q. 3. What do you mean by "FORWARD" and "BACKWARD" fields in 1ϕ IMs ? Explain why in case of 1ϕ IMs, the flux is pulsating in nature ? Explain why, 1ϕ IMs are not self starting ? Enlist the methods of starting of 1ϕ IMs. Also, mention its domestic applications.

Ans. Refer Q. 5.9, Unit-5.

Q. 4. Discuss why single-phase induction motors do not develop a starting torque ? Explain with the help of Double Revolving Field Theory. Describe construction and working of a shaded pole motor.

Ans. Refer Q. 5.10, Unit-5.

Q. 5. Discuss different methods of starting of single phase induction motor.

Ans. Refer Q. 5.12, Unit-5.

Q. 6. Explain the operation of stepper motor and state some important applications of stepper motor.

Ans. Refer Q. 5.14, Unit-5.

Q. 7. Explain starting methods of 1ϕ induction motor. What is repulsion motor ?

Ans. Refer Q. 5.18, Unit-5.

Q. 8. Explain construction and working principle of brushless DC motors.

Ans. Refer Q. 5.20, Unit-5.

☺☺☺

1 UNIT Synchronous Machine-I (2 Marks Questions)

1.1. What are the applications of synchronous machine ?

Ans.
1. For generation of 3ϕ power.
2. For improving power factor.
3. In large low head pumps, reciprocating pumps, compressors, rolling mills, ball mills, crushers and bulb grinders etc.

1.2. What is the formula of synchronous speed ?

Ans.

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

where, f = Supply frequency
P = Number of poles
N_s = Synchronous speed.

1.3. What do you understand by excitation emf ?

Ans. It is the emf induced in the armature winding due to field current (I_f) only.

1.4. What are the advantages of armature winding ?

Ans.
1. The harmonic emfs are reduced.
2. Distorting harmonics is eliminated.
3. It diminishes armature reaction and armature reactance.
4. The core is better utilized.

1.5. What are the characteristics of an infinite bus ?

Ans.
1. Terminal voltage is constant.
2. Frequency is constant.
3. Synchronous impedance is very small.

1.6. What are the reasons that alternators are operated in parallel ?

Ans.
1. Several alternators can supply a bigger load than a single alternator.
2. During periods of light load, one or more alternators may be shutdown, and those remaining operate at or near full load, and thus more efficiently.
3. When one machine is taken out, the remaining machines maintain the continuity of supply.

1.7. What are the methods of determination of voltage regulation ?

Ans.
1. Direct load test
2. Indirect methods
   i. Synchronous impedance method or EMF method
   ii. Ampere-turn method or MMF method
   iii. Zero power factor method or Potier's method.

1.8. What do you understand by armature reaction ?

Ans. The effect of armature (stator) flux on the flux produced by the rotor field poles is called armature reaction.

1.9. What do you mean by positive and negative voltage regulation of a synchronous alternator ?

AKTU 2015-16, Marks 02

Ans. Positive voltage regulation means synchronous generator is operating at lagging power factor. Negative voltage regulation means synchronous generator is operating at leading power factor.

1.10. What are the importances of armature reaction in three phase synchronous machine ? **AKTU 2015-16, Marks 02**

Ans. In synchronous generator, armature reaction weakens the main field flux with lagging power factor load while enhances the main field flux with leading power factor load.

1.11. What are the advantages of having field winding on the rotor and armature winding on the stator in case of synchronous machines ? **AKTU 2016-17, Marks 02**

Ans.
1. At high voltage, it is easier to insulate stationary armature winding.
2. Stationary armature can be cooled efficiently.

1.12. What do you mean by synchronous reactance ?

AKTU 2016-17, Marks 02

Ans. Synchronous reactance (X_s) is the ratio of induced emf and the steady state rms current. It is the sum of the armature reactance (X_{al}) and the magnetizing reactance (X_{ar}).
Mathematical expression is,
Synchronous reactance, $X_s = X_{al} + X_{ar}$.

1.13. Define "distribution factor" and "pitch factor".

AKTU 2016-17, Marks 02

Ans. **Coil span factor (or pitch factor) :** Coil span factor (K_c) is the ratio of vector sum of emfs to the arithmetical sum of emf induced in coil sides.

$$\therefore \quad K_c = \frac{\text{Vector sum of the induced emf/coil}}{\text{Arithmetic sum of induced emf/coil}}$$

$$= \frac{2\,E_S \cos\frac{\alpha}{2}}{2\,E_S} = \cos \alpha/2$$

where α is the angle by which the coil pitch falls short.

Distribution factor (or breadth factor, K_d) : It is ratio of vector sum of the emfs in the individual coil to the arithmetical sum if the coils would be one slot only.

$$\therefore \quad K_d = \frac{\text{Vector sum of emfs in individual coil}}{\text{Arithmetical sum of emfs if coils would be in one slots only}}$$

1.14. A 2 MVA, 3ϕ, 8-pole alternator is connected to 6000 V, 50 Hz bus-bars and has a synchronous reactance of 4 Ω per phase. Calculate the synchronizing power per mechanical degree of rotor displacement at no load. Assume normal excitation.

Ans.

Given : $P = 8$, $V_L = 6000$ V, $f = 50$ Hz, $X_s = 4\ \Omega$ per phase
To Find : Synchronizing power.

$p = P/2 = 4$, At no load, $\delta = 0$;

$E_f = V_P$

$$V_P = \frac{6000}{\sqrt{3}},\ E_f = \frac{6000}{\sqrt{3}}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

$$P_{sy} = \left(\frac{3V_P E_f}{X_s}\cos\delta\right)\frac{p\pi}{180} = \frac{3}{4} \times \frac{6000}{\sqrt{3}} \times \frac{6000}{\sqrt{3}} \times 1 \times \frac{4\pi}{180}$$

$= 628.318$ kW/mech degree

1.15. Synchronizing power and synchronous speed of a machine are 628.318 kW/mech degree and 750 rpm. Calculate the synchronizing torque per mechanical degree of rotor displacement at no load.

Ans.

Given : P_{sys} = 628.318 kW/mech degree, N_s = 750 rpm
To Find : τ_{sys}.

$$\tau_{sys} = \frac{P_{sys}}{2\pi n_s}$$

$$= \frac{628318}{2\pi \times \frac{750}{60}} = 8000 \text{ N-m}$$

☺☺☺

2 UNIT

Synchronous Machine-II (2 Marks Questions)

2.1. What do you understand by two reaction theory ?

Ans. The theory which gives method of analysis of the disturbing effects caused by salient pole construction is called two reaction theory. This theory proposes to resolve the given armature mmf into two mutually perpendicular components, direct axis (d-axis) and quadrature axis (q-axis).

2.2. Discuss the main characteristics of the 3ϕ synchronous motor.

Ans.

1. Synchronous motor operates only at synchronous speed $\left[N_s = \frac{120f}{P}\right]$.
2. On no-load, synchronous motor draws very little current from the supply mains to meet the internal losses.
3. If field excitation is small, the stator inductance will be more, so the motor draws lagging current and therefore power factor is low.
4. If the excitation is increased, the stator flux is neutralized by the rotor flux and therefore power factor becomes unity.

2.3. Write the demerits of 3ϕ synchronous motor.

Ans.

1. The cost per kW output is generally high.
2. It requires DC excitation which must be supplied from external source.
3. It cannot be used for variable speed jobs as there is no possibility of speed adjustment.
4. When overloaded it may fall out of synchronism and stop.

2.4. Write the main applications of the three-phase synchronous motor. **AKTU 2015-16, Marks 02**

Ans.

1. Used to regulate the voltage at the end of transmission lines.

2. Employed for the loads where constant speed is required.

2.5. What do you understand by locked rotor torque ?

Ans. It is the minimum torque at any angular rotor position that is developed with the rotor locked and rated voltage at rated frequency is applied to the terminals. This torque is provided by the stator windings.

2.6. What is running torque ?

Ans. It is the torque developed by the motor under running conditions. It is determined by the power rating and speed of the driven machine.

2.7. What do you mean by pull in torque ?

Ans. The pull in torque is the maximum constant torque at rated voltage and frequency under which a motor will pull a connected load into synchronism when the DC motor excitation is applied.

2.8. Define pull out torque.

Ans. It is the maximum value of torque which a synchronous motor can develop at rated voltage and frequency without losing synchronism.

2.9. What happens when the load on a synchronous motor is increased ?

Ans.

1. The torque angle δ increases.
2. The armature current I_a drawn from the supply increases.
3. The phase angle ϕ increases in the lagging direction.

2.10. Draw the V-curve and inverted V-curve of a synchronous motor.

AKTU 2015-16, Marks 02

Ans.

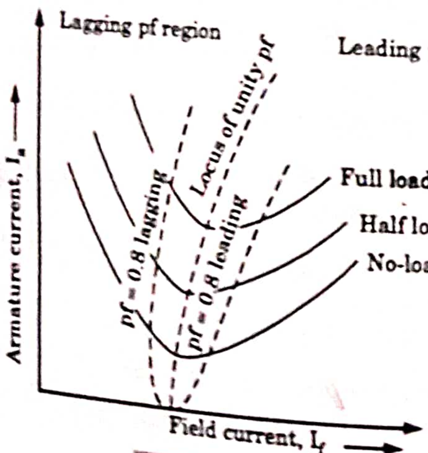


Fig. 2.10.1. V-curve.

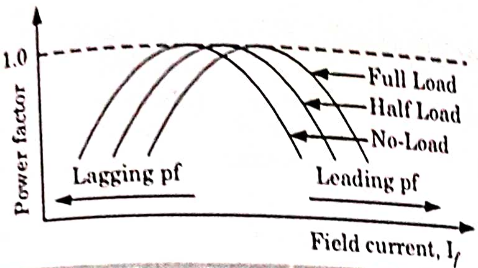


Fig. 2.10.2. Power factor versus field current at different loads (Inverted V-curve).

2.11. What are the causes of hunting ?

Ans.

1. Sudden changes of load.
2. Faults occurring in the system which the generator supplies.
3. Sudden changes in the field current.
4. Cyclic variation of the load torque.

2.12. What are the effects of hunting ?

Ans.

1. It can lead to loss of synchronism.
2. It can cause variations of the supply voltage producing undesirable lamp flicker.
3. It increases the possibility of resonance.
4. Large mechanical stresses may develop in the rotor shaft.
5. The machine losses increase and the temperature of the machine rises.

2.13. What are the techniques used in reduction of hunting ?

Ans.

1. By using damper windings.
2. By using flywheels.
3. By designing synchronous machines with suitable synchronizing power coefficients.

2.14. Write any two main comparisons of 3ϕ synchronous motor and induction motor.

Ans.

S. No.	Synchronous motor	Induction motor
1.	A synchronous motor is a doubly excited machine. Its armature winding is energized from a DC source.	An induction motor is a singly excited machine. Its stator winding is energized from an AC source.
2.	It is not self-starting. It has to be run upto synchronous speed by some means before it can become synchronized to AC supply.	An induction motor has got self starting torque.

2.15. What is damper windings ?

Ans. In the pole faces of salient rotor, small holes are provided and copper bars are inserted in the slots. The ends of all the bars are short circuited by copper rings to make closed circuit. This winding is called as damper winding.

2.16. Explain the basic role of damper winding in synchronous machines.

AKTU 2015-16, Marks 02

Ans.
1. It opposes hunting and tries to settle down rotor quickly to equilibrium position.
2. At starting, the synchronous motor can be started as an induction motor due to damper winding.

2.17. What do you understand by term mechanical vibration in a synchronous machine ?

AKTU 2015-16, Marks 02

Ans. Mechanical vibration is the movement of a synchronous machine or machine part back and forth from its position of rest. It is the response of a system to some internal or external force applied to the system.

2.18. Why is synchronous motor not self-starting ?

AKTU 2016-17, Marks 02

Ans. The speed with which rotating magnetic field is rotating, is so high that it is unable to rotate the rotor from its initial position, due to the inertia of rotor. So under any case, whatever may be the starting position of rotor, synchronous motor is not self starting.

☺☺☺

3 UNIT

Three Phase Induction Machine-I (2 Marks Questions)

3.1. Write the types of 3ϕ induction motors.

Ans.
1. Squirrel-cage induction motor.
2. Wound-rotor or slip-ring induction motor.

3.2. What are the advantages of cage rotor and wound rotor ?

Ans. **Advantages of the cage rotor :**
1. Lesser maintenance and cheaper
2. Higher power factor
3. Reduced risk of sparking because of absence of brushes.

Advantages of wound rotor :
1. High starting torque and low starting current
2. Speed control is easy due to addition of external resistance.

3.3. Why external resistors are provided in rotor circuit ?

Ans.
1. To increase the starting torque and decrease the starting current.
2. To control the speed of the rotor.

3.4. Draw the equivalent circuit of induction motor.

Ans.

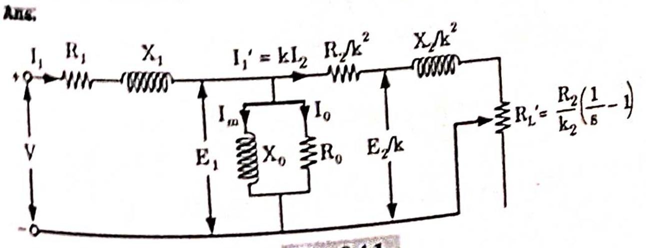


Fig. 3.4.1.

3.5. Draw torque-slip characteristics of 3ϕ induction motor.

Ans.

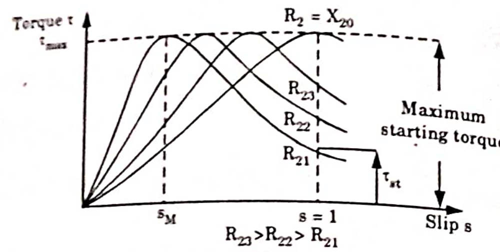


Fig. 3.5.1.

3.6. What do you understand by induction generator ?

Ans. An induction generator is a type of alternating current electrical generator that uses the principles of electromagnetic induction to produce power. When induction machine is driven above synchronous speed, then it is said induction generator (Asynchronous generator).

3.7. What are the applications of induction generator ?

Ans.

1. In hydro-ohmic power stations having a variable low head water supply.
2. For installation in small power station.
3. For braking purpose in railway work.

3.8. Draw torque-slip characteristics curve of an induction machine.

Ans.

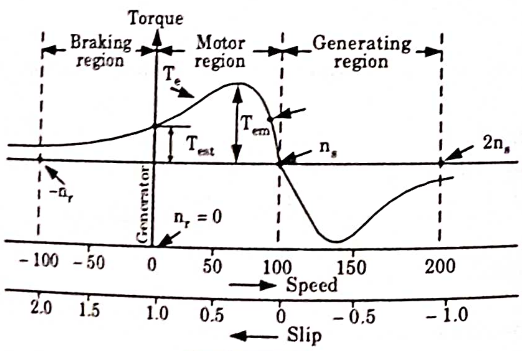


Fig. 3.8.1.

3.9. Draw the power flow diagram for three-phase induction motor. **AKTU 2016-17, Marks 02**

Ans.

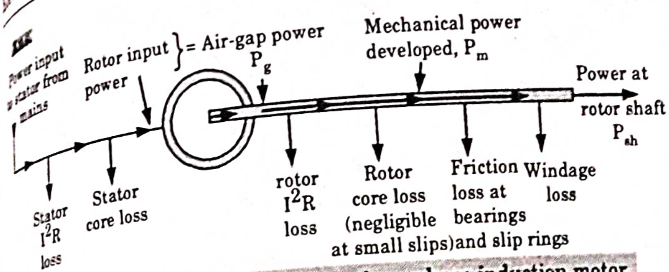


Fig. 3.9.1. Power flow diagram for a three phase induction motor.

3.10. Explain the principle of operation of a three-phase induction motor. **AKTU 2015-16, Marks 02**

Ans. It works on the principle of electromagnetic induction. It states that an emf is induced in a coil when the magnetic flux linking the same coil changes with time. It is denoted as

$$e = \frac{Nd\phi}{dt}$$

where,
e = Emf induced
N = Number of turns
ϕ = Flux linkage
t = Time.

3.11. What is the condition for producing maximum torque in three-phase induction motor ?

Ans. The condition for producing maximum torque in three-phase induction motor is that its slip must be equal to the ratio of rotor resistance at standstill to the rotor reactance at standstill. Such a slip is denoted as s_m given by $\frac{R_2}{X_2}$.

3.12. What is the speed of rotor mmf with respect to its stator mmf of a 3-phase induction motor ?

Ans. The rotor is running at a speed N_r and rotor field at $(N_s - N_r)$ with respect to stator in the same direction hence the net speed of the rotor field with respect to stator is $N_r + (N_s - N_r) = N_s$ which is same as the speed of stator field. Hence the speed of rotor mmf with respect to stator mmf is zero.

3.13. Differentiate between squirrel-cage rotor and wound rotor type induction motors. **AKTU 2016-17, Marks 02**

Ans.

S. No.	Squirrel-cage rotor	Wound or slip ring rotor
1.	Construction is very simple.	Construction is complicated.
2.	As permanently shorted, external resistance cannot be added.	Resistance can be added externally.
3.	Slip rings and brushes are absent.	Slip rings and brushes are present to add external resistance.

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4 UNIT

Three Phase Induction Machine-II (2 Marks Questions)

4.1. Why starter is necessary for starting an induction motor ?

AKTU 2016-17, Marks 02

Ans. A starter is needed for a three-phase induction motor because at the time of starting, it draws large amount of current which causes damage to adjoining equipments. Thus a starter is needed in order to limit starting current.

4.2. What are the types of starter used in starting of 3ϕ induction motor ?

Ans.

1. Direct on-line starter
2. Star-delta starter
3. Auto-transformer starter.

4.3. What are the functions of starter ?

Ans.

1. To reduce the heavy starting current.
2. To provide overload and under-voltage protection.

4.4. What are the merits of inner and outer cage of double-cage induction motor ?

Ans. **Merits of inner cage :**

1. The leakage reactance is high.
2. The resistance is small.

Merits of outer cage :

1. It provides high starting torque.
2. Its resistance is large enough to limit starting current and improve power pf.

4.5. Draw torque-speed characteristics of deep-bar cage motors.

Ans.

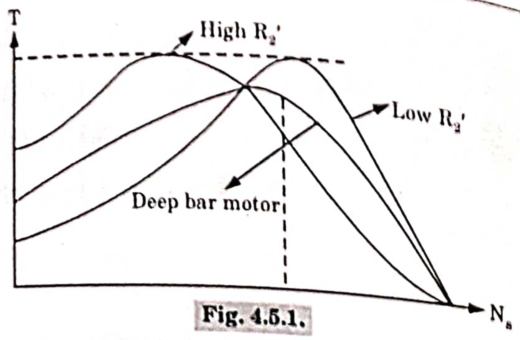

Fig. 4.5.1.

4.6. Sketch torque-speed characteristics of a double-cage induction motor.

Ans.

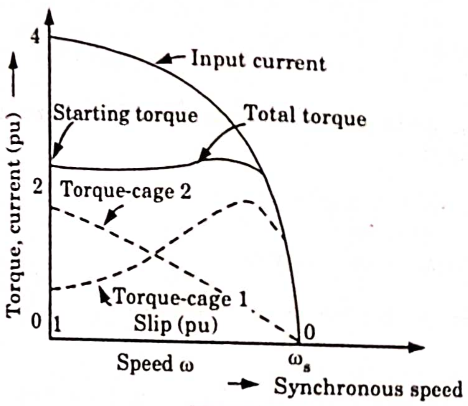

Fig. 4.6.1.

4.7. State the terms cogging and crawling in three-phase induction motor. **AKTU 2015-16, Marks 02**

OR

Define "cogging" phenomenon in induction motor.

AKTU 2016-17, Marks 02

Ans. **Cogging :** The phenomenon of magnetic locking between stator and rotor teeth is called cogging or teeth locking.

Crawling : The tendency of the motor to run at a stable speed as low as one-seventh of the normal speed N_s and being unable to pick up its normal speed is known as crawling of motor.

4.8. What are the different methods of speed control of induction motors ?

Ans.
1. Pole changing
2. Stator voltage control
3. Supply frequency control
4. Rotor resistance control
5. Slip energy recovery.

4.9. What are the disadvantages of the rotor resistance control method ?

Ans.
1. Efficiency is low due to additional losses in resistors connected in the rotor circuit.
2. Efficiency is reduced at low speed because of higher slips.

4.10. Give various applications of three-phase induction motors.

AKTU 2015-16, Marks 02

Ans.
1. For loads requiring high starting torque and where a lower starting current is required.
2. Used in conveyors, cranes, pumps, elevators and compressors.

4.11. Why does a 3ϕ induction motor always run at less than the synchronous speed ? **AKTU 2016-17, Marks 02**

Ans. If rotor is assumed to run at synchronous speed N_s in the direction of rotating field, then there would be no flux-cutting action, no emf in rotor conductors, no current in rotor bars and therefore no developed torque. Thus, the rotor of 3ϕ induction motor can never attain synchronous speed.

4.12. Write down the advantages of double-cage rotor induction motor over single squirrel-cage motor.

Ans.
1. High starting torque
2. Excellent running performance
3. Low starting current
4. With the proper choice of inner and outer cage parameters, wide range of torque-slip characteristics can be obtained.

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5 UNIT

Single Phase Induction Motor (2 Marks Questions)

5.1. Why 1ϕ induction motor is not self starting ?

Ans. When a single phase supply is connected to the stator winding, a pulsating magnetic field is produced. Pulsating magnetic field resolve in two rotating magnetic field, each of equal magnitude but rotating in opposite direction. Consequently the two torques are equal and opposite. Hence, at standstill, the net torque is zero. Therefore, a single phase induction motor is not self starting.

5.2. What do you understand by double-revolving field theory ?

Ans. The double-revolving field theory of single phase induction motors states that a stationary pulsating magnetic field can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions.

5.3. Write the forward field and backward field equation.

Ans. $b(\alpha) = \frac{1}{2}\beta_{max} \sin(\omega t - \alpha) + \frac{1}{2}\beta_{max} \sin(\omega t + \alpha)$

Forward Field : $\frac{1}{2}\beta_{max} \sin(\omega t - \alpha)$

Backward Field : $\frac{1}{2}\beta_{max} \sin(\omega t + \alpha)$.

5.4. What do you mean by forward slip in single phase induction motor ?

Ans. Slip, $s = \frac{n_s - n_r}{n_s}$

where, n_s = Stator speed

n_r = Rotor speed

Therefore, the direction in which the rotor is started initially will be called the forward field.

$$s_f = \frac{n_s - n_r}{n_s} = 1 - \frac{n_r}{n_s}$$

5.5. What is the relation between forward and backward slip ?

Ans.
$$s_f = \frac{n_s - n_r}{n_s} \quad ...(5.5.1)$$

$$s_b = \frac{n_s + n}{n_s} \quad ...(5.5.2)$$

Adding eq. (5.5.1) and (5.5.2),

$$s_f + s_b = \left(1 - \frac{n_r}{n_s}\right) + \left(1 + \frac{n_r}{n_s}\right)$$

$$s_f + s_b = 2$$

$$s_b = 2 - s_f.$$

5.6. Explain the equivalent circuit of a single-phase induction motor. **AKTU 2015-16, Marks 02**

Ans. Single-phase induction motor is considered as consisting of two motors having a common stator winding and two imaginary rotors which rotate in opposite direction. Equivalent circuit of single phase induction motor consists of :

Stator impedance is $(R_1 + jX_1)$.

At standstill the impedance of each rotor referred to main stator winding is $(R_2'/2 + j X_2'/2)$.

At running condition,

Effective rotor resistance in portion of circuit associated with forward rotating flux is $R_2'/2s$. The effective rotor resistance in the portion of circuit associated with the backward rotating flux is $R_2'/2(2 - s)$.

5.7. Draw torque-speed characteristics of 1ϕ induction motor.

Ans.

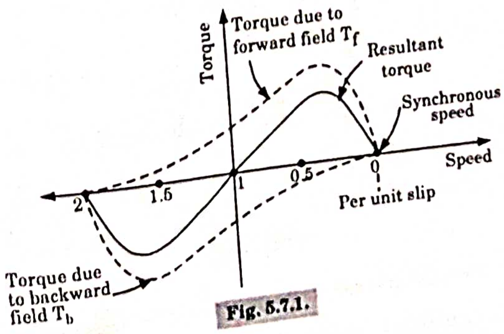

Fig. 5.7.1.

5.8. What are the starting methods of 1ϕ induction motor ?
OR
What are the types of 1ϕ induction motor ?

Ans.
1. Split-phase motor
2. Capacitor-start motor
3. Capacitor-start capacitor-run motor
4. Permanent split capacitor motor
5. Shaded-pole motor.

5.9. Sketch torque-speed characteristics of split-phase motor.

Ans.

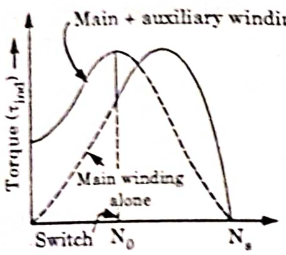

Fig. 5.9.1.

5.10. Draw torque-speed characteristic of capacitor-start motor.

Ans.

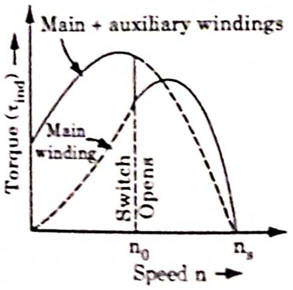

Fig. 5.10.1.

5.11. What are the applications of capacitor-start motors ?

Ans.
1. In pumps and compressors, and refrigerators and air conditioner compressors.
2. They are also used for conveyors and some machine tools.

5.12. What are the applications of two-value capacitor motor or capacitor-start capacitor-run motors ?

Ans.
1. Used for loads of higher inertia requiring frequent starts where the maximum pull out torque and efficiency required are higher.
2. They are used in pumping equipment, refrigeration, air compressors etc.

5.13. Write the applications of permanent-split capacitor motors.

Ans.
1. Used for fans and blowers in heaters and air conditioners
2. To drive refrigerator compressors.
3. They are also used to drive office machinery.

5.14. What do you understand by shaded-pole motor ?

Ans. A shaded pole motor is a single phase induction motor provided with an auxiliary short circuited winding or winding displaced in magnetic position from the main winding.

5.15. What are the applications of universal motor ?

Ans.
1. Potable drills
2. Hair dryers
3. Grinders
4. Table fans.

5.16. What are the applications of stepper motor ?

Ans. Stepper motor is used as paper feed motor in typewrites and printers positioning of print heads, pen in X-Y plotters, recording heads in computer disk drives and in positioning of work table and tools in numerically controlled machine equipment.

5.17. Calculate the stepping angle for a three-phase, 24-pole permanent magnet stepper motor.

AKTU 2016-17, Marks 02

Ans.
$$\alpha = \frac{360°}{m_s P_r} = \frac{360}{3 \times 24} = 5°$$

5.18. Explain brushless DC motor.

Ans. A brushless DC motor is a polyphase synchronous motor with a permanent magnet rotor. This motor cannot operate without its electronic controller. Therefore a brushless DC motor is a motor drive system that combines into one unit an AC motor, solid state inverter and a rotor position sensor.

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