# Chapter 4

# Induction Motors

**LEARNING OBJECTIVES**

*After reading this chapter, you will be able to understand:*

- Principle of operation
- Rotor current and power factor
- Power stages in an induction motor
- Synchronous watt
- Rotor torque and breakdown torque
- Equivalent circuit of the rotor
- Starting of induction motors
- Double squirrel cage motor
- Speed control of induction motor
- Revolving field theory of single phase induction motor
- Capacitor split phase motors
- Shaded pole single-phase motor
- Repulsion start induction motor

## Introduction

Three-phase induction motors (IMs) are the widely used AC motors due to their low cost, simple and rugged construction, high reliability, high efficiency. IMs have good speed regulation, less maintenance, simple starting arrangement, reasonable overload capacity. Conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In DC motors, the electric power is conducted directly to the armature (i.e., rotating part) through brushes and commutator. Hence in this sense, a DC motor can be called a conduction motor. However, in AC motors, the rotor does not receive electric power by conduction but by induction. This is why such motors are known as IMs. An IM can be treated as a rotating transformer. Unlike a transformer due to the presence of air gap, IM has more magnetizing currents, almost lagging 90° the applied voltage and therefore p.f. is low: The no-load current of IM is about 30% to 50% of full-load current, whereas in transformer no-load current is only 2% to 6% of full-load current.

## Constructional Details

The IMs essentially consists of two parts:

(a) A stationary part called stator
(b) The revolving part, called rotor

### *Stator*

The stator of an IM is made up of a number of stampings, which are slotted on the inner periphery to receive the windings. The stator carries a 3-phase winding which may be star or delta connected and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed.

The number poles $P$, produced in the rotating field is $P = 2n$, where $n$ is the number of stator slots/pole/phase.

### *Rotor*

Rotor is made up of thin laminations of the same material as stator. These laminations are slotted on the outer periphery. There are two types of rotors.

1. Squirrel-cage rotor: Motors employing this type of rotor are known as squirrel-cage induction motors (SCIMs)
2. Phase wound (or) wound rotor: The motors employing this type of rotor are variously known as ‘phase-wound’ motors or ‘wound’ motors or ‘slip-ring’ motors

## Slip-ring Rotor

- Has slotted armature
- Provided with 3-phase double-layer distributed winding housed in the rotor slots

- The rotor windings are connected in star
- The open ends are connected to slip rings
- Brushes resting on the slip rings are further externally connected to a 3-phase star-connected rheostat. This makes possible
  - (a) to increase the starting torque and decrease the starting current and
  - (b) to control the speed of the motor
- A cage motor has a higher efficiency than a slip-ring IM
- A slip-ring IM has a high starting torque and a low starting current
- When 3-phase windings displaced in space by 120°, are fed by three-phase currents displaced in time by 120°, they produce a resultant magnetic flux, which rotates in space. This type of field is known as rotating magnetic field (R.M.F.)
- The resultant flux is of constant value = $\frac{3}{2}\phi_m$, i.e., 1.5 times the maximum values of the flux due to any phase
- The resultant flux rotates around the stator at synchronous speed given by

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

- The direction of R.M.F. depends upon the phase sequence

## Principle of Operation

- When the 3-phase stator windings, are fed by a 3-phase supply, then a magnetic flux of constant magnitude but rotating at synchronous speed, is set up. The flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary. Due to the relative speed between the rotating flux and the rotor conductors, an emf is induced in rotor conductors. Since the rotor bars or conductors form a closed circuit, a current is established by the induced emf. The rotor currents generate rotor flux which in turn interacts with the stator flux. The interaction of stator and rotor fluxes produces a torque which makes the rotor to rotate in the direction of R.M.F.
- A 3-phase IM is self-starting. An IM runs at a speed slightly less than the synchronous speed. Hence it is known as an asynchronous motor. It cannot run at synchronous speed.

### Slip

The difference between the synchronous speed $N_s$ and the actual speed $N$ of the rotor is known as slip. It is usually expressed as a percentage of the synchronous speed $N_s$.

$$\text{Slip } s = \frac{N_s - N}{N_s}$$

$N_s - N$ is called slip speed.

The slip speed expresses the speed of the rotor relative to the field.

Frequency of rotor current or emf

$$\text{Rotor frequency } f_2 = sf_1$$

where $s$ = slip and $f_1$ = supply frequency

When rotor is at standstill, $N = 0$, and $s = 1.0$ and $f_2 = f_1$

- Air-gap flux is rotating synchronously, relative to the stator (or stationary space) but at slip speed relative to the rotor.

## Solved Examples

**Example 1:** A voltmeter gives 120 oscillation per minute when connected to the rotor of an IM.

The stator frequency is 50 Hz. Calculate the slip of the motor?

**Solution:**

$$f' = s\,f$$

$$\text{The rotor circuit frequency } f' = \frac{120}{60} = 2\text{ Hz}$$

$$s = \frac{f'}{f} = \frac{2}{50} = 0.04$$

$$\%\text{ slip} = 4\%$$

### Rotor Current and Power Factor

If $R_2$ and $X_2$ are the resistance and reactance at standstill per phase of rotor and $E_2$ be the standstill induced emf per phase

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

$$\text{Rotor power factor} = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

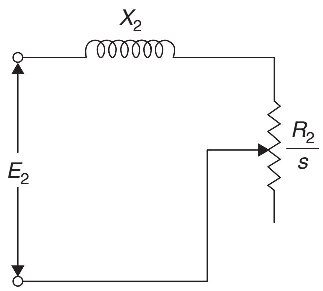
When motor running with slip $s$, then the rotor current/phase

$$I_2 = \frac{sE_2}{Z_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \text{ or } \frac{E_2}{\sqrt{\left(\frac{r_2}{s}\right)^2 + X_2^2}}$$

Now the rotor power factor

$$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}} = \frac{\frac{R_2}{s}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}}$$

This equation gives the rotor equivalent circuit as shown below:




## Relation Between Torque and Rotor Power Factor

In case of an IM, the torque is proportional to the product of flux per stator pole and the rotor current. However there is one more factor that has to be taken into account, i.e., the power factor of the rotor.

$\therefore \quad T_2 \propto \phi I_2 \cos \phi_2 \quad$ or $\quad T = k\phi I_2 \cos \phi_2$

where $I_2$ = Rotor current at standstill
$\phi_2$ = Angle between rotor emf and rotor current
$k$ = A constant

Denoting rotor emf at standstill by $E_2$, we have that

$$E_2 \propto \phi$$

$\therefore \quad T \propto E_2 I_2 \cos \phi_2 \quad$ or $\quad T = k_1 E_2 I_2 \cos \phi_2$

where $k_1$ is another constant.

**Example 2:** The rotor of a 4-pole, 50-Hz slip-ring IM has a resistance of 0.20 Ω per phase and runs at 1440 rpm at full load. Calculate the external resistance per phase which must be added to lower the speed to 1300 rpm, the torque being the same as before

**Solution:** The motor torque is given by

$$T = \frac{KsR_2}{R_2^2 + (sX_2)^2}$$

Since, $X_2$ is not given,

$$T = \frac{KsR_2}{R_2^2} = \frac{Ks}{R_2}$$

In the first case $T_1 = Ks_1 / 1\ \Omega$

In the second case, $T_2 = Ks_2/(R_2 + r)$,

where $r$ is the external resistance per phase, added to the rotor circuit

Since $\quad T_1 = T_2$

$\therefore \quad Ks_1 / R_2 = Ks_2/(R_2 + r)$

Or $\quad (R_2 + r)/R_2 = s_2/s_1$

Now, $\quad N_S = 120 \times 5/4 = 1500$ rpm.

$N_1 = 1440$ rpm, $N_2 = 1300$ rpm.

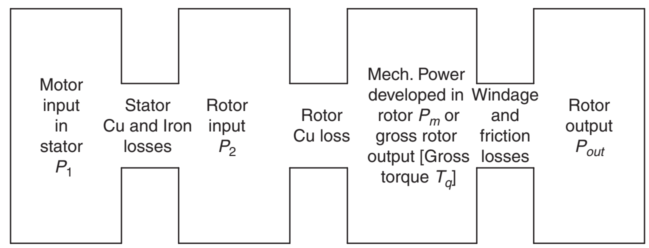
$$\therefore \quad s_1 = \frac{1500 - 1440}{1500} = 0.04$$

$$s_2 = \frac{1500 - 1300}{1500} = 0.133$$

$$\therefore \quad \frac{0.2 + r}{0.2} = \frac{0.133}{0.04}$$

$$\therefore \quad r = 0.465\ \Omega$$

## Power Stages in an IM




Stator iron loss depends on the supply frequency and the flux density in the iron core. It is practically constant. The iron loss of the rotor is, however, negligible because frequency of rotor currents under normal running conditions is always small.

### Torque Developed by an IM

An IM develops gross torque $T_g$ due to gross rotor output $P_m$. Its value can be expressed either in terms of rotor input $P_2$ or rotor gross output $P_m$ as given below:

$$T_g = \frac{P_2}{\omega_s} = \frac{P_2}{2\pi N_s}$$

or $\quad T_g = \frac{P_m}{\omega} = \frac{P_m}{2\pi N}$ ($N$ and $N_s$ are in rps)

in terms of rotor output.

The shaft torque is due to output power $P_{out}$ which is less than $P_m$ because of rotor friction and windage losses.

$$\therefore \quad T_{sh} = \frac{P_{out}}{\omega} = \frac{P_{out}}{2\pi N}$$

The difference between $T_g$ and $T_{sh}$ equals the torque lost due to friction and windage loss in the motor.

### Some Important Relations

$$\frac{\text{Rotor Cu loss}}{\text{Rotor input}} = s$$

Rotor gross output = $(1 - s)$ Rotor input

$$\frac{\text{Rotor Cu loss}}{\text{Rotor gross output}} = \frac{s}{1 - s}$$

$$\text{Rotor efficiency, } \frac{P_m}{P_2} = \frac{N}{N_s}$$

If some power $P_2$ is delivered to a rotor, then a part $sP_2$ is lost in the rotor itself as copper loss and the remaining $(1 - s)P_2$ appears as gross mechanical power $P_m$ (Including friction and windage losses)

$$\therefore \quad P_2 : P_m : I^2R :: 1 : (1 - s) : s$$

## IM Torque Equation

The gross torque $T_g$ developed by an IM is given by

$$T_g = \frac{P_2}{2\pi N_s} \quad - N_s \text{ in rps}$$

$$= \frac{60P_2}{2\pi N_s} = \frac{9.55P_2}{N_s} \quad - N_s \text{ in rpm}$$

Now $\quad P_2$ = rotor Cu loss/s

$$= 3I_2^2R_2/s$$

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} = \frac{sKE_1}{\sqrt{R_2^2 + (sX_2)^2}}$$

where $K$ is rotor/stator turn ratio per phase

$$\therefore \quad P_2 = 3 \times \frac{s^2E_2^2R_2}{R_2^2 + (sX_2)^2} \times \frac{1}{s}$$

$$\therefore \quad T_g = \frac{P_2}{2\pi N_s} = \frac{3}{2\pi N_s} \times \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

## Synchronous Watt ($T_{sw}$)

Synchronous watt is that torque which, at the synchronous speed of the machine under consideration, would develop a power of 1 watt.

$$\text{Rotor input} = T_{SW} \times 2\pi N_s$$

$$\therefore \quad T_{SW} = \frac{\text{Rotor input}, P_2}{2\pi \times N_s}$$

$$= \frac{1}{\omega_s} \cdot \frac{N_s}{N} \cdot P_g = \frac{1}{\omega_s} \cdot \frac{N_s}{N} . P_m$$

Synchronous wattage of an IM equals the power transferred across the air-gap to the rotor.

$\therefore$ Torque in synchronous watt

$$= \text{Rotor input} = \frac{\text{Rotor Cu loss}}{s}$$

$$= \frac{\text{Gross output power}, P_m}{(1-s)}$$

Starting torque, $T_{st}$:

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

**Example 3:** A 3-$\phi$, 50 Hz IM has a full load speed of 1440 rpm. What is slip and rotor frequency of the IM?

(A) 6%, 4 Hz (B) 10%, 46 Hz
(C) 8%, 6 Hz (D) 4%, 2 Hz

**Solution:** (D)

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

$$N = N_s(1 - S) \Rightarrow S = 4\%$$

$$\Rightarrow \quad f_r = S \times f_s \quad \Rightarrow \quad f_r = 2 \text{ Hz}$$

**Example 4:** An 8-pole, 50 Hz, 3-$\phi$ slip-ring IM has effective rotor resistance of 0.8 Ω/ph. Stalling speed is 650 rpm. The resistance required in the rotor phase to obtain the maximum torque at starting?

(A) 0.42 Ω (B) 0.52 Ω
(C) 0.48 Ω (D) 0.58 Ω

**Solution:** (B)

$$N_s = 750 \text{ rpm}$$

$$S_b = 13.33\%$$

$$\Rightarrow S_b = \frac{R^2}{X^2} = 0.6\ \Omega$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2}, \ T_{st} = T_{max}$$

Here $\quad a = 1$

$$\Rightarrow a = \frac{R_2 + r}{X_2}$$

$$\Rightarrow r = .52\ \Omega$$

**Example 5:** The rotor power output of 3-$\phi$ IM is 15 kW and the corresponding slip is 4%. The rotor ohmic loss will be

(A) 600 W (B) 625 W
(C) 650 W (D) 700 W

**Solution:** (B)

$$\text{Rotor loss} = P_g \times \left(\frac{S}{1-S}\right)$$

$$= 15 \times \frac{0.04}{1 - 0.04} = 625 \text{ W}$$

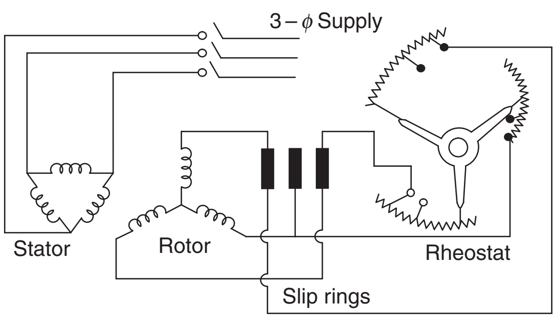
## Starting Torque of a SCIM

The resistance of a SCIM is fixed and small compared to its reactance which is very large at start because at standstill, frequency of the rotor currents equals the supply frequency. Hence, the starting current $I_2$ of the rotor though very large in magnitude, lags by an angle nearly equal to 90°, which results in poor starting torque. It is roughly 1.5 times the full-load torque, although the starting current is 5 to 7 times the full-load current. Hence SCIMs are not useful where the motor has to start against heavy loads.

## Starting Torque of a Slip-ring Motor

The starting torque of such a motor is increased by improving its power factor by adding external resistance in the rotor circuit from the star-connected rheostat, the rheostat being progressively cut out as the motor gathers speed. Addition of external resistance, however, increases the rotor impedance and so reduces the rotor current. At first, the effect of improved power factor predominates the current-decreasing effect of impedance. Hence, starting torque is increased. But after a certain point, the effect of increased impedance predominates the effect of improved power factor so the torque starts decreasing.

## Starting Torque of a Slip-ring Motor Starting Arrangement




## Condition for Maximum Starting Torque

Starting torque is maximum when rotor resistance equals rotor reactance.

i.e., $R_2 = X_2$

Effect of change in supply voltage on starting torque

$$T_{st} = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

Now $E_2 \propto$ supply voltage V

$$\therefore \quad T_{st} = \frac{KV^2 R_2}{R_2^2 + X_2^2},$$

where $k$ is yet another constant.

$$\therefore \quad T_{st} \propto v_2$$

The torque is very sensitive to any changes in supply voltage Torque under running conditions:

$$T = \frac{3}{2\pi N_s} \cdot \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

## Condition for Maximum Torque (or Breakdown Torque) under Running Conditions

Breakdown torque of a motor is the maximum torque; a motor will develop under increasing load conduction without an abrupt drop in speed and power. It is also sometimes known as pullout torque.

The torque under running conditions is maximum at that value of slip '$s$', which makes rotor reactance per phase equal to rotor resistance per phase.

Slip corresponding to maximum torque is '$s$' = $\frac{R_2}{X_2}$

$$T_{max} = \frac{3}{2\pi N_s} \cdot \frac{E_2^2}{2X_2} \text{ Nm}$$

1. The maximum torque is independent of rotor resistance.
2. The speed or slip at which maximum torque occurs is determined by the rotor resistance. Torque becomes maximum when rotor reactance equals its resistance. Hence, by varying rotor resistance (possible only with slip-ring motors) maximum torque can be made to occur at any desired slip.
3. Maximum torque varies inversely as standstill reactance. Hence, it should be kept as small as possible.
4. Maximum torque varies directly as the square of the applied voltage.
5. For obtaining maximum torque at starting ($s$ = 1), rotor resistance must be equal to rotor reactance.

## Rotor Torque and Breakdown Torque (Pull Out Torque)

The rotor torque $T$ at any slip $s$ can be expressed in terms of the maximum (or breakdown) torque $T_b$ as

$$T = T_b \left[ \frac{2}{\left(\frac{s_b}{s}\right) + \left(\frac{s}{s_b}\right)} \right]$$

where $T_b$ = Breakdown or maximum torque
$s_b$ = Breakdown or pull-out slip

## Torque/speed or Torque/Slip Curves

$$T \propto \phi I_2 \cos \phi_2 \text{ or}$$

$$T = K\phi \frac{sE_2 R_2}{R_2^2 + (sX_2)^2}$$

At normal speeds, close to synchronous speed, the term $sX_2$ is small and hence negligible compared to $R_2$.

$$\therefore \quad T \propto \frac{s}{R_2} \quad \text{or}$$

$T \propto s$ if $R_2$ is constant. Hence, for low values of slip (or close to $N_s$) the torque/slip (torque/speed) curve is approximately a straight line. As slip increases (i.e., motor speed falls due to increasing load on the motor), the torque also increases and becomes maximum when $s = \frac{R_2}{X_2}$.

As the slip further increases (i.e., motor speed falls) with further increase in motor load, then $R_2$ becomes negligible as compared to $sX_2$.

Therefore, for large values of slip

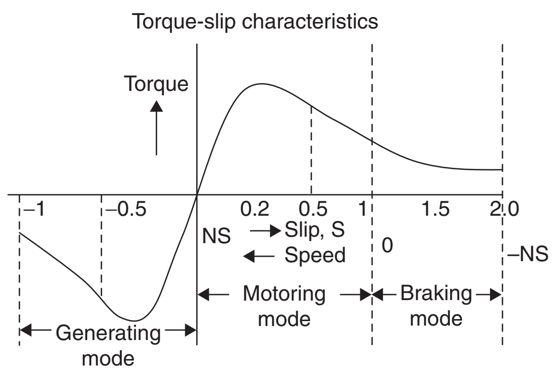
$$T \propto \frac{s}{(sX_2)^2} \propto \frac{1}{s}$$

Hence, the torque/slip curve is a rectangular hyperbola. Beyond the point of maximum torque, any further increase in motor load results in decrease of torque developed by motor. The result is that motor slows down and operation of the motor lies between the values of $s = 0$ and that corresponding to maximum torque.

The maximum torque does not depend on $R_2$, but the exact location of $T_{max}$ is dependent on it. Greater the $R_2$, greater is the value of slip at which the maximum torque occurs.

## Torque–slip (or) Torque–speed Characteristics

Torque–slip (or) Torque–speed characteristics of three-phase IM under different modes as shown below.




When speed varies from 0 to $N_S$ and slip varies from 0 to 1 then the IM operates under motoring mode. If the slip goes to negative value and speed greater than synchronous speed. Then the Induction machine operates under generating mode. Similarly if the speed is negative and slip is greater than unity then the motor operates under Braking mode.

## Effect of Change in Supply Voltage on Torque and Speed

$$T = \frac{K\phi s E_2 R_2}{R_2^2 + (sX_2)^2}$$

As $E_2 \propto \phi \propto V$, where $V$ is the supply voltage

$\therefore \quad T \propto sV^2$

Torque at any speed is proportional to the square of the applied voltage. Changes in supply voltage affect both starting torque and running torque.

If supply voltage $V$ decreases, then torque $T$ also decreases. Hence, for maintaining the same torque, slip increases, i.e., speed falls.

Let $V$ change to $V'$, $s$ to $s'$ and $T$ to $T'$

then $\frac{T}{T'} = \frac{sV^2}{s'V'^2}$

**Example 6:** The power input to a 415 V, 50 Hz, 6-pole, 3-$\phi$ IM running at 975 rpm is 40 kW. The stator losses are 1 kW and friction and windage losses are 2 kW. The efficiency of the motor is

(A) 92.5% (B) 91%
(C) 90.06% (D) 88%

**Solution:** (C)

$\Rightarrow \quad S = \frac{N_S - N}{N_S} = 0.025$

Rotor Cu loss = $S \times$ Rotor Input

= $0.025 \times (40 - 1)$

Total loss = 3975 W

Output = 36,025 W

$$\%\ \text{Efficiency} = \frac{\text{Output}}{\text{Input}} = 90.06\%$$

$$= \frac{36025}{4000} \times 100 = 90.06\%$$

## Important Relations

(a) Ratio of full-load torque and maximum torque

$$\frac{T_{fl}}{T_{max}} = \frac{2as_f}{a^2 + s_f^{\,2}},$$

where $a = \frac{R_2}{X_2}$

$s_f$ – full-load slip

In fact $a = s_m$, slip corresponding to maximum torque.

In that case the ratio $\frac{T_{fl}}{T_{max}}$ is given by

$$\frac{T_{fl}}{T_{max}} = \frac{2s_m s^2{}_f}{s_m + s_f^{\,2}}$$

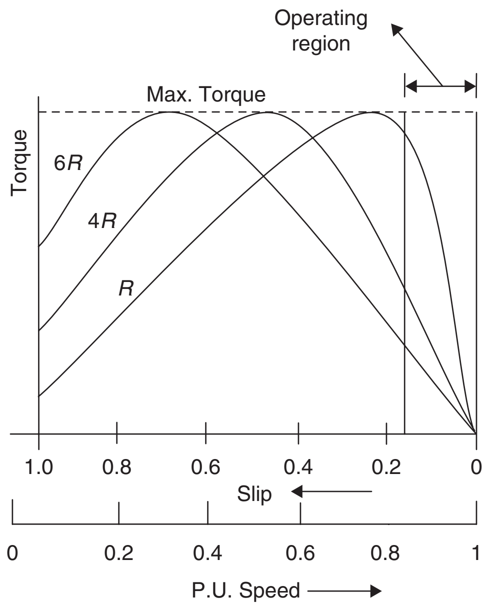
In general,

$$\frac{\text{Operating torque at any slips}}{\text{Maximum torque}} = \frac{2as}{a + s^2}$$

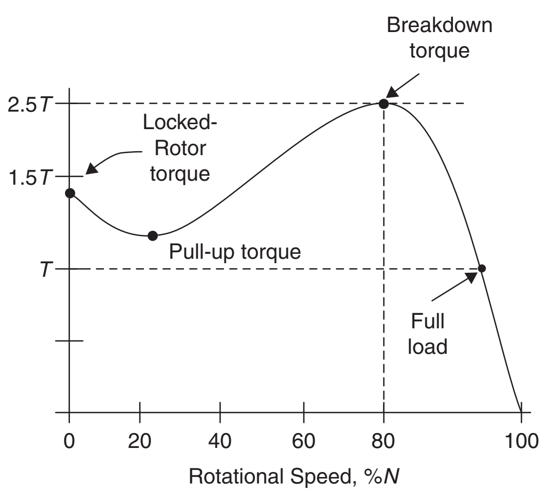
(b) Ratio of staring torque and maximum torque

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1 + a^2}$$

where $a = \frac{R_2}{X_2}$




## Torque/Speed Curve




**Example 7:** A 12-pole 3-phase, 600-V 50-Hz, star-connected, IM has rotor-resistance and standstill reactance of 0.02 and 0.4 Ω per phase, respectively. Calculate:

(a) Speed corresponding to maximum torque.

(b) Ratio of full-load torque to maximum torque, if the speed is 495 rpm.

**Solution:** $N_S = \dfrac{120 \times 50}{12} = 500$ rpm

For $r = 0.02$ and $x = 0.4$ Ω, the slip corresponding to maximum torque is related is

$$S_{MT} = a = r_2/x_2 = \frac{0.02}{0.4} = 0.05$$

(a) Corresponding speed

$$= 500\,(1 - S_{MT}) = 500\,(1 - 0.05)$$
$$= 475 \text{ rpm}$$

(b) Full-load speed = 495 rpm

$$S_f = 0.01$$

$$\frac{\text{Full-load torque}}{\text{Maximum torque}} = \frac{2a\,s_f}{a^2 + s_f^{\,2}}$$

$$= \frac{2 \times 0.05 \times 0.01}{0.05^2 + 0.01^2} = 0.38$$

**Example 8:** An 8-pole 50-Hz, 3-phase, slip-ring IM has effective rotor resistance of 0.08 Ω/ph. Stalling speed is 650 rpm. How much resistance must be inserted in the rotor phase to obtain the maximum torque at starting? Ignore magnetizing current and stator leakage impedance.

**Solution:** The stalling speed corresponding to stalling (or maximum torque) and to maximum slip under running conditions.

$$N_S = 120 \times 50/8 = 750 \text{ rpm}$$

Stalling speed is = 650 rpm

$s_b$ = slip corresponding to max torque.

$$s_b = \frac{750 - 650}{750} = \frac{2}{15}$$

$$= 0.133 \text{ or } 13.33\%$$

$$s_b = R_2/X_2$$

$$\therefore \quad X_2 = 0.08 \times 15/2 = 0.6\ \Omega$$

$$\frac{T_{st}}{T_{\max}} = \frac{2a}{1 + a^2}$$

Since $T_{st} = T_{\max}$

$$\therefore \quad 1 = \frac{2a}{1 + a^2} \quad \text{or} \quad a = 1$$

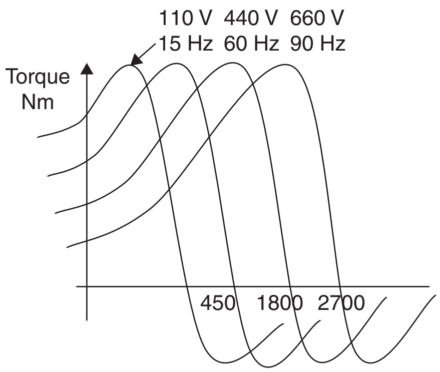
Let $r$ be the external resistance per phase added to the rotor circuit, then

$$A = \frac{R_2 + r}{x_2} \quad \text{or} \quad 1 = \frac{0.08 + r}{0.6}$$

$$\therefore \quad r = 0.52\ \Omega/\text{phase}$$

## Shape of Torque/Speed Curve

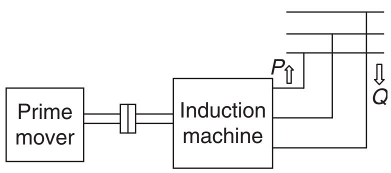
For a SCIM shape of its torque/speed curve depends on the voltage and frequency applied to its stator. In practice, supply voltage and frequency are varied in the same proportion in order to maintain a constant flux in the air gap. Under those conditions, shape of the torque/speed curve remains the same but its position along the $X$-axis (i.e., speed axis) shifts with frequency.




Above fig shows torque/speed curve of an 11 kW, 440 V, 60 Hz, 3-phase SCIM. Since the shape of the torque/speed curve remains same at all frequencies, it follows that torque developed by an SCIM is the same whenever slip-speed is the same.

### Induction Generator

When run faster than its synchronous speed, an IM runs as a generator called an induction generator. To run the IM faster than its synchronous speed a prime mover is needed.




For creating its own magnetic field, it absorbs reactive power '$Q$' from the line and delivers active power 'P' to the 3-phase line. The active power is directly proportional to the slip above the synchronous speed.

## Equivalent Circuit of the Rotor

When motor is loaded, the rotor current $I_2$ is given by

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

From the above relation it appears that the rotor circuit which actually consists of a fixed resistance $R_2$ and a variable reactance $sX_2$ (proportional to slip) connected across $E_r = sE_2$ (figure 1(a)) can be looked upon as equivalent to a rotor circuit having a fixed reactance $X_2$ connected in series with a variable resistance $\frac{R_2}{s}$ (inversely proportional to slip) and supplied with constant voltage $E_2$ as shown in fig (b).

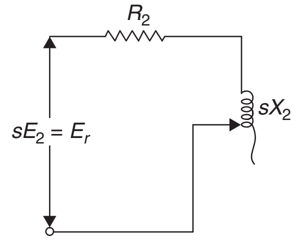



**Figure 1(a)**

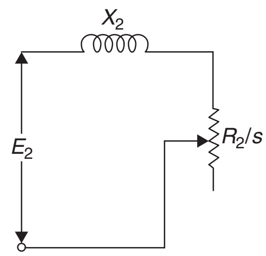



**Figure 1(b)**

Now, the reactance $\frac{R_2}{s} = R_2 + R_2\left(\frac{1}{s} - 1\right)$

It consists of two parts:

1. The first part $R_2$ is the rotor resistance itself and represents the rotor Cu loss.
2. The second part is $R_2\left(\frac{1}{s} - 1\right)$. This is known as the load resistance $R_L$ and is the electrical equivalent of the mechanical load on the motor

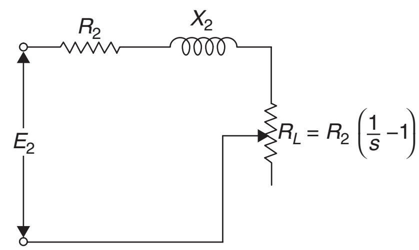
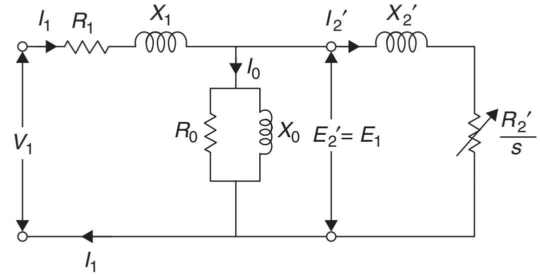
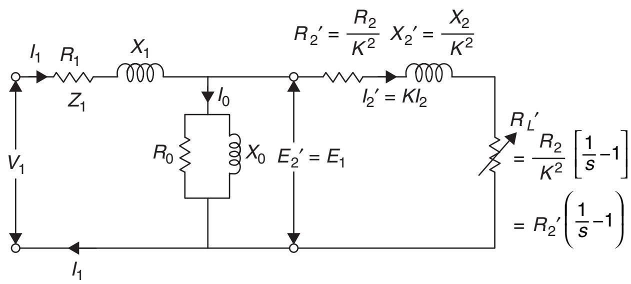



**Figure 1(c)**

### Equivalent Circuit of an IM

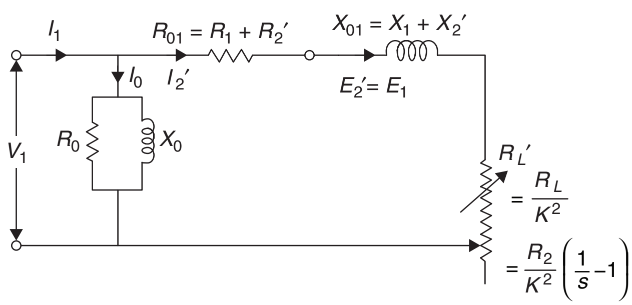
The equivalent circuit of an IM where all values have been referred to primary, i.e., stator is shown in the below figure.






Here, '$K$' refers to the transformation ratio of the given machine. Since IMs can be visualized as three-phase transformers with a rotating secondary; '$K$' is the effective turns ratio.

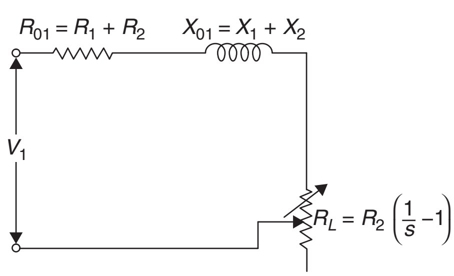
The exciting circuit may be transferred to left, to make calculations simple, thereby we get approximate equivalent circuit of the IM.




## Condition for Maximum Power Output

Approximate equivalent circuit of an IM with the following assumptions is shown in figure.

1. Exciting circuit is omitted, i.e., $I_0$ is neglected and
2. $K$ is assumed unity




With the above assumptions, the power output is maximum when the equivalent load resistance is equal to the standstill leakage impedance of the motor.

i.e., $R_L = Z_{01}$

Corresponding slip, $s = \dfrac{R_2}{R_2 + Z_{01}}$

Maximum gross power output,

$$P_{gmax} = \frac{3V_1^2}{2(R_{01} + Z_{01})}$$

where $V_1$ is voltage/phase of the motor and $K$ has been taken as unity.

## Starting of IMs

An IM at rest is like a transformer with a short-circuited secondary. Therefore, if normal supply voltage is applied to the stationary motor, a very large initial current, i.e., 5 to 7 times the full-load current is taken by the primary and develop only 1.5 to 2.5 times their full-load torque.

- The wound-rotor IMs are started by introducing external resistance across the slip-rings which also improves the starting torque.
- SCIMs are started by applying a reduced voltage at starting and then increasing to the full line voltage as the motor picks up speed.

## Direct-switching or Line Starting of IMs

- No effort is made to reduce the starting current. Motors of small capacity can be started by direct-switching.

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{sc}}{I_{fl}}\right)^2 S_{fl}$$

## Starting of SCIMs

A reduction in the stator applied voltage can be accomplished in three ways

(a) Stator resistance (or) reactor starting
(b) Auto-transformer starting
(c) Star-delta starting

**(a)** Stator resistance or reactor starting:

- A resistor or a reactor is inserted in between motor and supply terminals. Their purpose is to drop some voltage and hence reduce the initial current drawn by the motor.
- If the stator voltage is reduced to the fraction '$x$' (of the rated voltage) the short-circuit current also reduced to the fraction '$x$'

i.e., $I_{st} = \dfrac{xV_1}{Z_1} = xI_{sc}$

$$\frac{T_{st}}{T_{fl}} = \left[\frac{I_{st}}{I_{fl}}\right]^2 \cdot s_{fl}$$

$$= \left(\frac{xI_{sc}}{I_{fl}}\right)^2 \cdot s_{fl}$$

$$= x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 \cdot s_{fl}$$

## Starting Torque with Reactor Starting

$$\text{Starting torque with direct switching} = \left(\frac{xV_1}{V_1}\right)^2 = x^2$$

## Auto-transformer Starting

The reduction in the stator impressed voltage is accomplished by means of auto-transformer

$$I_{st} = \frac{xV_1}{Z_1} = xI_{sc}$$

Neglecting the no-load current of the auto-transformer, primary $VA$ = secondary VA.

i.e., $I_L V_1 = xV_1 I_{st}$, where $I_L$ is line (primary) current

$$\therefore \quad I_{st} = \frac{I_L}{x} = xI_{sc}$$

$$\therefore \quad I_L = x^2 I_{sc}$$

$$\frac{T_{st}}{T_{fl}} = \left[\frac{X\ I_{sc}}{I_{fl}}\right]^2 \cdot s_{fl} = x^2\left[\frac{I_{sc}}{I_{fl}}\right]^2 \cdot s_{fl}$$

## Star-delta Starting

This method of starting is used for motors designed to operate normally in delta. Initially, the stator winding is connected in star, so that the voltage applied to the stator is $\left(\frac{1}{\sqrt{3}}\right)$ times the voltage. After the motor attains a speed nearly equal to the steady-state speed, the stator winding are connected in delta.

Let $V_L$ be the line voltage with stator winding star-connected, then starting current/phase

$$= \left(\frac{V_L}{\sqrt{3}}\right)\frac{1}{Z_{sc}} = (I_L)_Y$$

with stator connected in delta the starting current/phase

$$(I_{st})_D = V_L\left(\frac{1}{Z_{sc}}\right)$$

and the line current

$$(I_{st})_{L\Delta} = \sqrt{3}\,(I_{st})_{\Delta}$$

$$\therefore \quad (I_L)_Y = (I_{st})_Y = \frac{V_L}{\sqrt{3}Z_{sc}} = \frac{1}{\sqrt{3}}(I_{st})_{\Delta}$$

$$\therefore \quad \frac{\text{Starting line current with star-connected stator}}{\text{Starting line current with delta-connected stator}} = \left(\frac{1}{\sqrt{3}}\right)\left(\frac{1}{\sqrt{3}}\right) = \frac{1}{3}$$

$$(I_{st})_Y = \frac{1}{\sqrt{3}}(I_{sc})_D$$

$$\frac{\text{Starting torque with startor}}{\text{Starting torque in direct switching}}$$

$$= \frac{\left(\frac{V_L}{\sqrt{3}}\right)^2}{V_L^{\ 2}} = \frac{1}{3}$$

$$\frac{\text{Starting torque with star} - \Delta \text{ starter}, T_{st}}{\text{Full load torque with stator winding in } \Delta, (T_{FL})_{\Delta}}$$

$$= \frac{\frac{1}{\omega_s}(I_{st})_Y^2\frac{r_2}{1}}{\frac{1}{\omega_s}(I_{fl})_{\Delta}^2\frac{r_2}{s_{fl}}}$$

$$= \frac{1}{3}\left[\frac{(I_{sc})_{\Delta}}{(I_{fl})_{\Delta}}\right]^2 \cdot s_{fl}$$

**Common Data for Examples 9 to 11:**
An SCIM has a starting current of 6 times the full-load current at a slip of 0.04. Calculate the line current and starting torque in PU of full-load values of the following methods.

**Example 9:** Direct switching

**Solution:** In Direct switching method,
Line current = Starting current

Starting current , $I_{st} = 6I_{fL}$

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 \times s_{fl} = (6)^2 \times 0.04$$

$$= 1.44 \text{ PU}$$

**Example 10:** Auto-transformer starting with motor current limited to 2.0 PU

**Solution:** Line current $= x \cdot I_{st} = x^2 I_s = \frac{1}{9}6I_{fl} = \frac{2}{3}I_{fl}$

$$I_{SC} = 6I_{fl}$$

$$\therefore \quad x = \frac{I_{st}}{I_{sc}} = \frac{1}{3}$$

$$\frac{T_{st}}{T_{fl}} = \left(\frac{xI_{sc}}{I_{fl}}\right)^2 \times s_{fl} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 \times s_{fl}$$

$$= \frac{1}{9}\times 36\times 0.04$$

$$= 0.16 \text{ PU}$$

**Example 11:** Star-delta starting.

During starting period the motor is star-connected

**Solution:** $I_{st}$ per phase $= \frac{1}{\sqrt{3}} I_{sc}$ per phase

$$= \frac{1}{\sqrt{3}} \times 6I_{FL} = 3.45 \text{ PU}$$

$$\frac{T_{st}}{T_{fl}} = \left[\frac{I_{st}}{I_{fl}}\right]^2 s_{fl}$$

$$= \left[\frac{I_{SC}}{\sqrt{3}I_F}\right]^2 s_{fl}$$

$$= \frac{1}{3}\left[\frac{I_{SC}}{I_{FL}}\right]^2 s_{fl}$$

$$= \frac{1}{3}\times(6)^2\times 0.04 = 0.48 \text{ PU}$$

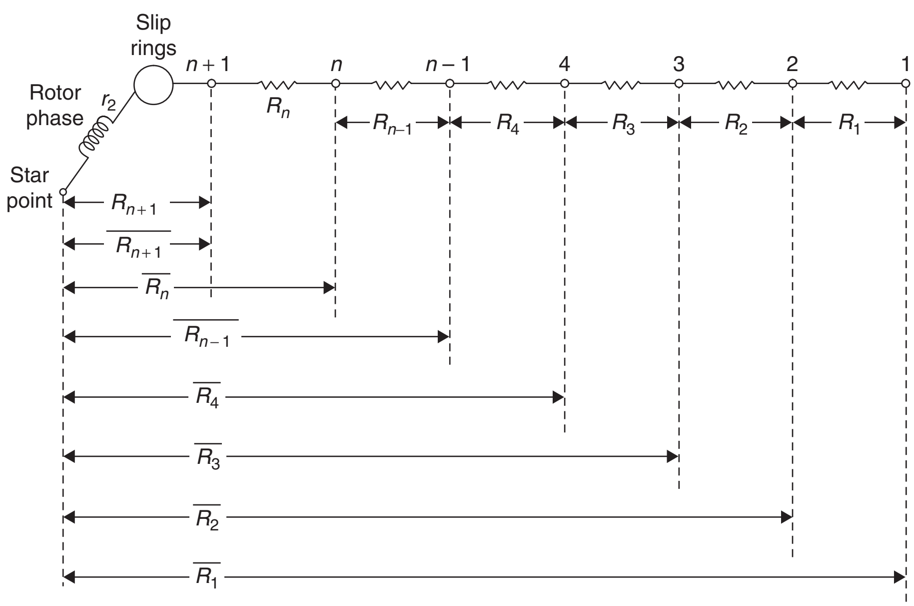
## Starting of Wound-rotor Motors

All the starting methods that are used for SCIM are applicable to wound rotor IMs also. However, in a wound rotor IM, the starting current is limited for a safe value by increasing the impedance of the rotor circuit at the time of starting. This is possible since an external resistance can be included in the rotor circuit at the time of starting the motor. It is gradually cut out as the motor comes up to speed.

Rotor resistance starting offers the following advantages

1. It is simple and cheap
2. It limits starting current to a safe value
3. It can increase the starting torque even to a value equal to the pull-out torque
4. The rotor p.f. (and hence the starting p.f.) is improved

## Calculation of Starter Resistance Steps




### *Assumptions*

1. During the start-up period, the load torque remains constant
2. No-load current of the motor is neglected
3. The input current varies between a maximum of $I_{1\max}$ and a minimum of $I_{1\min}$

$$\frac{\bar{R}_2}{\bar{R}_1} = \frac{\bar{R}_3}{\bar{R}_2} = \ldots\ldots = \frac{\bar{R}_n}{\bar{R}_{n-1}}$$

$$= \frac{\bar{R}_{n+1}}{\bar{R}_n} = \frac{r_2}{\bar{R}_n} = \gamma\,(\text{say})$$

Then $\bar{R}_2 = \bar{R}_1\gamma, \bar{R}_3 = \bar{R}_2\gamma = \bar{R}_1\gamma^2; \ldots \bar{R}_{n+1} = \bar{R}_1\gamma^n = r_2$

$\gamma = \sqrt[n]{s_m}$, where $s_m$ is the slip under normal operating conditions.

$$R_1 = \bar{R}_1 - \bar{R}_2 = (1-\gamma)\bar{R}_1$$

$$R_2 = \bar{R}_2 - \bar{R}_3 = (1-\gamma)\bar{R}_2$$

$$= (1-\gamma)\,\gamma\,\bar{R}_1 = \gamma R_1$$

$$R_3 = \gamma^2 R_1; \ldots\ldots R_n = \gamma^{n-1} R_1$$

## Crawling

This problem is found, particularly in SCIM. They sometimes exhibit a tendency to run stably at speeds as low as one-seventh of their synchronous speed, $N_s$. This phenomenon is known as crawling of an IM.

This is due to 7th harmonic currents in the three stator windings which have a phase difference of $7 \times 120° = 2 \times 360° + 120° = 120°$.

They set up a forward speed equal to $\frac{1}{7}$ th of the synchronous speed of the fundamental torque.

## Cogging or Magnetic Locking

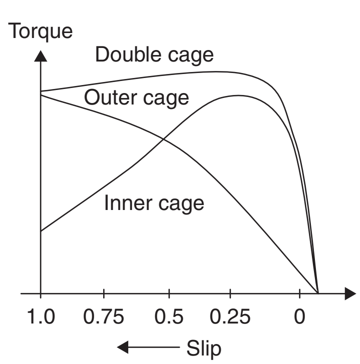
The rotor of a SCIM sometimes refuses to start at all, particularly when the voltage is low

This happens when the number of stator teeth $S_1$ is equal to number of rotor teeth $S_2$ and is due to the magnetic locking between the stator and rotor teeth. This is because of the minimum reluctance of magnetic path when the stator and rotor teeth face each other rather than when the teeth of one element are opposite to the slots on the other. It is in such positions of minimum reluctance that the rotor tends to remain fixed and thus cause serious trouble during starting. Cogging of SCIMs can be easily overcome by making the number of rotor slots prime to the number of stator slots.

## Double SCIM

The main disadvantage of SCIM is its poor starting torque, which can be overcome by having a cage of high resistance. The motor has two independent cages on the same rotor, one inside the other.

The outer cage has high resistance and low ratio of reactance to resistance whereas the inner cage has low resistance but, being situated deep in the rotor has a large ratio of reactance-to-resistance. Hence, the outer cage develops maximum torque at starting, while the inner cage does so at about 15% slip.




## Speed Control of IM

The speed control techniques of an IM can be mainly classified as

1. Control from stator side
   (a) by changing the applied voltage or line voltage control
   (b) by changing the applied frequency
   (c) by changing the number of stator poles
2. Control from rotor side
   (d) rotor rheostat control
   (e) by operating two motors in concatenation or cascade
   (f) by injecting an emf in the rotor circuit (secondary foreign voltage control)

Voltage control, rotor-resistance control and secondary foreign voltage control methods are commonly known as slip control methods.

## Changing the Applied Voltage

This method is the cheapest and the easiest, but is rarely used because

1. A large change in voltage is required for a relatively small change in speed.
2. This large change in voltage will result in a large change in the flux density thereby seriously disturbing the magnetic conditions of the motor.

## Changing the Applied Frequency

This method is also used very rarely.

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

## Changing the Number of Stator Poles

Change of number of poles is achieved by having two or more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different speeds. This method is easily applicable to SCIMs because the squirrel-cage rotor adopts itself to any reasonable number of stator poles.

## Rotor Rheostat Control

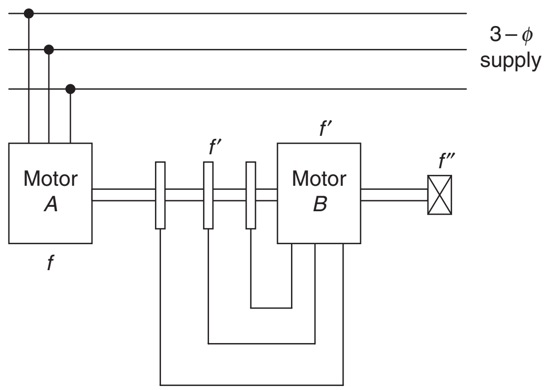
This method is applicable to slip-ring motors alone. The motor speed is reduced by introducing an external resistance in the rotor circuit.

### *Drawbacks of Rotor Rheostat Control*

1. With increase in rotor resistance, $I^2R$ losses also increase which decreases the operating efficiency of the motor. The losses are directly proportional to the reduction in speed.
2. Double dependence of speed, not only on $R_2$ but on load as well.

## Cascade or Concatenation or Tandem Connection

In this method, two motors are used and are ordinarily mounted on the same shaft, so that both run at the same speed.




The stator winding of the main motor $A$ is connected to the mains, while that of the auxiliary motors $B$ is fed from rotor circuit of motor $A$.

There are at least three ways in which the combination may be run.

1. Main motor A may be run separately from the supply. In that case, the synchronous speed is $N_{sa} = \dfrac{120f}{P_a}$, where $P_a$ = number of stator poles of motor $A$.
2. Auxiliary motor $B$ may be run separately from the mains (with motor $A$ being disconnected). In that case, synchronous speed is $N_{sb} = \dfrac{120f}{P_b}$, where $P_b$ = Number of stator poles of motor B.
3. The combination may be connected in cumulative cascade, i.e., in such a way that the phase rotation of the stator fields of both motors is in the same direction. The synchronous speed of the cascaded set, in this case, is $N_{sc} = \dfrac{120f}{(P_a + P_b)}$.
4. The fourth possible connection is the differential cascade. In this method, the phase rotation of stator field of motor $B$ is opposite to that of motor $A$. This reversal of phase rotation of stator of motor $B$ is obtained by interchanging any of its two leads. The synchronous speed of the set is $N_{sc} = \dfrac{120f}{(P_a \sim P_b)}$ (for $P_a \neq P_b$).

   As differentially cascaded set has a very small or zero starting torque, this method is rarely used. Moreover, the above expression for synchronous speed becomes meaningless for $P_a = P_b$.
5. $V/f$ control.

   We know that Torque ($\tau$)

   $$= \frac{\text{power}}{\omega} = \frac{\eta\sqrt{3}V\,1\cos\phi}{N}$$

   ($N$ is the speed)

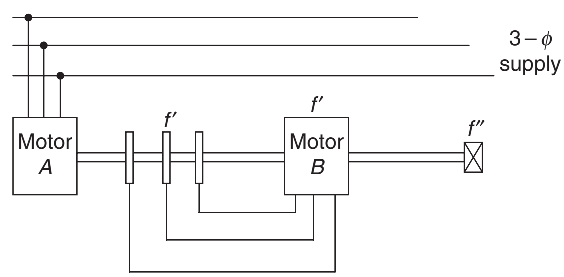
   But; $N = \dfrac{120f}{P}(1-S)$

   Now, if voltage and frequency are constant, torque stays constant and if torque stays constant and $V/f$ = constant; slip remains the same.

**Example 12:** A 4-pole IM and a 6-pole IM are connected in cumulative cascade. The frequency in the secondary circuit of the 6-pole motor is observed to be 2.0 Hz. Determine the slip in each machine and combined speed of the set. (supply frequency = 50 Hz)

**Solution:** Speed of cascaded set

$$N_{SC} = 120 \times 50/(4 + 6) = 600 \text{ rpm}$$




$$s = \frac{f''}{f} = \frac{2}{50} = 0.04$$

Let $N$ be the actual speed of concatenated set,

$$\therefore \quad 0.04 = \frac{600 - N}{600} \text{ or } N = 576 \text{ rpm}$$

$$N_{sa} = 120 \times 50/4 = 1500 \text{ rpm}$$

$$s_a = \frac{1500 - 576}{1500}$$

$$= 0.616 \text{ or } 61.6\%$$

$$f' = s_a f$$

$$= 0.616 \times 50$$

$$= 30.8 \text{ Hz}$$

$N'$ = Synchronous speed of 6-pole motor with frequency $f'$

$$= 120 \times 30.8/6 = 616 \text{ rpm}$$

$$s_b = \frac{N' - N}{N} = \frac{616 - 576}{616}$$

$$= 0.064$$

or 6.4%

### Injecting an emf in the Rotor Circuit

In this method, speed of an IM is controlled by injecting a voltage in the rotor circuit. The injected voltage must have the same frequency as the slip frequency. There is no restriction to phase of the injected emf In this method,

1. Any speed, within the working range can be obtained and smooth speed control is possible.
2. By adjusting the phase and magnitude of the injected emf, the power factor of the system can be improved.

## Revolving Field Theory of Single-Phase IM

A single-phase IM has a stator winding and a squirrel-cage rotor. When an alternating quantity given, it can be represented two oppositely rotating vectors of half magnitude.

$$F = 1/2\, F_m \cos(\theta - \omega t) + 1/2\, F_m \cos(\theta + \omega t)$$

In the above equation first one is the forward rotating field with half of the maximum value of the pulsating mmf along the axis of the winding then the slip of the rotor with respect to the forward rotating field.

$$s_f = \frac{(N - N)}{N_s} = s$$

The second term is the backward rotating field with half the magnitude. The slip corresponding one is $s_b = 2 - s$

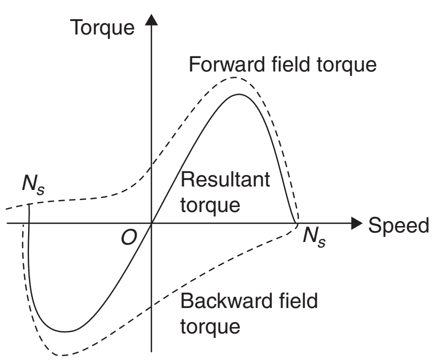



**Figure 2** Torque speed characteristics of single winding single-phase motor

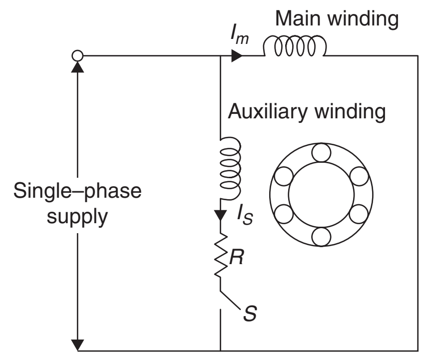
### Single-phase Induction Motors

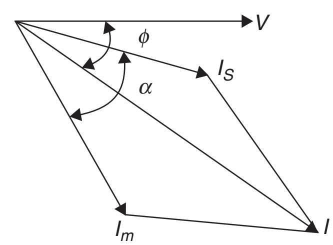
A single-phase IM is not self-starting. To make the motor self-starting, it is temporarily converted into a two-phase motor during starting period. For this purpose, in addition to the main winding, the stator of a single-phase motor is provided with an extra winding, known as starting (or auxiliary winding). The currents flowing through these windings should have a phase difference of 90° so that the motor behaves like a two-phase motor. These two currents produce a rotating magnetic field and hence make the motor self-starting.

The following are the methods by which necessary phase-difference between the two currents can be obtained.

#### *Split Phase Machine*

The main winding has low resistance but high reactance whereas the starting winding has a high resistance but low reactance. Hence the current $I_s$ drawn by the starting winding lags behind the applied voltage $V$ by a small angle whereas current $I_m$ taken by the main winding lags behind $V$ by a very large angle.




The phase angle between '$I'_s$' and '$I'_m$' is made as large as possible (i.e., near to 90°) because the starting torque of a split-phase motor is proportional to $\sin\alpha$. A centrifugal switch '$S$' is connected in series with the starting winding and is located inside the motor to automatically isolate the starting winding from the supply when the motor speed has reached 70% to 80% of steady state speed.

The value of resistance of auxiliary winding, $r_a$ for the production of maximum torque at starting is

$$r_a = \left(\frac{x_a}{x_m}\right)(r_m + Z_m)$$

or $$r_a = \left(\frac{N_a}{N_m}\right)^2 (r_m + z_m)$$

($\because$ reactance $\propto$ square of number of turns)

### Capacitor Split-phase Motors

In these motors, the phase displacement between the main winding current $I_m$ and auxiliary winding current $I_a$ is produced by connecting a capacitor in series with the auxiliary winding.

The starting torque ∝ $I_a.I_m.\sin\beta$

where $\beta$ = angle between $I_a$ and $I_m$. By choosing suitable value of capacitance, the angle $\beta$ can be made 90° at standstill, which results in highest possible starting torque but best compromise with the running torque is to make $\beta$ slightly less than 90°. This type of starting gives the highest starting torque.

Capacitor split-phase motors can be further classified as

1. Capacitor start induction run
2. Capacitor start capacitor run

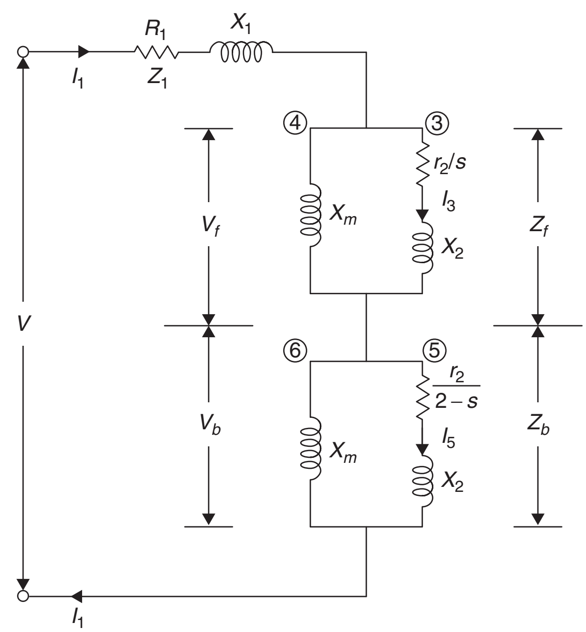
The value of capacitive reactance to be inserted in series with the auxiliary winding to get maximum starting torque is

$$X_c = X_a + \frac{r_a \cdot r_m}{Z_m + X_m}$$

$$\therefore \text{ The value of capacitor, } C = \left(\frac{1}{\omega X_c}\right) \text{ farad}$$

## Equivalent Circuit of a Single-phase IM

A single-phase IM may be viewed as consisting of two motors, having a common stator winding, but with their respective rotors revolving in opposite directions. The equivalent circuit of such a motor based on double field revolving theory is shown in fig.




The stator impedance is $Z = R_1 + jX_1$. The impedance of each rotor is $(r_2 + jx_2)$, where $r_2$ and $x_2$ represent half the actual rotor values in stator terms (i.e., $x_2$ stands for half the standstill reactance of the rotor, as referred to stator) Since iron loss has been neglected, the magnetizing branch is shown consisting of magnetizing reactance only. Each rotor has been assigned half the magnetizing reactance (i.e., $x_m$ represents half the actual reactance). The impedance of the 'forward running' rotor is

$$Z_f = \frac{jx_m\left(\frac{r_2}{s} + jx_2\right)}{\frac{r_2}{s} + j(x_m + x_2)}$$

and it runs with a slip of $s$.

The impedance of backward running rotor is

$$Z_b = \frac{jx_m\left(\frac{r_2}{2-s} + jx_2\right)}{\frac{r_2}{2-s} + j(x_m + x_2)}$$

and it runs with a slip of $(2 - s)$. Under standstill conditions $V_f = V_b$, but under running conditions $V_f$ is almost 90% to 95% of applied voltage.

The forward torque in synchronous watt is

$$T_f = \frac{I_3^2 r_2}{s}.$$

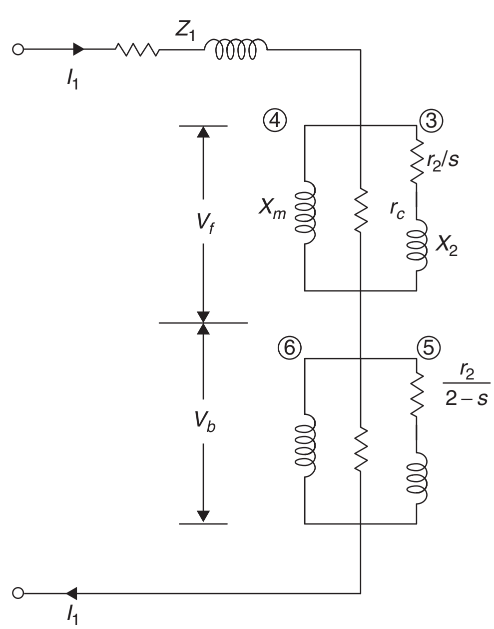
Similarly backward torque is

$$T_b = \frac{I_5^2 r_2}{2-s}$$

The total torque is $T = T_f - T_b$

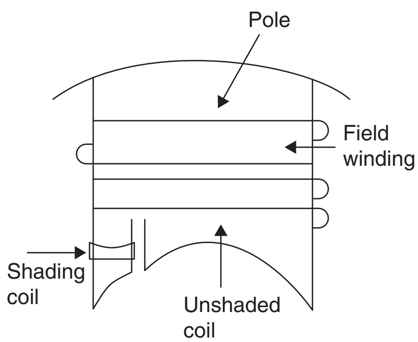
## Equivalent Circuit with Core Loss

The core loss can be represented by an equivalent resistance which may be connected in parallel as shown in fig.

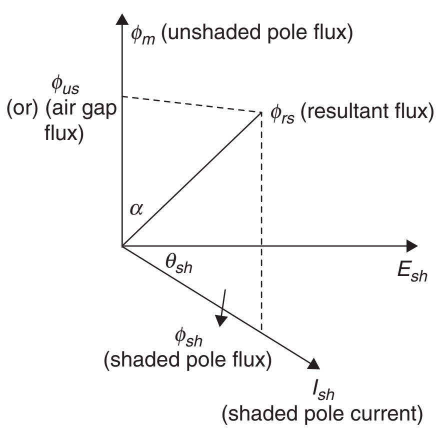


## Shaded-pole Single-phase Motor

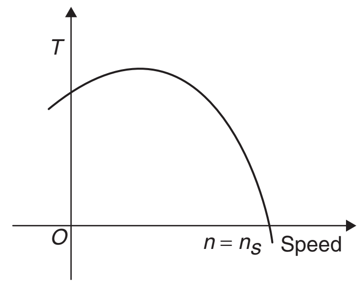
In this type motor, the small portion of each pole is covered with a short-circuited copper coil known as shading coil (or) shaded portion of the pole, The other part of the pole is known as unshaded part as shown in the figure. When an alternating current passed through the coil, the motor rotates in the direction of unshaded portion to shaded portion.




Below phasor diagram shows the flux and induced emf of the shaded-pole IM.




The Torque speed characteristics of the shaded-pole motor show below:




## Repulsion Start IM

In Repulsion motors the rotor and stator windings are inductively coupled. In these motors the stator has a distributed winding and the rotor is similar to the DC motor armature, i.e., the windings are connected to commutator. The Repulsion start IM start as a repulsion motor by the transformer action and the motor run as an IM by short-circuiting the commutator segment using a centrifugal switch.

## Reluctance Motor

The reluctance motor is just similar to unexcited salient-pole synchronous machine, In these motor the stator produces a rotating field and the reluctance of the magnetic path offered by the rotor to the rotating field is a function of the space angle. Then the rotor aligns in the minimum reluctance path with respect to the synchronous rotating flux. The motor is self-starting by the induction principle by providing short-circuited copper bars in the rotor.

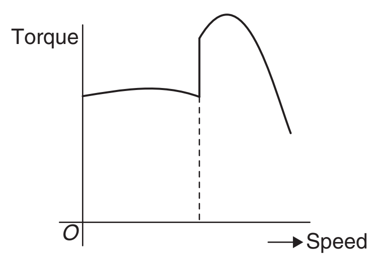



**Figure 3** Reluctance motor torque–speed characteristics

## EXERCISES

### Practice Problems I

***Directions for questions 1 to 27:*** Select the correct alternative from the given choices.

1. A 3-$\phi$, 50 Hz IM has a full load speed of 1440 rpm. What is slip and rotor frequency of the IM?
   (A) 6%, 4 Hz (B) 10%, 46 Hz
   (C) 8%, 6 Hz (D) 4%, 2 Hz
2. An 8-pole, 50 Hz, 3-$\phi$ slip-ring IM has effective rotor resistance of 0.8 Ω/ph. Stalling speed is 650 rpm. The resistance required in the rotor phase to obtain the maximum torque at starting?
   (A) 0.42 Ω (B) 0.52 Ω
   (C) 0.48 Ω (D) 0.58 Ω
3. The rotor power output of 3-$\phi$ IM is 15 kW and the corresponding slip is 4%. The rotor ohmic loss will be
   (A) 600 W (B) 625 W
   (C) 650 W (D) 700 W
4. In case of 3-$\phi$ IM, shaft power is 2700 W and mechanical losses are 180 W. At a slip of 4%, the rotor ohmic losses are
   (A) 115.2 W (B) 120 W
   (C) 108 W (D) 105 W
5. A 3-$\phi$ IM having a star-connected rotor has an induced emf of 80 V between slip-rings at stand still on open circuit. Find the current and power factor when the slip-rings are connected to 3 Ω/phase rheostat?

(A) 8.85 A and 0.748 Lag
(B) 8.16 A and 0.707 Lag
(C) 9.5 A and 0.8 Lag
(D) 9.5 A and 0.6 Lag

**6.** A 3-$\phi$ IM is driving the full-load torque which is independent of speed. If the line voltage drops to 85% of the rated value, the increase in motor Cu losses is ________

(A) 123% (B) 33%
(C) 38.4% (D) 33.6%

**7.** If the supply voltage of a 3-$\phi$ SCIM is reduced by 20% then the maximum torque will

(A) increase by 20%
(B) decrease by 20%
(C) increase by 36%
(D) decrease by 36%

**8.** A cascaded set of IM, consists of two motors $A$ and $B$ with 4 poles and 6 poles, respectively. The motor A is connected to a 50 Hz supply. What is the speed of the set ______?

(A) 3000 rpm (B) 600 rpm
(C) 1500 rpm (D) 1000 rpm

**9.** A 3-$\phi$ IM has a full-load slip of 3% at normal voltage. Which one of the following will be the value of the slip of the motor if it develops the same torque theoretically while operating at 110% of its normal voltage?

(A) 2.48% (B) 0.248
(C) 0.483% (D) 4.83%

**10.** A 6-pole, 3-$\phi$, 60 Hz IM runs at 1000 rpm, developing maximum torque. Rotor resistance per phase is 1.2 Ω. Neglecting stator impedance, then for developing maximum torque, the external resistance to be connected in series with the each rotor phase will be

(A) 7.2 Ω (B) 6 Ω
(C) 1.44 Ω (D) 1.2 Ω

**Common Data for Questions 11 and 12:**

A 400 V, 4-pole 3-$\phi$ 50 Hz, IM has a rotor resistance and reactance per phase of 0.02 Ω and 0.2 Ω, respectively. Stator to rotor turns ratio is 4.

**11.** The $T_{max}$ and corresponding slip of motor.

(A) 320 Nm, 10% (B) 320 Nm, 20%
(C) 159.23 Nm, 10% (D) 159.23 Nm, 20%

**12.** The full-load slip and power output, if the maximum torque is twice the full-load torque, are ______?

(A) .027, 12.16 kW (B) 0.373, 12.16 kW
(C) 0.27, 16.18 kW (D) 0.373, 14.3 kW

**Common Data for Questions 13 and 14:**

A 3-$\phi$, star-connected 400 V, 50 Hz, 4-pole IM has the following per phase constants in ohm referred to stator and

$Nr = 1440$ rpm.

$R_1 = .15\ \Omega,\ x_1 = .45\ \Omega,\ r_2 = 0.12\ \Omega$

$x_2 = 0.45\ \Omega,\ x_m = 28.5\ \Omega$

**13.** The stator current $I_1$ is _________?

(A) $71.06\angle{-21.47}°$ (B) $122.97\angle{-21.47}°$
(C) $71.06\angle{-36.47}°$ (D) $122.97\angle{-36.47}°$

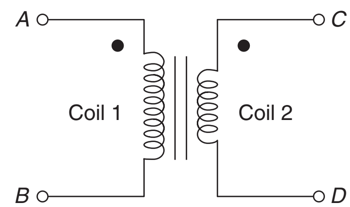
**14.** The mechanical power developed is ________

(A) 87.73 kW (B) 6.45 kW
(C) 41.73 kW (D) 100.49 kW

**15.** The power input to a 415 V, 50 Hz, 6-pole, 3-$\phi$ IM running at 975 rpm is 40 kW. The stator losses are 1 kW and friction and windage losses are 2 kW. The efficiency of the motor is

(A) 92.5% (B) 91%
(C) 90.06% (D) 88%

**Common Data for Question 16:**




The figure above shows coils 1 and 2, with dot markings as shown, having 2000 and 3000 turns, respectively. Both the coils have a rated current of 25 A. Coil-1 is excited with single phase, 400 V, 50 Hz supply.

**16.** In the auto-transformer obtained in above question the current in each coil is

(A) coil-1 is 15 A and coil-2 is 10 A.
(B) coil-1 is 10 A and coil-2 is 25 A.
(C) coil-1 is 10 A and coil-2 is 15 A.
(D) coil-1 is 25 A and coil-2 is 10 A.

**17.** A three-phase slip-ring IM is fed from the rotor side with stator winding short-circuited. The frequency of the currents flowing in the short-circuited stator winding is

(A) zero.
(B) supply frequency.
(C) slip frequency.
(D) frequency corresponding to rotor speed.

**18.** Skew is used in IMs in order to reduce torque due to

(A) space harmonics.
(B) slot harmonics.
(C) time harmonics.
(D) reverse rotating fields.

**19.** An IM is fed from a balanced three – phase supply at rated voltage and frequency through a bank of three single-phase transformers connected in delta – delta. One unit of the bank develops fault and is removed. Then

(A) single phasing will not occur but the motor terminal voltages will become unbalanced and the machine can be loaded to the extent of 57.7% of its rating.
(B) the machine can be loaded to the extent of 57.7% of its rating with balanced supply at its terminals.

(C) the machine can be loaded to the extent of 66.66% with balanced supply at its terminals.
(D) single phasing will occur and the machine fails to start.

**20.** A 3-phase, delta-connected IM fed from unbalanced supply will have
(A) zero sequence currents.
(B) negative sequence component current.
(C) less heating of the rotor.
(D) All of these.

**21.** In case of a split-phase motor, the phase shift between currents in the two windings is around
(A) 120°. (B) 90°.
(C) 80°. (D) 30°.

**22.** In an IM, if the air-gap is increased
(A) speed will reduce.
(B) breakdown torque will reduce.
(C) efficiency will improve.
(D) power factor will be lowered.

**23.** A three-phase SCIM has a full load efficiency of 0.85 and a maximum efficiency of 0.9. It is operated at a slip of 0.65 by applying a reduced voltage. The efficiency of the motor at this operating point is
(A) is less than 0.5.
(B) greater than 0.6.
(C) in the range of 0.85 ± 0.05.
(D) None of the above

**24.** A single-phase IM with identical main and auxiliary windings can be made self-starting by connecting
(A) a capacitor in series with the main winding.
(B) a capacitor in series with the auxiliary winding.
(C) a capacitor across the supply terminals.
(D) the main and auxiliary windings in series.

**25.** Which of the following starting method for an IM is inferior in view of the poor starting torque per ampere of the line current drawn?
(A) Star-Delta method
(B) Direct on line starting
(C) Auto-transformer method of starting
(D) Series inductor method of starting

**26.** The type of single-phase IM having the highest power factor at full load is
(A) Split-phase type
(B) Shaded-pole type
(C) Capacitor-start type
(D) Capacitor-run type

**27.** A plot of input power versus voltage was drawn from the no – load test readings (at different supply voltages) of a 3-phase IM. This curve was extrapolated to intersect the Y-axis. The intersection point yields
(A) stray load loss.
(B) stator copper loss.
(C) core loss.
(D) friction and windage loss.

## Practice Problems 2

***Directions for questions 1 to 50:*** Select the correction alternative from the given choices.

**1.** The speed of the rotor field of an IM is (s is the slip and $N_s$, the synchronous speed)
(A) $s \times N_s$ in the same direction as stator field
(B) $N_s$ in the same direction as stator field
(C) $s \times N_s$ in the opposite direction as stator field
(D) $N_s$ in the opposite direction as that of stator field

**2.** The rotor of a three-phase IM draws a current which is lagging at a power factor of 0.707. The spatial displacement between stator and rotor magnetic field is
(A) 45° (B) 90°
(C) 135° (D) 180°

**3.** A synchronous motor and an IM are connected to a common bus. For the power factor to be unity at the bus,
(A) synchronous motor should be over excited
(B) synchronous motor should be under excited
(C) the speed of synchronous motor and synchronous speed of IM should be same
(D) synchronous motor is normally excited

**4.** The starting current of an IM is 6 times the full-load current. If the full-load slip is 3%, ratio of starting torque to full-load torque is
(A) 1.2 (B) 1.08
(C) 0.8 (D) 0.6

**5.** The rotor power output of a 3-$\phi$ **IM** is 12 kW at a slip of 4%. The rotor copper losses would be
(A) 400 W (B) 500 W
(C) 600 W (D) 700 W

**6.** The rotor resistance per phase of a 4-pole 3-phase, 50 Hz IM is 1.4 Ω. It develops maximum torque at 1250 rpm. For developing maximum torque at starting, the resistance to be connected in series with each rotor phase will be
(A) 8.4 ohm (B) 1.4 ohm
(C) 7.2 ohm (D) 7 ohm

**7.** A 3-$\phi$ IM operating at rated voltage has a full-load slip of 4%. It is now operated at 110% of rated voltage. What should be the value of slip theoretically, if it develops the same torque?
(A) 3.30% (B) 0.330%
(C) 1.483% (D) 4.83%

**8.** A 3-$\phi$ supply is given to the rotor of a 3-$\phi$ slip-ring IM with short-circuited stator. The frequency of current in the stator is
(A) supply frequency
(B) frequency corresponding to rotor speed
(C) slip frequency
(D) zero

**9.** A 3-$\phi$ IM running at 4% slip takes an input power of 10 kW. If stator resistance and core losses are assumed negligible, then the torque developed in synchronous watts is
(A) 12 kW (B) 9 kW
(C) 10 kW (D) 0.4 kW

**10.** A 3-$\phi$, 6-pole, 50 Hz IM is delivering 3500 W at a slip of 0.04. Stray losses are found to be 100 W. The gross torque is
(A) 3750 synchronous watts
(B) 35.81 Nm
(C) Either A or B
(D) 41.58 kgm

**11.** A 3-$\phi$ 4-pole 400 V 50 Hz Y-connected IM has rotor resistance of 0.1 Ω and stand still reactance of 0.3 Ω. The effective stator to rotor turns ratio is 4. If the motor is to drive a constant-load torque of 100 Nm, the minimum resistance to be added in series in rotor circuit for the motor to start on load
(A) 0.01 Ω (B) 0.11 Ω
(C) 0.02 Ω (D) 0.22 Ω

**12.** A 3-$\phi$ IM has a rotor resistance of 0.02 Ω/phase. If the resistance is increased to 0.04 Ω /phase, the maximum torque
(A) increase by 50%
(B) becomes two times
(C) remains unaltered
(D) will reduce to half

**13.** When the stator of a 3-$\phi$ IM is excited with a 3-$\phi$ balanced supply, the rotor of the IM runs in same direction as the rotating stator magnetic field. The law that is obeyed here is
(A) Faraday's law of electromagnetic induction
(B) Lenz's law
(C) Fleming's left hand rule
(D) Newton's law of motion

**14.** An SCIM having a rated slip of 2.5% on full load has a starting torque of 0.9 full-load torque, then starting current is
(A) equal to full-load current
(B) twice full-load current
(C) four times full-load current
(D) six times full-load current

**15.** Maintaining the voltage to frequency ratio of an IM constant, the frequency of voltage applied is increased. Assuming stator impedance is zero, maximum torque
(A) increases and occurs at large values of slip
(B) remains constant and occurs at smaller values of slip
(C) remains constant and occurs at larger values of slip
(D) increases and occurs at smaller values of slip

**16.** In an SCIM, blocked rotor test is done determines its equivalent
(A) to determine shunt resistance and reactance as seen from rotor
(B) to determine series resistance and reactance as seen from rotor
(C) to determine shunt resistance and reactance as seen from the stator
(D) to determine series resistance and reactance as seen from the stator

**17.** An ac IM is used for a speed control application is driven from an inverter. Name plate details of motor $V$ : 415, $V_{ph}$ : 3, $f$ : 50 Hz, $N$ : 1440 rpm. Keeping $v/f$ constant, inverter output frequency is set to 40 Hz and motor is operated at half rated slip. The running speed of motor is
(A) 1200 rpm (B) 1140 rpm
(C) 1176 rpm (D) 1340 rpm

**18.** Both frequency and voltage of a 3-$\phi$ IM, driving a constant-load torque are halved. Ignore stator impedance and core losses. In this condition,
(A) Flux in the air gap remains constant
(A) Stator current remains constant
(C) The per unit slip remains constant
(D) Difference between synchronous speed and actual speed remains constant
Among the above, correct statements are
(A) A, B, D (B) B, C, D
(C) A and D (D) All the above are correct

**19.** Only the main winding of a 1-$\phi$ IM is excited. The forward and backward rotating fields
(A) are equal
(B) are zero
(C) forward rotating field is more than backward rotating field
(D) forward rotating field is less than backward rotating field

**20.** The main winding impedance and auxiliary winding impedance of a single-phase 4-pole, capacitor-start IM has the following stand still values.

$Z_m$ (main) = 3 + $j$4 Ω

$Z_a$ (aux) = 12 + $j$10 Ω

Value of capacitor required to produce 90° phase difference between currents in main winding and auxiliary winding
(A) 167.53 $\mu$F (B) 197.53 $\mu$F
(C) 267.53 $\mu$F (D) 287.53 $\mu$F

**21.** A 400 V, 10 kW, 6-pole 50 Hz Y-connected IM has full-load slip of 5%. The output torque of machine at full load is
(A) 2.9 Nm (B) 92.5 Nm
(C) 100.51 Nm (D) 248.73 Nm

**22.** The single-phase IM that has the greatest power factor at full load is
(A) split-phase type
(B) shaded-pole type
(C) capacitor-start type
(D) capacitor-run type

**23.** A 3-$\phi$ IM runs in anticlockwise direction when supplied with a phase sequence of R − B − Y. For a clockwise rotation, the phase sequence should be
(A) Y − R − B (B) B − Y − R
(C) B − R − Y (D) either (A) or (B)

**24.** For an IM ratio of rotor power output to air gap power is
(A) $(1 - s)^2$ (B) $(1 - s)$
(C) $\sqrt{1-s}$ (D) $\left(1-\sqrt{s}\right)$

**25.** The voltage applied to a 3-$\phi$ IM, running at no load is reduced to one half from the rated value. Then the speed and stator current
(A) decreases and increases, respectively
(B) both decreases
(C) both remain practically constant
(D) remain same and decreases, respectively

**26.** A 3-$\phi$ IM is started DOL at the rated voltage. If starting current is 4 times full-load current, and full-load slip is 5% ratio of starting torque to full-load torque is
(A) 0.2 (B) 0.4
(C) 0.8 (D) 1

**27.** The rotor resistance of a 1-$\phi$ IM, driving a fan load is made high in order to achieve
(A) high efficiency
(B) low starting torque
(C) quick acceleration
(D) reduced size

**28.** The equivalent circuit parameters of a 3-phase 6-pole 400 V, 50 Hz Y-connected IM are as follows.

$$r_1 = 0.9\ \Omega,\ r_2' = 0.7\ \Omega,\ x_1 = x_2' = 1.4\ \Omega,\ x_m = 40\ \Omega$$

The starting torque when motor is started direct on line
(A) 105.06 Nm (B) 195.06 Nm
(C) 235.06 Nm (D) 285.06 Nm

**29.** The no load and blocked rotor test data for a 3-$\phi$, 10 kW, 400 V, 4-pole, 50 Hz star-connected IM drawing 20 A on full load is as given

No load test: 400 V 5 A 1120 W

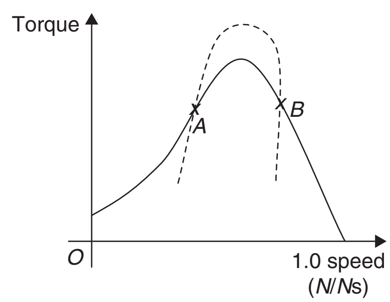
Blocked rotor: 70 V 16 A 692 W

Estimate the full load efficiency of motor
(A) 77% (B) 82%
(C) 83.4% (D) 86%

**30.** A 400 V, 50 Hz, 25 hp, 3-$\phi$ IM is drawing 25 A current at 0.8 p.f. lag. Stator and rotor Cu losses are 10 kW and 700 W, respectively. Friction and windage losses are 950 W and core loss is 1100 W. The air gap power of the motor will be
(A) 10.806 kW (B) 12.85 kW
(C) 16.32 kW (D) 11.95 kW

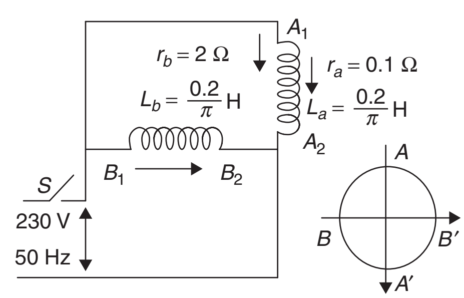
**31.** A 3-$\phi$, 400 V, 50 Hz, 4-pole, 1400 rpm, Y-connected SCIM is controlled from a 3-$\phi$ voltage source inverter with constant v/f control. The motor has the following parameters referred to the stator. $R_r' = 1.0\ \Omega$, $X_s = X_r' = 20\ \Omega$. Neglecting stator resistance and rotational losses, the stator line to line voltage and frequency to obtain maximum torque at starting will be
(A) 323 V, 40.3 Hz
(B) 266.6 V, 33.3 Hz
(C) 100 V, 12.5 Hz
(D) 200 V, 25 Hz

**32.** Figure below shows the speed torque curves of a 3-$\phi$ SCIM and its load. Points A and B represents the operating conditions. Which among them is stable




(A) A (B) B
(C) both are stable (D) none are stable

**33.** $AA'$ and $BB'$ are the axes of the main winding $A_1A_2$ and auxiliary winding $B_1B_2$, respectively, of a 230 V, 50 Hz 1-$\phi$ IM. The direction of axes shows the direction of flux when currents in winding are as shown in the figure. When switch $S$ is closed,




(A) motor rotates clockwise
(B) motor rotates anticlockwise
(C) motor rotates momentarily and comes to a halt
(D) motor does not rotate

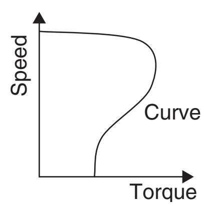
**34.** In a shaded-pole IM, the rotor runs from
(A) shaded portion to the unshaded portion of the pole while flux in shaded pole leads that of unshaded pole

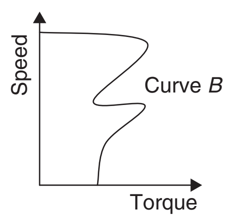
(B) shaded portion to the unshaded portion of the pole while flux in the shaded pole lags that of unshaded pole
(C) unshaded portion to shaded portion and flux in the unshaded pole leads that of shaded pole
(D) unshaded portion to the shaded portion, and flux in unshaded pole lags that of shaded pole

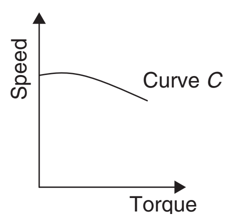
**35.** A 3-$\phi$ 50 Hz IM has a full load speed of 960 rpm. For this motor, the speed of stator field with respect to revolving rotor field is
(A) 1000 rpm (B) 0 rpm
(C) 40 rpm (D) 960 rpm

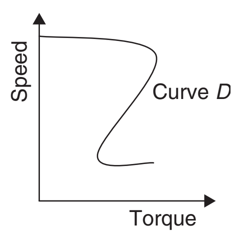
**36.** Two slip-ring IMs having number of poles 6 and 2, respectively, are connected in cascade. If supply frequency is 50 Hz, speed of the main motor is
(A) 1500 rpm (B) 3000 rpm
(C) 750 rpm (D) 1000 rpm

**37.** The torque speed characteristics of a repulsion start induction run motor is

(A) 


(B) 


(C) 

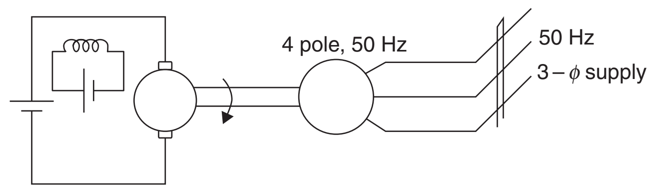

(D) 


(A) Curve A (B) Curve B
(C) Curve C (D) Curve D

**38.** The power output of an induction machine is minimum when
(A) when equivalent resistance is equal to equivalent reactance of the motor
(B) equivalent resistance equal to slip multiplied by equivalent reactance
(C) when slip is equal to zero
(D) when slip is equal to one

**39.** The main winding and auxiliary winding current of a 2 winding single-phase IM are $I_m$ = 15 A and $I_a$ = 7.5 A at stand still. The auxiliary winding current leads the main winding current by $\alpha = 45°$ electrical. The two windings are in space quadrature and the effective number of turns are $N_m$ = 150 and $N_a$ = 175. Amplitude of forward rotating stator mmf is
(A) 1508 AT (B) 1237 AT
(C) 1045 AT (D) 653 AT

**40.** A separately excited **DC** machine is coupled to a 50 Hz, 3-phase 4-pole induction machine as shown in the figure. The **DC** machine is energized first and machines rotate at 1600 rpm. The induction machine is also connected to a 50 Hz 3-$\phi$ source, phase sequence being consistent with the direction of rotation. In steady state,




(A) both machine acts as generators
(B) **DC** machine acts as generator and induction machine motor
(C) **DC** machine acts as motor and induction machine generator
(D) both machines acts as motor

**41.** Which type of motor is most suitable for a computer printer drive?
(A) Reluctance motor
(B) Hysteresis motor
(C) Shaded-pole motor
(D) Stepper motor

**42.** By adding resistance in the rotor circuit of a slip-ring IM, the starting current and torque, compared to DOL
(A) both are reduced
(B) both are increased
(C) starting current is reduced but starting torque is increased
(D) starting current is increased and starting torque is reduced

**43.** An IM is connected to a 3-$\phi$ supply constituting three 1-$\phi$ transformers connected in Delta–Delta configuration. If one transformer is removed, then
(A) single phasing occurs and machine does not start
(B) single phasing does not occur and the terminal voltages become unbalanced and machine can be loaded to 57.7% of its rated capacity
(C) machine can be loaded to 57.7% of rated capacity with balanced supply at the terminals
(D) machine can be loaded to 66.67% of its rated power with balanced supply at terminals

**44.** The skewing of rotor slots in a 3-$\phi$ IM reduces
(A) harmonic torques and noise but increases torque
(B) harmonic torques and noise but increases starting torque
(C) noise but increases breakdown torque and harmonic torque
(D) harmonic torque, noise and breakdown torque and starting torque

**45.** If the air gap of an IM is increased, then
(A) pull out torque is reduced
(B) power factor is lowered

(C) efficiency is improved
(D) speed is reduced

**Common Data for Questions 46 and 47:**
The starting current of a 3-$\phi$ SCIM is 8 times the full-load current and the full-load slip is 5%.

**46.** If an auto transformer is used to reduce voltage at starting, the auto transformer ratio to provide 2 PU starting torque
(A) 79% (B) 57.7%
(C) 70.7% (D) 82%

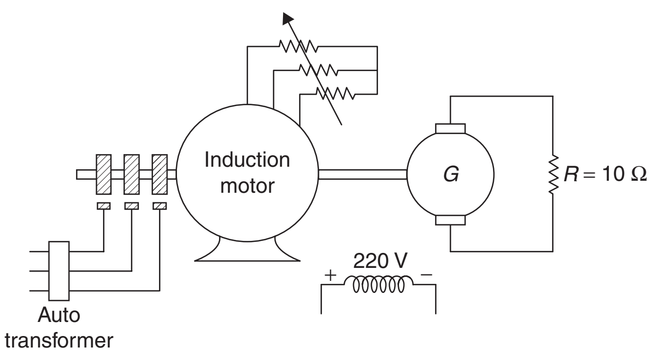
**47.** If a starting torque of 0.5 PU is required, then starting current in PU should be
(A) 2.16 (B) 4.16
(C) 3.75 (D) 3.16

**Common Data for Questions 48 and 49:**

A slip-ring IM has the following name plate details

$$V : 400\text{ V}, f : 50\text{ Hz, Poles 6, } V_{ph} : 3$$

It is fed from rotor side through an auto transformer and stator is connected to a variable resistance.




The motor is coupled to a 220 V, separately excited **DC** generator feeding power to fixed resistance of 20 Ω. By adjusting the variable resistance, motor is run at 960 rpm. Two watt meters used to measure input power gives the following readings → $W_1 = 2000$ W, $W_2 = -400$ W.

**48.** The speed of rotation of stator magnetic field with respect to rotor structure is
(A) 40 rpm in direction of rotation
(B) 40 rpm opposite to direction of rotation
(C) 1000 rpm in direction of rotation
(D) 1000 rpm opposite to direction of rotation

**49.** Neglecting all losses of both the machines, generator power output and current through resistance
(A) 64 W, 1.79 A
(B) 1236 W, 7.86 A
(C) 1536 W, 8.76 A
(D) 1880 W, 9.7 A

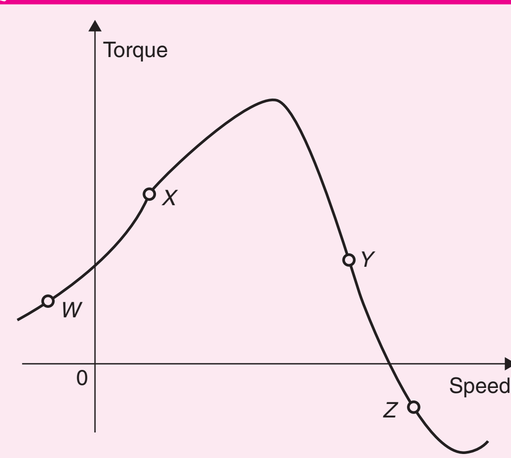
**Common Data for Question 50:**
Consists of two statements: one is Assertion (A) and the other is Reason (R). You have to examine these two statements and select the answer using the code given below.
(A) Both A and R are individually correct and R is the correct explanation of A
(B) Both A and R are individually correct, but R is not the correct explanation of A
(C) A is true but R is false
(D) A is false but R is true

**50.** A: The maximum value of developed torque in a 3-$\phi$ IM remains a constant for various speeds in the sub synchronous region in the v/f control.
R: The ratio of voltage and frequency over the considered speed range is maintained a constant and hence flux in the machine is almost constant.

## PREVIOUS YEARS' QUESTIONS

**1.** A 400 V, 15 kW, 4-pole, 50 Hz, Y-connected IM has full-load slip of 4%. The output torque of the machine at full load is **[2004]**
(A) 1.66 Nm (B) 95.50 Nm
(C) 99.47 Nm (D) 624.73 Nm

**2.** On the torque/speed curve of IM shown in the below figure, four points of operation are market as W, X, Y and Z. Which one of them represents the operation at a slip greater than 1? **[2005]**




(A) W (B) X
(C) Y (D) Z

**3.** For an IM, operating at a slip s, the ratio of gross power output to air gap power is equal to: **[2005]**

(A) $(1 - s)^2$ (B) $(1 - s)$

(C) $\sqrt{(1-s)}$ (D) $(1 - \sqrt{s})$

**4.** Under no load condition, if the applied voltage to an IM is reduced from the rated voltage to half the rated value, **[2005]**

(A) the speed decreases and the stator current increases

(B) both the speed and the stator current decrease

(C) the speed and the stator current remain practically constant

(D) there is negligible change in the speed but the stator current decreases

**5.** A three-phase cage IM is started by direct-on-line (DOL) switching at the rated voltage. If the starting current drawn is 6 times the full-load current, and the full-load slip is 4%, the ratio of the starting developed torque to the full-load torque is approximately equal to **[2005]**

(A) 0.24 (B) 1.44

(C) 2.40 (D) 6.00

**6.** In a single-phase IM driving a fan load, the reason for having a high resistance rotor is to achieve **[2005]**

(A) low starting torque

(B) quick acceleration

(C) high efficiency

(D) reduced size

**7.** Determine the correctness of otherwise of the following **Assertion [a]** and the **Reason [r].**

**Assertion:** Under *V*/*f* control of IM, the maximum value of the developed torque remains constant over a wide range of speed in the sub-synchronous region.

**Reason:** The magnetic flux is maintained almost constant at the rated value by keeping the ratio *V*/*f* constant over the considered speed range. **[2005]**

(A) Both [a] and [r] are true and [r] is the correct reason for [a]

(B) Both [a] and [r] are true but [r] is not the correct reason for [a]

(C) Both [a] and [r] are false

(D) [a] is true but [r] is false

**8.** For a single-phase capacitor start IM which of the following statements is valid? **[2006]**

(A) The capacitor is used for power factor improvement

(B) The direction of rotation can be changed by reversing the main winding terminals

(C) The direction of rotation cannot be changed

(D) The direction of rotation can be changed by interchanging the supply terminals

**9.** The speed of a 4-pole IM is controlled by varying the supply frequency while maintaining the ratio of supply frequency (*V*/*f*) constant. At rated frequency of 50 Hz and rated voltage of 400 V its speed is 1440 rpm. Find the speed at 30 Hz, if the load torque is constant. **[2006]**

(A) 882 rpm (B) 864 rpm

(C) 840 rpm (D) 828 rpm

**10.** A 3-phase, 4-pole, 400 V, 50 Hz, star-connected IM has following circuit parameters $r_1 = 1.0\ \Omega$, $r_2' = 0.5\ \Omega$, $x_1 = x_2' = 1.2\ \Omega$, $x_m = 35\ \Omega$ The starting torque when the motor is started direct-on-line is (use approximate equivalent circuit model) **[2006]**

(A) 63.6 Nm (B) 74.3 Nm

(C) 190.8 Nm (D) 222.9 Nm

**11.** A 3-phase, 10 kW, 400 V, 4-pole, 50 Hz, star-connected IM draws 20 A on full load. Its no load and blocked rotor test data are given below:

| | | | |
|---|---|---|---|
| No Load test: | 400 V | 6A | 1002 W |
| Blocked Rotor test: | 90 V | 15 A | 762 W |

Neglecting copper loss in no Load test and core loss in Blocked Rotor test, estimate motor's full load efficiency. **[2006]**

(A) 76% (B) 81%

(C) 82.4% (D) 85%

**12.** A three-phase SCIM has a starting torque of 150% and a maximum torque of 300% with respect to rated torque at rated voltage and rate frequency. Neglect the stator resistance and rotational losses. The value of slip for maximum torque is **[2007]**

(A) 13.48% (B) 16.24%

(C) 18.92% (D) 26.79%

**Common Data for Questions 13 to 15:**

A three-phase SCIM has a starting current of seven times the full-load current and full-load slip of 5%

**13.** If an autotransformer is used for reduced voltage starting to provide 1.5 per unit starting torque, the autotransformer ratio (%) should be **[2007]**

(A) 57.77% (B) 72.56%

(C) 78.25% (D) 81.33%

**14.** If a star-delta starter is used to start this IM, the per unit starting torque will be **[2007]**

(A) 0.607 (B) 0.816

(C) 1.225 (D) 1.616

**15.** If a starting torque of 0.5 per unit is required then. The per unit starting current should be **[2007]**

(A) 4.65 (B) 3.75

(C) 3.16 (D) 2.13

**16.** A 230 V, 50 Hz, 4-pole, single-phase IM is rotating in the clockwise (forward) direction at a speed of 1425 rpm. If the rotor resistance at standstill is 7.8 Ω then the effective rotor resistance in the backward branch of the equivalent circuit will be **[2008]**

(A) 2 Ω (B) 4 Ω
(C) 78 Ω (D) 156 Ω

**17.** A 400 V, 50 Hz, 30 hp, three-phase IM 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 **[2008]**

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

**18.** A 400 V, 50 Hz, 4-pole, 1400 rpm, star-connected SCIM has the following parameters referred to the stator.

$$R_r' = 1.0\ \Omega,\ X_s = X_r' = 1.5\ \Omega.$$

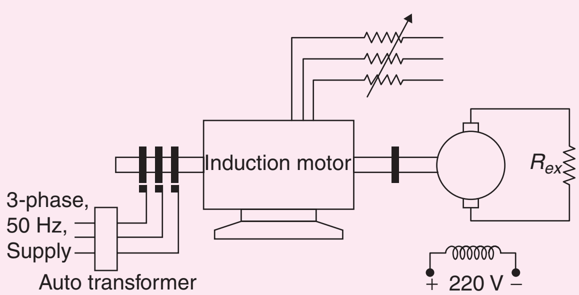
Neglect stator resistance and core and rotational losses of the motor.

The motor is controlled from a 3-phase voltage source inverter with constant $V/f$ control. The stator line-to-line voltage (rms) and frequency to obtain the maximum torque at starting will be **[2008]**

(A) 20.6 V, 2.7Hz
(B) 133.3 V, 16.7 Hz
(C) 266.6 V, 33.3 Hz
(D) 323.3 V, 40.3 Hz

**Common Data for Questions 19 and 20:**

A 3-phase, 440 V, 50 Hz, 4-pole, slip-ring IM is fed from the rotor side through an auto-transformer and the stator is connected to a variable resistance as shown in the figure.




The motor is coupled to a 220 V, separately excited DC generator feeding power to fixed resistance of 10 Ω. Two-wattmeter method is used to measure the input power to IM. The variable resistance is adjusted such that the motor runs at 1410 rpm and the following readings were recorded.

$$W_1 = 1800\text{ W},\ W_2 = -200\text{ W}$$

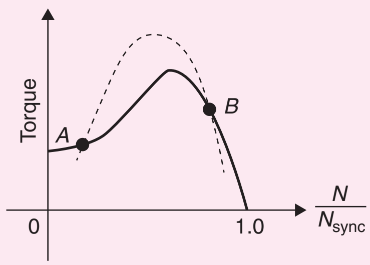
**19.** The speed of rotation of stator magnetic field with respect to rotor structure will be **[2008]**

(A) 90 rpm in the direction of rotation
(B) 90 rpm in the opposite direction of rotation
(C) 1500 rpm in the direction of rotation
(D) 1500 rpm in the opposite direction rotation.

**20.** Neglecting all losses of both the machines, the DC generator power output and the current through resistance ($R_{ex}$) will, respectively, be **[2008]**

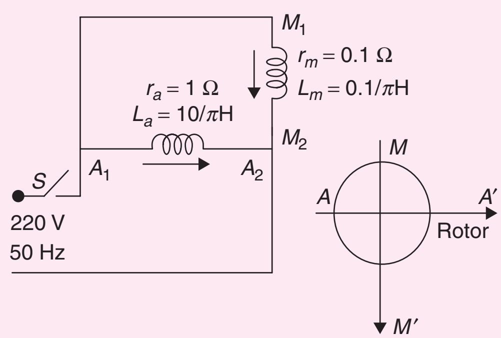
(A) 96 W, 3.10A (B) 120W, 3.46 A
(C) 1504 W, 12.26 A (D) 1880 W, 13.71 A

**21.** A 3-phase SCIM supplied from a balanced 3-phase source drives a mechanical load. The torque-speed characteristics of the motor (solid curve) and of the load (dotted curve) are shown. Of the two equilibrium points $A$ and $B$, which of the following options correctly describes the stability of $A$ and $B$? **[2009]**




(A) $A$ is stable $B$ is unstable
(B) $A$ is unstable $B$ is stable
(C) Both are stable
(D) Both are unstable

**22.** A 220 V, 50 Hz, single-phase IM has the following connection diagram and winding orientations shown. MM' is the axis of the main stator winding ($M_1M_2$) and $AA'$ is that of the auxiliary winding ($A_1A_2$). Directions of the winding axes indicate direction of flux when currents in the windings are in the directions shown. Parameters of each winding are indicated. When switch S is closed, the motor **[2009]**




(A) rotates clockwise
(B) rotates anticlockwise
(C) does not rotate
(D) rotates momentarily and comes to a halt

**23.** A balanced three-phase voltage is applied to a star-connected IM, the phase to neutral voltage being $V$. The stator resistance, rotor resistance referred to the stator, stator leakage reactance, rotor leakage reactance referred to the stator, and the magnetizing reactance are denoted by $r_s$, $r_r$, $x_s$, $x_r$ and $X_m$, respectively. The magnitude of the starting current of the motor is given by **[2010]**

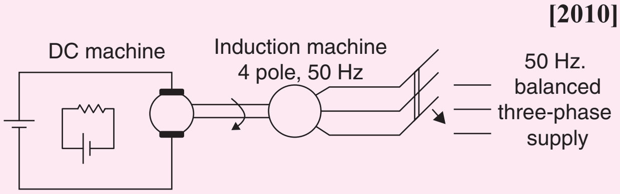
(A) $\dfrac{V}{\sqrt{(r_s+r_r)^2+(x_s+x_r)^2}}$

(B) $\dfrac{V}{\sqrt{r_s^2+(x_s+X_m)^2}}$

(C) $\dfrac{V}{\sqrt{(r_s+r_r)^2+(X_m+x_r)^2}}$

(D) $\dfrac{V}{\sqrt{r_s^2+(X_m+x_r)^2}}$

**24.** A separately excited DC machine is coupled to a 50 Hz, three-phase, 4-pole induction machine as shown in the figure. The DC machine is energized first and the machines rotate at 1600 rpm. Subsequently the induction machine is also connected to a 50 Hz, three-phase source, the phase sequence being consistent with the direction of rotation. In steady state, **[2010]**




(A) Both machines act as generators
(B) The DC machine acts as a generator, and the induction machine acts as a motor
(C) The DC machine acts as a motor, and the induction machine acts as a generator
(D) Both machines act as motors

**25.** A three-phase 440 V, 6-pole, 50 Hz, SCIM is running at a slip of 5%. The speed of stator magnetic field with respect to rotor magnetic field and speed of rotor with respect to stator magnetic field are. **[2011]**

(A) zero, −50 rpm (B) zero, 950 rpm
(C) 1000 rpm, −5 rpm (D) 1000 rpm, 950 rpm

**26.** The slip of an IM normally does not depend on **[2012]**

(A) rotor speed
(B) synchronous speed
(C) shaft torque
(D) core-loss component

**27.** The locked rotor current in a 3-phase, star-connected 15 kW, 4-pole, 230 V, 50 Hz IM at rated conditions is 50 A. Neglecting losses and magnetizing current, the approximate locked rotor line current drawn when the motor is connected to a 236 V, 57 Hz supply is **[2012]**

(A) 58.5 A (B) 45.0 A
(C) 42.7 A (D) 55.6 A

**28.** Leakage flux in an IM is **[2013]**

(A) flux that leaks through the machine
(B) flux that links both stator and rotor windings
(C) flux that links none of the windings
(D) flux that links the stator winding or the rotor winding but not both

**29.** A 4-pole IM, supplied by a slightly unbalanced three-phase 50 Hz source, is rotating at 1440 rpm. The electrical frequency in Hz of the induced negative sequence current in the rotor is **[2013]**

(A) 100 (B) 98
(C) 52 (D) 48

**30.** An 8-pole, 3-phase, 50 Hz IM is operating at a speed of 700 rpm. The frequency of the rotor current of the motor in Hz is _______. **[2014]**

**31.** A 3-phase, 50 Hz, 6-pole IM has a rotor resistance of 0.1 Ω and reactance of 0.92 Ω. Neglect the voltage drop in stator and assume that the rotor resistance is constant. Given that the full-load slip is 3%, the ratio of maximum torque to full-load torque is **[2014]**

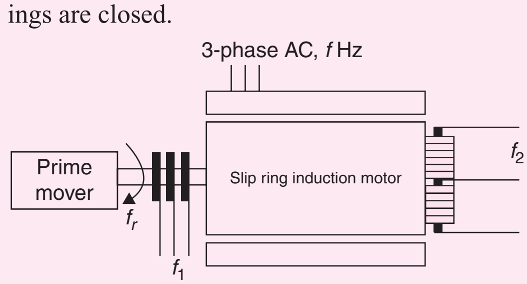
(A) 1.567 (B) 1.712
(C) 1.948 (D) 2.134

**32.** A three-phase, 4-pole, self-excited induction generator is feeding power to a load at a frequency $f_1$. If the load is partially removed, the frequency becomes $f_2$. If the speed of the generator is maintained at 1500 rpm in both the cases, then **[2014]**

(A) $f_1, f_2 > 50$ Hz and $f_1 > f_2$
(B) $f_1 < 50$ Hz and $f_2 > 50$ Hz
(C) $f_1, f_2 < 50$ Hz and $f_2 > f_1$
(D) $f_1 > 50$ Hz and $f_2 < 50$ Hz

**33.** A single-phase IM draws 12 MW power at 0.6 lagging power. A capacitor is connected in parallel to the motor to improve the power factor of the combination of motor and capacitor to 0.8 lagging. Assuming that the real and reactive power drawn by the motor remains same as before, the reactive power delivered by the capacitor in MVAR is _________ **[2014]**

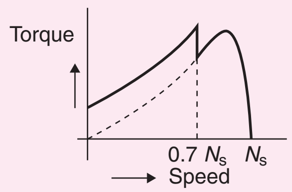
**34.** A three-phase slip-ring IM, provided with a commutator winding, is shown in the figure. The motor rotates in clockwise direction when the rotor windings are closed.

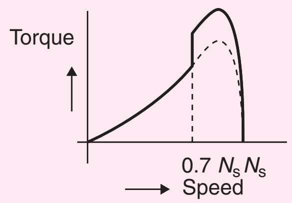


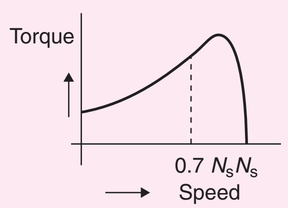

If the rotor winding is open-circuited and the system is made to run at rotational speed $f_r$ with the help of prime-mover in anticlockwise direction, then the frequency of voltage across slip rings is $f_1$ and frequency of voltage across commutation brushes is $f_2$. The values of $f_1$ and $f_2$, respectively, are **[2014]**

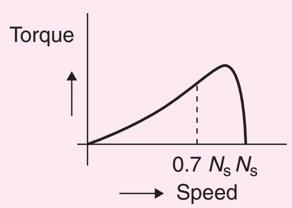
(A) $f+f_r$ and $f$ (B) $f-f_r$ and $f$
(C) $f-f_r$ and $f+f_r$ (D) $f+f_r$ and $f-f_r$

**35.** A single-phase IM is provided with capacitor and centrifugal switch in series with auxiliary winding. The switch is expected to operate at a speed of 0.7 Ns, but due to malfunctioning the switch fails to operate. The torque-speed characteristic of the motor is represented by **[2014]**

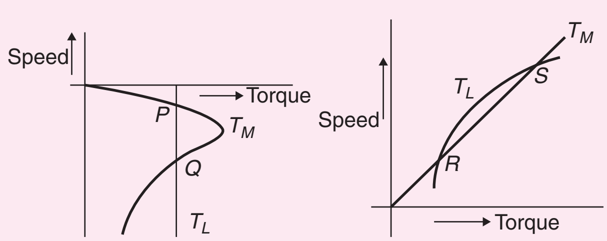
(A)



(B)



(C)



(D)



**36.** The torque-speed characteristics of motor $T_M$ and load ($T_L$) for two cases are shown in the figures (a) and (b). The load torque is equal to motor torque at points P, Q, R and S

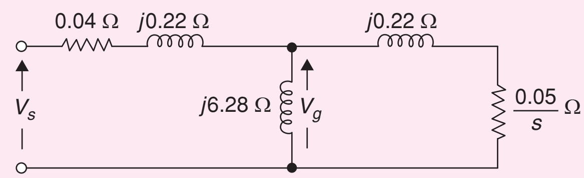


(a) (b)

The stable operating points are **[2014]**

(A) P and R (B) P and S
(C) Q and R (D) Q and S

**37.** The figure shows the per-phase equivalent circuit of a two-pole three-phase induction motor operating at 50 Hz. The "air-gap" voltage, $V_g$ across the magnetizing inductance, is 210 V rms, and the slip, s, is 0.05. The torque (in Nm) produced by the motor is ______. **[2015]**




**38.** A 220 V, 3-phase, 4-pole, 50 Hz induction motor of wound rotor type is supplied at rated voltage and frequency. The stator resistance, magnetizing reactance, and core loss are negligible. The maximum torque produced by the rotor is 225% of full load torque and it occurs at 15% slip. The actual rotor resistance is 0.03 |/phase. The value of external resistance (in Ohm) which must be inserted in a rotor phase if the maximum torque is to occur at start is ________. **[2015]**

**39.** The direction of rotation of a single-phase capacitor run induction motor is reversed by **[2016]**

(A) Interchanging the terminals of the AC supply
(B) Interchanging the terminals of the capacitor
(C) Interchanging the terminals of the auxiliary winding
(D) Interchanging the terminals of both the windings.

**40.** The starting line current of a 415V, 3-phase, delta connected induction motor is 120A, when the rated voltage is applied to its stator winding. The starting line current at a reduced voltage of 110V, in ampere is ________. **[2016]**

## Answer Keys

# Exercises

## Practice Problems 1

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1.** D | **2.** B | **3.** B | **4.** B | **5.** B | **6.** C | **7.** D | **8.** B | **9.** A | **10.** B |
| **11.** C | **12.** A | **13.** A | **14.** C | **15.** C | **16.** A | **17.** C | **18.** B | **19.** B | **20.** B |
| **21.** D | **22.** D | **23.** D | **24.** B | **25.** C | **26.** D | **27.** D | | | |

## Practice Problems 2

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1.** B | **2.** C | **3.** A | **4.** B | **5.** B | **6.** D | **7.** A | **8.** C | **9.** C | **10.** C |
| **11.** B | **12.** C | **13.** B | **14.** D | **15.** B | **16.** D | **17.** C | **18.** A | **19.** C | **20.** A |
| **21.** C | **22.** D | **23.** C | **24.** B | **25.** B | **26.** C | **27.** C | **28.** C | **29.** B | **30.** B |
| **31.** C | **32.** B | **33.** D | **34.** C | **35.** B | **36.** C | **37.** D | **38.** C | **39.** A | **40.** C |
| **41.** D | **42.** C | **43.** C | **44.** D | **45.** B | **46.** A | **47.** D | **48.** A | **49.** C | **50.** A |

## Previous Years' Questions

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1.** C | **2.** A | **3.** B | **4.** D | **5.** B | **6.** B | **7.** A | **8.** B | **9.** C | **10.** A |
| **11.** B | **12.** D | **13.** C | **14.** B | **15.** C | **16.** A | **17.** C | **18.** B | **19.** D | **20.** C |
| **21.** A | **22.** B | **23.** A | **24.** C | **25.** A | **26.** D | **27.** B | **28.** D | **29.** B | **30.** 3.35 |
| **31.** C | **32.** C | **33.** 7 | **34.** A | **35.** C | **36.** B | **37.** 400 to 403 | | **38.** 0.16 to 0.18 | |
| **39.** C | **40.** 31.8 | | | | | | | | |