Electrical Engineering

Electric Machines

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Electric Machines

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CHAPTER 7

Three Phase Induction Machine

Introduction

A polyphase induction motor is a singly-excited a.c. machine that is supplied power from a single ac source stator which is directly connected to a.c. source, and its rotor winding receives energy from stator by means of induction (i.e. transformer action). Balanced polyphase current in polyphase winding produce a constant-amplitude rotating m.m.f wave. Stator produced mmf wave and rotor produced mmf wave are stationary w.r.t each other, consequently the development of steady electromagnetic torque is possible at all speed but not at synchronous speed. The stator and rotor m.m.f waves combine to give the resultant air-gap flux density wave of constant amplitude and rotating at synchronous speed, then an induction motor can't run at synchronous speed, its speed is called asynchronous speed.

7.1 Stator

The stator of an Induction Motor (IM) consists of stator frame, stator core, polyphase (3 or 2-phase) distributed winding, two end covers, bearing etc. The stator core is a stack of cylindrical steel laminations which are slotted along inner periphery for 3-phase winding.

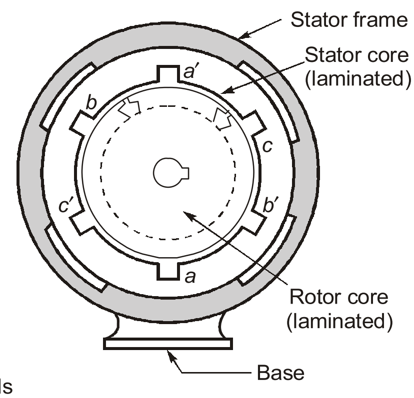


Figure 7.1 Stator

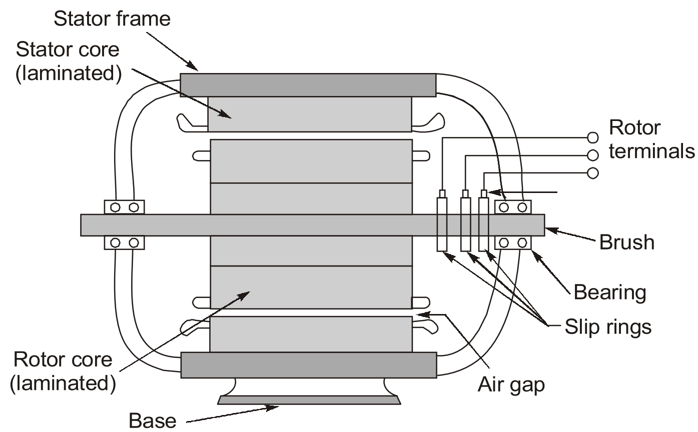


Figure - 7.2

Three coils aa', bb' and cc' represent the windings of the three phases a, b and c respectively. Three winding are space displaced by 120° electrical and may be connected in star or delta. Three-ϕ winding in the stator slots is uniformly distributed along the air-gap periphery.

The air gap between stator and rotor should be as small as possible, this will

1. Reduce the leakage flux between stator and rotor.
2. Gives better operating power factor of the IM.

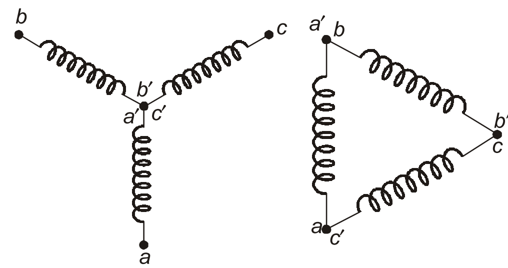


Figure - 7.3

7.2 Rotor

The IM has two types of Rotors :

1. Squirrel Cage Rotor
2. Wound Rotor (Slip Ring Rotor)

7.2.1 Squirrel Cage Rotor

Rotor windings consists of uninsulated conductors in the form of copper or aluminium bars embedded in semi-closed slots. Solid bars are short circuited by end rings of same material. These are welded, brazed or riveted with two end rings for better electrical connection. No external resistance can be inserted in the rotor circuit of a cage IM.

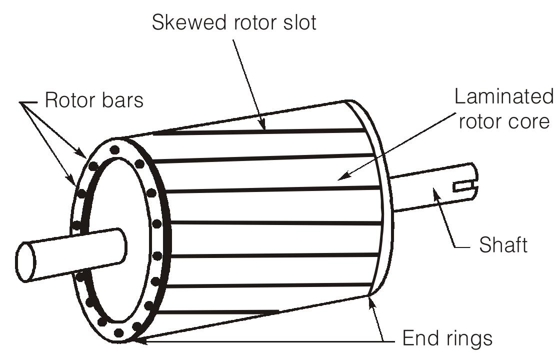


Figure - 7.4 Squirrel Cage Rotor

7.2.2 Wound-Rotor

The rotor windings is uniformly distributed and is usually connected in star. The three leads from the star connection are connected to three slip rings or collector rings mounted on but insulated from the shaft slip rings. The external resistors are inserted in series with the rotor winding for speed and starting torque control.

Wound rotor type of IM costs more than cage rotor IM.

1. Wound rotor IM used where speed control is required.
2. High starting torque is required.

In both the type of rotor slots are not parallel to the shaft axis i.e. the rotor slots are skewed for obtaining a quieter and smoother operation of the IM.

Squirrel cage IM is simpler and economical in construction than WRIM and SCIM requires less maintenance than WRIM.

7.3 Induction Motor as a Transformer

Induction motor is similar to transformer in many features. If winding of IM is star, then assumed open circuited so that rotor current is zero and no electromagnetic torque is developed, there balanced phase voltages at line frequency f_1 to the stator winding causes the production of a rotating magnetic field. This rotating flux cuts both the stator and stationary rotor conductor at synchronous speed, emfs of line frequency f_1 are induced in them. Per phase value of induced emf E_1 induced in them is

$$E_1 = \sqrt{2}\,\pi f_1 k_{\omega_1} N_1 \phi \qquad \text{...(i)}$$

Here, $N_1 \rightarrow$ stator series turns per phase

$k_{\omega 1} \rightarrow$ stator wdg factor

per phase value of emfs induced in the standstill rotors wdg is given by

$$E_2 = \sqrt{2}\,\pi f_1 k_{\omega 2} N_2 \phi \quad \text{...(ii)}$$

$N_2 \rightarrow$ rotor series turns per phase

$k_{\omega 2} \rightarrow$ rotor wdg factor

The emf or voltage ratio for

$$\frac{E_1}{E_2} = \frac{N_1 k_{\omega_1}}{N_2 k_{\omega_2}} = \frac{N_1'}{N_2'} \quad \text{...(iii)}$$

Here N'_1 and N'_2 are called the effective member of the stator-series turns per **phase**. It is similar to the voltage ratio of a **transformer.** A WRIM at standstill is similar to a transformer at no load.

If transformer is loaded, the m.m.f of the secondary current results in the primary current in order to draw more power from supply. It is similar to the increases in shaft load of induction motor. 3-ϕ IM with its blocked rotor is similar to the short circuit of transformer. Stator and rotor winding of IM passes through the leakage reactance and resistance similar to transformer.

7.4 Difference between IM and Transformer

- In IM motor, winding is **distributed** along the air gap periphery, in transformer primary and secondary wdgs being **concentrated**, require no winding factor and maximum value of core flux is used.
- In IM no load current varies from **30 to 50%** of full load current where as in transformer no load current varies from **2 to 6%** of full load. This is because in IM mutual flux crosses the air gap between stator and rotor whereas in transformer mutual flux complete its path through low reluctance **path of iron.**

7.5 MMF Induced in IM

If 3-ϕ balanced winding is excited by 3-ϕ balanced current 3-Identical windings are displaced by 120° in space.

$$i_a = I_m \cos\omega t$$

$$i_b = I_m \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$i_c = I_m \cos\left(\omega t + \frac{2\pi}{3}\right)$$

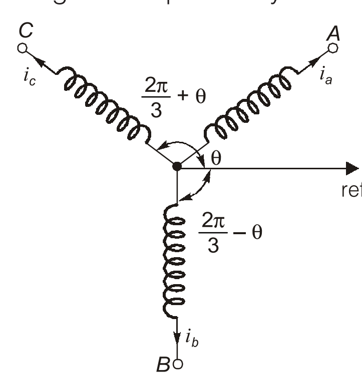


Figure - 7.5

The resultant mmf along the ref

$$f = f_a \cos\theta + f_b \cos\left(\frac{2\pi}{3} - \theta\right) + f_c \cos\left(\frac{2\pi}{3} + \theta\right)$$

$$= NI_m\left[\cos\omega t\cos\theta + \cos\left(\omega t - \frac{2\pi}{3}\right)\cos\left(\theta - \frac{2\pi}{3}\right) + \cos\left(\omega t + \frac{2\pi}{3}\right)\cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$= \frac{f_m}{2}\left[\cos(\omega t + \theta) + \cos(\omega t - \theta) + \cos\left(\omega t + \theta - \frac{4\pi}{3}\right) + \cos(\omega t - \theta) + \cos\left(\omega t + \theta + \frac{4\pi}{3}\right) + \cos(\omega t - \theta)\right]$$

$$3I_2^2 R_2 + 250 = \frac{0.04}{1-0.04}(25\times 746 + 1000)$$

$$3\times 35^2 R_2 = 818.75 - 250$$

$$R_2 = \frac{568.75}{3\times 35^2} = 0.154\ \Omega$$

4. (2864.72 Nm)

The breakdown slip is,

$$s_b = \frac{R_2}{X_2} = \frac{0.02}{0.08} = 0.25$$

Statement 1 is true.

The ratio of the torque developed at any slip s to be maximum torque is

$$\frac{T}{T_{max}} = \frac{2ss_b}{s_b^2 + s^2}$$

For starting torque $s = 1$, so

$$\frac{T_{st}}{T_{max}} = \frac{2(1)(0.25)}{(0.25)^2 + (1)^2} = 0.47$$

Thus, $T_{st} = 0.47\ T_{max}$

(47% of maximum torque)

Statement 2 is also true,

Synchronous speed,

$$n_s = \frac{120\times 60}{8} = 900 \text{ rpm}$$

$$\omega_s = \frac{2\pi}{60}\times n_s = 94.25 \text{ rad/s}$$

$$V_1 = 120 \text{ V}$$

Maximum torque developed by the motor

$$T_{dm} = \frac{3V_1^2}{2\omega_s}\left(\frac{s_b}{R_2}\right)$$

$$= \frac{3\times 120^2}{2\times 94.25}\left(\frac{0.25}{0.02}\right)$$

$$= 2864.72 \text{ Nm}$$

5. (856.8 rpm)

Given that,

$R_1 + jX_1 = 0.2 + j0.3$ (stator impedance)

$R_2 + jX_2 = 0.4 + j0.5$ (rotor impedance)

The equivalent impedance is

$$Z_e = R_e + jX_e$$

$$= R_1 + R_2 + j(X_1 + X_2)$$

$$= 0.6 + j0.8 = 1\angle 53.13°\ \Omega$$

The slip at which maximum power occurs

$$s_p = \frac{R_2}{R_2 + Z_e} = \frac{0.4}{0.4+1} = 0.286$$

The synchronous speed of the motor is

$$n_s = \frac{120\times 60}{6} = 1200 \text{ rpm}$$

The motor speed,

$$n = (1 - s_p)\, n_s$$

$$= (1 - 0.286)\, 1200 = 856.8 \text{ rpm}$$

6. (50 rpm)

Supply frequency,

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

No-load speed of motor,

$$N_0 = 1000 \text{ rpm}$$

Full load speed of motor,

$$N_f = 950 \text{ rpm}$$

Since no-load speed of motor is almost 1000 rpm, hence synchronous speed near to 1000 rpm is 1000 rpm

Poles on the motor,

$$P = \frac{120f}{N_s} = \frac{120\times 50}{1000} = 6$$

Percentage slip on full load,

$$= \frac{N_s - N}{N_s}\times 100$$

$$= \frac{1000 - 950}{1000}\times 100 = 5\%$$

Slip frequency,

$$f' = sf$$

$$= 0.05 \times 50 = 2.5 \text{ Hz}$$

Speed of rotor field with respect to rotor.

7. (57.23 kW)

Stator input,

$$P_s = 60 \text{ kW}$$

$$s = 3\% = \frac{3}{100} = 0.03 \text{ pu}$$

Stator losses = 1 kW

Stator output = 60 – 1 = 59 kW

Rotor input = Stator output = 59 kW

Total rotor copper loss

$= s \times$ rotor input

$= 0.03 \times 59 = 1.77$ kW

Rotor copper loss per phase

$$= \frac{1}{3} \times 1.77 = 0.59 \text{ kW}$$

Mechanical power developed

= Rotor input – rotor copper loss

= 59 – 1.77 = 57.23 kW

8. (0.12)

$$T_s = 1.5\, T_f$$
$$T_{max.} = 2\, T_f$$

For maximum torque,

$$s_{mT} = \frac{r_2}{x_2}$$

$$\frac{T_s}{T_{max.}} = \frac{1.5 T_f}{2 T_f} = \frac{2 s_{mT}}{1 + s_{mT}^2}$$

i.e. $1.5 s_{MT}^2 - 4 s_{mT} + 1.5 = 0$

$$\therefore \quad s_{mT} = 0.45$$

Also, $$\frac{T_f}{T_{max}} = \frac{T_f}{2T_f} = \frac{2 s_{mT}}{s_{mT}^2 + s^2}$$

At $s_{mt} = 0.45$, $s^2 - 4 s_{mt} s + s_{mT}^2 = 0$

$$\Rightarrow \quad s^2 - 4(0.45)s + (0.45)^2 = 0$$
$$s = 0.12$$

9. (0.45 τ_{fl})

$$I_{st} = 0.6\, I_{sc} = 0.6 \times 5\, I_{fl} = 3\, I_{fl}$$

$$\tau_{st} = \tau_{fl} \left(\frac{I_{st}}{I_{fl}} \right)^2 \times s_{fl} = \tau_{fl} (3)^2 \times 0.05$$
$$= 0.45\, \tau_{fl}$$

10. (9.1 Ω/ph)

$$R_1 = r_1 + r'_2 \text{ and } X_1 = x_1 + x'_2$$

The copper loss obtained during blocked rotor test = 2100 kW

i.e., $3 I_1^2 R_1 = 2100$

$$R_1 = \frac{2100}{3(15)^2} = 3.1\, \Omega/\text{phase}$$

$$\therefore \quad r'_2 = \frac{R_1}{2} = \frac{3.1}{2} \simeq 1.6\, \Omega/\text{ph}$$

The impedance Z_1 (referred to stator)

$$= \frac{200}{\sqrt{3} \times 15} = 7.7\, \Omega/\text{ph}$$

$$X_1 = x_1 + x'_2 = \sqrt{(7.7)^2 - (3.1)^2} = 7\, \Omega$$

$$\therefore \quad x'_2 = \frac{X_1}{2} = 3.5\, \Omega$$

$$\therefore \quad T = \frac{s E_1^2 r'_2}{r'^2_2 + x'^2_2 s^2}$$

$$\Rightarrow \quad \frac{0.03 (E_1^2)(1.6)}{(1.6)^2 + (0.03)^2 (3.5)^2} = \frac{E_1^2 (0.2)(r')}{(r')^2 + (0.2)^2 (3.5)^2}$$

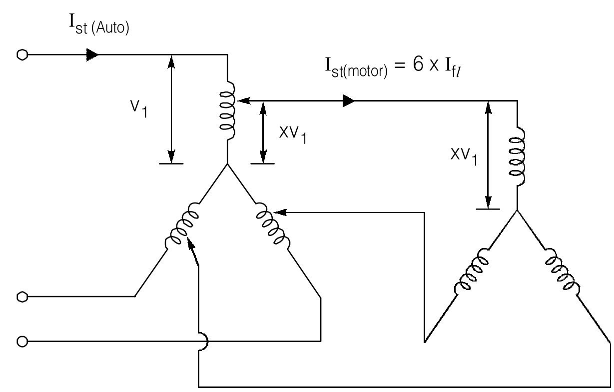
(1970 rpm, s = 0.03; 800 rpm, s = 0.2)

$$r' = 10.7 \text{ or } 0.05\, \Omega$$

extra resistance to be added with rotor is

$$= 10.7 - 1.6 = 9.1\, \Omega/\text{ph}$$

11. (141.7 - 141.8)



$$x = 60\% = 0.6$$

$$I_{fl(motor)} = \frac{50 \times 10^3}{\sqrt{3} \times 440} = 65.61 \text{ A}$$

$$I_{st\,(motor)} = 6\, I_{fl} = 6 \times 65.61 \text{ A}$$
$$= 393.65 \text{ A}$$

$$I_{st\,(Auto)} = x^2 I_{st(motor)}$$
$$= (0.6)^2 \times 393.65 \text{ A}$$
$$= 141.71 \text{ A}$$

12. (15.2 - 15.3)

$$N_s = \frac{120 f_1}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

$$s = \frac{f_2}{f_1} = \frac{1.5}{50} = 0.03 \text{ or } 3\%$$

$$N_r = (1 - s)\, N_s$$
$$= (1 - 0.03) \times 1000 = 970 \text{ rpm}$$

$$\omega_r = 2\pi N_r = \frac{2\pi \times 970}{60}$$
$$= 101.58 \text{ rad/s}$$

Shaft power output,

$$P = T\omega_r$$
$$= 150 \times 101.58$$
$$= 15236 \text{ W} = 15.236 \text{ kW}$$

16. In a self-excited induction generator, to keep the frequency of generated voltage constant with the increase in load, the speed of the induction machine should be
(a) increased
(b) decreased
(c) maintained less than the rated synchronous speed
(d) maintained more than the rated synchronous speed

17. A 3-phase delta-connected SCIM has a starting current I_d and a starting torque T_d at rated voltage. If the starting current and starting torque while the motor is started through star-delta starter and auto-transformer (with 60% voltage) starter alternatively are I_y, T_y and I_{out}, T_{out} respectively, then $\frac{I_y}{I_d}:\frac{I_{out}}{I_d}:\frac{T_y}{T_d}:\frac{T_{out}}{T_d}$ is equal to
(a) $\frac{1}{\sqrt{3}}:0.6:\frac{1}{\sqrt{3}}:0.6$
(b) $\frac{1}{3}:0.6:\frac{1}{3}:0.36$
(c) $\frac{1}{3}:0.36:\frac{1}{3}:0.36$
(d) $\frac{1}{\sqrt{3}}:0.36:\frac{1}{3}:0.6$

18. A 6 pole 3-phase induction motor develops maximum torque at 1000 rpm when operated from a 60 Hz supply. Rotor resistance per phase is 1.2 Ω. Neglect stator impedance. The speed at which it will develop maximum torque when operated from 50 Hz source is
(a) 1200 rpm (b) 1000 rpm
(c) 960 rpm (d) 800 rpm

19. A 4-pole, 50 Hz, 3-phase induction motor has blocked rotor reactance per phase which is four times the rotor resistance per phase. The speed at which maximum torque develops is
(a) 1050 rpm (b) 1125 rpm
(c) 1210 rpm (d) 1500 rpm

ANSWERS

1. (a)	2. (d)	3. (c)	4. (d)	5. (d)
6. (d)	7. (c)	8. (a)	9. (a)	10. (c)
11. (a)	12. (b)	13. (d)	14. (a)	15. (b)
16. (a)	17. (b)	18. (d)	19. (b)	

Student's Assignments 2 Explanation

1. (a)
1000 kVA at 0.8 p.f.,
$$Q_{absorbed} = 1000 \times \sin\phi = 1000 \times 0.6 = 600 \text{ KVAR}$$
750 kVA at 0.6 p.f.
$$Q_{delivered} = 750 \times 0.6 = 600 \text{ KVAR},$$
So, overall p.f. is unity.

2. (d)
Small air gap ⇒ lower reluctance ⇒ higher Inductance ⇒ smaller magnetising current as
$$I \propto \frac{1}{L}$$

3. (c)
As $T_{em} \propto V^2$

6. (d)
$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl}$$
For $T_{st} = T_{fl}$
$$\frac{I_{st}}{I_{fl}} = \sqrt{\frac{1}{s_{fl}}} = \sqrt{25} = 5$$

7. (c)
To eliminate n^{th} harmonic ⇒ $\frac{n\alpha}{2} = 90°$
where, α = chording angle
to eliminate 5^{th} harmonic
$$\Rightarrow \frac{5\times\alpha}{2} = 90° \Rightarrow \alpha = 36°$$

18. (d)

Slip at maximum torque

$$= \frac{r_2'}{\sqrt{R_{TH}^2 + (X_{TH} + x_2)^2}}$$

As stator impedance is neglected

$$\therefore \quad s_{mT} = \frac{r_2'}{x_2} = \frac{r_2'}{2\pi f L}$$

At 60 Hz,

$$n_s = 120 \times \frac{60}{6} = 1200 \text{ rpm}$$

$$n_r = 1000 \text{ rpm}$$

$$\therefore \quad s_{mT} = \frac{1200 - 1000}{1200} = \frac{1}{6}$$

At 50 Hz,

$$n_s = 120 \times \frac{50}{6} = 1000 \text{ rpm}$$

$$n_r = x \text{ rpm}$$

$$\therefore \quad s_{mT} = \frac{1000 - x}{1000}$$

$$\Rightarrow \quad \frac{1/6}{\frac{1000 - x}{1000}} = \frac{\frac{r_2'}{2\pi \times 60L}}{\frac{r_2'}{2\pi \times 50L}}$$

$$\Rightarrow \quad \frac{1000}{1000 - x} = \frac{5}{6} \times 6$$

$$\Rightarrow \quad 200 = 1000 - x$$

$$x = 800 \text{ rpm}$$

19. (b)

For maximum torque,

$$s_{max} = \frac{R}{X} = \frac{1}{4} = 0.25$$

Synchronous speed,

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

$$= 1500 \text{ rpm}$$

speed at maximum torque

$$= (1 - s_{max})\, N_s$$

$$= (1 - 0.25) \times 1500$$

$$= 1125 \text{ rpm}$$

■■■■