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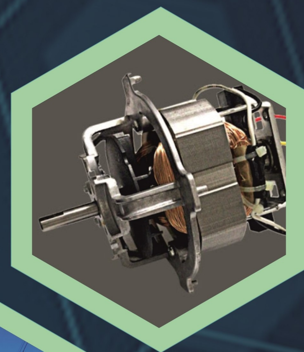

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ESE SYLLABUS

Single phase transformers, three phase transformers - connections, parallel operation, auto-transformer, energy conversion principles, DC machines - types, windings, generator characteristics, armature reaction and commutation, starting and speed control of motors, Induction motors - principles, types, performance characteristics, starting and speed control, Synchronous machines - performance, regulation, parallel operation of generators, motor starting, characteristics and applications, servo and stepper motors.

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Synchronous Machines (Weightage: 4-6 Marks) : Generation of 3-phase e.m.f. armature reaction, voltage regulation. Parallel operation of two alternators, synchronizing, control of active and reactive power. Starting and applications of synchronous motors.

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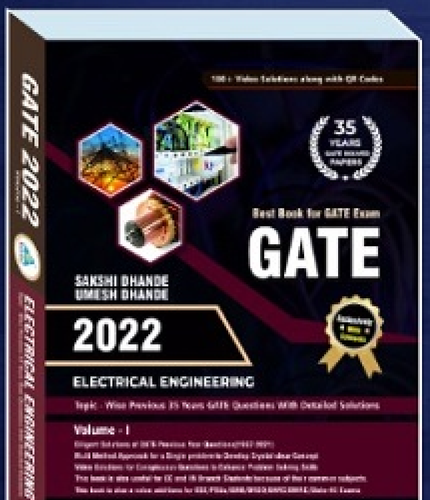

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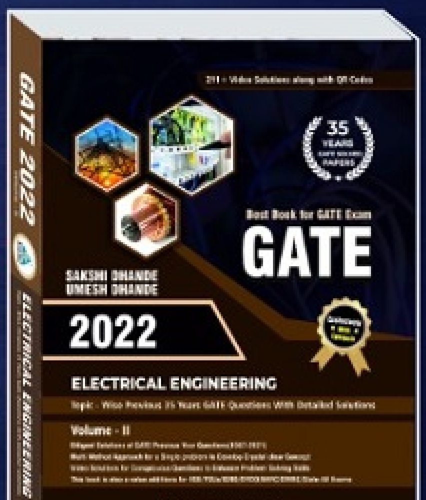

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CHAPTER 1

Synchronous Machine

Learning Objectives :

After reading this chapter you should be able to :

- Understand classification of synchronous machines.
- Explain construction and working of synchronous machines.
- Understand equivalent circuit and phasor diagrams.
- Understand different method of voltage regulation.
- Explain power flow equation and efficiency of salient pole and non-salient pole.
- Understand parallel operation of alternator.

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1.1 Introduction

Definition : Synchronous machine constitutes of both synchronous motors as well as synchronous generators. An AC system has some advantages over DC system. Therefore, the AC system is exclusively used for generation, transmission and distribution of electric power. The machine which converts mechanical power into AC electrical power is called as **Synchronous generator** or Alternator. However, if the same machine can be operated as a motor is known as **Synchronous motor.**

Features of synchronous machine :

Doubly excited machine : Synchronous machines are a doubly excited machine, i.e., two electrical inputs are provided to it. Its stator winding which consists of a three-phase supply, and rotor winding is energized to dc source.

Electromechanical transducer : A synchronous machine is just an electromechanical transducer which converts mechanical energy into electrical energy or vice versa.

Dynamically induced emf : The emf developed in synchronous machines is dynamically induced so there must be a relative motion between armature and field. This can happen in two cases :

1. Rotating armature and stationary field poles
2. Rotating field poles and stationary armature.

In a synchronous machine, the field winding is mostly on the rotor and armature winding is mostly on the stator. However, the field winding can be placed on stator while armature winding on rotor.

1.2 Electrical & Mechanical Degrees

Definition :

Mechanical degrees : The degree of physical or mechanical rotation in a single conductor in an alternator.

Electrical degrees : The degree or the cycle of emf induced in a single conductor in an alternator.

Consider a two pole alternator, when a conductor rotates in the field, the emf induced in the conductor will be maximum when the conductor is at the center of the pole and the emf induced will be minimum when the conductor is in the middle of the gap between the two poles, so when we consider the graph of the induced emf versus the position or degree of rotation. For one complete rotation of the conductor in the field, one complete cycle of emf is generated in the conductor (Positive half cycle at south-pole and negative half-cycle at north-pole).

The same way when we consider a 4-pole alternator a single conductor when completing one mechanical rotation will cross the four poles there by giving the induced emf graph with two positive half cycles and two negative half-cycles which gives us two complete cycles of induced emf.

So for One Mechanical rotation (360 degrees) the induced emf completes two cycles ($360 \times 2 = 720$ degrees in terms of the sine wave).

So, the relation between Electrical and Mechanical degrees can be written as,

$$\text{Electrical degrees} = \frac{\text{Number of poles}}{2} \times \text{Mechanical degrees}$$

i.e., $$\omega_e = \frac{P}{2}\omega_m$$

Frequency of induced emf : The frequency of the generated voltage depends upon the number of field poles and on the speed at which the field pole are rotated. One complete cycle of voltage is generated in an armature coil when a pair of field poles passes over the coil.

Let, $P =$ Number of poles, $N =$ Speed of the rotor in rpm, $f =$ Frequency of the induced emf.

From the discussion, we can write,

$$\text{One mechanical revolution of rotor} = \frac{P}{2} \text{ cycles of emf electrically}$$

Thus there are $\frac{P}{2}$ cycles per revolution.

As speed is N rpm, in one second, rotor will complete $\left(\frac{N}{60}\right)$ revolutions.

But cycle/sec = Frequency = f

$\therefore$ Frequency $f =$ (Number of cycle per revolution)$\times$(Number of revolutions per second)

$$\therefore \quad f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120} \text{ Hz} \qquad \text{(cycles per sec)}$$

Above equation give the relation between three quantities, the number poles P, the speed of the rotor N in rpm and the frequency f of an induced emf in Hz.

Synchronous speed : From the above expression, it is clear that for fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated emf constant at the required value. Such a speed is called **synchronous speed** of the alternator denoted as N_s.

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

1.3 Synchronous Generator or Alternator

Definition : The synchronous generator or alternator is an electrical machine that converts the mechanical power from a prime mover into an AC electrical power at a particular voltage and frequency. The frequency is an important property of A.C Electrical energy. Frequency is depending on the speed. To achieve fixed frequency, the machine must be always driven only at one speed is called the synchronous speed. That's reason these machines are called synchronous machines.

1.3.1 Working Principle of Synchronous Generator

An alternator operates on the same fundamental principle of electromagnetic induction as a DC generator i.e., when the flux linking a conductor changes, an e.m.f. is induced in the conductor, like a DC generator, an alternator also has an armature winding and a field winding.

But there is one important difference between the DC generator and alternator. In a DC generator, the armature winding is placed on the rotor in order to provide a way of converting alternating voltage generated in the winding to a direct voltage at the terminals through the use of a rotating commutator. The field poles are placed on the stationary part of the machine. Since no commutator is required in an alternator, it is usually more convenient and advantageous to place the field winding on the rotating part (i.e., rotor) and armature winding on the stationary part (i.e., stator).

An alternator has 3-phase winding on the stator and a DC field winding on the rotor. This DC source (called exciter) is generally a small DC shunt or compound generator mounted on the shaft of the alternator.

Alternator operation : The rotor winding is energized from the DC exciter and alternate N and S poles are developed on the rotor. When the rotor is rotated in anti-clockwise direction by a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles. Consequently, e.m.f. is induced in the armature conductors due to electromagnetic induction. The induced e.m.f. is alternating since N and S poles of rotor alternately pass the armature conductors. The direction of induced e.m.f. can be found by Fleming's right hand rule and frequency is given by,

$$f = \frac{PN}{120}$$

Where, N = Speed of rotor in r.p.m., P = Number of rotor poles.

The magnitude of the voltage induced in each phase depends upon the rotor flux, the number and position of the conductors in the phase and the speed of the rotor.

When the rotor is rotated, a 3-phase voltage is induced in the armature winding. The magnitude of induced e.m.f. depends upon the speed of rotation and the DC exciting current. The magnitude of e.m.f. in each phase of the armature winding is the same. However, they differ in phase by 120^0 electrical.

What are the advantages of having armature winding on stator?

Due to following reasons the most of the alternators in practice use armature winding on stator. For small voltage rating alternators rotating armature arrangement may be used.

1. **High generation voltage :** The generation level of a.c. voltage may be higher as 11 kV to 33 kV. This gets induced in the armature. For stationary armature large space can be provided to accommodate large number of conductors and the insulation.
2. **Avoid stress :** It is always better to protect high voltage winding from the centrifugal forces caused due to the rotation. So high voltage armature is generally kept stationary. This avoids the interaction of mechanical and electrical stresses.

3. **Easy operation :** It is easier to collect larger currents at very high voltages from a stationary member than from the slip ring and brush assembly. The voltage required to be supplied to the field is very low (110 V to 220 V d.c.) and hence can be easily supplied with the help of slip ring and brush assembly by keeping it rotating.
4. **Less sparking :** The problem of sparking at the slip rings can be avoided by keeping field rotating which is low voltage circuit and high voltage armature as stationary.
5. **Low inertia :** Due to low voltage level on the field side, the insulation required is less and hence field system has very low inertia. It is always better to rotate low inertia system than high inertia, as efforts required to rotate low inertia system are always less.
6. **High output :** Rotating field makes the overall construction very simple. With simple, robust mechanical construction and low inertia of rotor, it can be driven at high speeds. So greater output can be obtained from an alternator of given size.
7. **High efficiency :** With armature on the Stator and Field winding on the Rotor, only two slip rings are required due to which losses associated with slip ring and carbon brushes are reduced and efficiency increases.
8. **Better ventilation :** The ventilation arrangement for high voltage side can be improved if it is kept stationary.

1.3.2 Comparison of Rotating Field Over Stationary Field

Comparison of rotating field over stationary field are as follows :

S. No.	Rotating field or stationary armature	Stationary field or rotating armature
1.	Easy insulation.	Complex insulation.
2.	Easy cooling.	Cooling is not easy.
3.	High efficiency.	Low efficiency.
4.	Low cost and small size.	High cost and big size.
5.	Capacity above 25 kVA.	Capacity below 25 kVA.
6.	Brush drop is not appreciable.	Brush drop is appreciable.
7.	Requires two slip rings.	Requires four slip rings.
8.	Very low sparking and brush friction.	Very high sparking and brush friction.
9.	Poles are fixed to the rotating part and armature is placed on the stationary part.	Poles are fixed to the stationary part and armature is placed on the rotating part.

1.3.3 Construction of Alternators

In case of alternators the winding terminology is slightly different than in case of d.c. generators. In alternators the stationary winding is called **'Stator'** while the rotating winding is called **'Rotor'**. So most of alternators have stator as armature and rotor as field, in practice.

Stator : The stator is a stationary armature. The section of an alternator stator is shown in the figure (a).

This consists of a core and the slots to hold the armature winding similar to the armature of a dc generator. The stator core uses a laminated construction. It is built up of special steel stampings insulated from each other with varnish or paper. The laminated construction is basically to keep down eddy current losses. Generally choice of material is steel to keep down hysteresis losses. The entire core is fabricated in a frame made of steel plates. The core has slots on its periphery for housing the armature conductors. Frame does not carry any flux and serves as the support to the core. Ventilation is maintained with the help of holes cast in the frame.

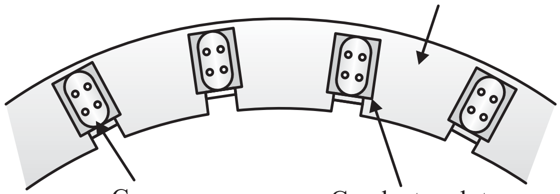


Fig. (a) Stator construction

Rotor :

There are two types of rotors used in alternators :

1. Salient pole type
2. Cylindrical type (Non-salient pole).

1. **Salient pole type rotor :** This is also called projected pole type as all the poles are projected out from the surface of the rotor. Construction of a salient pole rotor is as shown in the figure below.
   - The projected poles are made up from laminations of steel. The rotor winding is provided on these poles and it is supported by pole shoes.
   - Salient pole rotors have large diameter and shorter axial length.
   - They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.
   - As the rotor speed is lower, more number of poles are required to attain the required frequency. ($N_s = 120f/P$ therefore, $f = N_s*p/120$ i.e. frequency is proportional to number of poles). Typically, number of salient poles is between 4 to 60.
   - Salient pole rotors generally need damper windings to prevent rotor oscillations during operation.
   - These rotors have large diameters and small axial' lengths. The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine.
   - Salient pole synchronous generators are mostly used in hydro power plants.
   - Flux distribution is relatively poor than non-salient pole rotor, hence the generated emf waveform is not as good as cylindrical rotor.

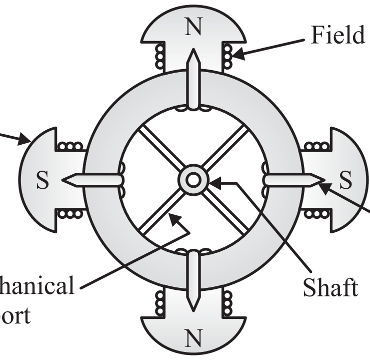
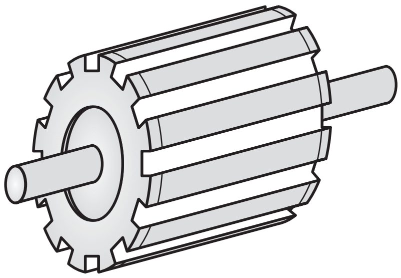
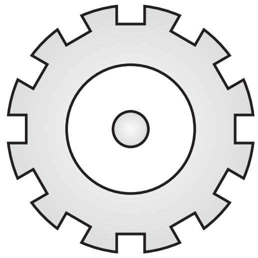


Fig. (b) Salient pole type rotor

2. **Cylindrical type (Non-salient pole) :** Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings. It is made up of solid steel. The construction of non-salient pole rotor (cylindrical rotor) is as shown in figure below. Sometimes, they are also called as drum rotor.



Cylindrical rotor



Cross sectional view

- They are smaller in diameter but having longer axial length.
- Cylindrical rotors are used in high speed electrical machines, usually 1500 RPM to 3000 RPM.
- Windage loss as well as noise is less as compared to salient pole rotors.
- Their construction is robust as compared to salient pole rotors.
- Number of poles is usually 2 or 4.
- Damper windings are not needed in non-salient pole rotors.
- Flux distribution is sinusoidal and hence gives better emf waveform.
- Non-salient pole rotors are used in nuclear gas and thermal power plants.
- Generally 2/3rd rotor periphery is slotted to accumulated field winding and 1/3rd of rotor periphery is left alone for formation of pole.

Solved Example 1

If the dimensions of all the parts of a synchronous generator, and the number of field and armature turns are doubled, then the generated voltage will change by a factor.

(A) 1　(B) 2　(C) 4　(D) 8

Sol. Phase emf induced, $E = 4.44 f N_{ph}\phi$

Where, $\phi =$ Flux per pole $= \frac{4}{P} B_p l r$

Dimensions are doubled i.e., $l' = 2l$ and $r' = 2r$

So, flux per pole, $\phi' = 4\phi$

Number of turns doubled i.e., $N' = 2N$

Frequency changes only when the poles are changed i.e. $f' = f$

Phase emf induced $E' = 4.44 f (2N_{ph})(4\phi) = \mathbf{8E}$ **Ans.**

Hence, the correct option is (D).

Solved Example 2

Two 3-ϕ alternators are such that one has twice the linear dimensions of the other. The field winding of each are excited to give identical sinusoidal air gap flux density waveform. Both have the same number of stator slots and identical winding patterns. The conductors per slot in big alternator is K times that of the smaller one. The value of K to get equal phase voltage at the same frequency is

(A) 8 (B) 4 (C) 0.5 (D) 0.25

Sol. Phase emf induced, $E = 4.44 f N_{ph}\phi = 4.44 f N_{ph}(B_m A)$

Total surface area of the alternator, $A = 2\pi rl$

Flux density B_m and frequency of both the alternator are same i.e., $A_2 = A_1$ (given)

Area of small alternator, $A_1 = 2\pi r_1 l_1$

Area of big alternator, $A_2 = 2\pi r_2 l_2 = 2\pi(2r_1)(2l_1) = 4A_1$

Conductors per slot in small alternator $= \text{Conductor}_{\text{slot}}$

The conductors per slot in big alternator is K times that of the smaller one i.e.

Conductors per slot in big alternator $= K \times \text{Conductor}_{\text{slot}}$

To get $E_2 = E_1$ then $A_2 N_{ph_2} = A_1 N_{ph_1}$

$$4A_1 \times K \times \text{Conductor}_{\text{slot}} = A_1 \times \text{Conductor}_{\text{slot}}$$

$$K = \frac{1}{4} = \mathbf{0.25}$$ **Ans.**

Hence, the correct option is (D).

Scan for Video Solution

Solved Example 3

Two mechanically coupled alternators deliver power at 50 Hz and 60 Hz respectively. The highest speed of the alternator is

(A) 3600 rpm (B) 3000 rpm (C) 600 rpm (D) 1500 rpm

Sol. **Given :** Frequency of first alternator $f_1 = 50\,\text{Hz}$,

Frequency of second alternator $f_2 = 60\,\text{Hz}$

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

If both alternators are coupled then both will rotate at same speed i.e. N_s

So, $N_{s_1} = N_{s_2}$

$$\therefore \qquad \frac{120\times 50}{P_{50\text{Hz}}}=\frac{120\times 60}{P_{60\text{Hz}}}$$

$$\frac{P_{60\text{Hz}}}{P_{50\text{Hz}}}=\frac{6}{5}$$

In order to get maximum speed, multiply with minimum no. of poles i.e. ‘2’

$$\frac{P_{60}}{P_{50}}=\frac{6}{5}\times\frac{2}{2}=\frac{12}{10}$$

Now,
$$N_s=\frac{120\times 50}{P_{50\text{Hz}}}=\frac{120\times 50}{10}=600\,\text{rpm}$$

$$N_s=\frac{120\times 60}{P_{60}}=\frac{120\times 60}{12}=\mathbf{600\,rpm}$$ **Ans.**

Hence, the correct option is (C).

TEST 1

Q.1 A hydraulic turbine having rated speed of 250 rpm is connected to a synchronous generator. In order to produce power at 50 Hz, the number of poles required in the generator are **[GATE 2004]**

(A) 6　　(B) 12
(C) 16　　(D) 24

Q.2 A 10 pole, 25 Hz alternator is directly coupled to and is driven by 60 Hz synchronous motor. What is the number of poles for the synchronous motor? **[ESE 2007]**

(A) 48　　(B) 12
(C) 24　　(D) 16

Q.3 Four important parameters of alternators have comparatively larger or smaller values, depending upon the type of the alternator. In comparison to a steam turbine driven alternator, a hydraulically driven machine will have which of the following combinations? **[ESE 2004]**

	Number of armature conductors	Axial length of armature	Number of poles	Operating speed
(A)	Smaller	Larger	Smaller	Higher
(B)	Larger	Smaller	Larger	Lower
(C)	Larger	Larger	Smaller	Lower
(D)	Smaller	Smaller	Larger	Higher

Q.4 In a cylindrical rotor synchronous machine, the phasor addition of stator and rotor mmfs is possible because **[ESE 2001]**

(A) two mmfs are rotating in opposite direction
(B) two mmfs are rotating in same direction at different speed
(C) two mmfs are stationary wrt each other
(D) one mmf is stationary and the other mmf is rotating

Q.5 A 6 pole machine is rotating at a speed of 1200 rpm. This speed in mechanical rad/sec and electrical rad/sec are :

(A) $40\pi, \frac{40\pi}{3}$　　(B) $120\pi, 40\pi$
(C) $20\pi, 60\pi$　　(D) $40\pi, 120\pi$

Numerical Answer Type Questions

Armature Winding

Q.1 Determine the breadth and pitch factor for three phase winding with two slots per pole per phase. The coil span is five slot pitches.

Q.2 A 3-phase, 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, sinusoidal distributed. Determine the phase and line voltages.

Q.3 The stator of a 3-phase alternator has 9 slots per pole and carries a balanced 3-phase double layer winding. The Coils are short pitched and the coil pitch is 7 slots. Find the distribution factor and pitch factor.

Q.4 A 3-phase, 16-pole, alternator has star winding with 144 slots and 10 conductors per slot. The flux per pole is 0.035 Wb and speed is 370 rpm. Calculate :

(a) Frequency

(b) Phase and line voltage

Equivalent Circuit for Non-Salient or Cylindrical Rotor Synchronous Generator

Q.1 A 3-phase star connected alternator delivering current at 0.8 power factor lagging. At no load, the terminal voltage is 3500 V and at full load of 2280 kW, it is 3300 V. Calculate the terminal voltage when delivering current to a 3-phase, star connected load having a resistance of $8\ \Omega$ and a reactance of $6\ \Omega$ per phase. Assume constant speed and field excitation.

Q.2 A 1000 kVA, 6.6 kV, 3-phase, star connected alternator has $X_s = 25\ \Omega$ per phase. It supplies rated load at rated voltage 0.8 power factor lagging. Calculate terminal voltage with same excitation at full load but at 0.8 power factor leading.

Q.3 A 2000 kVA, 11 kV, 3-phase star connected alternator has synchronous impedance $Z_s = 0.3 + j5\ \Omega$ per phase. It delivers full load current at a p.f. of 0.8 lagging and normal rated voltage. Compute the terminal voltage for the same excitation and current at 0.8 p.f. leading.

Q.4 A 3-phase, 10 kVA, 400 V, 50 Hz star connected alternator supplies the rated load at 0.8 power factor lagging. If the armature resistance is $0.5\ \Omega$ and synchronous reactance is $10\ \Omega$, find the torque angle.

Q.5 A 3-phase alternator delivers power to a balanced 3-phase load. It is observed that the open circuit emf phasor leads the corresponding terminal voltage phasor by 15^0 . Neglecting the effect of harmonics, the angle between the axis of the main field mmf and the axis of armature mmf will be in electrical degree when load power factor is

(a) 0.707 lagging (b) 0.707 leading

(c) unity

Voltage Regulation of an Alternator

Q.1 A 3-phase star connected alternator is rated at 1500 kVA, 11 kV. The armature effective resistance and synchronous reactance are $1.2\,\Omega$ and $24\,\Omega$ per phase respectively. Calculate the percentage regulation for a load of 1200 kW at power factor of
(a) 0.8 lagging
(b) 0.8 leading

Q.2 A 3-phase, 10 kVA, 400 V, 50 Hz star connected alternator supplies the rated load at 0.8 power factor lagging. If the armature resistance is $0.5\,\Omega$ and synchronous reactance is $10\,\Omega$, find the torque angle and voltage regulation.

Q.3 A 3-phase, star connected, round rotor synchronous generator rated at 10 kVA, 230 V has an armature resistance of $0.5\,\Omega$ per phase and a synchronous reactance of $1.2\,\Omega$ per phase. Calculate the percentage regulation at full load at power factor of
(a) 0.8 power factor lagging,
(b) 0.8 power factor leading,
(c) Determine the power factor such that the voltage regulation is zero on full load.

Q.4 An alternator has synchronous reactance of 20% and negligible resistance. Calculate its voltage regulation when working at full load :
(a) 0.8 power factor lag,
(b) Unity power factor and
(c) 0.8 power factor lead.

Q.5 A 3-phase star connected alternator is rated at 1600 kVA, 13500 V. The armature effective resistance and synchronous reactance are 1.5 ohm and 30 ohm respectively per phase. Calculate the percentage regulation for a 1280 kW at power factor of
(a) unity power factor,
(b) 0.8 lagging and
(c) 0.8 pf leading.

Multiple Choice Questions

EMF Equation of Synchronous Machine

Q.1 An alternator delivers the power at 40 Hz frequency. If this alternator is coupled to another alternator delivering power at 25 Hz, the two highest possible speeds of the set will be
(A) 300 rpm, 150 rpm
(B) 150 rpm, 100 rpm
(C) 600 rpm, 300 rpm
(D) 2400 rpm, 1500 rpm

Q.2 A three phase alternator has a phase sequence of RYB for its three output voltages. In case the field current is reversed, the phase sequence will become
(A) RBY (B) RYB
(C) YRB (D) None of these

Q.3 If ϕ_m is the maximum value of flux due to any one phase, then resultant flux in 2-phase and 3-phase a.c. machines would respectively be given by
(A) ϕ_m and $1.5\phi_m$; both rotating
(B) ϕ_m and $1.5\phi_m$; both stand still

(C) ϕ_m, stand still and $1.5\phi_m$, rotating

(D) $1.5\phi_m$ and $2\phi_m$; both rotating

Q.4 A synchronous machine has its field winding on the stator and polyphase armature winding on the rotor. When running under steady state conditions, its air gap field is :

1. stationary wrt stator
2. rotating at synchronous speed N_S wrt stator
3. rotating at N_S in the direction of rotor rotation
4. rotating at double the N_S wrt rotor
5. rotating at N_S wrt rotor
6. rotating in a direction opposite to rotor rotation

From these, the correct answer is :

(A) 2, 5 (B) 1, 4, 6

(C) 2, 4, 6 (D) 1, 3, 5

Q.5 A synchronous motor coupled to the alternator to link up a 60 Hz system to 25 Hz system. The three highest possible speeds of the system will be

(A) 300 rpm, 150 rpm, 100 rpm

(B) 300 rpm, 150 rpmm, 75 rpm

(C) 300 rpm, 300 rpm, 150 rpm

(D) 600 rpm, 300 rpm, 150 rpm

Armature Winding

Q.1 A rotating field type 4 pole, 1500 rpm, three phase alternator has flux per pole = 1.5 Wb and coil span is 156^0 electrical. It has 60 slots on armature and number of conductor per slot is 16. Calculate induced emf per phase.

(A) 44.95 kV (B) 49.85 kV

(C) 52.56 kV (D) 54.23 kV

Q.2 A 10 MVA, 11 kV, 50 Hz, 3-phase star connected synchronous generator is driven at 300 rpm. The armature winding is housed in 360 slots with 6 conductors per slot. The coil span is five-sixth of a pole pitch. Calculate the flux per pole required to give 11 kV line voltage on open circuit.

(A) 0.095 Wb (B) 0.077 Wb

(C) 0.068 Wb (D) 0.086 Wb

Common Data for Questions 3 & 4

A 4 pole, 50 Hz, synchronous generator has 48 slots in which a double layer winding is used. Each coil has 10 turns and is short pitched by an angle to 36^0 electrical. The fundamental flux per pole is 0.025 Wb. **[GATE 2006]**

Q.3 The line-to-line induced emf (in volts), for a three phase star connection is approximately

(A) 808 (B) 888

(C) 1400 (D) 1538

Q.4 The line-to-line induced emf (in volts), for a two phase connection is approximately

(A) 1143 (B) 1332

(C) 1617 (D) 1791

Q.5 A 4-pole, 3-phase, double-layer winding is housed in a 36-slot stator for an AC machine with 60^0 phase spread. Coil span is 7, short pitched. Number of slots in which top and bottom layers belong to different phases is **[GATE 2003]**

(A) 24 (B) 18

(C) 12 (D) 0

Armature Reaction

Q.1 A synchronous generator is feeding a zero power factor (lagging) load at rated current. The armature reaction is **[GATE 2006]**

(A) magnetizing
(B) demagnetizing
(C) cross-magnetizing
(D) ineffective

Q.2 The flux per pole in a synchronous motor with the field circuit ON and the stator disconnected from the supply is found to be 25 mWb. When the stator is connected to the rated supply with the field excitation unchanged, the flux per pole in the machine is found to be 20 mWb while the motor is running on no-load. Assuming no-load losses to be zero, the no-load current drawn by the motor from the supply **[GATE 2002]**

(A) lags the supply voltage.
(B) leads the supply voltage.
(C) is in phase with the supply voltage.
(D) is zero.

Q.3 When does a synchronous motor operate with leading power factor current? **[ESE 2007]**

(A) While it is under excited
(B) While it is critically excited
(C) While it is over excited
(D) While it is heavily loaded

Q.4 If the field of a synchronous motor is underexcited, the power factor will be **[ESE 2003]**

(A) Lagging
(B) Leading
(C) Unity
(D) More than unity

Q.5 Match the **List-I (Power factor)** with **List-II (Armature reaction of an alternator)** and select the correct answer using the codes given below the lists **[ESE 2000]**

List-I		List-II	
A.	UPF	**1.**	Fully demagnetizing
B.	ZPF lagging	**2.**	Fully magnetizing
C.	ZPF leading	**3.**	Cross-magnetizing
D.	Intermediate lagging	**4.**	Partly cross-magnetizing and partly demagnetizing

Codes :

	A	B	C	D
(A)	3	1	4	2
(B)	3	1	2	4
(C)	1	3	2	4
(D)	1	3	4	2

Answer of Test - 1 (Based on EMF Equation of Synchronous Machine)

1.	**D**	**2.**	**C**	**3.**	**B**	**4.**	**C**	**5.**	**B**

Explanation of Test - 1 (Based on EMF Equation of Synchronous Machine)

Sol.1

Given : Speed $N = 250\,\text{rpm}$

Frequency $f = 50\,\text{Hz}$.

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

$$250 = \frac{120 \times 50}{P}$$

Number of poles required $P = 24$ **Ans.**

Hence the correct option is (D).

Sol.2

Given : Number of poles of alternator $P_1 = 10$

Frequency of alternator $f_1 = 25\,\text{Hz}$

Frequency of motor $f_2 = 60\,\text{Hz}$.

If both are coupled then both will rotate at same speed i.e. N_s .

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

So, $N_{s_1} = N_{s_2}$

$$\therefore \quad \frac{120 \times 25}{10} = \frac{120 \times 60}{P_2}$$

Number of poles for the synchronous motor,

$P_2 = 24$ **Ans.**

Hence, the correct option is (C).

Sol.3

Generally Hydraulically driven machines are verticaly mounted, mostly they are "salient pole synchronous machines". These machines has larger rotor diameter to accommodate more number of poles and more number of armature conductors.

But power output $\propto D^2 L \propto$ volume of rotor, so inorder to get fixed terminal voltage and power output as $D\uparrow, L\downarrow$, i.e.,

1. Rotor length should be low.
2. Axial length of armature turns should be small.

Generally $D = 5L$ for sailent pole machine.

Note : Due to saliency, this type of rotor is not mechanically balanced well, so should driven at low speed to avoid large centrifugal forces.

Hence, the correct option is (B).

Sol.4

To produce the torque, both stator and rotor field are stationary with each other but due to torque angle both field vector are not possible with each other hence phasor addition only possible.

Hence, the correct option is (C).

Sol.5

Given : Speed $N = 1200$ rpm

Number of pole $P = 6$.

Frequency, $f = \dfrac{PN}{120}$

$$f = \frac{6 \times 1200}{120} = 60\ \text{cycles/sec.}$$

1 cycle = 360° electrical degrees = 2π electrical radians

Frequency f in electrical radians per sec

$= 60 \times 2\pi$ electrical radians/sec

$= 120\pi$ elect radians/sec **Ans.**

Speed in mechanical radians/sec

$$= \frac{2}{P} \times \text{Speed in electrical rad/sec}$$

$$= \frac{2}{P} \times 120\pi$$

$$= \frac{2}{6} \times 120\pi = 40\pi \text{ mechanical rad/sec.}$$ **Ans.**

Hence, the correct option is (B).

Explanation of NAT Questions (Based on Armature Winding)

Sol.1

Given : Number of slot per pole per phase = 2

Coil span = 5 slots.

i.e., $m = \dfrac{\text{Slots}}{\text{Poles} \times \text{Phase}} = 2$

$$\text{Pole pitch} = \frac{\text{Slots}}{\text{Pole}} = 2 \times \text{Phase} = 2 \times 3 = 6$$

$$\text{Slot angle, } \beta = \frac{180^0 \times \text{Pole}}{\text{Slots}} = \frac{180^0}{\text{Slots / Pole}}$$

$$\beta = \frac{180^0}{6} = 30^0$$

$$\text{Breadth factor, } K_d = \frac{\sin(m\beta/2)}{m\sin(\beta/2)}$$

$$K_d = \frac{\sin(2 \times 30^0/2)}{2\sin(30^0/2)} = \mathbf{0.966} \quad \textbf{Ans.}$$

Pole pitch = 6 slots

Coil span = 5 slots

Short pitch = Pole pitch − Coil span

= 6 − 5 = 1 slot

Short pitch angle, $\alpha = 1 \times \beta = 30^0$

$$\text{Pitch factor, } K_p = \cos\left(\frac{\alpha}{2}\right) = \cos\left(\frac{30^0}{2}\right) = \mathbf{0.966}$$

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Sol.2

Given : Number of pole $P = 8$

Number of slots = 120

Flux per pole $\phi_p = 0.05\text{ Wb}$

Frequency $f = 50\text{ Hz}$, Conductor per slot = 8.

Number of slot per pole per phase,

$$m = \frac{\text{Slots}}{\text{Poles} \times \text{Phase}} = \frac{120}{8 \times 3} = 5$$

$$\text{Slot angle, } \beta = \frac{180^0 \times \text{Poles}}{\text{Slots}} = \frac{180^0 \times 8}{120} = 12^0$$

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

$$K_d = \frac{\sin(5 \times 12^0/2)}{5\sin(12^0/2)} = 0.9567$$

Conductors per slot = 8

Total number of conductor per phase,

$$Z_{ph} = \frac{\text{Conductors}}{\text{Phase}}$$

$$Z = \frac{\text{Conductors}}{\text{Slots}} \times \frac{\text{Slots}}{\text{Phase}}$$

$$Z = 8 \times \frac{120}{3} = 320$$

Total number of turns per phase,

$$N_{ph} = \frac{Z_{ph}}{2} = \frac{320}{2} = 160$$

Induced emf per phase, $E_{ph} = 4.44 K_d f \phi_p N_{ph}$

$$E_{ph} = 4.44 \times 0.9567 \times 50 \times 0.05 \times 160$$

$$E_{ph} = \mathbf{1.7\text{ kV}} \quad \textbf{Ans.}$$

Line voltage, $E_L = \sqrt{3} \times$ Phase voltage

$$E_L = \sqrt{3} \times 1.7\text{ kV} = \mathbf{2.94\text{ kV}} \quad \textbf{Ans.}$$

Sol.3

Given : Number of slot /pole = 9

Coil pitch = 7 slot.

Number of slot per pole per phase,

$$m = \frac{\text{Slot}}{\text{Pole} \times \text{Phase}} = \frac{9}{3} = 3$$

$$\text{Slot angle, } \beta = \frac{180 \times \text{Poles}}{\text{Slots}} = \frac{180}{9} = 20^0$$

Distribution factor,

$$K_d = \frac{\sin m\dfrac{\beta}{2}}{m\sin\dfrac{\beta}{2}} = \frac{\sin\dfrac{3 \times 20}{2}}{3\sin\dfrac{20}{2}} = \mathbf{0.96} \quad \textbf{Ans.}$$

$$\text{Pole pitch} = \frac{\text{Slots}}{\text{Pole}} = 9\text{ slots}$$

Coil span $=7$ slots

Short pitch = Coil pitch – Coil span

$=9-7=2$ slots

Short pitch angle $\alpha=2\times\beta=2\times20=40^0$

Pitch factor, $K_p=\cos\left(\frac{\alpha}{2}\right)=\cos\frac{40}{2}=\mathbf{0.9397}$

Ans.

Sol.4

Given : Number of poles $P=16$

Number of slots = 144

Flux per pole $\phi_p=0.035\,\text{Wb}$

Conductor per slot = 10

Synchronous speed $N_s=370\,\text{rpm}$.

(a) Frequency :

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

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

$f=\frac{370\times16}{120}=\mathbf{49.33\ Hz}$ **Ans.**

(b) Phase and line voltage :

Number of slot per pole per phase,

$m=\frac{\text{Slots}}{\text{Poles}\times\text{ Phase}}=\frac{144}{16\times3}=3$

Slot angle, $\beta=\frac{180^0\times\text{Poles}}{\text{Slots}}$

$\beta=\frac{180^0\times16}{144}=20^0$

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

$K_d=\frac{\sin(3\times20^0/2)}{3\sin(20^0/2)}=0.9597$

Total number of conductor per phase,

$Z_{ph}=\frac{\text{Conductors}}{\text{Phase}}=\frac{\text{Conductors}}{\text{Slots}}\times\frac{\text{Slots}}{\text{Phase}}$

$Z_{ph}=10\times\frac{144}{3}=480$

Total number of turns per phase,

$N_{ph}=\frac{Z_{ph}}{2}=\frac{480}{2}=240$

Induced emf per phase,

$E_{ph}=4.44K_d f\phi_p N_{ph}$

$E_{ph}=4.44\times0.9597\times49.33\times0.035\times240$

$\therefore\quad E_{ph}=\mathbf{1.765\ kV}$ **Ans.**

Line voltage, $E_L=\sqrt{3}\times$ Phase voltage

$E_L=\sqrt{3}\times1.765\text{ kV}=\mathbf{3.057\ kV}$ **Ans.**

Explanation of NAT Questions (Based on Equivalent Circuit for Non-Salient or Cylindrical Rotor Synchronous Generator)

Sol.1

Given : No load line voltage $=3500$ V

Full load line voltage $=3300$ V

Full load power $P_L=2280$ kW

Load resistance $R_a=8\ \Omega$

Load reactance $X_s=6\ \Omega$.

At 0.8 power factor lagging i.e., $\cos\phi=0.8$

$\therefore\quad \phi=\cos^{-1}0.8=36.86^0$

$\therefore\quad \sin\phi=\sin36.86=0.6$

No load phase voltage $=\frac{3500}{\sqrt{3}}=2020.7$ V ,

Full load phase voltage $=\frac{3300}{\sqrt{3}}=1905.3$ V

$P_L=\sqrt{3}V_LI_L\cos\phi$

$2280\times10^3=\sqrt{3}\times3300\times I_L\times0.8$

Armature current,

$I_a=I_L=\frac{2280\times10^3}{\sqrt{3}\times3300\times0.8}=498.6$ A

Voltage drop per phase for a current of 498.6 A

= 2020.7 – 1905.3 = 115.4 V

Voltage drop per phase for 1 A current

$$= \frac{115.4}{498.6} = 0.2315$$

Let I be the current supplied by the alternator. Then, the voltage drop per phase supplying a current I at 0.8 power factor lagging = 0.2315 I Volts.

Terminal voltage per phase for supplying a current I at 0.8 power factor lagging

$$= 2020.7 - 0.2315\, I$$

Load impedance,

$$Z_L = \sqrt{R_L^2 + X_L^2} = \sqrt{8^2 + 6^2} = 10\ \Omega$$

Load terminal voltage $= Z_L I = 10\,I$ Volts

$$\therefore \quad 10\,I = 2020.7 - 0.2315\,I$$

$$I = 197.5\ \text{A}$$

Terminal voltage per phase

$$= Z_L I = 197.5 \times 10 = 1975\ \text{V}$$

Terminal line voltage, $V_L = \sqrt{3} \times 1975$ V

$$V_L = \mathbf{3420.8\ V}$$ **Ans.**

Sol.2

Given : Power $S = 1000$ kVA

Line voltage $V_L = 6.6$ kV .

Terminal voltage, $V_T = \frac{V_L}{\sqrt{3}} = \frac{6600}{\sqrt{3}} = 3810.5$ V

Full load armature current,

$$I_a = \frac{S}{\sqrt{3} \times V_L} = \frac{1000 \times 10^3}{\sqrt{3} \times 6.6 \times 10^3} = 87.48\ \text{A}$$

Synchronous reactance, $X_s = 25\ \Omega$ per phase

At 0.8 power factor lagging,

$$\cos\phi = 0.8$$

$$\phi = \cos^{-1} 0.8 = 36.86^0$$

Lagging armature current,

$$I_a = 87.48\angle -36.86^0\ \text{A}$$

Generated emf per phase, $E_f = V_T + jI_a X_s$

$$E_f = 3810.5 + 87.48\angle -36.86^0 \times j25$$

$$E_f = 5413\angle 18.86^0\ \text{V per phase}$$

Now excitation is fixed i.e. E_f is constant.

At 0.8 power factor leading,

$$\cos\phi = 0.8$$

$$\phi = \cos^{-1} 0.8 = 36.86^0$$

Leading armature current,

$$I_a = 87.48\angle 36.86^0\ \text{A}$$

Let new terminal voltage be V_T ,

$$V_T = E_f - jI_a X_s$$

$$V_T = 5413\angle 18.86^0 - j87.48\angle 36.86^0 \times 25$$

$$V_T = 6434.3\ \text{V per phase}$$

Terminal line voltage,

$$V_L = \sqrt{3}\,V_T = \sqrt{3} \times 6434.3\,\text{V}$$

$$V_L = \mathbf{11.144\ kV}$$ **Ans.**

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Sol.3

Given : Power $S = 2000$ kVA

Line voltage $V_L = 11$ kV

Synchronous impedance $Z_s = 0.3 + j5\ \Omega$ per phase.

Terminal voltage,

$$V_T = \frac{V_L}{\sqrt{3}} = \frac{11000}{\sqrt{3}} = 6350.85\ \text{V}$$

Full load armature current,

$$I_a = \frac{S}{\sqrt{3} \times V_L} = \frac{2000 \times 10^3}{\sqrt{3} \times 11 \times 10^3} = 105\ \text{A}$$

At 0.8 power factor lagging, $\cos\phi = 0.8$

$$\phi = \cos^{-1} 0.8 = 36.86^0$$

Lagging armature current, $I_a = 105\angle -36.86^0$ A

Generated emf per phase, $E_f = V_T + I_a Z_s$

$$E_f = 6350.85 + 105\angle -36.86^0 \times (0.3 + j5)$$

$$E_f = 6703\angle 3.43^0\ \text{V per phase}$$

Now, excitation is fixed i.e. E_f is constant.

At 0.8 power factor leading,

$\cos\phi = 0.8$

$\phi = \cos^{-1} 0.8 = 36.86^0$

Leading armature current, $I_a = 105\angle 36.36^0$ A

Let new terminal voltage be,

$V_T = E_f - I_a Z_s$

$V_T = 6703\angle 3.43^0 - 105\angle 36.86^0 \times (0.3 + j5)$

$V_T = 6980.82$ V per phase

Terminal line voltage

$V_L = \sqrt{3} V_T = \sqrt{3} \times 6980.82 \text{ V} = \mathbf{12.091 \text{ kV}}$ **Ans.**

Sol.4

Full load or rated value, $S = 10$ kVA

and $V_L = 400$ V

Synchronous impedance,

$Z_s = R_a + jX_s = (0.5 + j10)\ \Omega$

Terminal voltage per phase,

$V_T = V_L / \sqrt{3} = 400 / \sqrt{3} = 230.9$ V

Full load armature current,

$$I_a = \frac{S}{\sqrt{3} \times V_L} = \frac{10000}{\sqrt{3} \times 400} = 14.43 \text{ A}$$

At 0.8 pf lagging, $\cos\phi = 0.8 \Rightarrow \phi = 36.86^0$

$I_a = 14.43\angle -36.86^0$ A

Generated emf per phase, $E_F = V_T + I_a Z_s$

$E_f = 230.9 + 14.43\angle -36.86^0 \times (0.5 + j10)$

$E_f = 341.8\angle 18.97^0$ V

$\therefore$ Torque angle, $\boldsymbol{\delta = 18.97^0}$ **Ans.**

Sol.5

Given : Power factor $\cos\phi = 0.707$ lagging

Torque angle $\delta = 15^0$

Power factor angle $\phi = \cos^{-1} 0.707 = 45^0$.

(a) 0.707 power factor lagging :

Angle between the axis of the main field mmf and the axis of armature mmf i.e.

Angle between F_f and $F_a = 90^0 + \psi$

Angle between F_f and $F_a = 90^0 + (\phi + \delta)$

Angle between

F_f and $F_a = 90^0 + 45^0 + 15^0$

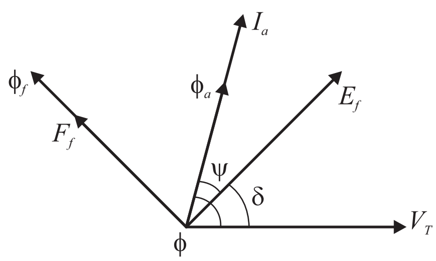
Angle between

F_f and $F_a = \mathbf{150^0}$ **electrical** **Ans.**

(b) 0.707 power factor leading :

For leading power factor following two case are occur

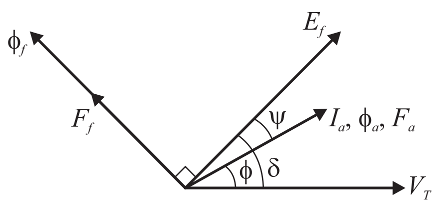
Case-1 : When $\phi > \delta$,



From the phasor diagram it is clear when $\phi > \delta$ then $\psi = \phi - \delta$

F_a lags F_F by $90^0 - \psi = 90^0 - \phi + \delta$

Case 2 : When $\phi < \delta$,



From the phasor diagram it is clear when $\phi < \delta$ then $\psi = \delta - \phi$

F_a lags F_F by $90^0 + \psi = 90^0 + \delta - \phi$

In this case $\phi > \delta$ so $\psi = \phi - \delta$

Angle between F_f and $F_a = 90^0 - \psi$

$= 90^0 - \phi + \delta = 90^0 - 45^0 + 15^0$

Angle between

F_f and $F_a = \mathbf{60^0}$ **electrical.** Ans.

(c) Unity power factor $\phi = 0^0$ i.e., $\phi < \delta$

So, $\psi = \delta - \phi$

Angle between, F_f and $F_a = 90^0 + \psi$

$= 90^0 - \phi + \delta = 90^0 + 15^0 - 0^0$

Angle between

F_f and $F_a = \mathbf{105^0}$ **electrical.** Ans.

Explanation of NAT Questions (Based on Voltage Regulation of an Alternator)

Sol. 1

Given : Armature resistance $R_a = 1.2\ \Omega$

Synchronous reactance $X_s = 24\ \Omega$

Load power $P_L = 1200$ kW

Line voltage $V_L = 11000$ V .

$$\cos\phi = 0.8$$

$$\therefore \quad \phi = \cos^{-1} 0.8 = 36.86^0$$

$$\therefore \quad \sin\phi = \sin 36.86 = 0.6$$

Terminal voltage, $V_T = \dfrac{V_L}{\sqrt{3}}$

$$V_T = \frac{11000}{\sqrt{3}} = 6350.85 \text{ V}$$

(a) At 0.8 power factor lagging :

Load power $P_L = \sqrt{3} V_L I_L \cos\phi$

$$1200 \times 10^3 = \sqrt{3} \times 11000 \times I_L \times 0.8$$

Armature current,

$$I_a = I_L = \frac{1200 \times 10^3}{\sqrt{3} \times 11000 \times 0.8} = 78.72 \text{ A}$$

Generated emf at lagging pf,

$$E_f = \sqrt{(V_T \cos\phi + I_a R_a)^2 + (V_T \sin\phi + I_a X_s)^2}$$

$$E_f = \sqrt{(6350.85 \times 0.8 + 78.72 \times 1.2)^2 + (6350.85 \times 0.6 + 78.72 \times 24)^2}$$

$$E_f = 7968.68 \text{ V}$$

$$\% \text{ Voltage regulation} = \frac{E_f - V_T}{V_T} \times 100\%$$

$$= \frac{7968.68 - 6350.85}{6350.85} \times 100\%$$

$$= \mathbf{25.47\%}$$ Ans.

(b) At 0.8 power factor leading :

Load power $P_L = \sqrt{3} V_L I_L \cos\phi$

$$1200 \times 10^3 = \sqrt{3} \times 11000 \times I_L \times 0.8$$

Armature current,

$$I_a = I_L = \frac{1200 \times 10^3}{\sqrt{3} \times 11000 \times 0.8} = 78.72 \text{ A}$$

Generated emf at leading pf,

$$E_f = \sqrt{(V_T \cos\phi + I_a R_a)^2 + (V_T \sin\phi - I_a X_s)^2}$$

$$E_f = \sqrt{(6350.85 \times 0.8 + 78.72 \times 1.2)^2 + (6350.85 \times 0.6 - 78.72 \times 24)^2}$$

$$E_f = 5520.25 \text{ V}$$

$$\% \text{ Voltage regulation} = \frac{E_f - V_T}{V_T} \times 100\%$$

$$= \frac{5520.25 - 6350.85}{6350.85} \times 100\%$$

$$= \mathbf{-13.07\%}$$ Ans.

Sol. 2

Given : Power $S = 10$ kVA

Line voltage $V_L = 400$ V

Armature resistance $R_a = 0.5\ \Omega$

Synchronous reactance $X_s = 10\ \Omega$.

Terminal voltage, $V_T = \dfrac{V_L}{\sqrt{3}} = \dfrac{400}{\sqrt{3}} = 230.9$ V

Full load armature current,

$$I_a = \frac{S}{\sqrt{3} \times V_L} = \frac{10000}{\sqrt{3} \times 400} = 14.43 \text{ A}$$

Synchronous impedance,

$$Z_s = R_a + jX_s = (0.5 + j10)\ \Omega$$

At 0.8 power factor lagging :

$$\cos\phi = 0.8$$

$$\phi = \cos^{-1}(0.8) = 36.86^0$$

Current, $I_a = 14.43\angle -36.86^0$ A

Generated emf per phase, $E_f\angle\delta = V_T + I_a Z_s$

$$E_f\angle\delta = 230.9 + 14.43\angle -36.86^0 \times (0.5 + j10)$$

$$E_f\angle\delta = 341.8\angle 18.97^0\ \text{V}$$

$\therefore$ Torque angle, $\delta = \mathbf{18.97^0}$ **Ans.**

$$\%\ \text{Voltage regulation} = \frac{E_f - V_T}{V_T}\times 100\%$$

$$= \frac{341.8 - 230.9}{230.9}\times 100\% = \mathbf{48\%}$$ **Ans.**

Sol.3

Given : Armature resistance $R_a = 0.5\ \Omega$

Synchronous reactance $X_s = 1.2\ \Omega$

Power $S = 10$ kVA, Line voltage $V_L = 230$ V.

Terminal voltage, $V_T = \frac{V_L}{\sqrt{3}} = \frac{230}{\sqrt{3}} = 132.8$ V

Full load armature current,

$$I_a = \frac{S}{\sqrt{3}\times V_L} = \frac{10000}{\sqrt{3}\times 230} = 25.1\ \text{A}$$

(a) At 0.8 power factor lagging :

i.e., $\cos\phi = 0.8$

$\therefore\ \phi = \cos^{-1} 0.8 = 36.86^0$

$\therefore\ \sin\phi = \sin 36.86 = 0.6$

Generated emf at lagging pf,

$$E_f = \sqrt{(V_T\cos\phi + I_a R_a)^2 + (V_T\sin\phi + I_a X_s)^2}$$

$$E_f = \sqrt{(132.8\times 0.8 + 25.1\times 0.5)^2 + (132.8\times 0.6 + 25.1\times 1.2)^2}$$

$$E_f = 161.76\ \text{V}$$

$$\%\ \text{Voltage regulation} = \frac{E_f - V_T}{V_T}\times 100\%$$

$$= \frac{161.76 - 132.8}{132.8}\times 100\% = \mathbf{21.8\%}$$ **Ans.**

(b) At 0.8 power factor leading :

i.e., $\cos\phi = 0.8$

$\therefore\ \phi = \cos^{-1} 0.8 = 36.86^0$

$\therefore\ \sin\phi = \sin 36.86 = 0.6$

Generated emf at leading pf,

$$E_f = \sqrt{(V_T\cos\phi + I_a R_a)^2 + (V_T\sin\phi - I_a X_s)^2}$$

$$E_f = \sqrt{(132.8\times 0.8 + 25.1\times 0.5)^2 + (132.8\times 0.6 - 25.1\times 1.2)^2}$$

$$E_f = 128.71\ \text{V}$$

$$\%\ \text{Voltage regulation} = \frac{E_f - V_T}{V_T}\times 100\%$$

$$= \frac{128.71 - 132.8}{132.8}\times 100 = \mathbf{-3.08\%}$$ **Ans.**

(c) Zero voltage regulation :

Condition for zero voltage regulation,

$$\therefore\ \cos(\theta_z + \phi) = -\frac{I_a Z_s}{2V_T}$$

$$Z_s = R_a + jX_s = 0.5 + j1.2$$

$$Z_s = 1.3\angle 67.38^0 = Z_s\angle\theta_z$$

$$\cos\left(\phi + 67.38^0\right) = \frac{-25.1\times 1.3}{2\times 132.8}$$

$$(\phi + 67.38) = \cos^{-1}(-0.123)$$

$$\phi = 97.056 - 67.38 = 29.68^0$$

$\therefore$ Power factor for zero voltage regulation $= \cos\phi = \mathbf{0.87\ lead}$ **Ans.**

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Sol.4

Given : Full load armature current $I_a = 1$ pu,

Full load terminal voltage $V_T = 1$ pu,

Synchronous reactance $X_s = 20\% = 0.2$ pu, Armature resistance $R_a = 0$

(a) A 0.8 power factor lagging :

i.e., $\cos\phi = 0.8$

$\therefore \quad \phi = \cos^{-1} 0.8 = 36.86^0$

$\therefore \quad \sin\phi = \sin 36.86 = 0.6$

Generated emf,

$$E_f = \sqrt{(V_T \cos\phi + I_a R_a)^2 + (V_T \sin\phi + I_a X_s)^2}$$

$$E_f = \sqrt{(1\times 0.8)^2 + (1\times 0.6 + 1\times 0.2)^2} = 1.1313$$

$$\% \text{ Voltage regulation} = \frac{E_f - V_T}{V_T}\times 100\%$$

$$= \frac{1.1313-1}{1}\times 100\% = \mathbf{13.13\%}$$ **Ans.**

(b) At unity power factor :

Generated emf,

$$E_f = \sqrt{(V_T + I_a R_a)^2 + (I_a X_s)^2}$$

$$= \sqrt{(1+0)^2 + (1\times 0.2)^2} = 1.0198$$

% Voltage regulation

$$= \frac{E_f - V_T}{V_T}\times 100\% = \frac{1.0198-1}{1}\times 100\%$$

$= \mathbf{1.98\%}$ **Ans.**

(c) At 0.8 power factor lead :

i.e., $\cos\phi = 0.8$

$\therefore \quad \phi = \cos^{-1} 0.8 = 36.86^0$

$\therefore \quad \sin\phi = \sin 36.86 = 0.6$

Generated emf,

$$E_f = \sqrt{(V_t \cos\phi + I_a R_a)^2 + (V_T \sin\phi - I_a X_s)^2}$$

$$E_f = \sqrt{(1\times 0.8)^2 + (1\times 0.6 - 1\times 0.2)^2} = 0.8944$$

% Voltage regulation

$$= \frac{E_f - V_T}{V_T}\times 100\% = \frac{0.8944-1}{1}\times 100\%$$

$= \mathbf{-10.56\%}$ **Ans.**

Sol.5

Given : Armature resistance $R_a = 1.5\ \Omega$

Synchronous reactance $X_s = 30\ \Omega$

Load power $P_L = 1280$ kW

Line voltage $V_L = 13500$ V .

Terminal voltage, $V_T = \dfrac{V_L}{\sqrt{3}}$

$$V_T = \frac{13500}{\sqrt{3}} = 7794.23 \text{ V}$$

In star connection,

Line current = Phase current = Armature current

$I_a = I_L$

(a) Unity power factor :

$\cos\phi = 1 \quad \Rightarrow \quad \phi = 0^0 \quad \Rightarrow \quad \sin\phi = 0$

$P_L = \sqrt{3} V_L I_L \cos\phi$

$1280\times 10^3 = \sqrt{3}\times 13500 \times I_L \times 1$

$I_a = I_L = 54.74$ A

Generated emf at unity power factor,

$$E_f = \sqrt{(V_T + I_a R_a)^2 + (I_a X_s)^2}$$

$$E_f = \sqrt{(7794.23 + 54.74\times 1.5)^2 + (54.74\times 30)^2}$$

$E_f = 8045.7$ V

$$\% \text{ Voltage regulation} = \frac{E_F - V_T}{V_T}\times 100\%$$

$$= \frac{8045.7 - 7794.23}{7794.23}\times 100\% = \mathbf{3.22\%}$$

Ans.

(b) 0.8 lagging power factor :

$\cos\phi = 0.8 \Rightarrow \phi = 36.86^0 \Rightarrow \sin\phi = 0.6$

$P_L = \sqrt{3} V_L I_L \cos\phi$

$1280\times 10^3 = \sqrt{3}\times 13500\times I_L \times 0.8$

$I_a = I_L = 68.43$ A

Generated emf at lagging pf,

$$E_f = \sqrt{(V_T \cos\phi + I_a R_a)^2 + (V_T \sin\phi + I_a X_s)^2}$$

$$E_f = \sqrt{(7794.23\times 0.8 + 68.43\times 1.5)^2 + (7794.23\times 0.6 + 68.43\times 30)^2}$$

$E_f = 9244.24$ V

$$\% \text{ Voltage regulation} = \frac{E_F - V_T}{V_T} \times 100\%$$

$$= \frac{9244.24 - 7794.23}{7794.23} \times 100\% = \mathbf{18.6\%}$$

Ans.

(c) 0.8 leading power factor :

$$\cos\phi = 0.8 \Rightarrow \phi = 36.86^0 \Rightarrow \sin\phi = 0.6$$

$$P_L = \sqrt{3} V_L I_L \cos\phi$$

$$1280 \times 10^3 = \sqrt{3} \times 13500 \times I_L \times 0.8$$

$$I_a = I_L = 68.43 \text{ A}$$

Generated emf at leading pf,

$$E_f = \sqrt{(V_T \cos\phi + I_a R_a)^2 + (V_T \sin\phi - I_a X_s)^2}$$

$$E_f = \sqrt{(7794.23 \times 0.8 + 68.43 \times 1.5)^2 + (7794.23 \times 0.6 - 68.43 \times 30)^2}$$

$$E_f = 6859.6 \text{ V}$$

$$\% \text{ Voltage regulation} = \frac{E_F - V_T}{V_T} \times 100\%$$

$$= \frac{6859.6 - 7794.23}{7794.23} \times 100\% = \mathbf{-11.99\%}$$

Ans.

Explanation of Multiple Choice Questions (Based on EMF Equation of Synchronous Machine)

Sol.1

Given : Frequency of first alternator $f_1 = 40\,\text{Hz}$

Frequency of second alternator $f_2 = 25\,\text{Hz}$

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

If both alternators are coupled then both will rotate at same speed i.e., N_s .

So, $N_{s_1} = N_{s_2}$

$$\therefore \quad \frac{120 \times 40}{P_{40\text{Hz}}} = \frac{120 \times 25}{P_{25\text{Hz}}}$$

$$\frac{P_{25}}{P_{40}} = \frac{5}{8}$$

First possible condition when $P = 2$, the ratio is

$$\frac{P_{25}}{P_{40}} = \frac{10}{16}$$

$$N_s = \frac{120 \times 25}{P_{25}} = \frac{120 \times 25}{10} = 300\,\text{rpm}$$

Ans.

$$N_s = \frac{120 \times 25}{P_{40}} = \frac{120 \times 40}{16} = 300\,\text{rpm}$$

Second possible condition when $P = 4$, the ratio is,

$$\frac{P_{25}}{P_{40}} = \frac{20}{32}$$

$$N_s = \frac{120 \times 25}{P_{25}} = \frac{120 \times 25}{20} = 150\,\text{rpm}$$

Ans.

$$N_s = \frac{120 \times 25}{P_{40}} = \frac{120 \times 40}{32} = 150\,\text{rpm}$$

Ans.

Hence, the correct option is (A).

Sol.2

If direction of field current is reversed, then there is no change in its phase sequence. Usually the phase sequence of alternator can be changed by changing/reversing the direction of rotor rotation. But not depends on field current direction.

Hence, the correct option is (B).

Sol.3

In a 2 phase and 3 phase AC machine, rotating MMF is produced with magnitudes of ϕ_m and $\dfrac{3}{2}\phi_m$.

Hence, the correct option is (A).

Sol.4

The armature field/air gap field

1. The main field (mmf or poles) is stationary w.r.t stator
   ∴ The armature field(mmf or poles) must be stationary w.r.t stator because the two fields armature field and main field must be stationary w.r.t each other.
2. Hence armature field (mmf or poles) will rotate in opposite direction to rotor (Armature) rotation.
3. The armature field will rotate at double the N_s w.r.t rotor.

Hence, the correct option is (B).

Sol.5

Given : Frequency of first alternator $f_1 = 60\,\text{Hz}$

Frequency of second alternator $f_2 = 25\,\text{Hz}$

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

If both alternators are coupled then both will rotate at same speed i.e. N_s

So, $N_{s_1} = N_{s_2}$

∴ $$\frac{120\times 60}{P_{60\,\text{Hz}}} = \frac{120\times 25}{P_{25\,\text{Hz}}}$$

$$\frac{P_{25}}{P_{60}} = \frac{5}{12}$$

First possible condition when $P = 2$, the ratio is

$$\frac{P_{25}}{P_{60}} = \frac{10}{24}$$

$$N_s = \frac{120\times 25}{P_{25}} = \frac{120\times 25}{10} = 300\,\text{rpm}$$

Ans.

Second possible condition when $P = 4$, the ratio is

$$\frac{P_{25}}{P_{60}} = \frac{20}{48}$$

$$N_s = \frac{120\times 25}{P_{25}} = \frac{120\times 25}{20} = 150\,\text{rpm}$$

Ans.

Third possible condition when $P = 6$, the ratio is

$$\frac{P_{25}}{P_{60}} = \frac{30}{72}$$

$$N_s = \frac{120\times 25}{P_{25}} = \frac{120\times 25}{30} = 100\,\text{rpm}$$

Ans.

Hence, the correct option is (A).

Explanation of Multiple Choice Questions (Based on Armature Winding)

Sol.1

Given : Number of poles $P = 4$

Number of slots = 60

Flux per pole $\phi_p = 1.5\,\text{Wb}$

Conductor per slot = 16

Synchronous speed $N_s = 1500\,\text{rpm}$

Coil span $= 156^0$.

Number of slot per pole per phase,

$$m = \frac{\text{Slots}}{\text{Poles}\times\text{Phase}} = \frac{60}{4\times 3} = 5$$

Slot angle, $\beta = \dfrac{180^0\times\text{Poles}}{\text{Slots}} = \dfrac{180^0\times 4}{60} = 120^0$

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

$$K_d = \frac{\sin(5\times 12^0/2)}{5\sin(12^0/2)} = 0.9567$$

Pole pitch $= 180^0$, Coil span $= 156^0$

Short pitch angle, α = Pole pitch – Coil span

$$\alpha = 180^0 - 156^0 = 24^0$$

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

$$K_p = \cos\left(\frac{24^0}{2}\right) = 0.978$$

Total number of conductor per phase,

$$Z_{ph} = \frac{\text{Conductors}}{\text{Phase}}$$

$$Z_{ph} = \frac{\text{Conductors}}{\text{Slots}} \times \frac{\text{Slots}}{\text{Phase}}$$

$$Z_{ph} = 16 \times \frac{60}{3} = 320$$

Total number of turns per phase,

$$N_{ph} = \frac{Z_{ph}}{2} = \frac{320}{2} = 160$$

Frequency, $f = \frac{PN_s}{120} = \frac{1500 \times 4}{120} = 50 \text{ Hz}$

Induced emf per phase,

$$E_{ph} = 4.44 K_p K_d f \phi_p N_{ph}$$

$$E_{ph} = 4.44 \times 0.9567 \times 0.978 \times 50 \times 1.5 \times 160$$

$\therefore \quad E_{ph} = 49.851 \text{ kV}$ **Ans.**

Hence, the correct option is (B).

Sol.2

Given : Synchronous speed $N_s = 300 \text{ rpm}$,

Line voltage $E_L = 11 \text{kV}$,

Total number of slot = 360,

Conductor per slot = 6,

Phase voltage $E_{ph} = \frac{11000}{\sqrt{3}} = 6351 \text{ V}$

Slot per pole per phase,

$$m = \frac{\text{Slots}}{\text{Poles} \times \text{Phase}} = \frac{360}{20 \times 3} = 6$$

Synchronous speed, $N_s = \frac{120 f}{P} = 300 \text{ rpm}$

Number of poles, $P = \frac{120 f}{N_s} = \frac{120 \times 50}{300} = 20$

Slot angle, $\beta = \frac{180^0 \times \text{Poles}}{\text{Slots}} = \frac{180^0 \times 20}{360} = 10^0$

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

$$K_d = \frac{\sin(6 \times 10^0/2)}{6 \sin(10^0/2)} = 0.956$$

Coil span $= \frac{5}{6} \times \text{Pole pitch} = \frac{5}{6} \times 180^0 = 150^0$

Short pitch angle, $\alpha = \text{Pole pitch} - \text{Coil span}$

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

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

$$K_p = \cos\left(\frac{30^0}{2}\right) = 0.966$$

Total number of conductor per phase,

$$Z_{ph} = \frac{\text{Conductors}}{\text{Phase}}$$

$$Z_{ph} = \frac{\text{Conductors}}{\text{Slots}} \times \frac{\text{Slots}}{\text{Phase}}$$

$$Z_{ph} = 6 \times \frac{360}{3} = 720$$

Total number of turns per phase,

$$N_{ph} = \frac{Z_{ph}}{2} = \frac{720}{2} = 360$$

Induced emf per phase,

$$E_{ph} = 4.44\, K_p K_d f \phi_p N_{ph}$$

Flux per pole, $\phi_p = \frac{E_{ph}}{4.44 K_p K_d f N_{ph}}$

$$\phi_p = \frac{6351}{4.44 \times 0.966 \times 0.956 \times 50 \times 360}$$

$\phi_p = 0.086 \text{ Wb}$ **Ans.**

Hence, the correct option is (D).

Sol.3

Given : Number of pole $P = 4$

Frequency, $f = 50$ Hz, Number of slots = 48

Flux per pole $\phi_p = 0.025$ Wb

Number of turns in each coil $= 10$.

For double layer winding :

Number of coils = Number of slots = 48

So, total number of turns, $N = 48 \times 10 = 480$

Turns per phase,

$$N_{ph} = \frac{\text{Number of turns}}{\text{phase}} = \frac{480}{3} = 160$$

Number of slots per pole per phase,

$$m = \frac{\text{Slots}}{\text{Pole} \times \text{Phase}} = \frac{48}{4 \times 3} = 4$$

Slot angle, $\beta = \dfrac{180 \times \text{poles}}{\text{slots}} = \dfrac{180 \times 4}{48} = 15^0$

For n^{th} Harmonic, distribution factor is given by,

$$K_{dn} = \frac{\sin\dfrac{nm\beta}{2}}{m\sin\dfrac{n\beta}{2}}$$

Hence, the fundamental distribution factor is given by,

$$K_{d_1} = \frac{\sin\dfrac{m\beta}{2}}{m\sin\dfrac{\beta}{2}} = \frac{\sin\dfrac{4 \times 15}{2}}{4\sin\dfrac{15}{2}} = 0.957$$

For n^{th} Harmonic, pitch factor is given by,

$$K_{pn} = \cos\frac{n\alpha}{2}$$

Hence, the fundamental pitch factor is given by,

$$K_{p_1} = \cos\frac{\alpha}{2} = \cos 18^0 = 0.951$$

Winding factor is given by,

$$K_{w_1} = K_{p_1} K_{d_1} = 0.951 \times 0.957 = 0.91$$

Induced emf per phase is given by,

$$E_{ph} = 4.44 K_p K_d \phi_p \, f \, N_{ph}$$

$$E_{ph} = 4.44 \times 0.951 \times 0.957 \times 0.025 \times 50 \times 160$$

$$E_{ph} = 808 \text{ V}$$

Line voltage, $E_L = \sqrt{3} E_{ph} = \sqrt{3} \times 808 = 1400$ V

Ans.

Hence, the correct option is (C).

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Sol.4

For 2-phase,

Number of slots per pole per phase,

$$m = \frac{\text{Slots}}{\text{Pole} \times \text{Phase}} = \frac{48}{4 \times 2} = 6$$

Turns per phase, $N_{ph} = \dfrac{\text{Number of turns}}{\text{phase}}$

$$N_{ph} = \frac{480}{2} = 240$$

Distribution factor for 2- phase,

$$K_{d_{2\text{-}\phi}} = \frac{\sin\left(\dfrac{m\beta}{2}\right)}{m\sin\left(\dfrac{\beta}{2}\right)} = \frac{\sin\dfrac{6 \times 15}{2}}{6\sin\dfrac{15}{2}} = 0.903$$

Induced emf per phase is given by,

$$E_{ph} = 4.44 K_p K_d \phi_p \, f \, N_{ph}$$

$$E_{ph} = 4.44 \times 0.951 \times 0.903 \times 0.025 \times 50 \times 240$$

$$E_{ph} = 1143.85 \text{ V}$$

Line voltage,

$E_L = \sqrt{2} E_{ph} = \sqrt{2} \times 1143.85 = 1617$ V **Ans.**

Hence, the correct option is (C).

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Sol.5

Given : Number of poles $P = 4$

Number of slots = 36, Phase spread, $\sigma = 60^0$

Coil span = 7 slots.

Number of slots per pole per phase,

$$m = \frac{\text{Slots}}{\text{Pole} \times \text{Phase}} = \frac{36}{4 \times 3} = 3$$

Pole pitch, $\dfrac{\text{Slots}}{\text{Pole}} = \dfrac{36}{4} = 9$

Short pitch = Pole pitch – Coil span

$= 9 - 7 = 2$ slots

Since, coil is short pitched by 2 slots so it is shifted left side by 2 slots.

Hence, same phase slots $= (m-2)\times\frac{\text{Slots}}{m}$

$$= (3-2)\times\frac{36}{3} = 12$$

Different phase slots $= 36 - 12 = 24$

Hence, the correct option is (A).

Explanation of Multiple Choice Questions (Based on Armature Reaction)

Sol. 1

For lagging load is the current will be shifted in space by an angle 90^0.From maximum emf which coincide with center of pole. The armature flux and field flux act directly opposite to each other. Thus, armature reaction of the alternator at lagging zero power factor is a purely demagnetizing type. That means, armature flux directly weakens main field flux.

Hence, the correct option is (B).

Sol. 2

With the field circuit ON and the stator disconnected from the supply,

$$\phi_r = \phi_m = 25 \text{ mWb}$$

When the stator is connected to the rated supply with the field excitation unchanged,

$$\phi_r = \phi_m + \phi_{ar} = 20 \text{ mWb}$$

The observation here is when motor is in operation the net flux decreasing i.e.,

$$\phi_r = \phi_m - \phi_{ar} = 20 \text{ mWb}$$

$\therefore$ Effect of Armature reaction is due to demagnetization i.e, and it happens in leading power factor. So the no load current drawn by motor leads the supply voltage

Hence, the correct option is (B).

Sol. 3

In case of motor under zero power factor leading condition of alternator, the effect of armature reaction mmf is purely demagnetizing. And $\phi_f > \phi_r$ machine is to be said as over excited to maintained terminal voltage.

Hence, the correct option is (C).

Sol. 4

Machine is to be said as under excited to maintained terminal voltage i.e $\phi_f < \phi_r$. It is obtained when the motor under zero power factor lagging loading condition of alternator, the effect of armature reaction mmf is purely magnetizing.

Hence, the correct option is (A).

Sol. 5

The effect of armature reaction mmf on main filed mmf of alternator and motor is tabulated below.

S. No.	Power factor	Synchronous generator		Synchronous motor	
		Armature Reaction	Excitation	Armature reaction	Excitation
1.	Unity Power Factor	Cross Magnetizing	Normal	Cross Magnetizing	Normal
2.	Zero power Factor Lagging	Purely Demagnetizing	Over	Purely Magnetizing	Under
3.	Zero power Factor Leading	Purely Magnetizing	Under	Purely Demagnetizing	Over
4.	Lagging Power Factor	Cross Magnetizing + Demagnetizing	Slightly Over	Cross Magnetizing + Magnetizing	Slightly Under
5.	Leading Power Factor	Cross Magnetizing + Magnetizing	Slightly Under	Cross Magnetizing + Demagnetizing	Slightly Over

From the above table.

Hence, the correct option is (B).

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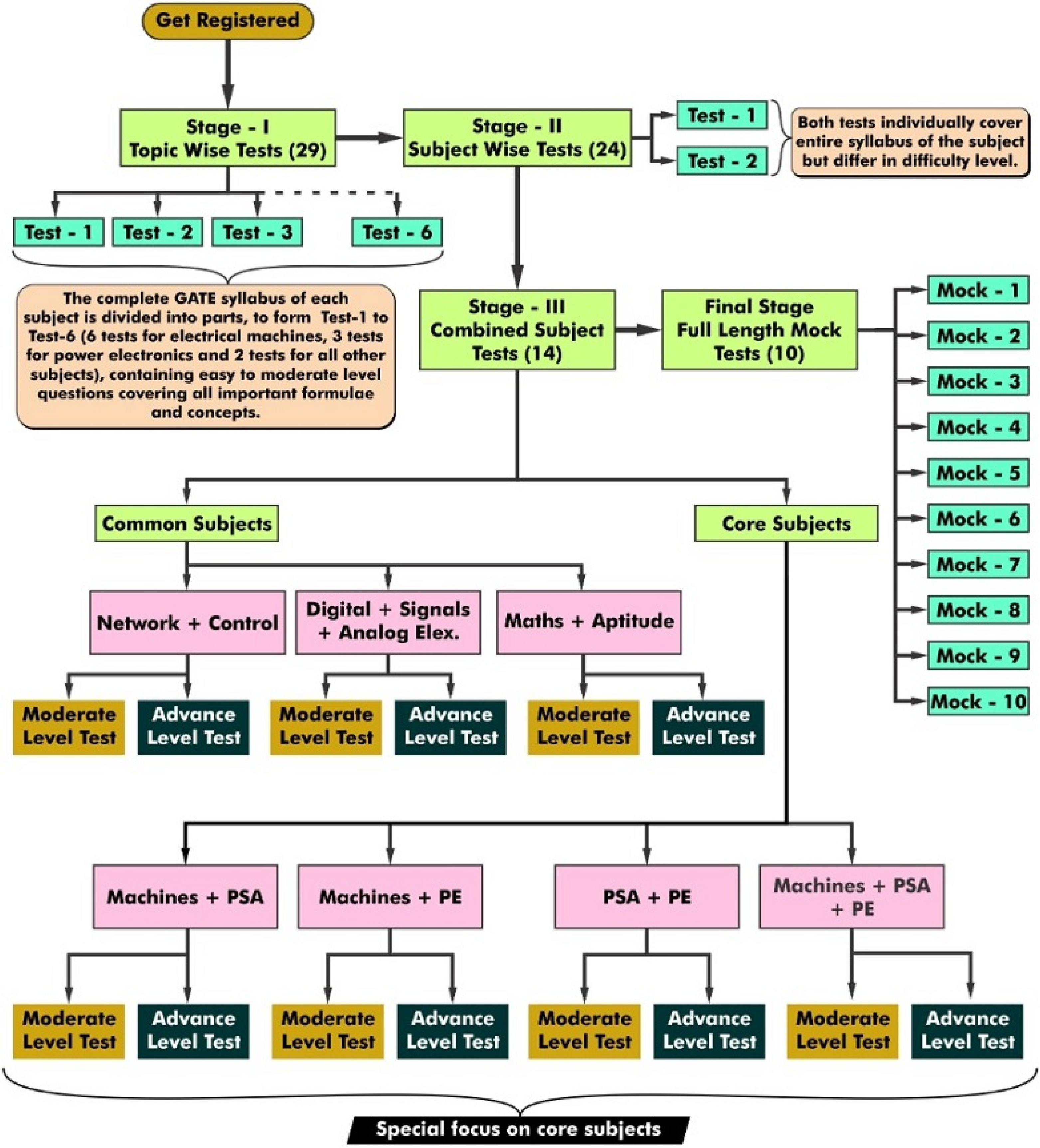

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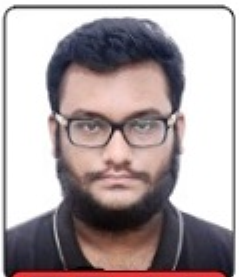
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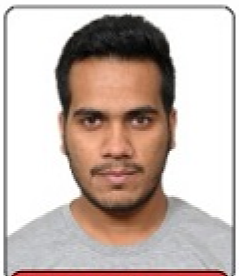
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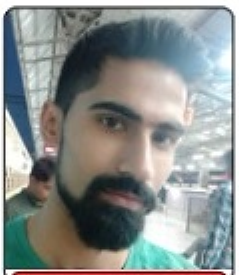
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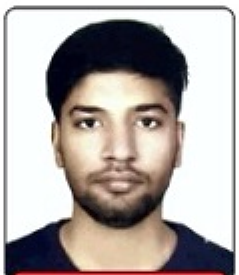
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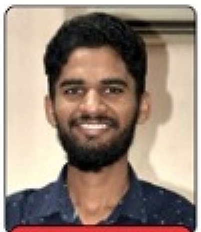
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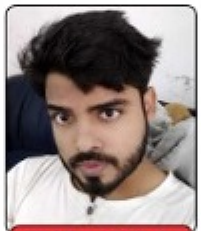
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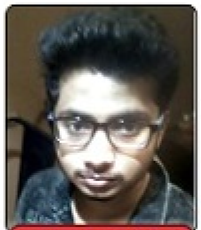
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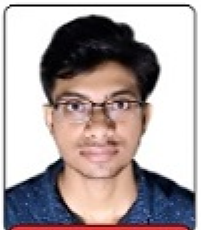
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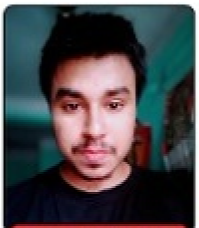
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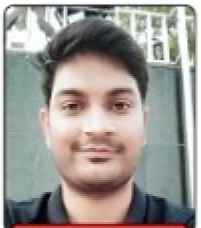
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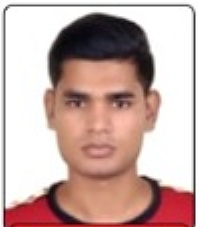
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CHAPTER 2

Induction Machine

Learning Objectives :

After reading this chapter you should be able to :

- Understand basic of induction machine.
- Explain construction and working of induction machine.
- Understand equivalent circuit diagrams.
- Understand torque and power equations.
- Explain different test of induction machines.
- Understand starting and speed control of induction machine.

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2.1 Introduction

An induction machine is basically a rotating machine. It is either to convert mechanical energy to electrical energy (Induction generator) and to convert electrical energy to mechanical energy (Induction motor)

Construction-wise there is no difference between induction generator and induction motor, the same machine can be used as either generator or a motor.

- If the input is electrical energy, then it work as an induction motor
- If the input is mechanical energy, then it work as an induction generator

Induction machines have two modes :

1. Motoring mode; $N_r < N_s$
2. Generating mode; $N_r > N_s$

Where, N_r = Rotor speed and N_s = Synchronous speed.

At $N_r = N_s$ induction motor doesn't operate. Induction machine is also called asynchronous machine. In induction machine the two windings are stator winding and rotor winding. Induction machine is singly excited machine like Transformer. Induction machine and transformer both are operated on same principle i.e. mutual induction principle. Induction machine is basically a transformer with a rotating short circuited secondary.

The phasor diagram and equivalent circuit of 3-ϕ induction motor are almost similar to those in a transformer. In Induction motor, the magnetizing current is 30-50% of rated current. Induction machine is a variable frequency machine (i.e. slip frequency). This machine is electro-mechanical energy conversion machine. In Induction machine magnetic circuit is discontinuous magnetic circuit or composite magnetic circuit. (Air gap is the magnetic path between stator and rotor)

Reluctance offered to the flux is high as compared with transformer due to air gap. Induction motor is just similar to D.C shunt motor and has D.C shunt motor type characteristics (D.C shunt motor is replaced by Induction motor). Speed control of Induction machine is very difficult.

Mechanical power output of induction motor, $P = \frac{2\pi NT}{60}$

Note : Power output of induction motor is directly proportional to speed.

Advantages of induction motors over DC motors :

Because of some of the following advantages, the induction motors are replacing the dc motors, in various applications. The advantages are :

1. Low cost.
2. It can produce sufficient torque.
3. Ruggedness, smaller size and weight.
4. Speed control by using thyristors can give a wide range of speeds.
5. Low maintenance requirement since the squirrel cage induction motor does not use the commutators and brushes.

6. They can operate in dusty and explosive environments, because the brushes are not being used. Therefore there is no possibility of sparking.
7. They can operate at higher speeds, of the order of 12000 rpm. This is again possible as the brushes are absent so no friction.
8. Its torque speed characteristics is similar to dc shunt motor characteristics. So it runs at almost constant speed at all loads.

Disadvantages of induction motors over DC motors :

1. Low starting torque.
2. Lagging and low power factor.
3. The efficiency of induction motors varies with speed.
4. Speed control by electrical methods is not easy.
5. In induction motors the flux and armature (stator) current cannot be controlled separately, as there is only stator winding and rotor is not accessible for the user.

Applications of induction motor :

1. Conveyors
2. Food and chemical industries
3. Pumps
4. Extruders
5. Paper and sugar industries etc.
6. Fans
7. Chemical, textile, mines and traction etc.

Difference of induction machine and transformer :

Induction machine and transformer both operate on the principle of electromagnetic induction or mutual induction and hence there are many similarities between the two machines. But still there are certain differences mainly due to the fact that one is a rotating machine while other is static machine. Differences are as follows :

1. A Transformer is a static device, whereas motor is a dynastic machine contains on moving parts.
2. A transformer transfers electrical power from one circuit to another without changing the supply frequency, i.e. it only step-up or step-down the level of voltage and current, whereas induction motor converts electrical power into mechanical power.
3. In a transformer, the frequency of induced EMF and current in the secondary is same as supply frequency, i.e. primary and secondary frequency is constant while in an induction motor, the frequency of current and EMF on stator remains same, whereas the frequency of the rotor is variable which depends on slip and slip further depends on motor loads. The frequency of induced EMF on the rotor is equal to slip times the stator frequency.
4. In a transformer, both the input and output energy (primary and secondary) is in the form of electrical energy, whereas in motor, the supply energy in the rotor is in electrical form and the stator energy converted to the mechanical form of energy.
5. A transformer is an alternating flux machine while induction motor is a rotating flux machine.
6. In a transformer, mostly a ferromagnetic iron core is used as a medium for the passage of flux from primary to secondary, whereas in an induction motor, the air gap is used between rotor and stator.

7. A transformer can be operated at any kind of power factor depends on load while induction motor operated on lagging power factor because it draws lagging current to magnetize the rotor field at starting and operating due to air gap.
8. A transformer efficiency is always higher than the induction motor efficiency because there is no moving parts in a transformer, whereas mechanical losses occurs in an induction motor as it is not static machine like a transformer.

Difference between synchronous motor and induction motor :

Synchronous Generator is popular because it generates constant frequency output but Induction Generator is not so popular because it generates power at variable frequency. Differences are as follows :

S. No.	Synchronous motor	Induction motor
1.	Construction is complicated	Construction is simpler, particularly in case of cage rotor.
2.	Not self-starting.	Self-starting.
3.	Separate dc source is required for rotor excitation.	Rotor gets excited by the induced emf. So separate source is not necessary.
4.	The speed is always synchronous irrespective of load.	The speed is always less than synchronous but never synchronous.
5.	Speed control is not possible.	Speed control possible though difficult.
6.	As load increases, load angle increases, keeping speed constant as synchronous.	As load increases, the speed keeps on decreasing.
7.	By changing excitation, the motor power factor can be changed from lagging and leading.	It always operates at lagging power factor and power factor control is not possible.
8.	It can be used as synchronous condenser for power factor improvement.	It cannot be used as a synchronous condenser.
9.	Motor is sensitive to sudden load changes and hunting results.	Phenomenon of hunting is absent.
10.	Motor is costly and requires frequent maintenance.	Motor is cheap specially cage motors are maintenance free.

2.2 Rotating Magnetic Fields

Definition : When balanced poly-phase currents flow in balanced poly phase windings a rotating magnetic field is produced which rotates in synchronous speed. In other words, all poly-phase a.c. machines are associated with rotating magnetic fields in their air gap.

The induction motor operates on the principle of rotating magnetic field which is produced by the stator winding of the induction motor in the air gap between the stator and rotor.

The stator is three phase winding which can be either star connected or delta connected. Whenever the ac supply is connected to the stator winding line current I_R, I_Y and I_B start flowing and these line currents are phase shifted by 120^0 with respect to each other.

Due to each line current a sinusoidal flux is produced in the air gap. These fluxes have the same frequency as that of the line current and they are also 120^0 phase shifted with respect to each other.

Let the flux produced by the line current I_R is ϕ_R, flux produced by I_Y is ϕ_Y and flux produced by I_B is ϕ_B.

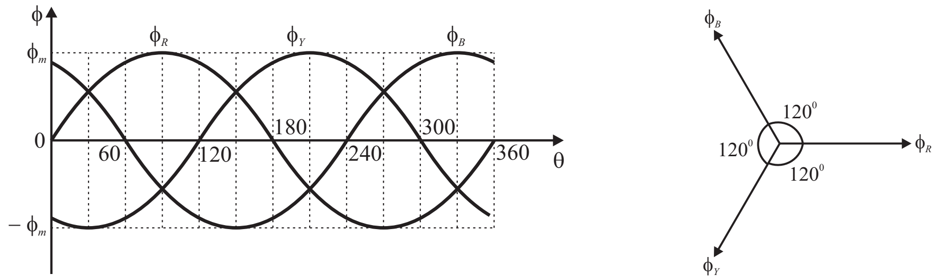


Fig. (a)

$$\phi_R = \phi_m \sin\omega t \quad \ldots(i)$$

$$\phi_Y = \phi_m \sin(\omega t - 120^0) \quad \ldots(ii)$$

$$\phi_B = \phi_m \sin(\omega t - 240^0) \quad \ldots(iii)$$

Total flux ϕ_m in the air gap between the stator and rotor is equal to the phasor sum of the three component fluxes,

$$\phi_m = \phi_R + \phi_Y + \phi_B$$

Let the phasor ϕ_R as the reference phasor and all the angle expressed and drawn with respect to this phasor at different value of ωt such as 0^0, 60^0, 120^0 and 180^0 and obtain the value of ϕ_m.

Case 1 : For first condition assume $(\omega t = 0^0)$

Put the value of ωt in equation (i), (ii) and (iii), we get

$$\phi_R = \phi_m \sin 0^0 = 0$$

$$\phi_Y = \phi_m \sin(0^0 - 120^0) = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(0^0 - 240^0) = \frac{\sqrt{3}}{2}\phi_m$$

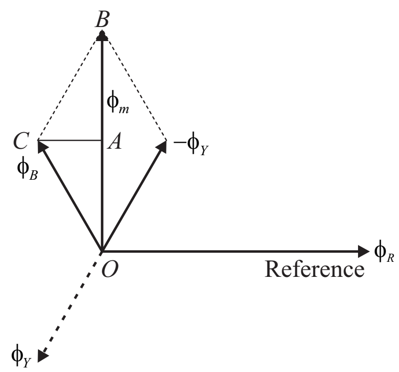


Fig. (b) Phasor diagram when $\omega t = 0$

Draw a perpendicular line in OB for finding magnitude of ϕ_m.

In figure (b), $\phi_m = OB = 2 \times OA$

and $OA = OC\cos 30^0$ ...(iv)

And we know that, $OC = \phi_B = \frac{\sqrt{3}}{2}\phi_m$

Put this value of OC in equation (iv), we get

$$OA = \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = \frac{3}{4}\phi_m$$

and $$\phi_m = OB = 2\times\frac{3}{4}\phi_m = \frac{3}{2}\phi_m$$

In phasor diagram shown that when $\omega t = 0$, ϕ_m lead by ϕ_R by 90^0 and magnitude is $\frac{3}{2}\phi_m$.

Case 2 : Assume $(\omega t = 60^0)$

Put the value of ωt in equation (i), (ii) and (iii),

$$\phi_R = \phi_m \sin 60^0 = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = \phi_m \sin(60^0 - 120^0) = -\frac{\sqrt{3}}{2}\phi_m$$

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

Draw a perpendicular line in OB for finding magnitude of ϕ_m.

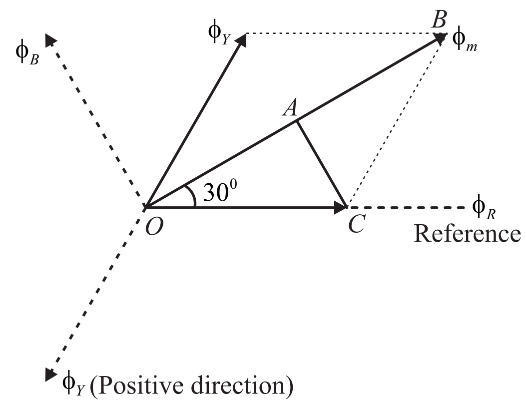


Fig. (c) Phasor diagram when ωt = 60^0

In figure (c), $\phi_m = OB = 2\times OA$

and $OA = OC\cos 30^0$ ...(v)

And we know that, $OC = \phi_R = \frac{\sqrt{3}}{2}\phi_m$

Put this value of OC in equation (v),

$$OA = \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = \frac{3}{4}\phi_m$$

and $$\phi_m = OB = 2\times\frac{3}{4}\phi_m = \frac{3}{2}\phi_m$$

In phasor shown that when $\omega t = 60$, ϕ_m lead by ϕ_R by 30^0 and magnitude is $\frac{3}{2}\phi_m$.

Case 3 : Assume $(\omega t = 120^0)$

Put the value of ωt in equation (i), (ii) and (iii), we get

$$\phi_R = \phi_m \sin 120^0 = \frac{\sqrt{3}}{2}\phi_m$$

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

$$\phi_B = \phi_m \sin(120^0 - 240^0) = -\frac{\sqrt{3}}{2}\phi_m$$

Draw a perpendicular line in OB for finding magnitude of ϕ_m.

In figure (d), $\phi_m = OB = 2 \times OA$

and $OA = OC\cos 30^0$ ...(vi)

And we know that, $OC = \phi_R = \frac{\sqrt{3}}{2}\phi_m$

Put this value of OC in equation (vi), we get

$$OA = \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = \frac{3}{4}\phi_m$$

and $$\phi_m = OB = 2\times\frac{3}{4}\phi_m = \frac{3}{2}\phi_m$$

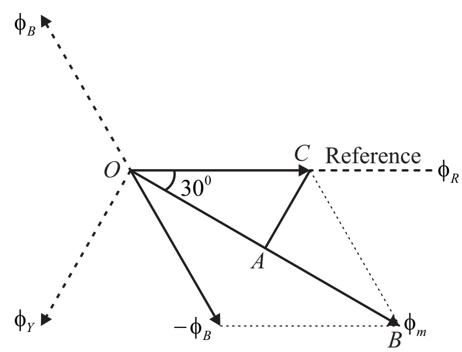


Fig. (d) Phasor diagram when $\omega t = 120^0$

In phasor diagram shown that when $\omega t = 120$, ϕ_m lags by ϕ_R by 30^0 and magnitude is $\frac{3}{2}\phi_m$.

Case 4 : Assume $\omega t = 180^0$

Put the value of ωt in equation (i), (ii) and (iii),

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

$$\phi_Y = \phi_m \sin(180^0 - 120^0) = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(180^0 - 240^0) = -\frac{\sqrt{3}}{2}\phi_m$$

Draw a perpendicular line in OB for finding magnitude of ϕ_m.

In figure (e), $\phi_m = OB = 2\times OA$

and $OA = OC\cos 30^0$ ...(vii)

and we know that, $OC = \phi_Y = \frac{\sqrt{3}}{2}\phi_m$

Put this value of OC in equation (vii),

$$OA = \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = \frac{3}{4}\phi_m$$

and $$\phi_m = OB = 2\times\frac{3}{4}\phi_m = \frac{3}{2}\phi_m$$

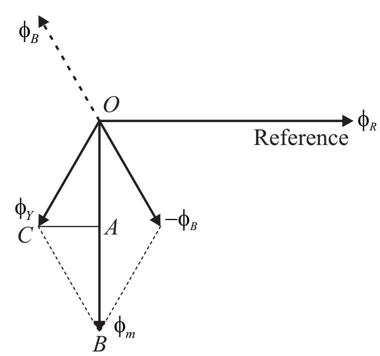


Fig. (e) Phasor diagram when $\omega t = 180^0$

In phasor diagram shown that when $\omega t = 180$, ϕ_m lags by ϕ_R by 90^0 and magnitude is $\frac{3}{2}\phi_m$.

So, the conclusion is that, the magnitude ϕ_m at any value of ωt from 0^0 to 360^0 is same and rotates in the clock wise direction in space.

Important term related to speed of rotating resultant MMF :

1. **Mechanical degrees :** The degree of physical or mechanical rotation in a single conductor in an alternator.

2. **Electrical degrees :** The degree or the cycle of emf induced in a single conductor in an alternator.

Consider a two pole alternator, when a conductor rotates in the field, the emf induced in the conductor will be maximum when the conductor is at the center of the pole and the emf induced will be minimum when the conductor is in the middle of the gap between the two poles, so when we consider the graph of the induced emf versus the position or degree of rotation. For one complete rotation of the conductor in the field one complete cycle of emf is generated in the conductor (positive half cycle at south-pole and negative half-cycle at north-pole).

The same way when we consider a 4 pole alternator a single conductor when completing one mechanical rotation will cross the four poles there by giving the induced emf graph with two positive half cycles and two negative half-cycles which gives us two complete cycles of induced emf.

So, for one mechanical rotation (360 degrees) the induced emf completes two cycles ($360 \times 2 = 720$ degrees in terms of the sine wave).

So, the relation between electrical and mechanical degrees can be written as,

$$\text{Electrical degrees} = \frac{\text{Number of poles}}{2} \times \text{Mechanical degrees}$$

i.e.,
$$\theta_e = \frac{P}{2}\theta_m$$

3. **Frequency of induced emf :** The frequency of the generated voltage depends upon the number of field poles and on the speed at which the field pole are rotated. One complete cycle of voltage is generated in an armature coil when a pair of field poles passes over the coil. Let, $P =$ Number of poles, $N =$ Speed of the rotor in rpm, $f =$ Frequency of the induced emf.

From the discussion, we can write,

One mechanical revolution of rotor $= \frac{P}{2}$ cycles of emf electrically.

Thus there are $\frac{P}{2}$ cycles per revolution.

As speed is N rpm, in one second, rotor will complete $\left(\frac{N}{60}\right)$ revolutions.

But cycle/sec = Frequency = f

∴ Frequency, $f =$ Number of cycle per revolution × Number of revolutions per second

$$\therefore \quad f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120} \text{ Hz} \qquad \text{(cycles per sec)}$$

Above equation give the relation between three quantities, the number poles P, the speed of the rotor N in rpm and the frequency f of an induced emf in Hz.

4. **Synchronous speed :** From the above expression, it is clear that for fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated emf constant at the required value. Such a speed is called **synchronous speed** of the alternator denoted as N_s.

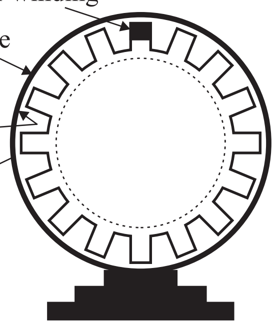
So, $$N_s = \frac{120 f}{P}$$

2.3 Construction of Induction Motor

Definition : Three phase **Induction motor** mainly consists of two parts called as the **Stator** and the **Rotor**. The stator is the stationary part of the induction motor, and the rotor is the rotating part. The construction of the stator is similar to the three-phase synchronous motor, and the construction of rotor is different for the different machine.

2.3.1 Stator

As its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it. Shape of stator is hollow cylindrical.



The stator of the three-phase induction motor consists of three main parts :

1. Stator frame,
2. Stator core
3. Stator winding or field winding.

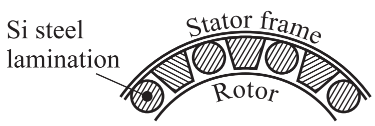
1. **Stator frame :** It is the outer part of the **three phase induction motor**. Its main function is to support the stator core and the field winding. It acts as a covering, and it provides protection and mechanical strength to all the inner parts of the induction motor. The frame is either made up of die-cast or fabricated steel. The frame of three phase induction motor should be strong and rigid as the air gap length of three phase induction motor is very small. Otherwise, the rotor will not remain concentric with the stator, which will give rise to an unbalanced magnetic pull.
2. **Stator core :** The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current loss, the stator core is laminated. These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick. All the stamping are stamped together to form stator core, which is then housed in stator frame. The stamping is made up of silicon steel, which helps to reduce the hysteresis loss occurring in the motor.
3. **Stator winding or field winding :** The slots on the periphery of the stator core of the three-phase induction motor carry three phase windings. We apply three phase ac supply to this three-phase winding. The winding wound on the stator of three phase induction motor is also called field winding, and when this winding is excited by three phase ac supply, it produces a rotating magnetic field.

The three phases of the winding are connected either in star or delta depending upon which type of starting method we use. We start the squirrel cage motor mostly with star-delta starter and hence the stator of squirrel cage motor is delta connected. We start the slip ring three-phase induction motor by inserting resistances so, the stator winding of slip ring induction motor can be connected either in star or delta.

Shapes of stator slots (types of slots) : The shape of slots has an important effect upon the operating performance of the motor as well as the problem of installing the winding. In general three types of slots can be used in three phase induction machines, namely

1. Open slots 2. Semi-closed slots 3. Closed slots

1. **Open slots :** The representation of open type slots is shown in figure.



Advantages :

(i). When open slots are used, winding coils can be formed and insulated completely before they are inserted in the slots.

(ii) Easy for repair.

(iii) Avoids excessive slot leakage.

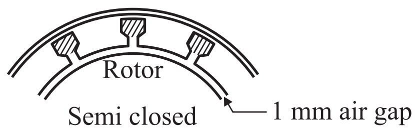
(iv) Leakage reactance is less in open type slot. Therefore more amount of power will be transferred from stator to rotor and torque production is high.

Disadvantages :

(i) Inserting winding into the slots is difficult.

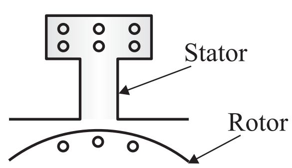
(ii) More leakage flux, reactance of leakage flux is high. Therefore less amount of power will be transferred from stator to rotor and torque production is less.

2. **Semi-closed slots :** The representation of semi closed type slots is shown in figure.



Advantages :

(i) The average air gap length between stator and rotor is less as shown below figure.



(ii) Flux distribution is uniform and harmonics are less.

(iii) The operation of motor is smooth.

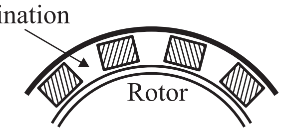
Disadvantages :

(i) Inserting windings into the slot is difficult task.

(ii) More leakage flux.

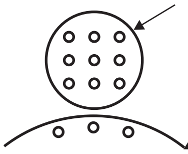
(iii) Less amount of power will be transferred from stator to rotor. Hence, torque production is less.

3. **Closed slots :** The representation of closed type slots is shown in figure.



Advantages :

(i) The average air gap length between stator and rotor is very less therefore machine draw very less exciting current as shown in below figure,



(ii) Flux distribution is uniform. Hence, harmonics are almost absent.

(iii)The operation of motor is very smooth.

Disadvantages :

(i) It is very difficult to place windings into slots.

(ii) The leakage flux is very high.

(iii)Power transfer from stator to rotor is very less. Hence, production of toroque is also very less.

Conclusion :

- Magnetizing current, $I_m(\text{open}) > I_m(\text{semi open}) > I_m(\text{closed})$
- No load power factor, $\cos\phi_0(\text{open}) < \cos\phi_0(\text{semi}) < \cos\phi_0(\text{closed type})$
- Leakage reactance, $X_l(\text{open}) < X_l(\text{semi open}) < X_l(\text{closed})$
- Torque production, $T(\text{open}) > T(\text{semi open}) > T(\text{closed})$
- Harmonic torque, Open > Semi open > Closed.

In general semi open type slots are preferred in induction machine. Open type slots are preferred in DC machines and synchronous machine.

Comparison of different slot in stator :

Open slot	Close slot	Semi closed
Net air gap is more.	Net air gap is least.	Moderate.
Requires more magnetising current to maintain flux.	Loss magnetising current.	Moderate magnetizing.
W.r.t. magnetising current operating PF is low.	Better power factor.	Moderate power factor.
Offers more reluctance to leakage flux and less leakage reactance.	High leakage and high leakage reactance.	Moderate.

W.r.t. leakage reactance operating power factor is better.	Low operating power factor.	Moderate operating power factor.
Non uniform air gap produce slot or teeth or space harmonic.	No slot harmonics.	Moderate slot harmonics.

2.3.2 Rotor

The rotor is the rotationary part of machine, which is connected to mechanical load through shaft. The conversion of electrical power into mechanical power take place. The rotor is placed inside the stator. The rotor core is also laminated in construction and uses cast iron. It is cylindrical, with slots on its periphery.

The rotor conductors or winding is placed in the rotor slots. The two types of rotor constructions which are used for induction motors are,

1. Squirrel cage rotor
2. Slip ring or wound rotor

1. Squirrel cage rotor : The rotor core is cylindrical and slotted on its periphery. The rotor consists of uninsulated copper or aluminium bars called rotor conductors. The bars are placed in the slots. These bars are permanently shorted at each end with the help of conducting copper ring called end ring.

The bars are usually brazed to the end rings to provide good mechanical strength. The entire structure looks like a cage, forming a closed electrical circuit. So the rotor is called squirrel cage rotor. The construction is shown in the figure (a).

As the bars are permanently shorted to each other through end ring, the entire rotor resistance is very-very small. Hence this rotor is also called short circuited rotor. As rotor itself is short circuited, no external resistance can have any effect on the rotor resistance.

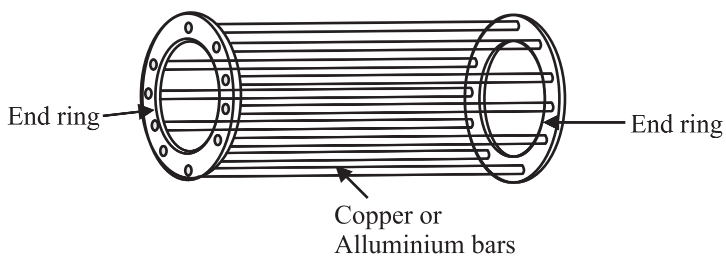


Fig. (a) Squirrel cage rotor

Hence no external resistance can be introduced in the rotor circuit. So slip ring and brush assembly is not required for this rotor. Hence the construction of this rotor is very simple.

In this type of rotor, the slots are not arranged parallel to the shaft axis but are skewed as shown in the figure (b).

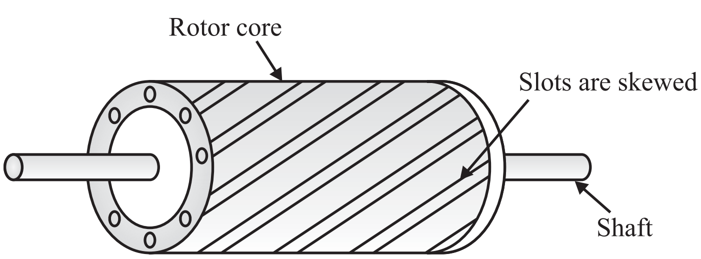


Fig. (b) Skewing in rotor construction

Advantages of skewing are :

(i) A magnetic hum i.e. noise gets reduced due to skewing hence skewing makes the motor operation quieter.

(ii) It makes the motor operation smooth.

(iii)The stator and rotor teeth may get magnetically locked. Such a tendency of magnetic locking gets reduced due to skewing.

(iv) It increases the effective transformation ratio between stator and rotor.

Advantages of squirrel cage induction motor :

(i) They are low cost.

(ii) Require less maintenance (as there are no slip rings or brushes).

(iii)Good speed regulation (they are able to maintain a constant speed).

(iv)High efficiency in converting electrical energy to mechanical energy (while running, not during startup).

(v) Have better heat regulation (i.e. don't get as hot).

(vi)Small and lightweight.

(vii)Explosion proof (as there are no brushes which eliminate the risks of sparking).

Disadvantages of squirrel cage mnduction motor :

(i) Very poor speed control.

(ii) Although they are energy efficient while running at full load current, they consume a lot of energy on startup.

(iii)They are more sensitive to fluctuations in the supply voltage. When the supply voltage is reduced, induction motor draws more current. During voltage surges, increase in voltage saturates the magnetic components of the squirrel cage induction motor.

(iv)They have high starting current and poor starting torque (the starting current can be 5-9 times the full load current; the starting torque can be 1.5-2 times the full load torque).

Application of squirrel cage induction motor :

(i) Squirrel cage induction motors are commonly used in many industrial applications.

(ii) They are particularly suited for applications where the motor must maintain a constant speed, be self-starting, or there is a desire for low maintenance.

(iii)These motors are commonly used in :

- Centrifugal pumps
- Industrial drives (e.g. to run conveyor belts)
- Large blowers and fans
- Machine tools
- Lathes and other turning equipment

2. **Slip ring rotor/Slip ring induction motor or wound rotor :** In this type of construction, rotor winding is exactly similar to the stator. The rotor carries a three phase star or delta connected, distributed winding, wound for same number of poles as that of stator. The rotor construction is laminated and slotted. The slots contain the rotor winding. The three ends of three phase winding, available after connecting the winding in star or delta, are permanently connected to the slip rings. The slip rings are mounted on the same shaft.

We have seen that slip rings are used to connect external stationary circuit to the internal rotating circuit. So in this type of rotor, the external resistances can be added with the help of brushes and slip ring arrangement, in series with each phase of the rotor winding. This arrangement is shown in the figure (c).

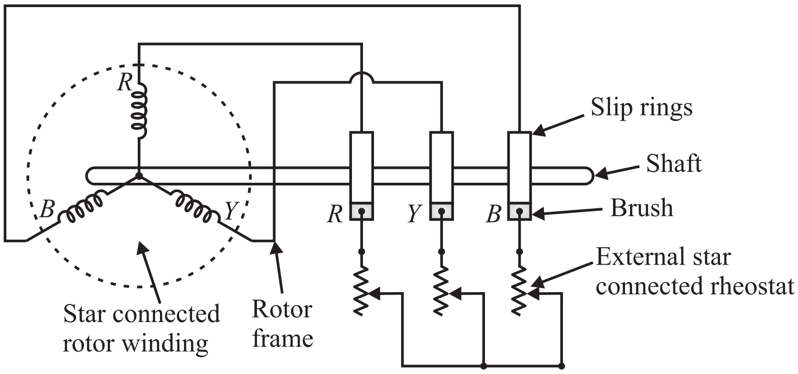


Fig. (c) Slip rings or wound rotor

This way the value of rotor resistance per phase can be controlled. This helps us to control some of the important characteristics of the motor like starting torque, speed etc.

Advantages of slip ring induction motor :

(i) High starting torque with low starting current. The maximum starting can be achieved in the slip ring motor compared to the squirrel-cage motor by inserting an external resistor in each phase of the rotor circuit and cutting the resistance during start-up.

(ii) The main advantage of slip ring induction motor is that its speed can be controlled easily.

(iii) The speeds can be adjusted in the case of the slip ring induction motor (wound rotor) by inserting a resistor. Therefore, slip ring motors are considered variable speed motors.

(iv) A squirrel cage induction motor takes 600% to 700% of the full load current. But a slip ring induction motor takes a very low starting current approximately 250% to 350% of the full load current.

Disadvantages slip ring induction motor :

(i) The initial and maintenance cost is more compared to the squirrel cage motor due to the presence of slip rings, brushes, short circuit devices, etc.

(ii) The speed regulation is deficient when operating with external resistors in the rotor circuit.

(iii) The efficiency and power factor of the slip ring motor are lower compared to the squirrel cage induction motor.

(iv) Sensitivity to fluctuations in supply voltage.

Application of slip ring induction motor :

(i) They are used in areas where high starting torque is required. And where squirrel cage induction motors cannot be used because of their high starting currents.

(ii) These motors are used with high inertia loads.

(iii) Wound Rotor Induction Motor is used in applications which require smooth start and adjustable speed.

(iv) Some of the applications of this motor include cranes, mills, hoists and conveyors.
(v) Wound rotor induction motor is also used in fans, blowers and mixers.
(vi) They are used in large pumps in water industry.

Function of external resistance in slip ring induction motor :

(i) It increases the starting torque produced by induction motor.
(ii) It is also increases the rotor power factor at the time of starting.
(iii) It limits the starting current drawn by induction motor. Therefore no external starting methods are required to start this induction motor.
(iv) If external resistance is varied on running condition then the speed of induction motor will be controlled. This method of speed controlling is called resistance speed controlling.

- In running condition leakage flux is high and hence leakage reactance of rotor is high. Therefore power transfer from stator to rotor is less and the machine has less running torque.
- Slip ring induction motor has good starting performance but inferior running performance (high excitation current, low no load and full load power factor, low torque under running condition) when compared to squirrel cage induction machine.

Comparison of squirrel cage and slip ring induction motor/Slip ring rotor :

S. No.	Slip ring rotor or wound rotor	Squirrel cage rotor
1.	Rotor consists of a three phase winding similar to the stator winding.	Rotor consists of bars which are shorted at the ends with the help of end rings.
2.	Construction is complicated.	Construction is very simple.
3.	Resistance can be added externally.	As permanently shorted, external resistance cannot be added.
4.	Slip rings and brushes are present to add external resistance.	Slip rings and brushes are absent.
5.	The construction is delicate and due to brushes, frequency maintenance is necessary.	The construction is robust and maintenance free.
6.	The rotors are very costly.	Due to simple construction, the rotors are cheap.
7.	Only 5% of induction motors in industry use slip ring rotor.	Very common and almost 95% induction motors use this type of rotor.
8.	High starting torque can be obtained.	Moderate starting torque which cannot be controlled.
9.	Rotor resistance starter can be used.	Rotor resistance starter cannot be used.
10.	Rotor must be wound for the same number of poles as that of stator.	The rotor automatically adjusts itself for the same number of poles as that of stator.

11.	Speed control by rotor resistance is possible.	Speed control by rotor resistance is not possible.
12.	Rotor copper losses are high hence efficiency is less.	Rotor copper losses are less hence have higher efficiency.
13.	Used for lifts, hoists, cranes, elevators, compressors etc.	Used for lathes, drilling machines, fans, blowers, water pumps, grinders, printing machines etc.

Solved Example 1

A 3 phase, 6 pole, 50 Hz induction motor has a slip of 1 % at no load and 3% at full load. Determine :

(a) Synchronous speed
(b) No load speed
(c) Full load speed
(d) Frequency of rotor current at stand still.
(e) Frequency of rotor current at full load.

Sol. **Given :** Number of pole $P = 6$, Frequency $f = 50\text{ Hz}$, Slip at no load = 0.01, Slip at full load = 0.03.

(a) Synchronous speed, $N_s = \frac{120f}{P} = \frac{120\times 50}{6} = \mathbf{1000\ rpm}$ **Ans.**

(b) Slip at no load = 0.01,
No load speed, $N_r = N_s(1-s) = 1000(1-0.01) = \mathbf{990\ rpm}$ **Ans.**

(c) Slip at full load = 0.03,
Full load speed, $N_r = N_s(1-s) = 1000(1-0.03) = \mathbf{970\ rpm}$ **Ans.**

(d) At stand still, $N_r = 0$, so $s = 1$
Rotor frequency, $f' = sf = 1\times 50 = \mathbf{50\ Hz}$ **Ans.**

(e) Slip at full load = 0.03
Rotor frequency, $f' = sf = 0.03\times 50 = \mathbf{1.50\ Hz}$ **Ans.**

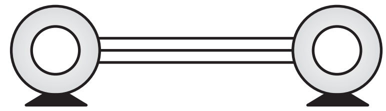
Solved Example 2

A 12 pole, 3 phase alternator is coupled to an engine running at 500 rpm. It supplies an induction motor which has a full load speed of 1440 rpm. Find the slip of the motor.

Sol. **Given : Alternator :** Number of pole $P = 12$, Synchronous speed $N_s = 500\text{ rpm}$.

Induction motor : Rotor speed = 1440 rpm.

In alternator,



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

$\therefore$ Frequency $f = \frac{N_s P}{120} = \frac{500\times 12}{120} = 50\text{ Hz}$

This frequency supply induction motor.

In induction motor, assuming number of poles, when synchronous speed comes near by the rotor speed.

Synchronous speed, $N_s = \dfrac{120 f}{P} = \dfrac{120\times 50}{4} = 1500\,\text{rpm}$

Percentage slip $(\% s) = \dfrac{N_s - N_r}{N_s}\times 100 = \dfrac{1500-1440}{1500}\times 100 = \mathbf{4\%}$ **Ans.**

Scan for Video Solution

TEST 1

Q.1 A three phase induction motor run at 290 rpm at full load with 50 Hz supply. Find number of pole of motor and slip.

Q.2 The frequency of the supply to the stator of an 8-pole induction motor is 50 Hz and the rotor frequency is 3 Hz. Determine :

(a) The slip

(b) The rotor speed.

Q.3 The frequency of the e.m.f. in the stator of a 4 pole induction motor is 50 Hz and that in the rotor is 1.5 Hz. What is the slip? At what speed is the motor running?

Q.4 A 3-phase slip-ring induction motor is wound for 4 poles on stator and 6 poles on rotor. When 3-phase balanced voltage source at 50 Hz is applied to the motor, it will run at :

(A) 1500 rpm (B) 1000 rpm

(C) 750 rpm (D) zero speed

Q.5 A 6 pole, 50 Hz wound rotor induction motor when supplied at the rated voltage and frequency with slip ring open circuited, developed a voltage of 100 V between any two rings. If the rotor is driven by an external means at 1000 rpm opposite to the direction of stator field, the frequency of voltage across slip rings will be **[ESE 2000]**

(A) zero (B) 50 Hz

(C) 100 Hz (D) 200 Hz

Q.6 A 3-phase induction motor has 2 poles and is connected to 400 V, 50 Hz supply. When the slip is 4%, calculate the actual rotor speed and rotor frequency.

(A) 2880 rpm, 2 Hz

(B) 3120 rpm, 2 Hz

(C) 2880 rpm, 48 Hz

(D) 3120 rpm, 48 Hz

Q.7 In a 4 pole, 3-phase, 50 Hz induction machine the slip rings are open circuited. The frequency of the voltage across slip rings is 75 Hz. The rotor is driven at speeds of

(A) 750 rpm, 3750 rpm

(B) 750 rpm, 2250 rpm

(C) 1500 rpm, 2250 rpm

(D) 1500 rpm, 3750 rpm

Numerical Answer Type Questions

Types of Load on Electric Motors

Q.1 A 3-ϕ, 4 pole slip ring induction motor is connected to 3-ϕ, 50 Hz supply from the rotor side through slip rings. The stator terminals are shorted and machine is found to be running at 1440 rpm. Determine :

(a) Frequency of stator current

(b) Speed of rotor magnetic field with respect to rotor

(c) Speed of SMF with respect to rotor and its direction with respect to rotor rotation.

(d) Speed of SMF with respect to RMF.

Magnetic Fields in Induction Motor

Q.1 An 8-pole, 3-phase, 50 Hz induction motor is operating at a speed of 700 rpm. Determine the frequency of the rotor current. **[GATE 2014]**

Q.2 A 50 Hz, 440 V, three-phase 4-pole induction motor develops half the rated torque at 1490 rpm. With the applied voltage magnitude remaining at the rated value, what should be its frequency if the motor has to develop the same torque at 1600 rpm? Neglect stator and rotor winding resistance, leakage reactance and iron losses.

Q.3 A 3-phase, 50 Hz induction motor has a full-load speed of 1440 r.p.m. For this motor, calculate the following :

(a) Number of poles

(b) Full-load slip and rotor frequency

(c) Speed of stator field with respect to

(i) Stator structure and

(ii) Rotor structure and

(d) Speed of rotor field with respect to

(i) Rotor structure

(ii) Stator structure and

(iii)Stator field.

Q.4 A 4-pole synchronous generator driven at 1500 rpm feeds a 6 pole induction motor which is loaded to run at a slip of 5%, what is the motor speed?

Q.5 A 6 pole, 50 Hz wound rotor induction motor when supplied at the rated voltage and frequency with slip rings open circuited, developed a voltage of 100 V between any two rings. Under the same conditions its rotor is now driven by external means at

(a) 1000 rpm opposite to the direction of rotation of stator field

(b) 1500 rpm in the direction of rotation of stator field

Find the voltage available between slip rings and its frequency in each of these cases.

Inverted Induction Motor

Q.1 A 4 pole, 3 phase slip ring induction motor is used as frequency changer. Its stator is excited 3-phase, 50 Hz supply. A load requiring 3-phase 20 Hz supply is connected rotor through three slip rings of SRIM

(a) At what two speeds the prime mover should drive rotor of slip ring induction motor?

(b) Find ratio of two voltages available at slip rings at two speeds.

Multiple Choice Questions

Magnetic Fields in Induction Motor

Q.1 An eight pole wound rotor induction motor operating on 60 Hz supply is driven at 1800 rpm by a prime mover in the opposite direction of the revolving magnetic field. The frequency of the rotor current is

(A) 60 Hz (B) 120 Hz

(C) 180 Hz (D) none

Q.2 A 3-phase, 4-pole squirrel cage induction motor has 36 stator and 28 rotor slots. The number of phases in the rotor is

(A) 3 (B) 9

(C) 7 (D) 8

Q.3 Induction motor can be regarded as a generalized transformer due to certain similarities except rated **[ESE -2020]**

(A) Frequency (B) Flux

(C) Speed (D) Induced emf

Q.4 An 8-pole, 3-phase, 50 Hz induction motor is operating at a speed of 700 rpm. The frequency of the rotor current of the motor in Hz is _____. **[GATE 2014]**

Q.5 The rotor of a three phase, 5 kW, 400 V, 50 Hz, slip ring induction motor is wound for 6 poles while its stator is wound for 4 poles. The approximate average no load steady state speed when this motor is connected to 400 V, 50 Hz supply is : **[GATE 2002]**

(A) 1500 rpm (B) 500 rpm

(C) 0 rpm (D) 1000 rpm

Equivalent Circuit of Induction Motor

Q.1 If the rotor power factor of a 3-phase induction motor is 0.866, the spatial displacement between the stator magnetic field and the rotor magnetic field will be

(A) 30^0 (B) 90^0

(C) 120^0 (D) 150^0

Q.2 A 3-phase, star-connected SRIM is fed from 200 V, 50 Hz source. Stator to rotor effective turns ratio is 2. At a rotor speed of 1440 rpm, the rotor induced emf per phase would be

(A) 4.62 V (B) 46.2 V

(C) 8.0 V (D) 9.24 V

Power Flow in Three Phase Induction Motor

Q.1 A 400 V, 50 Hz, 30 HP, three-phase induction motor is drawing 50 A current at 0.8 power factor lagging. The stator and rotor copper losses are 1.5 kW and 900 W respectively. The friction and windage losses are 1050 W and the core losses are 1200 W. The air-gap power of the motor will be **[GATE 2008]**

(A) 23.06 kW (B) 24.11 kW
(C) 25.01 kW (D) 26.21 kW

Q.2 A 36.775 kW, 6 pole, 50 Hz slip-ring induction motor runs at 960 rpm on full load with rotor current of 40 A. Allowing 300 W for copper loss in the short circuiting gear and 1200 W for mechanical loss, find resistance R_2 per phase of three phase rotor winding.

(A) 0.21 Ω (B) 0.31 Ω
(C) 0.41 Ω (D) 0.25 Ω

Q.3 The rotor of a 3-phase, 50 Hz and 4 pole induction motor takes 120 kW at 3 Hz, determine the rotor speed and the rotor copper losses.

(A) 1410 rpm, 6.8 kW
(B) 1520 rpm, 6.8 kW
(C) 1410 kW, 7.2 kW
(D) 1520 rpm, 7.2 kW

Q.4 The motor of the previous question. Has a stator copper loss of 3 kW, a mechanical loss of 2 kW and a stator core loss of 1.7 kW. Calculate the motor output at the shaft and the efficiency, neglect rotor core losses.

(A) 110.8 kW, 92%
(B) 114.6 kW, 88.85%
(C) 110.8 kW, 88.85%
(D) 114.6 kW, 92%

Q.5 A 3-ϕ, Δ-connected, 4 pole, 50 Hz induction motor has stator resistance of 0.4 Ω/phase at the operating temperature for line current of 20 A, the total stator input is 4000 W for negligible stator core loss. Determine internal power and torque developed.

(A) 3840 W, 24.45 Nm
(B) 3840 W, 28.32 Nm
(C) 3950 W, 28.32 Nm
(D) 3950 W, 24.45 Nm

Explanation of Test - 1 (Based on Magnetic Fields in Induction Motor)

Sol.1

Given : Frequency $f = 50\,\text{Hz}$

Rotor speed $N_r = 290\,\text{rpm}$.

If rotor speed is 290 rpm so synchronous speed N_s is near to rotor speed assume $N_s = 300\,\text{rpm}$

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

Number of pole, $P = \dfrac{120f}{N_s} = \dfrac{120\times 50}{300} = 20$ **Ans.**

Percentage slip, $(\%s) = \dfrac{N_s - N_r}{N_s}\times 100$

$= \dfrac{300-290}{300}\times 100 = 3.33\%$ **Ans.**

Sol.2

Given : Number of pole $P = 8$

Frequency $f = 50\,\text{Hz}$

Rotor frequency $f' = 3\,\text{Hz}$.

(a) Slip :

Rotor frequency $f' = sf$

$\therefore$ Slip $= \dfrac{f'}{f} = \dfrac{3}{50} = 0.06$ or 6% **Ans.**

(b) Synchronous speed,

$N_s = \dfrac{120f}{P} = \dfrac{120\times 50}{8} = 750\,\text{rpm}$ **Ans.**

Rotor speed, $N_r = N_s(1-s)$

$N_r = 750(1-0.06) = 705\,\text{rpm}$ **Ans.**

Sol.3

Given : Number of pole $P = 4$

Frequency $f = 50\,\text{Hz}$

Rotor frequency $f' = 1.5\,\text{Hz}$.

$\because$ Rotor frequency, $f' = sf$

$\therefore$ Slip, $s = \dfrac{f'}{f} = \dfrac{1.5}{50} = 0.03\,\text{p.u.} = 3\%$ **Ans.**

Synchronous speed,

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

Speed of the motor, $N_r = (1-s)N_s$

$N_r = (1-0.03)\times 1500 = 1455\ \text{r.p.m.}$ **Ans.**

Sol.4

With un-equal no. of phases of stator and rotor the induction machine operation is possible. Poles of stator must be equal to the poles of the rotor otherwise stator RMF and rotor RMF are not stationary with each other, hence torque production not possible.

Hence, the correct option is (D).

Sol.5

Given : Number of pole $P = 6$

Stator frequency $f = 50$ Hz

Motor speed $N_r = 1000$ rpm.

Frequency of voltage across slip ring,

$f_r = sf = 2\times 50 = 100$ Hz **Ans.**

Hence, the correct option is (C).

Sol.6

Given : Number of pole $P = 2$

Stator frequency $f = 50$ Hz

Voltage $V = 400$ V, Slip $s = 4\% = 0.04$.

Synchronous speed,

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

Rotor speed, $N_r = (1-s)N_s$

$N_r = (1-0.04)\times 3000 = 2880$ rpm **Ans.**

Rotor frequency, $f_r = sf = 0.04\times 50 = 2$ Hz.

Ans.

Hence, the correct option is (A).

Sol.7

Given : Number of pole $P = 4$

Stator frequency $f = 50$ Hz

Rotor frequency $f_r = 75$ Hz.

Synchronous speed,

$$N_s = \frac{120f}{P} = \frac{120\times 50}{4} = 1500 \text{ rpm}$$

Slip, $s = \frac{f_r}{f} = \frac{75}{50} = \pm 1.5$

Rotor speed at $s_1 = +1.5$,

$$N_{r_1} = (1-s_1)N_s$$

$$N_{r_1} = (1-1.5)\times 1500 = 750 \text{ rpm}$$ **Ans.**

Rotor speed at $s_2 = -1.5$,

$$N_{r_2} = (1-s_2)N_s$$

$$N_{r_2} = (1+1.5)\times 1500 = 3750 \text{ rpm}$$ **Ans.**

Hence, the correct option is (A).

Explanation of NAT Questions (Based on Types of Load on Electric Motors)

Sol. 1

Given : Rotor speed $N_r = 1440$ rpm

Number of pole $P = 4$

Supply frequency $f = 50$ Hz.

Synchronous speed,

$$N_s = \frac{120\times f}{P} = \frac{120\times 50}{4} = 1500 \text{ rpm}$$

Speed of RMF with respect to rotor, N_s = **1500 rpm** **Ans.**

Speed of SMF with respect to rotor N_s = **1500 rpm** **Ans.**

Speed of SMF with respect to RMF = **0** **Ans.**

Direction of SMF is opposite to the direction of rotor rotation as it is inverted motor.

Frequency of stator current

$$= s\times f_r = \frac{1500-1440}{1500}\times 50$$

$$= \frac{60}{1500}\times 50 = \mathbf{2\ Hz}$$ **Ans.**

Explanation of NAT Questions (Based on Magnetic Fields in Induction Motor)

Sol. 1

Given : Number of pole $P = 8$

Frequency $f = 50\,\text{Hz}$

Rotor speed $N_r = 700\,\text{rpm}$.

Synchronous speed,

$$N_s = \frac{120\,f}{P} = \frac{120\times 50}{8} = 750\,\text{rpm}$$

Full load slip, $s = \frac{N_s - N_r}{N_s}$

$$s = \frac{750-700}{750} = 0.066 = 6.6\%$$

Frequency of rotor current,

$$f' = s\,f = 0.066\times 50 = \mathbf{3.33\,Hz}$$ **Ans.**

Sol. 2

Given : Frequency $f = 50\,\text{Hz}$

Line voltage $V_L = 440\,\text{V}$

Number of pole $P = 4$, Speed $N_r = 1490\,\text{rpm}$

New speed $N_{rn} = 1600\,\text{rpm}$.

Synchronous speed,

$$N_s = \frac{120\,f}{P} = \frac{120\times 50}{4} = 1500\,\text{rpm}$$

Slip at speed of 1490 rpm,

$$s = \frac{N_s - N_r}{N_s} = \frac{1500-1490}{1500} = 0.00667$$

Since, torque develop by an induction motor,

$$T \propto sE_r^2$$

Slip 's' for constant torque and constant applied voltage remains unchanged

∴ New synchronous speed,

$$N_{sn} = \frac{N_{rn}}{1-s} = \frac{1600}{1-0.00667} = 1610.7\,\text{rpm}$$

∴ New frequency,

$$f_n = \frac{P \times N_{sn}}{120} = \frac{4 \times 1610.7}{120} = \mathbf{53.7\ Hz}$$

Ans.

Sol.3

Given : Frequency $f = 50$ Hz

Full load speed $N = 1440$ rpm .

(a) The use of full-load speed of 1440 rpm gives,

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

$$1440 = \frac{120 f}{P} = \frac{120 \times 50}{P}$$

$$P = \frac{120 \times 50}{1440} = 4 \times \frac{1}{6} \text{Poles}$$

Since the number of poles must be even and a whole number, the induction motor must have 4 poles. An induction motor runs at a speed, a little less than synchronous speed.

Therefore, poles = **4**. **Ans.**

(b) Synchronous speed,

$$N_s = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$$\text{Slip, } s = \frac{N_s - N_r}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

Rotor frequency,

$$f_r = sf = 0.04 \times 50 = \mathbf{2\ Hz}$$ **Ans.**

(c) (i) Speed of stator field with respect to stator structure $N_s = 1440$ r.p.m.

$$= \frac{2\pi \times 1440}{60} = \mathbf{150.8\ rad/sec}$$ **Ans.**

(ii) Speed of stator field with respect to revolving rotor structure $= N_s - N_r$

$$= 1500 - 1440 = 60 \text{ rpm}$$

$$= \frac{2\pi \times 60}{60} = \mathbf{6.283\ rad/sec}$$ **Ans.**

(d) (i) Speed of rotor field w.r.t. rotor structure

$= N_s - N_m$

= 60 r.p.m.

$$= \frac{2\pi \times 60}{60} = \mathbf{6.283\ rad/sec}$$ **Ans.**

(ii) Speed of rotor field w.r.t. stator structure

$= N_s = 1500$ r.p.m.

$$= \frac{2\pi \times 1500}{60} = \mathbf{157.08\ rad/sec}$$ **Ans.**

(iii) Since, both the stator and rotor fields are rotating at synchronous speed of 1500 rpm with respect to stator structure, speed of rotor field with respect to stator field is zero. Thus the stator and rotor fields are stationary with respect to each other.

Ans.

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Sol.4

Given : Number of pole $P = 4$

Generator speed = 1500 rpm

Number of pole in induction motor $P = 6$

Slip = 5% = 0.05.

Frequency of synchronous generator,

$$f = \frac{4 \times 1500}{120} = 50 \text{ Hz}$$

Synchronous speed of induction motor,

$$N_s = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

Motor slip, $s = 0.05$ (given)

Motor speed, $N_r = N_s(1 - s)$

$$N_r = 1000(1 - 0.05) = \mathbf{950\ rpm}$$ **Ans.**

Sol.5

Given : Number of pole $P = 6$

Stator frequency $f = 50$ Hz

Rotor voltage $V_2 = 100$ V.

(a) Synchronous speed,

$$N_s = \frac{120f}{p} = \frac{120\times50}{6} = 1000\,\text{rpm}$$

Rotor speed, $N_r = -1000$ rpm (given)

$$\text{Slip, } s = \frac{N_s - N_r}{N_s} = \frac{1000-(-1000)}{1000} = 2$$

Rotor frequency,

$f_r = sf = 2\times50 = \mathbf{100\,Hz}$ **Ans.**

Voltage available between slip ring,

$sV_2 = 2\times100 = \mathbf{200\ V}$ **Ans.**

(b) Rotor speed, $N_r = 1500$ rpm

$$\text{Slip, } s = \frac{N_s - N_r}{N_s} = \frac{1000-1500}{1000} = 0.5$$

Rotor frequency,

$f_r = sf = 0.5\times50 = \mathbf{25\,Hz}$ **Ans.**

Voltage available between slip ring

$= sV_2 = 0.5\times100 = \mathbf{50\,V}$ **Ans.**

Explanation of NAT Questions (Based on Inverted Induction Motor)

Sol. 1

Given : Number of pole $P = 4$

Supply frequency $f = 50$ Hz

Rotor frequency $f_r = 20$ Hz.

(a) Speed of rotor field with respect to stator

$$= \frac{120\times50}{4} = 1500 \text{ rpm}$$

Speed of rotor field with respect to rotor

$$= \frac{120\times20}{4} = 600 \text{ rpm}$$

Rotor can rotate in same or opposite direction to rotor field $n_r \pm 600 = 1500$

For positive sign,

$N = N_s - N_r = 1500 - 600 = \mathbf{900\ rpm}$

Ans.

For negative sign,

$N_r = N_s + N_r = 1500 + 600 = \mathbf{2100\ rpm}$

Ans.

(b) $$\text{Slip 1, } s_1 = \frac{N_s - N_r}{N_s} = \frac{1500-900}{1500} = 0.4$$

Slip 2,

$$s_2 = \frac{N_s - N_r}{N_s} = \frac{1500-2100}{1500} = -0.4$$

$\therefore$ Ratio of two voltage,

$\dfrac{E_2}{E_1} = \dfrac{s_2}{s_1} = \mathbf{-1}$ **Ans.**

Explanation of Multiple Choice Questions (Based on Magnetic Fields in Induction Motor)

Sol. 1

Given : Number of pole $P = 8$

Frequency $f = 80$ Hz

Rotor speed $N_r = 1800$ rpm.

Synchronous speed,

$$N_s = \frac{120f}{P} = \frac{120\times60}{8} = 900 \text{ rpm}$$

$$\text{Rotor frequency, } f_r = \frac{(N_s + N_r)\times P}{120}$$

$f_r = (900+1800)\times\dfrac{8}{120} = 180$ Hz **Ans.**

Hence, the correct option is (C).

Sol. 2

Given : Number of pole $P = 4$

Stator slop $= 36$, Rotor slot $= 28$.

In case of a squirrel cage motor, the number of phases is treated as number of Cu bars (or) slots per pole

$\therefore$ Number of phase in motor

$$=\frac{\text{Rotor slot}}{\text{Number of pole}}=\frac{28}{4}=7$$

Though the number of phase are different on stator and rotor, the induction motor operation is possible.

Hence, the correct option is (C).

Sol.3

In transformer frequency same on both sides. In induction frequency in rotor side $f_2 = sf$ where slip 's' depends upon frequency.

Hence, the correct option is (A).

Sol.4

Given : Supply frequency $f = 50\,\text{Hz}$

Number of poles $P = 8$

Rotor speed $N_r = 700$ rpm.

Synchronous speed is given by,

$$N_s = \frac{120f}{P} = \frac{120\times 50}{8} = 750\,\text{rpm}$$

Slip, $s = \frac{N_s - N_r}{N_s} = \frac{750-700}{750} = 0.067$

Frequency of rotor current is given by,

$$f_r = sf = 0.067\times 50 = 3.33\text{ Hz}$$

Hence, the frequency of the rotor current of the motor is **3.33 Hz**.

Sol.5

Given : Power P = 5 kW, Volatge V = 400 V

Frequancy f = 50 Hz

Number of stator poles P_s = 6 pole

Number of rotor poles P_r = 4 pole.

Here the number of poles on stator and rotor are different, the rotor and stator fields will have different speeds which produces a pulsating torque with zero average value in the rotor. Thus the speed of the rotor will be zero when stator and rotor have unequal poles.

Hence, the correct option is (C).

Explanation of Multiple Choice Questions (Based on Equivalent Circuit of Induction Motor)

Sol.1

Given : Rotor power factor $\cos\phi_r = 0.866$.

For 3-phase induction motor :

Spatial displacement $= 90 + \phi_2$

Where, 'ϕ_2' is power factor angle of rotor.

$\because$ From data, $\cos\phi_2 = 0.866$

$\therefore$ $\phi_2 = 30^0$

$\therefore$ Spatial displacement between stator and rotor magnetic field,

$M = 90^0 + 30^0 = 120^0$ **Ans.**

Hence, the correct option is (C).

Sol.2

Given : Voltage $V = 400$ V

Stator frequency $f = 50$ Hz

Stator to rotor turns ratio $\frac{N_1}{N_2} = 2$

Rotor speed $N_r = 1440$ rpm

$N_s = 1500$ rpm (assume).

Rotor speed, $N_r = (1-s)N_s$

$$1440 = (1-s)\times 1500$$

Slip, $s = 0.04$

The rotor induced emf per phase,

$$E_{2r} = sE_2 = 0.04\times\frac{200}{\sqrt{3}} = 4.61\text{ V}$$ **Ans.**

Hence, the correct option is (A).

Explanation of Multiple Choice Questions (Based on Power Flow in Three Phase Induction Motor)

Sol.1

Given : Output power $P_{out} = 30$ HP

Line voltage $V_L = 400\text{ V}$

Frequency $f = 50\text{ Hz}$

Motor line current $I_L = 50\text{ A}$

Power factor $\cos\phi = 0.8$

Rotor copper loss $= 900\text{ W}$

Stator copper loss $= 1500\text{ W}$

Stator core loss $= 1200\text{ W}$

Friction and windage loss = 1050 W.

Stator input power, $P_{in} = \sqrt{3} V_L I_L \cos\phi$

$$P_{in} = \sqrt{3} \times 400 \times 50 \times 0.8 = 27712.8\text{ W}$$

Rotor input P_g = Air gap power

= P_{in} − (stator copper loss + stator core loss)

∴ Air gap power,

$$P_g = 27712.8 - (1500 + 1200)$$

$$P_g = 25.012\text{ kW}$$ **Ans.**

Hence, the correct option is (C).

Sol.2

Given : Number of pole $P = 6$

Output power $P_{out} = 36775$ W

Frequency $f = 50$ Hz

Rotor speed $N_r = 960$ rpm

Rotor current $I_2 = 40$ A

Copper loss in short circuiting gear $= 300\text{ W}$

Mechanical loss = 1200 W.

Synchronous speed,

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

Slip, $$s = \frac{N_s - N_r}{N_s} = \frac{1000 - 960}{1000} = 0.04 \text{ or } 4\%$$

Mechanical power output

= Motor output + Mechanical losses

$$P_m = P_{out} + \text{Mechanical loss}$$

$$P_m = 36775 + 1200 = 37975\text{ W}$$

Rotor output = Mechanical power output + Short-circuiting gear loss

$$P_g = 37975 + 300 = 38275 \text{ W}$$

Rotor copper losses, $P_{cu} = s \times P_g$

$$P_{cu} = 0.04 \times 38275 = 1531\text{ W}$$

and $$P_{cu} = 3I_2^2 R_2$$

∴ Rotor resistance,

$$R_2 = \frac{P_{cu}}{3I_2^2} = \frac{1531}{3 \times 40^2} = 0.3189\,\Omega$$ **Ans.**

Hence, the correct option is (B).

Sol.3

Given : Supply frequency $f = 50$ Hz

Number of pole $P = 4$

Rotor input $P_g = 120$ kW and

Rotor frequency $f_r = 3$ Hz.

Slip, $$s = \frac{f_r}{f} = \frac{3}{50} = 0.06$$

and $$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

Rotor speed, $N_r = N_s(1 - s)$

$$N_r = 1500(1 - 0.06) = 1410 \text{ rpm}$$

Rotor copper loss,

$$P_c = sP_g = 0.06 \times 120 \text{ kW} = 7.2 \text{ kW}$$ **Ans.**

Hence, the correct option is (C).

Sol.4

Given : Stator copper loss = 3 kW

Mechanical loss = 2 kW

Stator core loss = 1.7 kW.

Stator loss = Stator copper loss

+ Stator core loss

$$= 3 + 1.7 = 4.7 \text{ kW}$$

Stator input power = Rotor input + Stator loss

$$P_{in} = 120 + 4.7 = 124.7 \text{ kW}$$

Mechanical power developed,

$$P_m = P_g - \text{Rotor copper loss}$$

$$P_m = 120 - 7.2 = 112.8 \text{ kW}$$ **Ans.**

Efficiency, $\eta = \dfrac{P_{sh}}{P_{in}} \times 100$

$$\eta = \frac{110.8}{124.7} \times 100 = 88.85\%$$ **Ans.**

Hence, the correct option is (C).

Sol.5

Given : Stator input $P_{in} = 4000$ W

Number of pole $P = 4$, Frequency $f = 50$ Hz

Stator resistance $R_1 = 0.4\ \Omega$

Stator current $I_1 = 20$ A.

Stator copper loss

$$= 3I_1^2 R_1 = 3 \times \left(\frac{20}{\sqrt{3}}\right)^2 \times 0.4 = 160 \text{ W}$$

Rotor input power, $P_g = P_{in} - \text{Stator loss}$

$$P_g = 4000 - 160 = 3840 \text{ W}$$

Synchronous speed,

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

Internal torque

$$= \frac{P_g}{\omega_s} = \frac{P_g}{2\pi \frac{N_s}{60}} = \frac{3840 \times 60}{1500 \times 2\pi} = 24.45 \text{ Nm}$$

Ans.

Hence, the correct option is (A).

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