

Code: 23EE3402

**II B.Tech - II Semester – Regular / Supplementary Examinations
APRIL 2026**

**INDUCTION AND SYNCHRONOUS MACHINES
(ELECTRICAL & ELECTRONICS ENGINEERING)**

Duration: 3 hours

Max. Marks: 70

Note: 1. This question paper contains two Parts A and B.

2. Part-A contains 10 short answer questions. Each Question carries 2 Marks.

3. Part-B contains 5 essay questions with an internal choice from each unit. Each Question carries 10 marks.

4. All parts of Question paper must be answered in one place.

BL – Blooms Level

CO – Course Outcome

PART – A

		BL	CO
1.a)	Define slip in a 3-phase induction motor.	L1	CO1
1.b)	Distinguish between squirrel cage and slip ring induction motors (any two points).	L2	CO1
1.c)	Explain what is meant by V/f control of induction motor.	L4	CO4
1.d)	Define slip at which maximum torque occurs.	L2	CO2
1.e)	Define single-phase induction motor.	L1	CO1
1.f)	Explain why an auxiliary winding is required for the operation of a single phase induction motor.	L2	CO2
1.g)	Define distribution factor.	L1	CO3
1.h)	State the conditions for synchronization of alternators.	L2	CO5
1.i)	State the principle of operation of a synchronous motor.	L2	CO1
1.j)	Why is a synchronous motor not self-starting?	L2	CO3

PART – B

			BL	CO	Max. Marks
UNIT-I					
2	a)	Explain the constructional features of squirrel cage and slip ring induction motors.	L2	CO1	5 M
	b)	Explain the working principle of 3-phase induction motor.	L2	CO1	5 M
OR					
3	a)	Derive the expression for synchronous speed and slip.	L3	CO2	5 M
	b)	Draw and explain the equivalent circuit of a 3-phase induction motor.	L3	CO2	5 M
UNIT-II					
4	a)	Explain the phenomena of crawling and cogging in induction motors.	L4	CO4	4 M
	b)	A 15kW, 400 V, 4-pole, 50Hz, 3-phase star connected induction motor gave the following test results. No Load Test: 400V, 9A, 1310W Blocked Rotor Test: 200V, 50A, 7100W Stator to rotor ohmic drops at standstill are assumed equal. Draw the circle diagram and evaluate i. Full load line current and slip. ii. Full load power factor and torque. iii. Efficiency at full load.	L4	CO4	6 M
OR					

5	a)	Name different methods of starting of 3-phase induction motors and explain any one method.	L4	CO4	5 M
	b)	Derive the condition for maximum torque and expression for starting torque.	L4	CO4	5 M
UNIT-III					
6	a)	Explain why a single-phase induction motor is not self-starting?	L2	CO2	2 M
	b)	Analyze any two starting methods used in single-phase induction motors.	L4	CO4	8 M
OR					
7	a)	Explain the construction and working of shaded pole motor.	L2	CO1	5 M
	b)	Explain double revolving field theory of single-phase induction motor.	L2	CO2	5 M
UNIT-IV					
8	a)	Explain the constructional features of salient pole and non-salient pole alternators.	L2	CO1	5 M
	b)	Derive the EMF equation of a synchronous generator.	L3	CO3	5 M
OR					
9	a)	Explain armature reaction in synchronous generators under different load power factors with phasor diagrams.	L4	CO3	5 M

	b)	Find the value of K_d for an alternator with 9 slots per pole for the following cases: i. One winding in all the slots. ii. One winding using only the first 2/3 of the slots per pole. iii. Three equal windings placed sequentially in 60° group.	L4	CO5	5 M
UNIT-V					
10	a)	Explain the construction and principle of operation of a synchronous motor.	L2	CO1	5 M
	b)	A 3- ϕ , 150 kW, 2300 V, 50 Hz, 1000 rpm salient-pole synchronous motor has $X_d=32 \Omega$ per phase and $X_q=20 \Omega$ per phase. Neglecting losses, calculate the torque developed by the motor if field excitation is so adjusted as to make the back e.m.f. twice the applied voltage and $\alpha=16^\circ$.	L4	CO5	5 M
OR					
11	a)	Explain the effect of load variation on power angle and stability of synchronous motor.	L4	CO5	5 M
	b)	Derive the expression for power developed in a synchronous motor.	L3	CO5	5 M

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Scheme of valuation

Scheme of valuation		
	PART-A	
1. a to j	Each Question carries 2 Marks	
	PART-B	
2. a)	Diagram of squirrel cage and slip ring induction motors. Explanation of constructional features	2 M 3 M
2. b)	Diagram of working principle of 3-phase induction motor Explanation of working principle of 3-phase induction motor.	2 M 3 M
3. a)	Deriving expression for synchronous speed Deriving expression for slip	3M 2 M
3. b)	Drawing equivalent circuit of a 3-phase induction motor Explanation of equivalent circuit of a 3-phase induction motor	2 M 3 M
4. a)	Explanation of phenomena of crawling in induction motors. Explanation of phenomena of cogging in induction motors	2 M 2 M
4. b)	Drawing circle diagram Calculation of i. Full load line current and slip. ii. Full load power factor and torque. iii. Efficiency at full load.	2 M 1M 2M 1M
5. a)	Name different methods of starting of 3-phase induction motors Explanation of any one method Diagram Explanation	1 M 2 M 2M
5. b)	Deriving the condition for maximum torque Expression for starting torque	4M 1M
6. a)	Explanation of why a single-phase induction motor is not self-starting	2M

6. b)	Explanation of any two starting methods used in single-phase induction motors Diagrams Explanation	4M 4M
7. a)	Diagrams of shaded pole motor. Explanation of working of shaded pole motor	2 M 3 M
7. b)	Explanation of double field revolving theory	5M
8. a)	Diagrams of salient pole and non-salient pole alternators Explanation of constructional features of salient pole and non-salient pole alternators	2 M 3 M
8. b)	Deriving expression for EMF equation of a synchronous generator	5M
9. a)	Armature reaction phasor diagrams Explanation of armature reaction under different load power factors	2 M 3 M
9. b)	Finding the value of K_d i. One winding in all the slots. ii. One winding using only the first 2/3 of the slots per pole. iii. Three equal windings placed sequentially in 60° group.	1M 2M 2M
10.a)	Diagram of Synchronous Motor Explanation of principle of operation of Synchronous Motor	2 M 3 M
10.b)	Calculation of total power developed Calculation of total torque developed	3M 2 M
11.a)	Explanation of the effect of load variation on power angle Explanation of the effect of load variation on stability of synchronous motor.	3 M 2 M
11.b)	Deriving expression for power developed in a synchronous motor	5M

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**INDUCTION AND SYNCHRONOUS MACHINES
(Electrical & Electronics Engineering)**

PART-A

Each Question carries 2 Marks

1.a) Define slip in a 3-phase induction motor.

The slip speed expressed as a fraction of the synchronous speed is called Slip.

$$\% \text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

1.b) Distinguish between squirrel cage and slip ring induction motors (any two points).

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

(Note : Any two points of the above table)

1.c) Explain what is meant by V/f control of induction motor.

V/f control is a speed control method where the supply voltage is varied in proportion to frequency so that the motor flux remains constant, enabling smooth speed control.

1.d) Define slip at which maximum torque occurs.

Torque developed in an induction motor will be maximum at a slip given by the ratio of rotor resistance to rotor standstill reactance.

i.e. $s = R_2/X_2$

1.e) Define single-phase induction motor.

A single-phase induction motor is an AC motor that operates on a single-phase power supply and works on the principle of electromagnetic induction.

1.f) Explain why an auxiliary winding is required for the operation of a single phase induction motor.

An auxiliary winding is required for the operation of a single-phase induction motor to produce rotating magnetic field and to develop torque at start.

1.g) Define distribution factor.

The distribution factor K_d is defined as:

$$K_d = \frac{\text{e. m. f. with distributed winding}}{\text{e. m. f. with concentrated winding}}$$

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

1.h) State the conditions for synchronization of alternators.

Terminal voltage, frequency and the phase sequence of the incoming machine must be the same as that of the bus bars.

1.i) State the principle of operation of a synchronous motor.

When a 3-phase AC supply is given to the stator, it produces a rotating magnetic field, which locks with the rotor magnetic field, causing the rotor to rotate at synchronous speed.

1.j) Why is a synchronous motor not self-starting?

A synchronous motor is not self-starting because at starting, the stator field rotates at synchronous speed, producing equal and opposite torques on the stationary rotor over a cycle, the rotor cannot lock with the rotating magnetic field resulting in zero net starting torque, so the motor cannot start by itself.

PART - B

UNIT-I

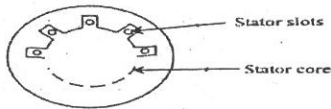
2 a) Explain the constructional features of squirrel cage and slip ring induction motors.

5 M

Construction of a 3-phase induction motor

- ✓ A 3-phase induction motor has two main parts (i) stator and (ii) rotor.

Stator:



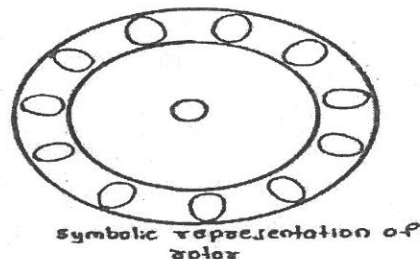
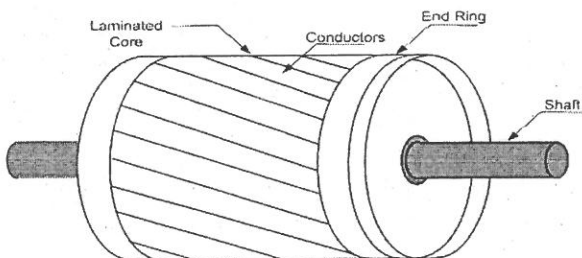
- ✓ It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses.
- ✓ A number of evenly spaced slots are provided on the inner periphery of the laminations
- ✓ The insulated conductors are placed in the stator slots and are suitably connected to form a balanced 3-phase star or delta connected circuit.
- ✓ When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced.
- ✓ This rotating field induces currents in the rotor by electromagnetic induction.

Rotor: -

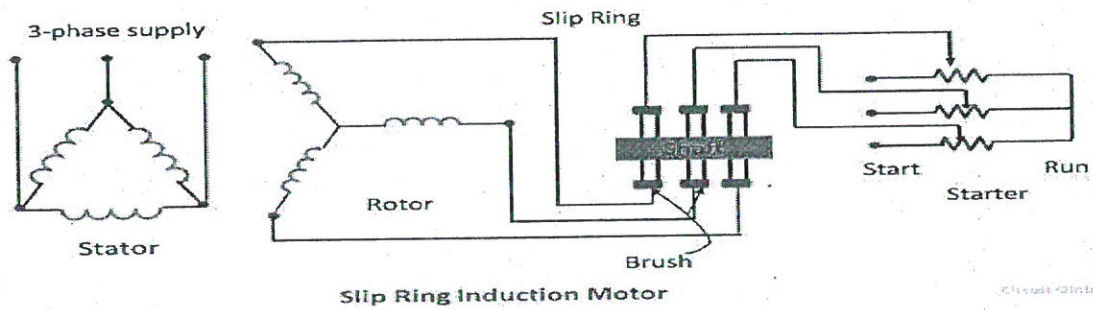
- ✓ Two types of rotors namely squirrel cage rotor and slip ring rotor or phase wound rotor can be used for the construction of 3-phase induction motor.
- ✓ Thus, due to the two different types of rotor, there are two types of 3-phase induction motor i.e, 1. squirrel cage induction motor 2. slipring induction motor

1. Squirrel cage Rotor:

- ✓ It is a laminated steel cylindrical core having slots on the outer periphery. one copper bar is placed in each slot. All these bars are short circuited at both ends by copper rings.
- ✓ The rotor slots are not quite parallel to the shaft but are purposely given a slight deviation known as Skewing.
- ✓ The figure shows the construction of squirrel cage rotor
- ✓ The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator.



(2) Slip ring rotor or phase wound rotor:



- ✓ It consists of a laminated cylindrical core and carries a 3- phase winding, similar to the stator winding. The rotor winding is uniformly distributed in the slots and is usually star-connected.
- ✓ The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring.
- ✓ The three brushes are connected to a 3-phase star-connected external resistance as shown in Fig.
- ✓ At starting, the external resistances are included in the rotor circuit to give a large starting torque.
- ✓ These resistances are gradually reduced to zero as the motor runs up to speed.

2 b) Explain the working principle of 3-phase induction motor.

5 M

Principle of Operation of a 3 phase induction motor:

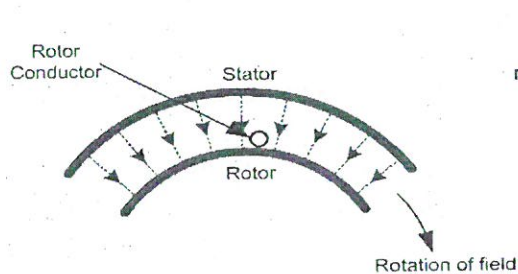


Fig: a

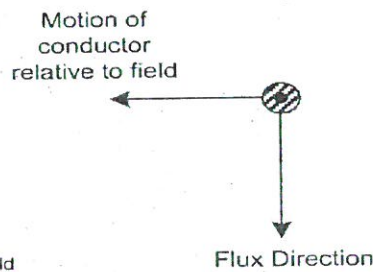


Fig: b

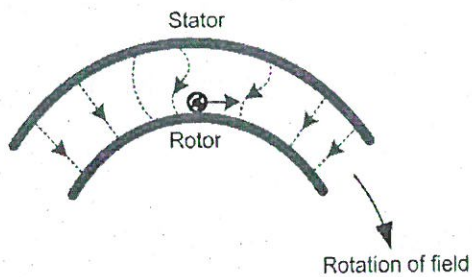


Fig: c

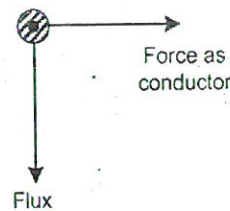


Fig: d

- For simplicity, let consider one conductor on the stationary rotor as shown in Figure (a). This conductor be subject to the rotating magnetic field produced when a three-phase supply is connected to the three phase winding of the stator.
- Let consider the rotation of the magnetic field be clockwise. A magnetic field moving clockwise has the same effect as a conductor moving anticlockwise in a stationary field. According to Faraday's law of electromagnetic induction, an emf will be induced in

the conductor. By completing the rotor circuit either using end rings or external resistances the induced emf causes current to flow in the conductor.

By using right hand rule, we can determine the direction of induced current in the conductor. Since the magnetic field is rotating clockwise and the conductor is stationary, we can assume that the conductor is in motion in the anticlock wise direction with respect to the magnetic field.

- By using right hand rule the direction of the induced current is outwards (shown as dot) in Figure (b). The current in the rotor conductor produces its own magnetic field as shown in Figure (c).
- We know that when a current carrying conductor is put in a magnetic field a force is produced on it. Thus, a force is produced on the rotor conductor. The direction of this force can be found by using left-hand rule as shown in Figure (d).
- It is seen that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field. The rotor conductor is in a slot on the circumference of the rotor, this force acts in a tangential direction to the rotor and develops a torque on the rotor.
- Similarly, torques are produced on all the rotor conductors. Since, the rotor is free to move then it starts rotating in the same direction as the rotating magnetic field. Thus, a three phase induction motor is self-starting motor.

3 a) Derive the expression for synchronous speed and slip.

5 M

For P poles, the rotating field makes one revolution in P/2 cycles of current.

$$\therefore \text{Cycles of current} = \frac{P}{2} \times \text{revolutions of field}$$

$$\text{or Cycles of current per second} = \frac{P}{2} \times \text{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

$$\therefore f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

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

If, N_s = Synchronous speed in r.p.m.
 N = Actual speed of rotor (or motor) in r.p.m.
 Slip speed = $N_s - N$

The slip speed expressed as a fraction of the synchronous speed is called **Slip**. It is denoted by S and it is usually expressed in percentage

$$\% \text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

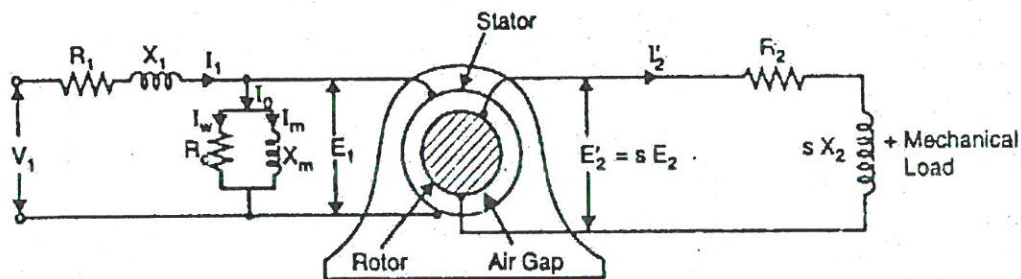
3 b) Draw and explain the equivalent circuit of a 3-phase induction motor. 5 M

Equivalent Circuit of 3-Phase Induction Motor

In a 3-phase induction motor, the stator winding is connected to 3-phase supply and the rotor winding is short-circuited.

- ✓ The energy is transferred magnetically from the stator winding to the short-circuited, rotor winding. Therefore, an induction motor may be considered to be a transformer with a rotating secondary (short-circuited).
- ✓ The stator winding corresponds to transformer primary and the rotor winding corresponds to transformer secondary.

- ✓ In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer. Fig. shows the equivalent circuit per phase for an induction motor.



Stator circuit.

- ✓ In the stator, the events are very similar to those in the transformer primary.
- ✓ The applied voltage per phase to the stator is V_1 , R_1 and X_1 are the stator resistance and leakage reactance per phase respectively. The applied voltage V_1 produces a magnetic flux which links the stator winding (i.e., primary) as well as the rotor winding (i.e., secondary).
- ✓ As a result, self-induced e.m.f. E_1 is induced in the stator winding and mutually induced e.m.f. $E'_2 (= s E_2 = s K E_1$ where K is transformation ratio) is induced in the rotor winding.
- ✓ The flow of stator current I_1 causes voltage drops in R_1 and X_1 .

$$V_1 = - E_1 + I_1(R_1 + j X_1) \quad \dots \text{phasor sum}$$

- ✓ When the motor is at no-load, the stator winding draws a current I_0 . It has two components viz., (i) Working component I_w which supplies the no-load motor losses and (ii) magnetizing component I_m which sets up magnetic flux in the core and the airgap.
- ✓ The parallel combination of R_c and X_m , therefore, represents the no-load motor losses and the production of magnetic flux respectively.

$$I_0 = I_w + I_m$$

Rotor circuit.

- ✓ Here R_2 and X_2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s , the rotor reactance will be $s X_2$.
- ✓ The induced voltage/phase in the rotor is $E'_2 = s E_2 = s K E_1$. Since the rotor winding is short-circuited, the whole of e.m.f. E'_2 is used up in circulating the rotor current I'_2 .
- ✓ The rotor current I'_2 is reflected as $I''_2 (= K I'_2)$ in the stator. The phasor sum of I''_2 and I_0 gives the stator current I_1 .

$$E'_2 = I'_2 (R_2 + j s X_2)$$

UNIT-II

4 a) Explain the phenomena of crawling and cogging in induction motors. 4 M

Crawling of Induction Motor: It has been found that induction motors, particularly the squirrel-cage type, the tendency of the motor to run at a stable speed as low as one-seventh of their synchronous speed N_s . This phenomenon is known as crawling of an induction motor.

- This action is due to the fact that the a.c. winding of the stator produces a flux wave, which is not a pure sine wave. It is a complex wave consisting of a fundamental wave, which revolves synchronously and odd harmonics like 3rd, 5th, and 7th etc, which rotate either in the forward or backward direction at $N_s/3$, $N_s/5$ and $N_s/7$ speeds respectively.
- As a result, in addition to the fundamental torque, harmonic torques are also developed,

whose synchronous speeds are $1/n$ th of the speed for the fundamental torque i.e. N_s/n , where n is the order of the harmonic torque. Since 3rd harmonic currents are absent in a balanced 3-phase system, they produce no rotating field and, therefore, no torque. Hence, total motor torque has three components: (i) the fundamental torque, rotating with the synchronous speed N_s (ii) 5th harmonic torque rotating at $N_s/5$ speed and (iii) 7th harmonic torque, having a speed of $N_s/7$.

The small amount of 5th harmonic reverse torque produces a braking action and may be neglected.

- The 7th harmonic currents in the three stator windings have a phase difference of $7 * 120^\circ = 2 * 360^\circ + 120^\circ = 120^\circ$. They set up a forward rotating field, with a synchronous speed equal to $1/7$ th of the synchronous speed of the fundamental torque.
- If we neglect all higher harmonics, the resultant torque can be taken as equal to the sum of the fundamental torque and the 7th harmonic torque, as shown in Fig. It is seen that the 7th harmonic torque reaches its maximum positive value just before $1/7$ th synchronous speed N_s , beyond which it becomes negative in value. Consequently, the resultant torque characteristic shows a dip which may become very pronounced with certain slot combinations.
- If the mechanical load on the shaft involves a constant load torque, it is possible that the torque developed by the motor may fall below this load torque.
- When this happens, the motor will not accelerate upto its normal speed but will remain running at a speed, which is nearly $1/7$ th of its full-speed. This is referred to as crawling of the motor.

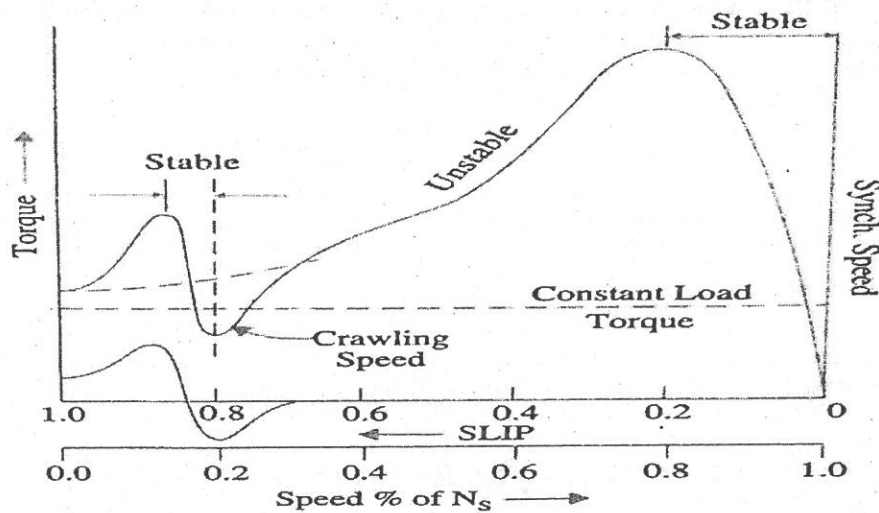


Figure. Torque-slip Characteristic of a 3-phase Induction motor showing the effect of harmonic torques

COGGING (OR) MAGNETIC LOCKING of Induction Motor:

- Sometimes, even when full voltage is applied to the stator winding, the rotor of a 3-phase cage induction motor fails to start. This happens when the number of stator and rotor slots are either equal or have an integral ratio. 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. These forces may create an alignment torque greater than the accelerating torque with consequent failure of the motor to start. This phenomenon of magnetic locking between stator and rotor teeth is called cogging.

- 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.
- In order to reduce or eliminate cogging the number of stator slots are never made equal to or have an integral ratio. Cogging can also be reduced by using skewed rotor.

b) A 15kW, 400 V, 4-pole, 50Hz, 3-phase star connected induction motor gave the following test results.

No Load Test: 400V, 9A, 1310W

Blocked Rotor Test: 200V, 50A, 7100W

Stator to rotor ohmic drops at standstill are assumed equal. Draw the circle diagram and evaluate

- Full load line current and slip.
- Full load power factor and torque.
- Efficiency at full load.

6 M

From No load test

$$I_0 = 9 \text{ A}, \quad W_0 = 1310 \text{ W}$$

$$\cos \phi_0 = \frac{W_0}{\sqrt{3} \cdot V_0 \cdot I_0} = \frac{1310}{\sqrt{3} \times 400 \times 9} = 0.21$$

$$\therefore \phi_0 = 77.87^\circ$$

From blocked rotor test,

$$I_{sc} = 50 \text{ A}, \quad W_{sc} = 7100 \text{ W}, \quad V_{sc} = 200 \text{ V}$$

$$\cos \phi_{sc} = \frac{W_{sc}}{\sqrt{3} \times V_{sc} \times I_{sc}} = \frac{7100}{\sqrt{3} \times 200 \times 50} = 0.4099$$

$$\phi_{sc} = 65.80^\circ$$

$$I_{SN} = I_{sc} \left(\frac{V_L}{V_{sc}} \right) = 50 \left(\frac{400}{200} \right) = 100 \text{ A}$$

$$W_{SN} = W_{sc} \left(\frac{I_{SN}}{I_{sc}} \right)^2 = 7100 \left(\frac{100}{50} \right)^2 = 28400 \text{ W}$$

$$\text{or } W_{SN} = \sqrt{3} \times V_{SN} \times I_{SN} \times \cos \phi_{sc} = \sqrt{3} \times 400 \times 100 \times 0.4099 = 28400 \text{ W.}$$

Choose the current scale to be 1 cm = 5 A.

1. Draw vector $OO' = I_0 = 9\text{A}$ i.e. 1.8 cm at $\phi_0 = 77.47^\circ$ from voltage axis.
2. Draw horizontal line from O' parallel to X-axis.
3. Draw vector $OA = I_{SN} = 100\text{A}$ i.e. 20 cm at $\phi_{sc} = 65.80^\circ$ from voltage axis.
4. Join $O'A$, this is output line.
5. Draw perpendicular bisector $O'A$ to meet horizontal line drawn from O' at C. This is the centre of the circle.
6. With C as centre and CO' as radius, draw a semicircle to meet horizontal line from O' at B.
7. Draw perpendicular from A on X-axis, meeting at point D.

$$l(AD) = 8.2 \text{ cm} = W_{SN}$$

$$\therefore \text{Power scale} = \frac{W_{SN}}{l(AD)} = \frac{28400}{8.2} = 3463.41 \text{ W/cm}$$

8. As the stator and rotor ohmic losses are equal, point E is mid-point of AF i.e. AE = AF.

Join O'E, this is the torque line.

9. To locate full load point, draw AA' such that

$$\begin{aligned} AA' &= 15 \text{ kW} = 15000 \text{ W} \\ &= \frac{15000}{3463.41} = 4.33 \text{ cm} \end{aligned}$$

10. Draw parallel to the output line from A' to meet circle at point P. This is the full load point.

11. Draw vertical line from P to intersect output line at Q, torque line at R, base line at S and X-axis at T.

So at full load,

(i)

$$\begin{aligned} \text{Line current} &= l(OP) \times \text{Current scale} \\ &= 6.9 \text{ cm} \times 5 = 34.5 \text{ A} \end{aligned}$$

$$\text{Slip} = \frac{QR}{PR} = \frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{0.4}{4.7} = 0.085 \text{ i.e. } 8.5 \%$$

(ii)

$$\begin{aligned} \text{p.f.} &= \cos(\text{angle made by OP w.r.t. voltage axis}) \\ &= \cos(33^\circ) = 0.8386 \text{ lag.} \end{aligned}$$

$$\text{Torque at full load} = PR$$

$$= 4.8 \times \text{Power scale} = 4.8 \times 3463.41$$

$$= 16624.36 \text{ syn-watts}$$

(iii)

$$\text{Efficiency, } \% \eta = \frac{\text{Output}}{\text{Input}} \times 100$$

$$= \frac{PQ}{PT} \times 100 = \frac{4.3}{5.8} \times 100 = 74.13$$

$$\text{Efficiency} = 74.13 \%$$

5 a) Name different methods of starting of 3-phase induction motors and explain any one method. 5 M

Methods of Starting 3-Phase Induction Motors:

- | | |
|-------------------------------|--------------------------------|
| (i) Direct-on-line Starter | (ii) Stator resistance Starter |
| (iii) Autotransformer Starter | (iv) Star-delta Starter |
| (v) Rotor resistance Starter | |

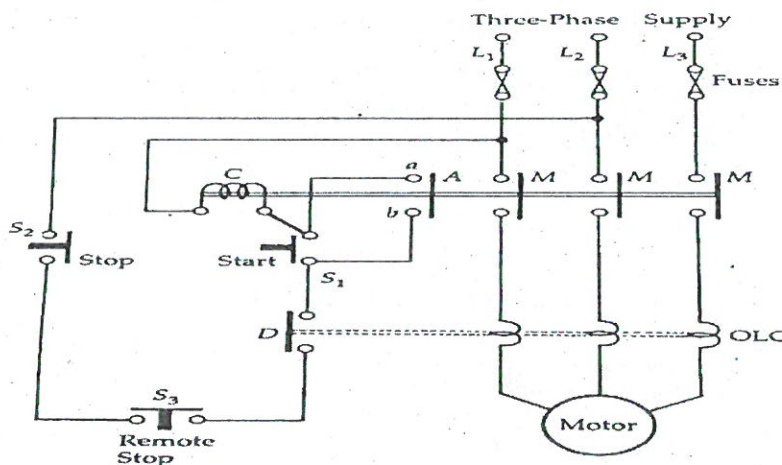
NOTE: Explanation of any one method.

Methods of Starting Squirrel-Cage Motors:

Direct On Line Starter (D.O.L.):

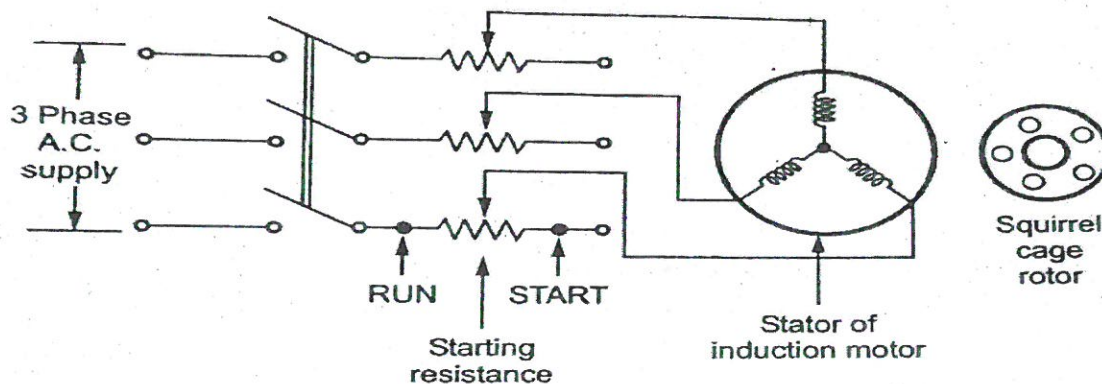
In the direct-on-line method of starting cage motors, the motor is connected by means of a starter across the full supply voltage. Figure shows the connections of the direct-on-line (D.O.L.) starter. It consists of a coil-operated contactor C controlled by start and stop push buttons which may be installed at convenient places remote from the starter. On pressing the START push button S_1 (which is normally held open by a spring) the contactor coil C is energised from two-line conductors L_1 and L_2 . The three main contacts M and the auxiliary contact A close and the terminals a and b are short-circuited. The motor is thus connected to the supply. When the pressure on S_1 is released, it moves back under spring action. Even then the coil C remains energised through ab. Thus, the main contacts M remain closed and the motor continues to get supply. For this reason, contact A is called hold-on-contact.

When the STOP push button S_2 (which is normally held closed by spring) 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.



Stator Resistance Starter

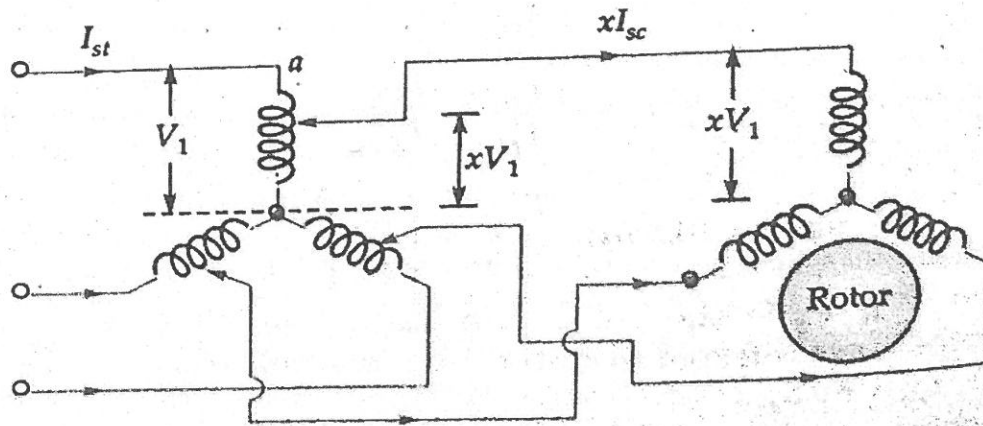
In order to apply the reduced voltage to the stator of the induction motor, three resistances are added in series with each phase of the stator winding. Initially the resistances are kept maximum in the circuit. Due to this large voltage gets dropped across the resistances. Hence a reduced voltage gets applied to the stator which reduces the high starting current. The schematic diagram showing stator resistances is shown in the Fig.



When the motor starts running, the resistances are gradually cut-off from the stator circuit. When the resistances are entirely removed from the stator circuit i.e. rheostats in RUN position then rated voltage gets applied to the stator. Motor runs with normal speed.

The starter is simple in construction and cheap. It can be used for both star and delta connected stator. But there are large power losses due to resistances. Also the starting torque of the motor reduces due to reduced voltage applied to the stator.

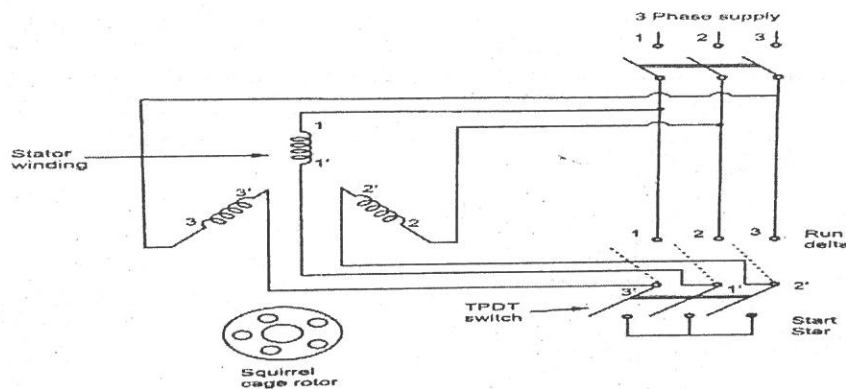
Autotransformer Starter:



In this method, the starting current is limited by using a 3 phase auto transformer to reduce the initial stator applied voltage.

A fraction xV_1 of the supplied voltage V_1 is applied to stator terminals at the time of starting. This reduces the motor current and also the current drawn from the supply. Then, the applied voltage to stator winding is gradually increased up to the rated voltage. Thus, the motor starts rotating with rated speed.

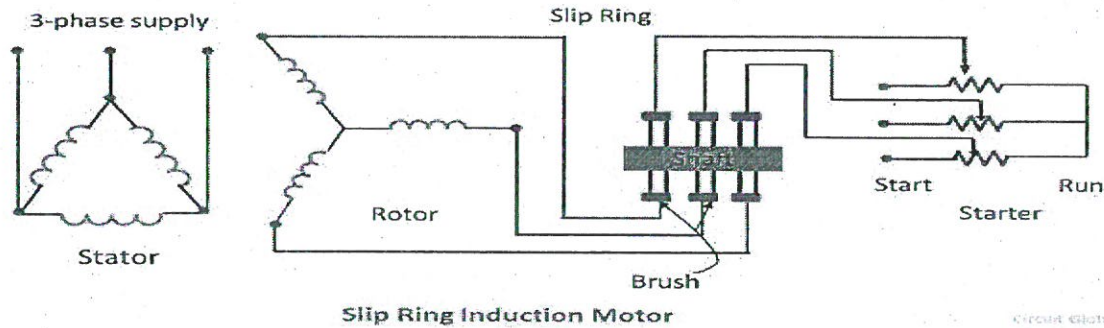
Star Delta Starter



Star-delta starter uses tripple pole double throw (TPDT) switch. The switch connects the stator winding in star at start. Hence per phase voltage gets reduced by the factor $1/\sqrt{3}$. Due to this reduced voltage, the starting current is limited. When the switch is thrown on other side, the winding gets connected in delta, across the supply. So it gets normal rated voltage. The windings are connected in delta when motor gathers sufficient speed. The arrangement of star-delta starter is shown in the Fig.

Rotor resistance Starter : To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor circuit at start.

This addition of the resistance in rotor is in the form of 3 phase star connected rheostat. The arrangement is shown in the Fig.



To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor circuit at start. This addition of the resistance in rotor is in the form of 3 phase star connected rheostat. The arrangement is shown in the Fig.

The external resistance is inserted in each phase of the rotor winding through slip ring and brush assembly. Initially maximum resistance is in the circuit. As motor gathers speed, the resistance is gradually cutoff. The operation may be manual or automatic.

The starting torque is proportional to the rotor resistance. Hence important advantage of this method is not only the starting current is limited but starting torque of the motor also gets improved. The only limitation of the starter is that it can be used only for slip ring induction motors as in squirrel cage motors, the rotor is permanently short circuited.

5 b) Derive the condition for maximum torque and expression for starting torque. 5 M
Maximum Torque Condition for Three Phase Induction Motor:

In the equation of torque,

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

For torque to be maximum, differentiate above equation w.r.t s and equate the results to zero.

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

$$\frac{d}{ds} \left[K \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \right] = 0$$

$$K \frac{d}{ds} \left[\frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \right] = 0$$

$$K \left[\frac{[R_2^2 + (s X_2)^2] (E_2^2 R_2) - (s E_2^2 R_2) (0 + 2s X_2 X_2)}{R_2^2 + (s X_2)^2} \right] = 0$$

$$\left\{ \text{since } \frac{d\left(\frac{U}{V}\right)}{ds} = \frac{V \frac{du}{ds} - U \frac{dv}{ds}}{V^2} \right\}$$

$$[R_2^2 + (s X_2)^2] (E_2^2 R_2) - (s E_2^2 R_2) (0 + 2s X_2 X_2) = 0$$

$$[R_2^2 + (s X_2)^2] E_2^2 R_2 = s E_2^2 R_2 (2s X_2^2)$$

$$R_2^2 + (s X_2)^2 = 2s^2 X_2^2$$

$$R_2^2 = 2(s X_2)^2 - (s X_2)^2$$

$$R_2^2 = (s X_2)^2$$

$$\boxed{R_2 = s X_2}$$

Starting torque is the torque produced by induction motor when it is started. We know that at start the rotor speed, N is zero.

$$\text{So, slip } s = \frac{N_s - N}{N_s} \text{ becomes 1.}$$

So, the equation of starting torque is easily obtained by simply putting the value of $s = 1$ in the equation of torque of the three-phase induction motor,

$$T_{st} = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

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

UNIT-III

6 a) Explain why a single-phase induction motor is not self-starting? 2 M

When a single-phase induction motor is connected to a single-phase supply, two fields of magnitude $\Phi_m / 2$ are developed. At start an equal in magnitude but **rotate opposite** in direction torques are set up by these two fields. Thus, net torque experienced by the rotor is zero at start. And hence the single-phase induction motor is not self starting.

6 b) Analyze any two starting methods used in single-phase induction motors. 8 M

Depending upon the methods of producing rotating stator magnetic flux, the single phase induction motors are classified as,

1. Split phase induction motor
2. Capacitor start induction motor
3. Capacitor start capacitor run induction motor
4. Shaded pole induction motor

NOTE: Explanation of any two method.

1. Split Phase Induction Motor:

This type of motor has single phase stator winding called main winding. In addition to this, stator carries one more winding called auxiliary winding or starting winding. The auxiliary winding carries a series resistance such that its impedance is highly resistive in nature. The main winding is inductive in nature.

Let I_m = Current through main winding and I_{st} = Current through auxiliary winding

As main winding is inductive, current I_m lags voltage V by a large angle Φ_m while I_{st} is almost in phase in V as auxiliary winding is highly resistive. Thus, there exists a phase difference of α

between the two currents and hence between the two fluxes produced by the two currents. This is shown in the Fig (a). The resultant of these two fluxes is a rotating magnetic field. Due to this, the starting torque, which acts only in one direction is produced.

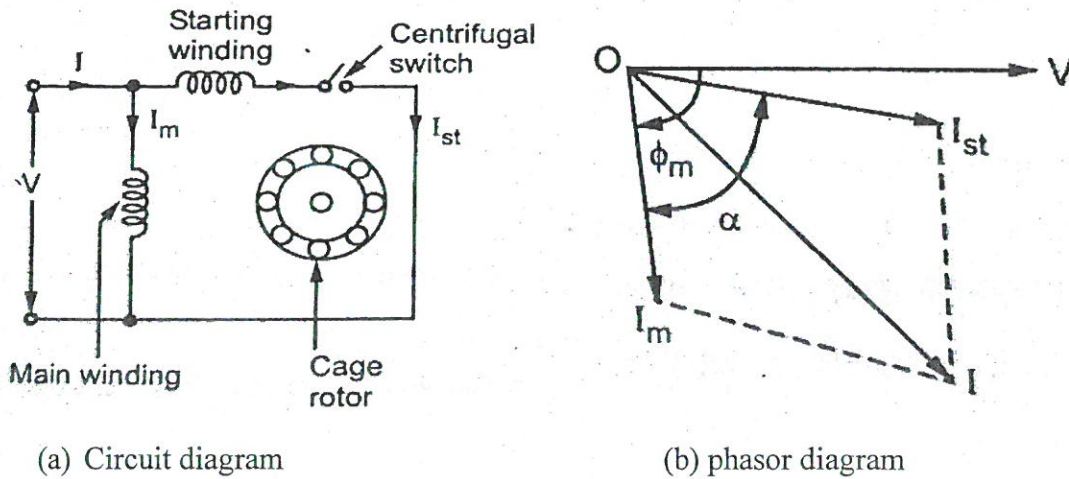


Fig. Split phase induction motor

The auxiliary winding has a centrifugal switch in series with it. When motor gathers a speed upto 75 % of the synchronous speed, centrifugal switch gets opened mechanically and in running condition auxiliary winding remains out of the circuit. So motor runs only on stator winding. So auxiliary winding is designed for short time use while the main winding is designed for continuous use. As the current I_m and I_{st} are splitted from each other by angle α at start the motor is commonly called split phase motor.

2.Capacitor Start Induction Motor and 3. Capacitor start capacitor run induction motor

The construction of this type of motor is similar to the resistance split phase type. The difference is that in series with the auxiliary winding the capacitor is connected. The capacitive circuit draws a leading current this feature used in this type to increase the split phase angle α between the two currents I_m and I_{st} .

Depending upon whether capacitor remains in the circuit permanently or is disconnected from the circuit using centrifugal switch these motors are classified as,

- a. Capacitor start motor and b. Capacitor start capacitor run motor

The construction of capacitor start motor is shown in the Fig. (1a). The current I_m lags the voltage by angle Φ_m while due to capacitor the current I_{st} leads the voltage by angle Φ_{st} . Hence there exists a large phase difference between the two currents which is almost 90° which is an ideal case. The phasor diagram is shown in the (1b)

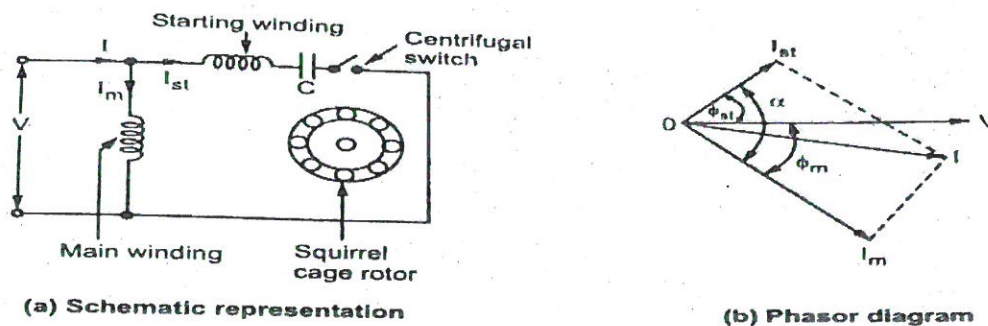


Fig: Capacitor Start Induction Motor

The starting torque is proportional to α and hence such motors produce very high starting torque. When speed approaches to 75 % of the synchronous speed, the starting winding gets disconnected due to operation of the centrifugal switch. The capacitor remains in the circuit only at start hence it is called capacitor start motors.

Key Point: In case of capacitor start capacitor run motor running capacitor remains permanently in the circuit. This improves the power factor.

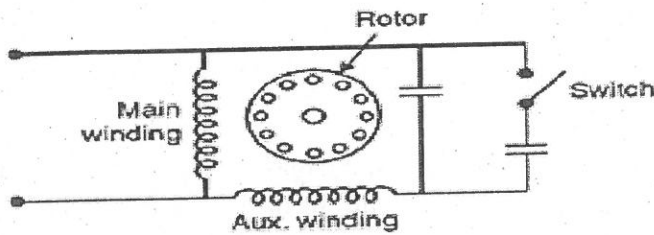


Fig. Capacitor start capacitor run motor

The phasor diagram remains same as shown in the Fig (b). The performance not only at start but in running condition also depends on the capacitor C hence its value is to be designed so as to compromise between best starting and best running condition.

4. Shaded Pole Induction Motor:

The production of rotating magnetic field can be explained as below:

The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in the Fig (a). The distribution of this flux in the pole area is greatly influenced by the role of copper shading band. Consider the three instants say t_1 , t_2 and t_3 during first half cycle of the flux as shown, in the Fig.(a).

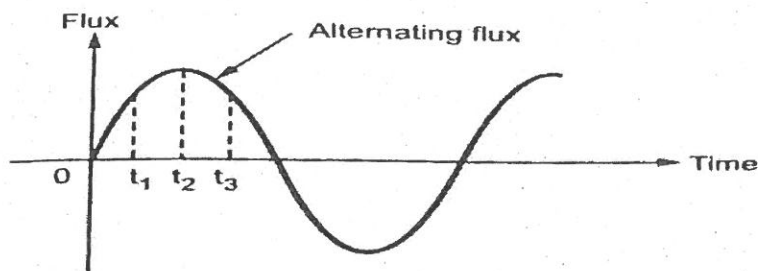


Fig. (a) Waveform of stator flux

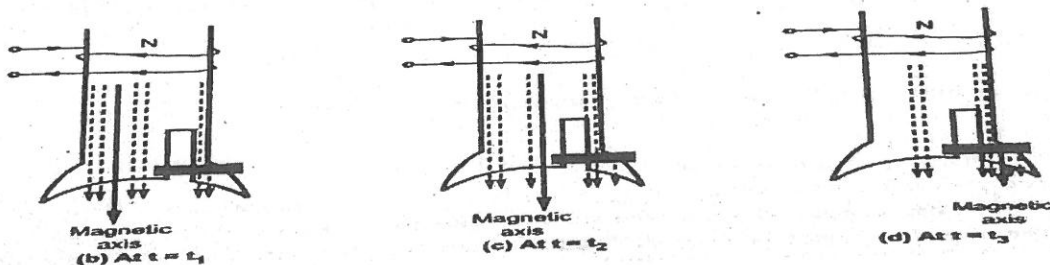


Fig. 1. Production of rotating magnetic field in shaded pole motor

At instant $t = t_1$, rate of rise of current and hence the flux is very high. Due to the transformer action, large e.m.f gets induced in the copper shading band. This circulates current through shading band as it is short circuited, producing its own flux. According to lenz's law, the direction of this current is so as to oppose the cause i.e. rise in current. Hence shading ring flux is opposing to the main flux. Hence there is crowding of flux in nonshaded part while weakening of flux in shaded part. Overall magnetic axis shifts in nonshaded part as shown in the Fig 1(b).

At instant $t = t_2$, rate of rise of current and hence the rate of change of flux is almost zero as flux almost reaches to its maximum value. So $d\Phi/dt = 0$. Hence there is very little induced emf in the shading ring. Hence the shading ring flux is also negligible, hardly affecting the distribution of the main flux. Hence the main flux distribution is uniform and magnetic axis lies at the centre of the pole face as shown in the Fig 1(c).

At instant $t = t_3$, the current and the flux is decreasing. The rate of decrease is high which again induces a very large e.m.f in the shading ring. This circulates current through the ring which produces its own flux. Now direction of the flux produced by the shaded ring current is so as to oppose the cause which is decrease in flux. So it oppose the decrease in flux means its direction is same as that of main flux, strengthening it. So there is crowding of flux in the shaded part as compared to nonshaded part. Due to this the magnetic axis shifts to the middle of the shaded part of the pole. This is shown in the Fig 1(d).

This sequence keeps on repeating for negative half cycle too. Consequently, this produces an effect of rotating magnetic field, the direction of which is from nonshaded part of the pole to the shaded part of the pole.

7 a) Explain the construction and working of shaded pole motor.

5 M

Shaded Pole Induction Motor: This type of motor consists of a squirrel cage rotor and stator consisting of salient poles i.e. projected poles. The poles are shaded i.e. each pole carries a copper band on one of its unequally divided part called **shading band**. Fig. shows 2 pole shaded pole Induction motor.

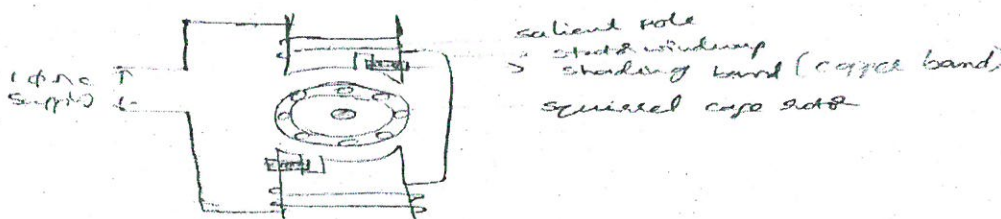


Fig (a) 2-pole shaded pole Induction Motor

Key Point: When single phase ac supply is given to the stator winding, due to shading provided to the poles, a rotating magnetic field is generated.

The production of rotating magnetic field can be explained as below:

The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in the Fig (a). The distribution of this flux in the pole area is greatly influenced by the role of copper shading band. Consider the three instants say t_1 , t_2 and t_3 during first half cycle of the flux as shown, in the Fig.(a).

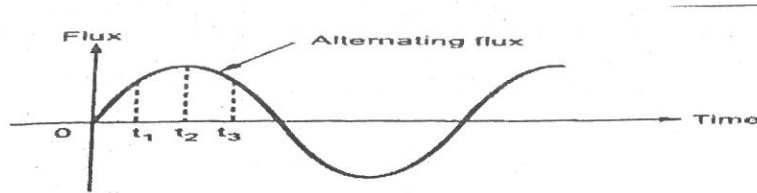


Fig. (a) Waveform of stator flux

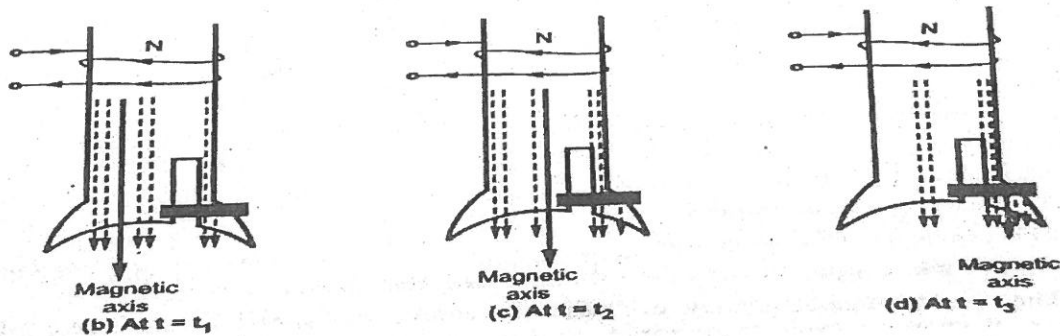


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This sequence keeps on repeating for negative half cycle too. Consequently, this produces an effect of rotating magnetic field, the direction of which is from nonshaded part of the pole to the shaded part of the pole.

7 b) Explain double revolving field theory of single-phase induction motor. 5 M

Double Revolving Field Theory:

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating quantity.

In case of single phase induction motors, the stator winding produces an alternating magnetic field having maximum magnitude of Φ_{1m} .

According to double revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e. $(\Phi_{1m} / 2)$. Both these components are rotating in opposite directions at the synchronous speed N_s which is dependent on frequency and stator poles.

Let Φ_f is forward component rotating in anticlockwise direction while Φ_b is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at that instant. So resultant of these two is the original stator flux.

The Fig. shows the stator flux and its two components Φ_f and Φ_b . At start both the components are shown opposite to each other in the Fig.(a). Thus, the resultant $\Phi_R = 0$. This is nothing but the instantaneous value of stator flux at start. After 90° , as shown in the Fig. (b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant Φ_R is the algebraic sum of the magnitudes of the two components.

So $\Phi_R = (\Phi_{1m} / 2) + (\Phi_{1m} / 2) = \Phi_{1m}$. This is nothing but the instantaneous value of the stator flux at $\theta = 90^\circ$ as shown in the Fig. (c). Thus, continuous rotation of the two components gives the original alternating stator flux.

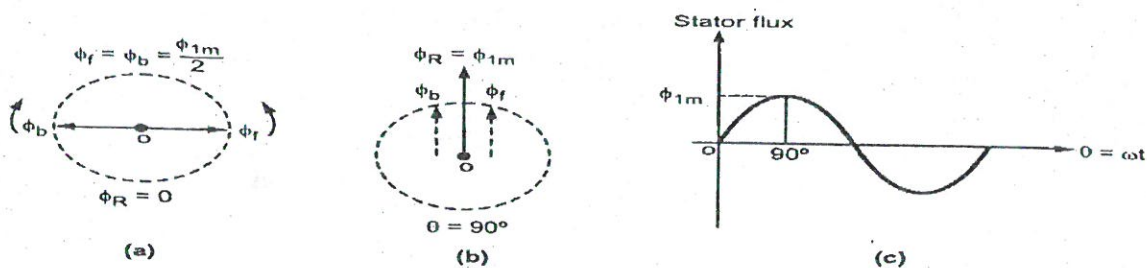


Fig. Stator flux and its two components

Both the components are rotating and hence get cut by the rotor conductors. Due to cutting of flux, e.m.f gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component Φ_f to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component Φ_b to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative. At start these two torques are equal in magnitude but rotate opposite in direction. Each torque tries to rotate the rotor in its own direction.

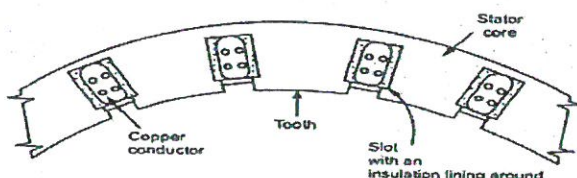
UNIT-IV

8 a) Explain the constructional features of salient pole and non-salient pole alternators.

5M

An alternator has 3-phase winding on the stator and a d.c. field winding on the rotor.

Stator: It is the stationary part of the machine and is built up of sheet-steel laminations insulated from each other having slots on its inner periphery to hold the armature windings. The core is laminated to reduce the eddy current losses and is made up of steel to minimize hysteresis loss. A cross section of the alternator stator is shown in Fig.

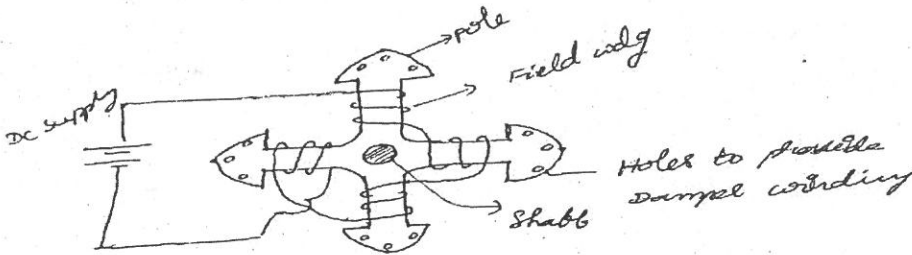


Rotor: The rotor carries the field winding which is supplied with direct current through two slip rings by a separate d.c. source (called exciter).

Rotor construction is of two types, namely;

- (i) Salient (or projecting) pole type
- (ii) Non-salient (or cylindrical) pole type

➤ **Salient (or projecting) pole type:** In this type, salient or projecting poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator as shown in Fig.



- The individual field pole windings are connected in series in such a way that when the field winding is energized by the d.c. exciter, adjacent poles have opposite polarities.
- **Low and medium-speed alternators** (120-400 r.p.m.) such as those driven by diesel engines or water turbines have salient pole type rotors due to the following reasons:

(a) The salient field poles would cause an excessive windage loss if driven at high speed and would tend to produce noise.

(b) Salient-pole construction cannot be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speeds.

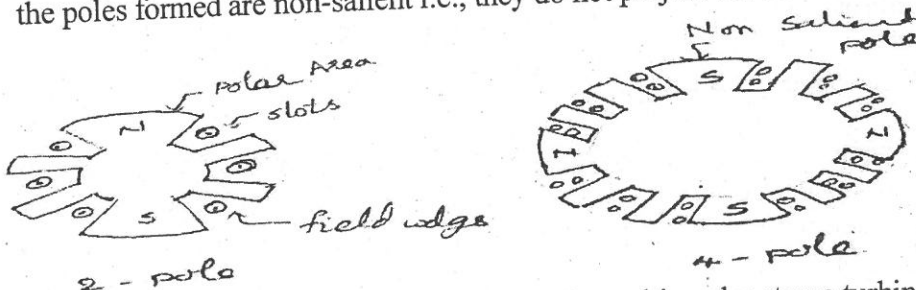
➤ Since a frequency of 50 Hz is required, we must use a large number of poles on the rotor of slow-speed alternators. Low-speed rotors always possess a large diameter to provide the necessary space for the poles. Consequently, salient-pole type rotors have large diameters and short axial lengths.

(i) **Non-salient (or cylindrical) pole type:**

➤ In this type, the rotor is made of smooth solid forged-steel radial cylinder having a number of slots along the outer periphery.

➤ The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c. exciter.

➤ The regions forming the poles are usually left unslotted as shown in Fig. It is clear that the poles formed are non-salient i.e., they do not project out from the rotor surface.



- High-speed alternators (1500 or 3000 r.p.m.) are driven by steam turbines and use non-salient type rotors. Since steam turbines run at high speed and a frequency of 50 Hz is required, we need a small number of poles on the rotor of high-speed alternators (also called turboalternators).
- The Cylindrical type rotor has small diameter and long axial length, such a construction

limits the centrifugal forces.

8 b) Derive the EMF equation of a synchronous generator.

5M

E.M.F. Equation of a synchronous generator:

- Let Z = No. of conductors in series per phase
 T = No. of turns per phase
 Φ = Flux per pole in Webers
 P = Number of poles
 f = frequency of induced emf in Hz
 N = Rotor speed in r.p.m.

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

i.e., $d\Phi = \Phi P$; $dt = 60/N$

Average e.m.f. induced in one stator conductor

$$= \frac{\text{Flux cut per revolution in Weber}}{\text{Time taken for one revolution}} = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi P N}{60} \text{ volts}$$

Since there are Z conductors in series per phase,

$$\text{Average e. m. f./phase} = \frac{\Phi P N}{60} \times Z$$

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

$$\text{Average e. m. f./phase} = \frac{\Phi P Z}{60} \times \frac{120f}{P}$$

$$\text{Average e.m.f./phase} = 2 f \Phi Z \text{ volts}$$

R.M.S. value of e.m.f./phase = Average value/phase * form factor

$$= 2 f \Phi Z \times 1.11 = 2.22 f \Phi Z \text{ volts}$$

$$E_{r.m.s.} / \text{phase} = 2.22 f \Phi Z \text{ volts}$$

If T is the no. of turns per phase, where $T = \frac{Z}{2}$

$$E_{r.m.s.} / \text{phase} = 4.44 f \Phi T \text{ volts}$$

This would have been the actual value of the induced voltage if all the coils in a phase were (i) full-pitched and (ii) concentrated or bunched in one slot (instead of being distributed in several slots under poles). But this not being so, the actually available voltage is reduced in the ratio of two factors. If K_c and K_d are the pitch factor and distribution factor of the armature winding, then,

$$E_{r.m.s.} / \text{phase} = 4.44 K_c K_d f \Phi T \text{ volts}$$

9 a) Explain armature reaction in synchronous generators under different load power factors with phasor diagrams 5 M

When the alternator is loaded, the armature flux modifies the air-gap flux. Its angle (electrical) w.r.t. main flux depends on the load p.f. This is illustrated in Fig.

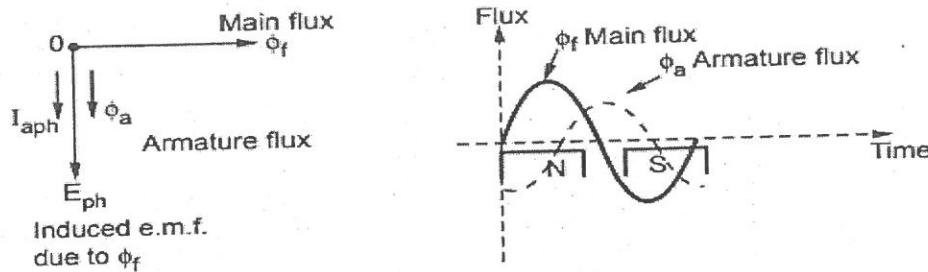


Fig. 2.5.1 Armature reaction for unity p.f. load

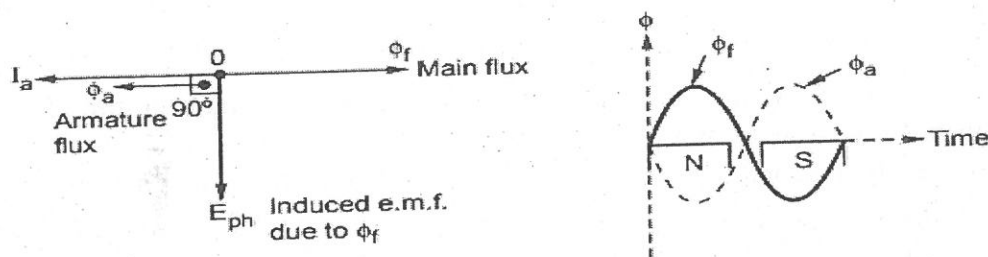


Fig. 2.5.2 Armature reaction for zero lagging p.f. load

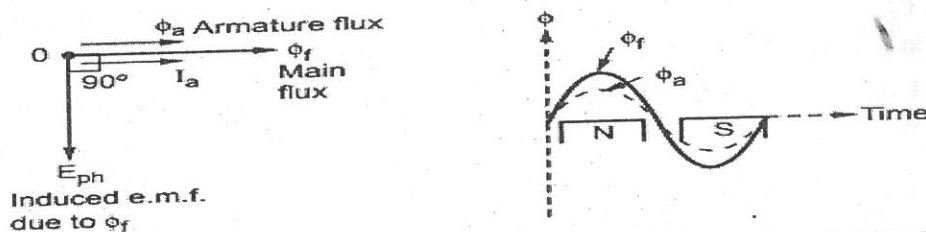


Fig. 2.5.3 Armature reaction for zero leading p.f. load

(a) When the load p.f. is unity, the effect of armature reaction is **wholly distorting**. In other words, the flux in the air-gap is distorted but not weakened. As shown in Fig.2.5.1, the armature flux is 90° electrical behind the main flux. The result is that flux is strengthened at the trailing pole tips and weakened at the leading pole tips. However, the average flux in the air-gap practically remains unaltered.

(b) When the load p.f is zero lagging, the effect of armature reaction is **wholly demagnetizing**. In other words, the flux in the air-gap is weakened. As shown in Fig. 2.5.2, the wave representing the main flux is moved backwards through 90° (elect.) so that it is in direct opposition to the armature flux. This considerably reduces the air-gap flux and hence the generated e.m.f. To keep the value of the generated e.m.f. the same, the field excitation will have to be increased to compensate for the weakening of the air-gap flux.

(c) When the load p.f is zero leading, the effect of armature reaction is **wholly magnetizing**. In other words, the flux in the air-gap is increased. As shown in Fig.2.5.3, the wave representing the main flux is now moved forward through 90° (elect.) so that it aids the armature flux. This considerably increases the air-gap flux and hence the generated e.m.f. To keep the value of the generated e.m.f the same, the field excitation will have to be reduced.

(d) For intermediate values of load p.f., the effect of armature reaction is partly distorting and partly weakening for inductive loads. For capacitive loads, the effect is partly distorting and partly strengthening. In practice, load on the alternator is generally inductive.

- 9 b) Find the value of K_d for an alternator with 9 slots per pole for the following cases:
- One winding in all the slots.
 - One winding using only the first 2/3 of the slots per pole.
 - Three equal windings placed sequentially in 60° group.
- 5 M

Solution. Here, $\beta = 180^\circ/9 = 20^\circ$ and values of m i.e. number of slots in a group are 9, 6 and 3 respectively.

$$\begin{aligned}
 (i) \quad m = 9, \quad \beta = 20^\circ, \quad k_d &= \frac{\sin 9 \times 20^\circ / 2}{9 \sin 20^\circ / 2} = 0.64 \left[\text{or } k_d = \frac{\sin \pi / 2}{\pi / 2} = 0.637 \right] \\
 (ii) \quad m = 6, \quad \beta = 20^\circ, \quad k_d &= \frac{\sin 6 \times 20^\circ / 2}{6 \sin 20^\circ / 2} = 0.83 \left[\text{or } k_d = \frac{\sin \pi / 3}{\pi / 3} = 0.827 \right] \\
 (iii) \quad m = 3, \quad \beta = 20^\circ, \quad k_d &= \frac{\sin 3 \times 20^\circ / 2}{3 \sin 20^\circ / 2} = 0.96 \left[\text{or } k_d = \frac{\sin \pi / 6}{\pi / 6} = 0.955 \right]
 \end{aligned}$$

UNIT-V

10 a) Explain the construction and principle of operation of a synchronous motor. 5 M

Operating Principle of synchronous motor

- Consider a 3-phase synchronous motor having two rotor poles N_R and S_R . Then the stator will also be wound for two poles N_S and S_S . The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding. The stator winding produces a rotating field which revolves round the stator at synchronous speed $N_s = (120 f/P)$. The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not turning. Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., $N_S - S_S$) and a pair of stationary rotor poles (i.e., $N_R - S_R$).
- Suppose at any instant, the stator poles are at positions A and B as shown in Fig 4.2 (a). It is clear that poles N_S and N_R repel each other and so do the poles S_S and S_R . Therefore, the rotor tends to move in the **anticlockwise** direction. After a period of half-cycle (or $1/2 f = 1/100$ second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in Fig 4.2 (b). Now S_S and N_R attract each other and so do N_S and S_R . Therefore, the rotor tends to move in the **clockwise** direction. Since the stator poles change their polarities rapidly, they tend to pull the rotor first in one direction on and then after a period of half-cycle in the other. Due to high inertia of the rotor, the motor fails to start.

Hence, a synchronous motor has **no self-starting torque** i.e., a synchronous motor cannot start by itself.

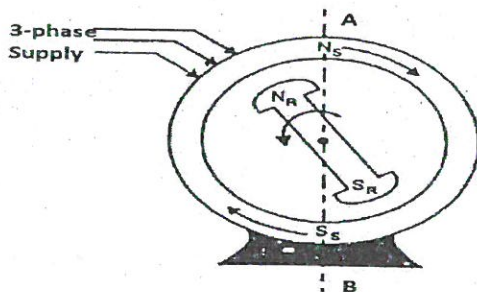


Fig: 4.2 (a)

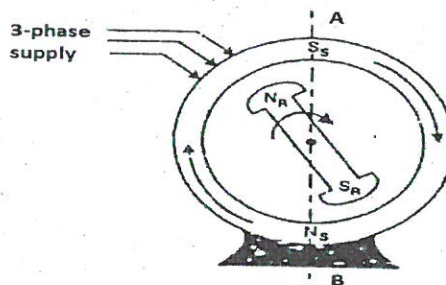


Fig: 4.2 (b)

If the rotor poles are rotated by some external means at such a speed that they interchange their positions along with the stator poles, then the rotor will experience a continuous unidirectional torque. This can be understood from the following discussion:

- (i) Suppose the stator field is rotating in the clockwise direction and the rotor is also rotated clockwise by some external means at such a speed that the rotor poles interchange their positions along with the stator poles.
- (ii) Suppose at any instant the stator and rotor poles are in the position shown in Fig 4.3(a). It is clear that torque on the rotor will be clockwise. After a period of half-cycle, the stator poles reverse their polarities and at the same time rotor poles also interchange their positions as shown in Fig 4.3 (b). The result is that again the torque on the rotor is clockwise. Hence a continuous unidirectional torque acts on the rotor and moves it in the clockwise direction. Under this condition, poles on the rotor always face poles of opposite polarity on the stator and a strong magnetic attraction is set up between them.

This mutual attraction locks the rotor and stator together and the rotor is virtually pulled into step with the speed of revolving flux (i.e., synchronous speed).

- (ii) If now the external prime mover driving the rotor is removed, the rotor will continue to rotate at synchronous speed in the clockwise direction because the rotor poles are magnetically locked up with the stator poles. It is due to this magnetic interlocking between stator and rotor poles that a synchronous motor runs at the speed of revolving flux i.e., synchronous speed.

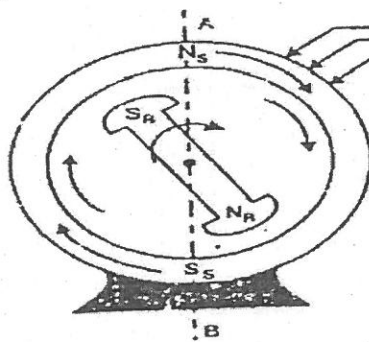


Fig: 4.3 (a)

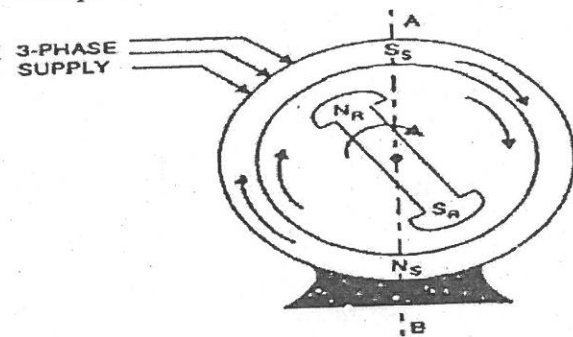


Fig: 4.3 (b)

b) A 3- Φ , 150 kW, 2300 V, 50 Hz, 1000 rpm salient-pole synchronous motor has $X_d = 32 \Omega$ per phase and $X_q = 20 \Omega$ per phase. Neglecting losses, calculate the torque developed by the motor if field excitation is so adjusted as to make the back e.m.f. twice the applied voltage and $\alpha = 16^\circ$. 5 M

Solution.

$$V = 2300 / \sqrt{3} = 1328 \text{ V}; E_b = 2 \times 1328 = 2656 \text{ V}$$

$$\text{Excitation power / phase} = \frac{E_b V}{X_d} \sin \alpha = \frac{2656 \times 1328}{32} \sin 16^\circ = 30,382 \text{ W}$$

$$\text{Reluctance power / phase} = \frac{V^2 (X_d - X_q)}{2 X_d X_q} \sin 2\alpha = \frac{1328^2 (32 - 20)}{2 \times 32 \times 20} \sin 32^\circ = 8760 \text{ W}$$

$$\text{Total power developed, } P_m = 3(30382 + 8760) = 117,425 \text{ W}$$

$$T_g = 9.55 \times 117,425 / 1000 = 1120 \text{ N-m}$$

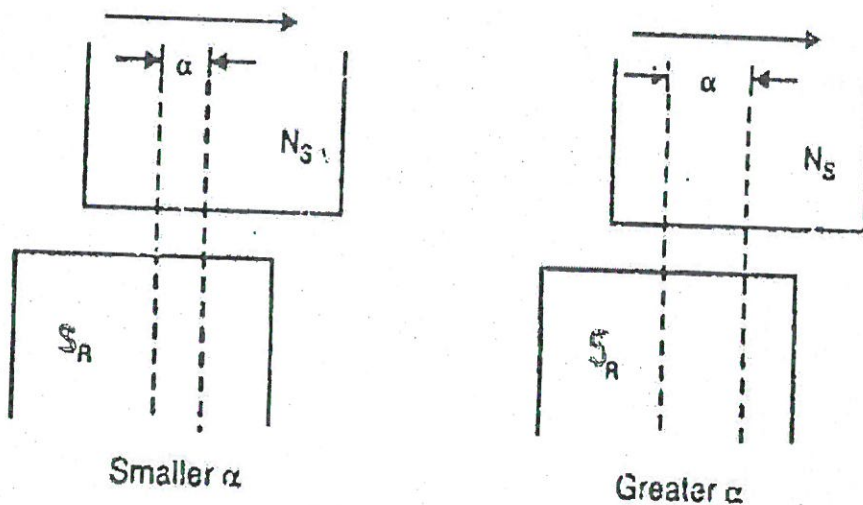
11 a) Explain the effect of load variation on power angle and stability of synchronous motor.

5 M

Synchronous Motor on Load

- In d.c. motors and induction motors, an addition of load causes the motor speed to decrease. The decrease in speed reduces the counter e.m.f. enough so that additional current is drawn from the source to carry the increased load at a reduced speed.
- This action cannot take place in a synchronous motor because it runs at a constant speed (i.e., synchronous speed) at all loads.
- When mechanical load is applied to a synchronous motor, The rotor poles fall slightly behind the stator poles while continuing to run at synchronous speed.
- The angular displacement between stator and rotor poles (called load angle or torque angle α) causes the phase of back e.m.f. E_b to change w.r.t. supply voltage V . This increases the net e.m.f. E_r in the stator winding. Consequently, stator current

$I_a = \frac{E_r}{Z_s}$ increases to carry the load.



The following points may be noted in synchronous motor operation:

- (i) A synchronous motor runs at synchronous speed at all loads. It meets the increased load not by a decrease in speed but by the relative shift between stator and rotor poles i.e., by the adjustment of torque angle α .
- (ii) If the load on the motor increases, the torque angle α also increases (i.e., rotor poles lag behind the stator poles by a greater angle) but the motor continues to run at synchronous speed. The increase in torque angle α causes a greater phase shift of back e.m.f. E_b w.r.t. supply voltage V . This increases the net voltage E_r in the stator winding. Consequently, armature current $I_a = \frac{E_r}{Z_s}$ increases to meet the load demand.
- (iii) If the load on the motor decreases, the torque angle α also decreases. This causes a smaller phase shift of E_b w.r.t. V . Consequently, the net voltage E_r in the stator winding decreases and so does the armature current $I_a = \frac{E_r}{Z_s}$.

The behavior of a synchronous motor under load variation is best understood using the power-angle ($P-\alpha$) relationship, which governs its stability.

Power-Angle Equation

$$P = \frac{EV}{X_s} \sin \alpha$$

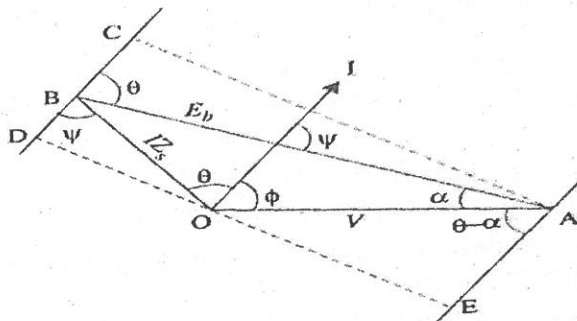
Where:

- P = power developed
- E = internal generated emf
- V = terminal voltage
- X_s = synchronous reactance
- α = power angle (torque angle)

Stability Consideration

- Stable operation occurs when: $0^\circ < \alpha < 90^\circ$
 Maximum power (steady-state stability limit) occurs at: $\alpha = 90^\circ$
 Beyond this point it becomes unstable operation.

b) Derive the expression for power developed in a synchronous motor. 5 M



θ to represent the angle between resultant voltage E_r and armature current I

ψ to represent the angle between the back emf and armature current I

α to represent the angle between the back emf and voltage

• In the figure:

- OA represents the supply voltage (per phase)
- $I_a = I$ is the armature current
- AB represents the back EMF (E_b) at a load angle α
- OB gives the resultant voltage:

$$E_r = IZ_s (\approx jIX_s \text{ if } R_a \text{ is negligible})$$

- Current I leads V by angle ϕ and lags behind E_r by angle θ

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

- Line CD is drawn at an angle θ to AB
- AC & ED are perpendicular to CD (and hence also perpendicular to AE)

Mechanical Power per Phase developed in the rotor is

$$P_m = E_b I \cos \psi \dots \dots (i)$$

From Triangle $\triangle OBD$:

$$BD = E_r \cos \psi = I Z_s \cos \psi$$

Also,

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

From Triangle $\triangle OAE$:

$$AE = V \cos (\theta - \alpha)$$

From Triangle $\triangle CBA$:

$$BC = E_b \cos \theta$$

Therefore,

$$BD = AE - BC$$

$$I Z_s \cos \psi = V \cos (\theta - \alpha) - E_b \cos \theta$$

$$I \cos \psi = \frac{V}{Z_s} \cos (\theta - \alpha) - \frac{E_b}{Z_s} \cos \theta$$

Substituting into equation (i):

$$P_m \text{ (per phase)} = E_b \left[\frac{V}{Z_s} \cos (\theta - \alpha) - \frac{E_b}{Z_s} \cos \theta \right]$$

Final Expression:

$$P_m = \frac{E_b V}{Z_s} \cos (\theta - \alpha) - \frac{E_b^2}{Z_s} \cos \theta \dots \dots (ii)$$