MODULE-4

Three Phase Induction Motor
and
Three Phase Synchronous Generators

THREE PHASE INDUCTION MOTOR

Introduction:

A three-phase induction motor is a three phase ac motor. These motors are widely used for many industrial applications. The advantages of induction motor are:

(1) Construction is simple, rugged, unbreakable.
(2) Low cost and highly reliable.
(3) It has high efficiency.
(4) It works with good power factor at rated load.
(5) Less maintenance
(6) Small IM are self starting and large motors starting arrangement is simple.

Disadvantages:

1. It's a constant speed motor, hence speed cannot be varied easily.
2. Its starting torque is less, compared to dc shunt motor.

Construction: A 3Φ IM has mainly two parts. Stator and Rotor.

Stator

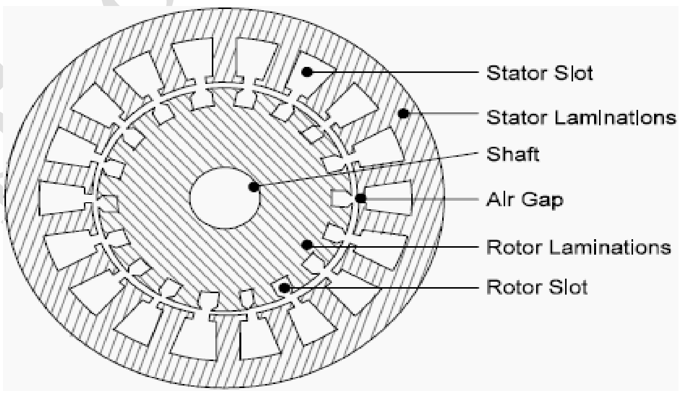


Fig. 4.1 Stator of three phase IM

1. The stator is enclosed in steel frame which has hallow cylindrical core made up of thin laminations of silicon steel to reduce eddy current loss and hysteresis loss.
2. The stator conductors are placed in the slots which are insulated from one another and from the slots.
3. Conductors are connected as a balanced three phase star or delta winding.
4. Windings are wound for a definite number of poles and speed.

$$N_s=120f/P$$

N_s= Synchronous speed

f=frequency

P=number of poles.

5. When 3Φ supply is applied to stator winding a magnetic field of constant magnitude rotating at synchronous speed is produced.
6. Rotating magnetic field is responsible for producing torque in the rotor.

Rotor: It is the rotating part of IM, which is mounted on the shaft to which the mechanical load is connected. There are two types are rotor: Squirrel cage rotor and Phase wound rotor.

Types – squirrel cage and wound rotor,

Squirrel cage rotor:

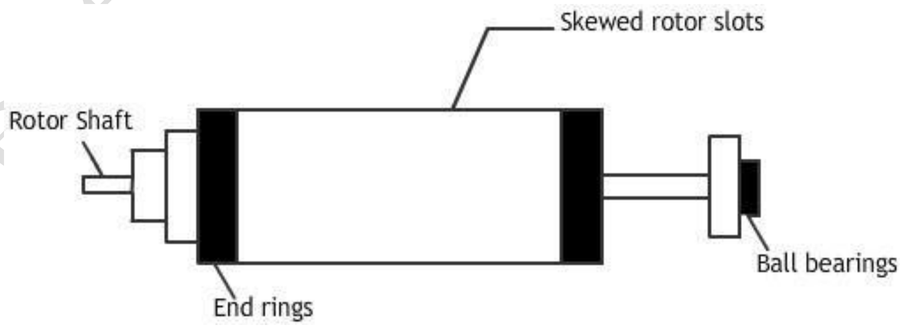


Fig 4.2(a): Squirrel cage induction motor

Almost 90% of IM are squirrel cage type, as their construction is simple and rugged. Its consists of cylindrical laminated core with slots for carrying rotor windings is shown in Fig 4.2(a). The rotor windings are heavy bars of copper or aluminum. Each slot has one bar of copper placed in it. All the bars are welded at both the ends of the end rings, thereby short circuiting both ends of the rotor. Slots are skewed to reduce the noise due to magnetic hum and to make the rotor run quietly. It also reduces the locking tendency between rotor and stator.

Advantages:

1.Simple and rugged construction and can withstand rough handling.

2.Low cost of maintenance and repair.

3. Good efficiency and power factor.

4. Simple star-delta starter is sufficient for starting.

Disadvantages:

1. Size of slip ring IM of same capacity is more than squirrel cage IM.

2. Costlier as the construction is complicated.

3. High maintenance cost and repair.

Applications:

Used for loads which require high starting torque such hoists, cranes, etc

Phase wound rotor:

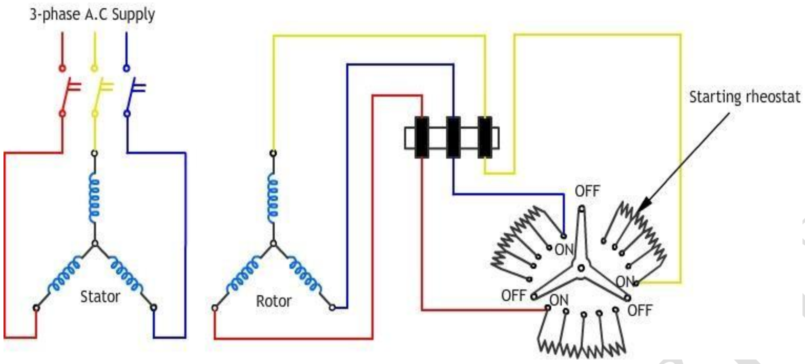


Fig 4.2(b): Phase wound rotor

The rotor is laminated, cylindrical having uniform slots on its outer periphery. A 3 phase which is star connected is placed in these slots is shown in Fig 4.2(b). The open end of star winding is brought out and connected to 3 insulated slip rings, mounted on the shaft with carbon brushes resting on them. Three brushes are externally connected to 3 phase star connected rheostat which is used as starter. When running under normal conditions the slip rings are automatically short circuited by means of metal collar, which is pushed along the shaft that connects all the rings. Brushes are lifted from slip rings to reduce frictional losses and wear and tear.

Advantages:

1.Has external resistance in the rotor circuit which is used to start.

2.Has high starting torque and low starting current.

3.Smooth running motor

4.Slip ring IM of very high capacity can be built.

5. Explosion proof due to absence of slip ring and brush.

Disadvantages:

1.Low starting torque, hence pf is also low.

2.Starting current is high, no smooth running.

Applications

Used for loads which require normal starting torque such as lathes,etc.

Concept of rotating magnetic field:

Fig: 4.3(a) Stator

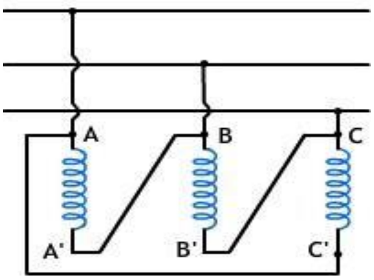


Fig: 4.3(b) Rotor.

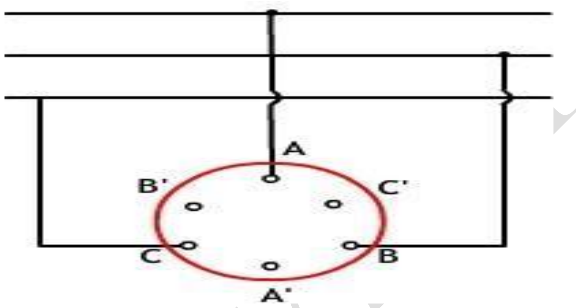
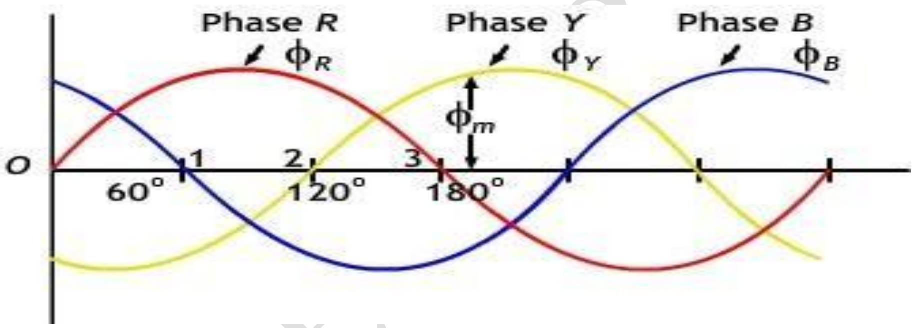


Fig: 4.3(c) Three phase waveform

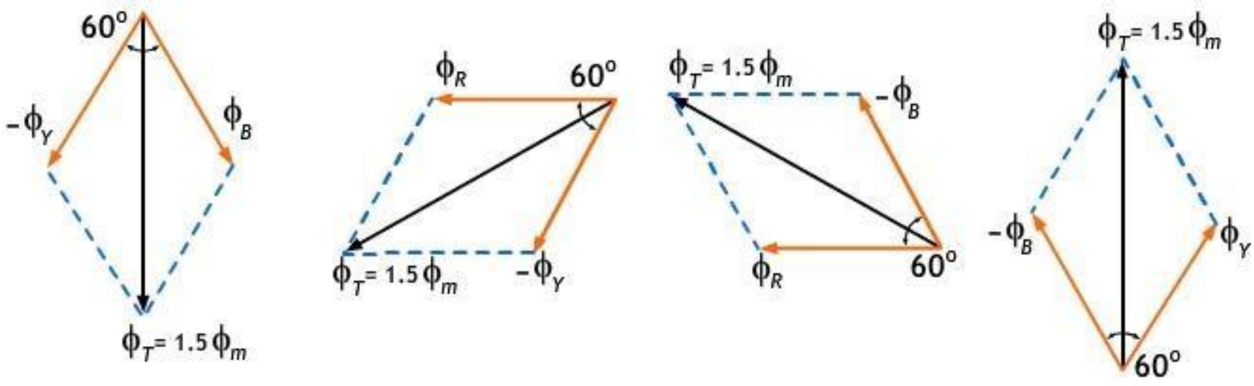


a) At $\theta = 0^o$

This corresponds to point O in the Fig of waveforms of phases R,Y and B.

$$\phi_R = 0, \ \phi_Y = -\frac{\sqrt{3}}{2}\phi_m, \ \phi_B = \frac{\sqrt{3}}{2}\phi_m$$

$$\therefore \phi_T = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60^\circ}{2} = \sqrt{3} \times \frac{\sqrt{3}}{2}\phi_m = \frac{3}{2}\phi_m$$



b) At θ =60 , corresponding to point 1 in the Fig5.4(c) of waveforms of phases R,Y and B.

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m \qquad \phi_Y = -\frac{\sqrt{3}}{2}\phi_m \qquad \phi_B = 0$$

$$\therefore \phi_T = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos 30° = \frac{3}{2}\phi_m$$

The resultant flux is again 3/ 2 Φ_m, but has rotated clockwise through an angle of 60At θ =120 i.e. corresponds to point 2 in the Fig of waveforms of phases R,Y and B

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m, \quad \phi_Y = 0, \phi_B = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_T = \frac{\sqrt{3}}{2}\phi_m$$

Thus, once again the resultant has the same value, but has further rotated clockwise through an angle of 60

d) At θ =180 , i.e. relating to point 3 in the Fig of waveforms of phases R,Y and B

$$\phi_R = 0, \quad \phi_Y = \frac{\sqrt{3}}{2}\phi_m, \quad \phi_B = -\frac{\sqrt{3}}{2}\phi_m$$

The resultant is 3/ 2 Φ_m , and has rotated clockwise through an additional angle of 60 or through an angle of 180° from the beginning. Thus, we come to the following conclusions

1. The resultant flux is of constant value = 3/ 2 Φ_m, i.e. 1.5 times the maximum value of the flux due to any phase.
2. The resultant flux rotates around the stator at synchronous speed $N_S = \frac{120f}{p}$by where P = number of stator poles and f = supply frequency in Hz.

Working principle:

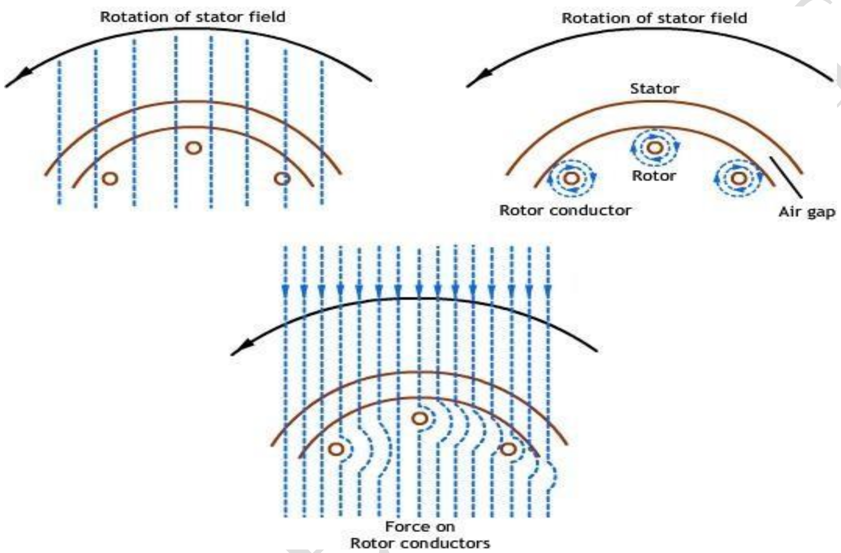


Fig: 4.4 Working principle of Induction motor

- When the stator of a 3-phase induction motor is connected to a 3-phase a.c supply, a rotating magnetic field is established which rotates at synchronous speed.
- The magnetic flux of constant amplitude, rotating at synchronous speed, passes through the air-gap and cuts the rotor conductors which are stationary.
- Due to the relative speed between the rotating flux and the stationary conductors an e.m.f is induced in the latter as per Faraday‟s Laws of Electromagnetic Induction.
- The frequency of the induced e.m.f is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors, and its direction is given by Fleming‟s Right-Hand Rule.
- Since the rotor conductors form a closed circuit, rotor current is produced, whose direction in terms of Lenz‟s Law is such as to oppose the very cause producing it.

- Here, the cause which produces the rotor current is the relative velocity between the rotating field and the stationary rotor.
- Hence, to reduce this relative speed, the rotor starts running in the same direction as the stator field in an effort to catch up with it.
- In Fig 5.5, the stator field is shown as rotating in an anticlockwise direction.
- The relative motion of the rotor with respect to the stator is clockwise.
- By applying the Right-hand Rule, the direction of the induced e.m.f in the rotor is outwards.
- So, the direction of the flux because of the rotor current alone is as shown in Fig.
- Considering the effect of both rotor and stator fields, the rotor conductors are subjected to a force tending to rotate them in the anticlockwise direction.
- Thus the rotor is made to rotate in the same direction as the stator field.
- As discussed earlier the rotor follows the stator field.
- In actual practice, the rotor can never reach the speed of the stator field.
- If it does so, there would be no relative movement between the stator field and rotor conductors, no induced rotor current, and therefore, no torque to drive the rotor.
- Hence, the rotor speed is always less than the speed of the stator field.
- The difference in the speed between stator field and rotor depends on the load.

Slip:

- The difference between the synchronous speed N_S and the actual speed N of the rotor is called slip speed. (The quantity N_S-N is sometimes called the slip-speed.)
- It is usually expressed as a percentage of synchronous speed.
- It is apparent that the rotor (or motor) speed is $N = N_S(1-S)$.
- In an induction motor, the change in slip from no-load to full-load is hardly 3 - 6%, so that the induction motor is essentially a constant speed motor

Frequency of Rotor Current:

- When the rotor is at standstill, the frequency of rotor current is the same as the supply frequency.
- When there is relative speed between the rotor and the stator field, the frequency of the induced voltage, and hence the current, in the rotor varies with the rotor speed i.e., slip
- Let at any speed N of the rotor, the frequency of the rotor current be f''.
- Hence, the frequency of rotor current (or e.m.f) may be obtained by multiplying the supply frequency by fractional slip.

Rotor Torque:

The torque T on the rotor is directly proportional to Rotor current at standstill, I_2

Magnitude of the rotating flux per stator pole, ϕ
$\cos\phi$ (p.f. of the rotor circuit)

ϕ = angle between rotor e.m.f. and rotor current

$T \alpha\ F\ I_2 \cos\phi$

$T \alpha\ E_2\ I_2 \cos\phi$

Torque-Slip Characteristics

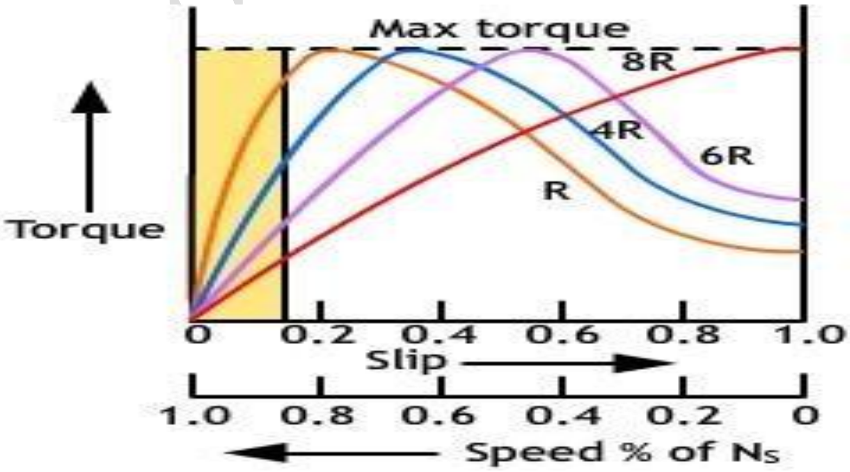


Fig: 4.5. Torque –slip characteristics.

- This maximum torque is known as pull-out or breakdown torque.
- When the slip increases beyond that corresponding to maximum torque, the term $(sX_2)^2$ increases very rapidly R_2^2 may be neglected as compared to $(sX_2)^2$.
- Thus, the torque is now inversely proportional to slip, and the torque-slip curve is a rectangular hyperbola.
- We see that any further increase in motor load beyond the point of maximum torque, results in decrease of torque developed by the motor.
- As a result, the motor slows down and ultimately stops.
- So, stable running of the motor lies between the values of s = 0 and that corresponding to maximum torque.

Problems:

The frequency of the emf in the stator of a 4-pole induction motor is 50 Hz and in the rotor is 1.5 Hz. What is the slip and at what speed is the motor running?

Solution:

Synchronous speed,

$f' = sf$

$1.5 = s \times 50$

S=0.03 0r 3%

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

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

$= 1500(1-0.03) = 1455$ rpm

Exercise Problems

1. A 12 pole , 3 phase alternator is coupled to an engine running at 500r.p.mIt supplies an IM, which has full load speed of 1440r.p.m Find the percentage slip and the number of poles the motor.

2. A 3–phase, 6 pole, 50Hz IM has a slip of 1% at no-load, and 3% at full load. Determine: i) Synchronous speed; ii) no-load speed; iii) full-load speed; iv)frequency of the rotor current at stand still ; v) frequency of the rotor current at full load.

3. A 3-phase, 8 pole,50Hz IM has a slip of 1% at no-load, and 3% at full load. Determine;

I) synchronous speed, ii) No-load speed, iii) Full load speed, iv) Frequency of rotor at standstill

4. The rotor induced voltage of a 3-phase, 4 –pole squirrel cage induction motor fed by a salient pole alternator is observed to make 1.5 alterations per second. The star connected alternator with 592, full pitched armature conductors in series per phase with distribution factor of 0.966 develops a line voltage of 6600 volts when the flux per pole is 60mWb. Determine the speed of the IM.

THREE PHASE SYNCHRONOUS GENERATORS

Introduction:

The machines generating ac emf are called as alternators. Theses work at specific constant speed called synchronous speed and hence in general called synchronous generators. The main difference b/w DC generators and alternators is that in alternators the field is rotating while armature is stationary and the commutator absent.

Principle of Operation:

- Alternator (A.C generator) operates on the basic principle of electromagnetic induction i.e., when a conductor moves across a magnetic field or vice versa, an emf is induced in the conductor (Dynamically induced emf).
- The magnetic poles are excited by D.C. supply with a source of 125 V or 250 V.
- The exciting current is obtained from small DC Generator which is mounted on the shaft of the synchronous machine.
- When the rotor is rotated by means of any prime mover the stator conductors are cut by magnetic field, hence an emf is induced in the stator conductor.
- The frequency of the induced emf is given by $f = PN/120$ Hz where P is the number of poles and N is the speed in rpm.

Advantages of Stationary Armature:

1. It is simpler to insulate a stationary armature winding.
2. It is easier to brace armature winding against any deformation.
3. Only two slip rings are required for D.C supply for the rotor circuit.
4. Higher speed of the rotating field is possible.
5. It is easy to take power out from the stationary armature.

Construction of Alternator

The alternator consists of two parts: Stator and Rotor. Most of the alternators has stator as armature and rotor as field.

Stator:

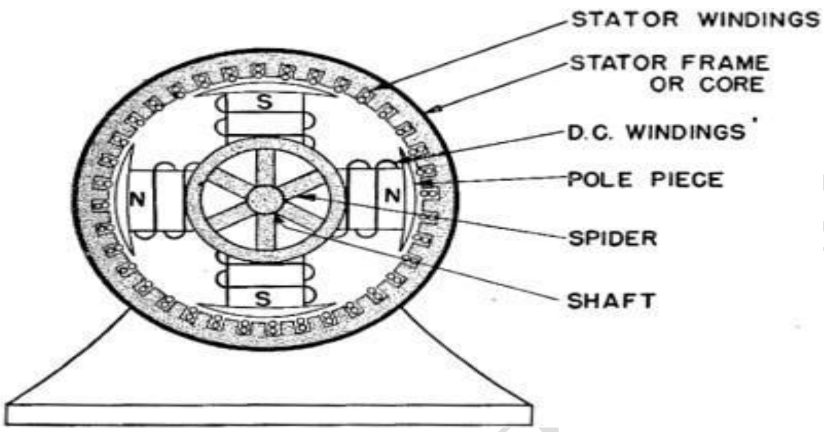


Fig: 4.6. Stator of alternator

It is stationary part of an alternator and it is built up of sheet steel of thin laminations having slots on its inner periphery (shown in Fig 4.6). A three-phase star connected winding is placed in the slots. The neutral of the winding is grounded. Steel is chosen to reduce hysteresis loss and laminated to reduce eddy current loss.

Rotor: There are two types rotors namely: Salient pole rotor and. Smooth cylindrical rotor

Salient pole rotor:

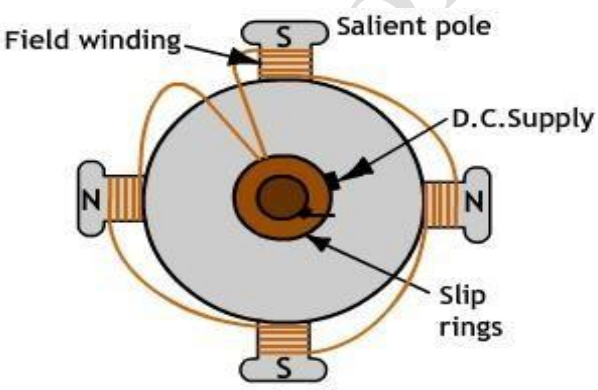


Fig:4.6(a) Salient pole Rotor

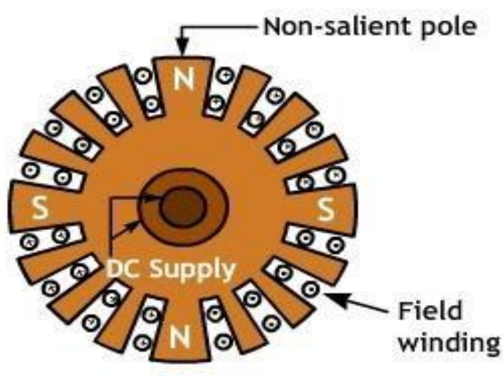


Fig:4.6(b) Smooth cylindrical Rotor

Salient pole Rotor:

This is known as projected pole type as all the poles are projected out from the surface of the surface. Poles are made of thick steel laminations and bolted to rotor. These rotors have large diameter and small axial lengths. Mechanical strength is less, preferred for low speed alternators(125rpm-500rpm)

Smooth cylindrical rotor:

This is known as non-salient type of rotor. The un slotted portions are the poles and surface is smooth which maintains uniform air gap b/w stator and rotor. These have small diameters and large axial lengths. Mechanically strong and can be used for high speed alternators (1500rpm-3000rpm)

Frequency of generated EMF:

If a conductor passes through a pair of poles, a complete cycle of emf will be induced. Let f = frequency of generated emf, P = no of poles, N =rpm speed .
Therefore, in one revolution, (P/2) pair of poles sweep past every armature conductor hence (P/2) emf cycles in one revolution. In one second there are N/60 revolutions of rotor. Therefore, number of cycles of the induced emf /sec = number of cycles/revolution x No. of revolutions/sec.

(P/2) x (N/60) = PN/120

i.e., f = PN/120 Hz.

EMF Equation of Synchronous Generator:

Let Z = number of conductors in series per phase P = number of poles

ϕ = Flux per pole in webers

f = frequency of induced emf in Hertz.

N = Speed of rotor in rpm

Average emf induced per conductor = d / dt = P

Frequency f = NP / 120 or N = 120f / P

(60 / N) = P N / 60 volts (1)

Average emf induced per conductor = (P / 60) *(120f / P) = 2f volts.

For Z conductors in series per phase we have,

If T = number of turns per phase, then Z = 2T

Substituting Z in equation (2) we get,

Average emf induced per phase = 4f T volts

R.M.S value of emf induced = 4.44f T volts …(K_f = RMS Value /Average Value = 1.11)

R.M.S value of actual emf induced per phase = 4.44*K_c*K_d*f T volts.

Winding Factor:

The armature winding (conductor) of an alternator is distributed over the entire armature. Generally, we use short pitched, distributed windings, due to which voltage induced in the armature will reduce. Short pitched windings are used to get better waveform and to reduce unwanted harmonics.

$K_w = K_p.K_d = 0.95$

Pitch Factor:

Pitch factor (K_p) = (vector sum of emf / arithmetic sum of emf) $K_p = \cos(\alpha/2)$

$K_p = 1$ for full pitched winding.

Distribution factor

K_d = emf with distributed winding / emf with concentrated winding

$K_d = \sin(m\beta/2)/(m\sin\beta/2)$

K_d = 1 for concentrated winding.

$\beta = 180^0$ / no. of slots per pole.

Problems:

1. The stator of an ac machine is wound for six poles, three phase. If the supply frequency is 25 Hz, what is the value of the synchronous speed?

   Solution: Ns= 120f/P = 500 rpm

2. Calculate the phase emf induced in a 4 pole, 3 phase, 50 Hz, star connected alternator with 36 slots and 30 conductors per slot. The flux per pole is 0.05 Webers. Assume factor of 0.95.

Solution:

Total number of slots = 36, Frequency f = NP / 120 = 375 x 16 / 120 = 50 Hz

No. of slots per phase = 36 / 3 = 12

No. of conductors per slot = 30

No. of conductors per phase= 12 x 30 = 360

No. of turns per phase = T = 360 / 2 = 180

Assuming full pitch winding, pitch factor $K_c = 1$

Phase emf = $E_{ph} = 4K_fK_cK_d$ f T volts

E_{ph} = 4 x 1.11 x 1 x 0.95 x 50 x 0.05 x 180=1898V

3. A 3-phase, 16 pole alternator has a star connected winding having 144 slots and 10 conductors per slot. The flux per pole is 0.03 Webers and speed is 375 rpm. Find the frequency and phase and line voltage. Winding Factor K_d = 0.96, Pitch factor K_c = 1.

Solution:

Flux per pole, ϕ = 0.03 Webers

Frequency f = NP / 120 = 375 x 16 / 120 = 50 Hz

No. of slots per phase = 144 / 3 = 48

No. of conductors per slot = 10

No. of conductors per phase=48 x 10 = 480

Turns per phase T = conductors per phase / 2 = 480/2 = 240

Form factor = K_f = 1.11

E.M.F generated per phase = $E_{ph} = 4K_fK_cK_d$ f T volts

= 4 x 1.11 x 1 x 0.96 x 50 x 0.03 x 240

= 1534 volts.

Line emf =$\sqrt{3}$x 1534=**2657 volts**

4. A 3-phase star connected alternator with 12 poles generates 1100 volts on open circuit at a speed of 500 rpm. Assuming 180 turns per phase, a distribution factor of 0.96 and full pitched coils, find the useful flux per pole.

Solution:

Given line emf = 1100 volts

E.M.F EMF per phase E_{ph} = 1100 /3 = 635 volts

f = NP / 120 = 500x12 / 120 = 50 Hz

$E_{ph} = 4K_fK_cK_d\ \Phi f\quad T$ volts

$K_f = 1.11$

For full-pitched winding
Pitch Factor = $K_c = 1$

Distribution

factor = $K_d = 0.96$

T = No. of turns per phase = 180

Substituting in (1)

$E_{ph} = 4K_fK_cK_d\ f\Phi T$

volts

$635 = 4 \times 1.11 \times 1 \times 0.96 \times 50 \times \quad \times 180$

Flux per pole $=\Phi$ = 635 / 4.44 x 0.96 x 50 x 180=**0.0165 Webers**

Exercise Problems

1. A 12 pole 500 rpm star connected alternator has 48 slots with 15 conductors per slots. The flux per pole is 0.02wb. The winding factor is 0.97 and pitch factor is 0.98. Calculate the phase emf and line emf.

2. A 4 pole 1500 rpm star connected alternator has 9 slots per pole and 8 conductors per slot. Determine the flux per pole to give a terminal voltage of 3300V. Take winding factor and pitch factor as unity

3. A 2 pole, 3 phase alternator running at 3000rpm has armature slot with two conductors in each slot. Calculate flux per pole required to generate a line voltage of 2300V.Distribution factor is 0.952 and pitch factor is 0.956?

4. A 3 phase, star connected synchronous generator driven at 900 r/min is require to generate a line voltage of 460 V at 60 Hz on open circuit. This stator has two slots per pole per phase, and 4 conductors/slot. Calculate i) Number of poles ii)the useful flux per pole.