

## UNIT – I

### Poly phase Induction Motors

#### OBJECTIVE

The aim of this chapter is to gather knowledge about the following topics of Induction motors.

1. Construction, types and principle of operation of 3-phase induction motors.
2. Equivalent circuit of 3-phase induction motor.
3. The performance calculation by means of finding torque, slip and efficiency.
4. Different types of starters like auto-transformer starter, star-delta starter.
5. Various methods of speed control 3-phase induction motor.
6. Principle of operation of single phase induction motor.

#### 1.1 INTRODUCTION

An **induction motor** (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction.

The induction motor with a wrapped rotor was invented by Nikola Tesla Nikola Tesla in 1882 in France but the initial patent was issued in 1888 after Tesla had moved to the United States. In his scientific work, Tesla laid the foundations for understanding the way the motor operates. The induction motor with a cage was invented by Mikhail Dolivo-Dobrovolsky about a year later in Europe. Technological development in the field has improved to where a 100 hp (74.6 kW) motor from 1976 takes the same volume as a 7.5 hp (5.5 kW) motor did in 1897. Currently, the most common induction motor is the cage rotor motor.

An electric motor converts electrical power to mechanical power in its rotor (rotating part). There are several ways to supply power to the rotor. In a DC motor this power is supplied to the armature directly from a DC source, while in an induction motor this power is induced in the rotating device. An induction motor is sometimes called a *rotating transformer* because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and the ability to control the speed of the motor

### 1.2 CONSTRUCTION

A typical motor consists of two parts namely stator and rotor like other type of motors.

1. An **outside stationary stator** having coils supplied with AC current to produce a rotating magnetic field,
2. An **inside rotor** attached to the output shaft that is given a torque by the rotating field.

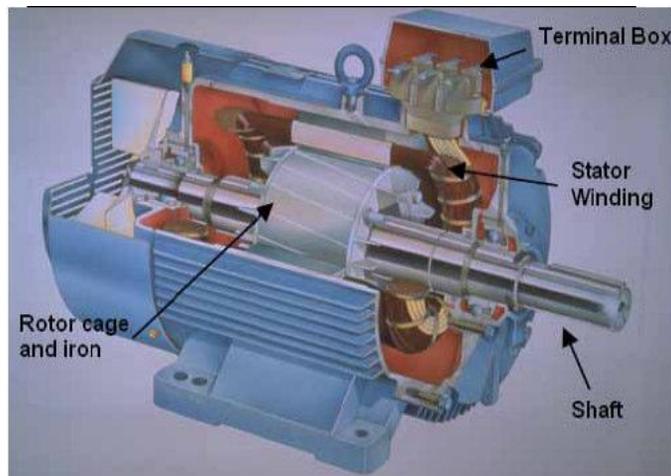


Figure. Induction motor construction

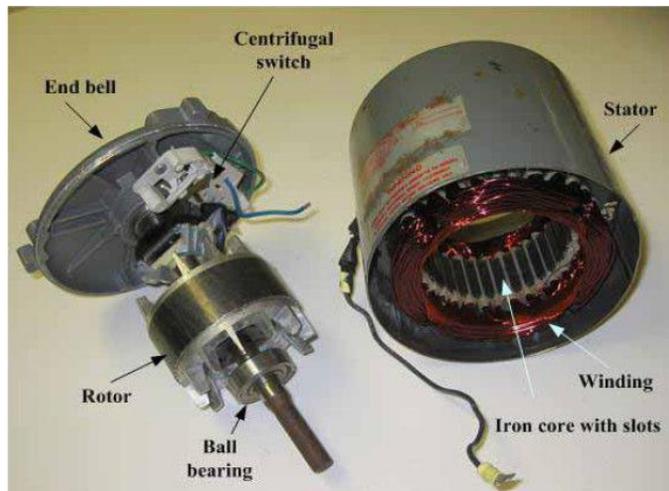


Figure. Induction motor components.

### 1.3 Stator construction

The stator of an induction motor is laminated iron core with slots similar to a stator of a synchronous machine. Coils are placed in the slots to form a three or single

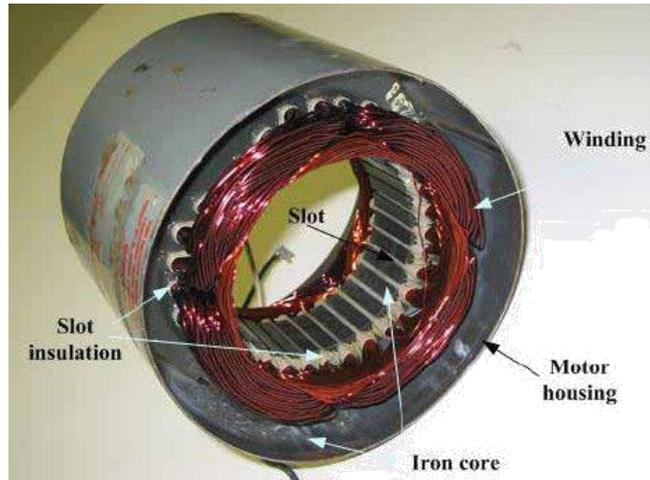


Figure. Single phase stator with windings.

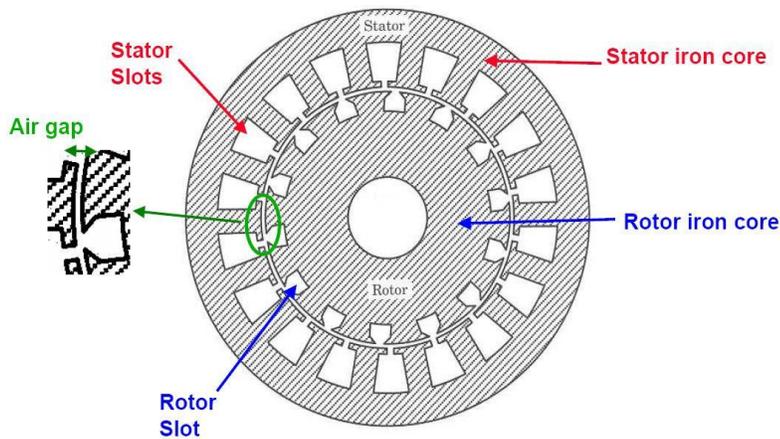


Figure. Induction motor magnetic circuit showing stator and rotor slots

### 1.4.Type of rotors

Rotor is of two different types.

1. Squirrel cage rotor
2. Wound rotor

### Squirrel-Cage Rotor

In *the squirrel-cage rotor*, the rotor winding consists of single copper or aluminium bars placed in the slots and short-circuited by end-rings on both sides of the rotor. Most of single phase induction motors have Squirrel-Cage rotor. One or 2 fans are attached to the shaft in the sides of rotor to cool the circuit.

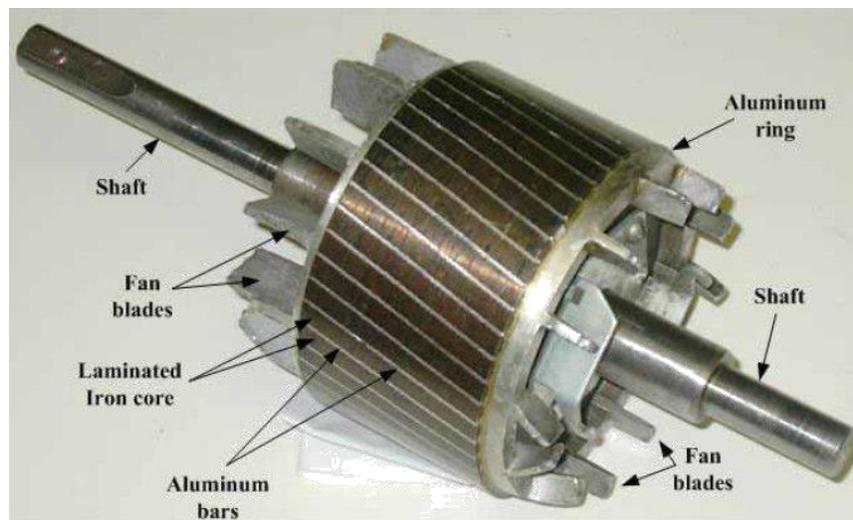
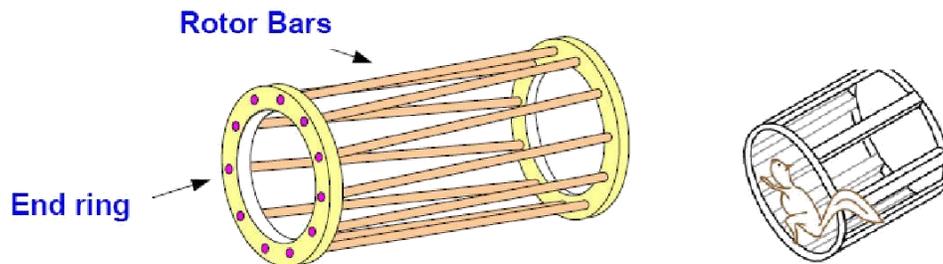


Figure. Squirrel cage rotor

### Wound Rotor

In the *wound rotor*, an insulated 3-phase winding similar to the stator winding wound for the same number of poles as stator, is placed in the rotor slots. The ends of the star-connected rotor winding are brought to three slip rings on the shaft so that a connection can be made to it for starting or speed control.

It is usually for large 3 phase induction motors.

Rotor has a winding the same as stator and the end of each phase is connected to a slip ring.

Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, so it is not so common in industry applications.

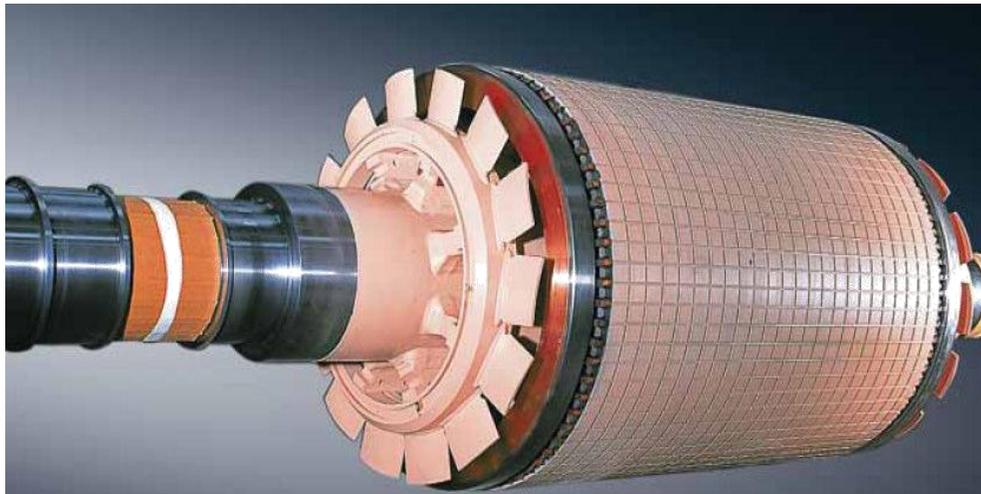


Figure. Wound rotor of a large induction motor. (Courtesy Siemens).

### 1.5.PRINCIPLE OF OPERATION

An AC current is applied in the stator armature which generates a flux in the stator magnetic circuit.

This flux induces an emf in the conducting bars of rotor as they are “cut” by the flux while the magnet is being moved ( $E = BVL$  (Faraday’s Law))

A current flows in the rotor circuit due to the induced emf, which in turn produces a force, ( $F = BIL$ ) can be changed to the torque as the output.

In a 3-phase induction motor, the three-phase currents  $i_a$ ,  $i_b$  and  $i_c$ , each of equal magnitude, but differing in phase by  $120^\circ$ . Each phase current produces a magnetic flux and there is physical  $120^\circ$  shift between each flux. The total flux in the machine is the sum of the three fluxes. The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in three-phase windings is called a **rotating magnetic flux or rotating magnetic field (RMF)**. RMF rotates with a constant speed (Synchronous Speed). Existence of a RFM is an essential condition for the operation of an induction motor.

If stator is energized by an ac current, RMF is generated due to the applied current to the stator winding. This flux produces magnetic field and the field revolves in the air gap between stator and rotor. So, the magnetic field induces a voltage in the short-circuited bars of the rotor. This voltage drives current through the bars. The interaction of the rotating flux and the rotor current generates a force that drives the motor and a torque is developed consequently. The torque is proportional with the flux density and the rotor bar current ( $F=BIL$ ). The motor speed is less than the synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

However, for these currents to be induced, the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced. If by some chance this happens, the rotor typically slows slightly until a current is re-induced and then the rotor continues as before. This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called **slip**. It is unitless and is the ratio between the relative speed of the magnetic field as seen by the rotor the (**slip speed**) to the speed of the rotating stator field. Due to this an induction motor is sometimes referred to as an asynchronous machine.

**SLIP**

The relationship between the supply frequency,  $f$ , the number of poles,  $p$ , and the synchronous speed (speed of rotating field),  $n_s$  is given by

$$n_s = \frac{120 f}{p}$$

The stator magnetic field (rotating magnetic field) rotates at a speed,  $n_s$ , the synchronous speed. If,  $n$  = speed of the rotor, the **slip,  $s$**  for an induction motor is defined as \_\_\_\_\_

At stand still, rotor does not rotate,  $n = 0$ , so  $s = 1$ .

At synchronous speed,  $n = n_s$ ,  $s = 0$

The mechanical speed of the rotor, in terms of slip and synchronous speed is given by,

$$n = (1-s) n_s$$

**Frequency of Rotor Current and Voltage**

With the rotor at stand-still, the frequency of the induced voltages and currents is the same as that of the stator (supply) frequency,  $f_e$ .

If the rotor rotates at speed of  $n$ , then the relative speed is the **slip speed**:

$$n_{slip} = n_s - n$$

$n_{slip}$  is responsible for induction.

Hence, the frequency of the induced voltages and currents in the rotor is,

$$f_r = s f_e. \text{ **Example 1:**}$$

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

Calculate:

- Synchronous speed
- Rotor speed
- Frequency of rotor current

**Solution:**

Synchronous speed:  $n_s = 120 f / p = (120 \times 60) / 6 = 1200 \text{ rpm}$

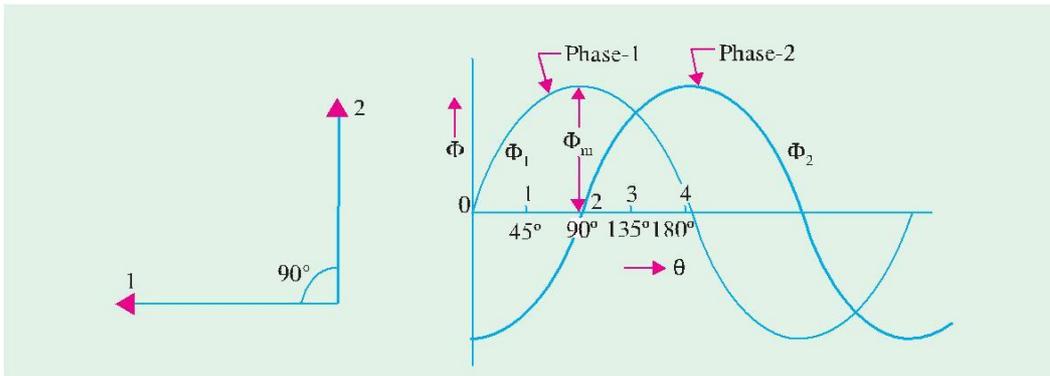
Rotor speed:  $n_r = (1-s) n_s = (1 - 0.05) (1200) = 1140 \text{ rpm}$

Frequency of rotor current:  $f_r = s f = (0.05) (60) = 3 \text{ Hz}$

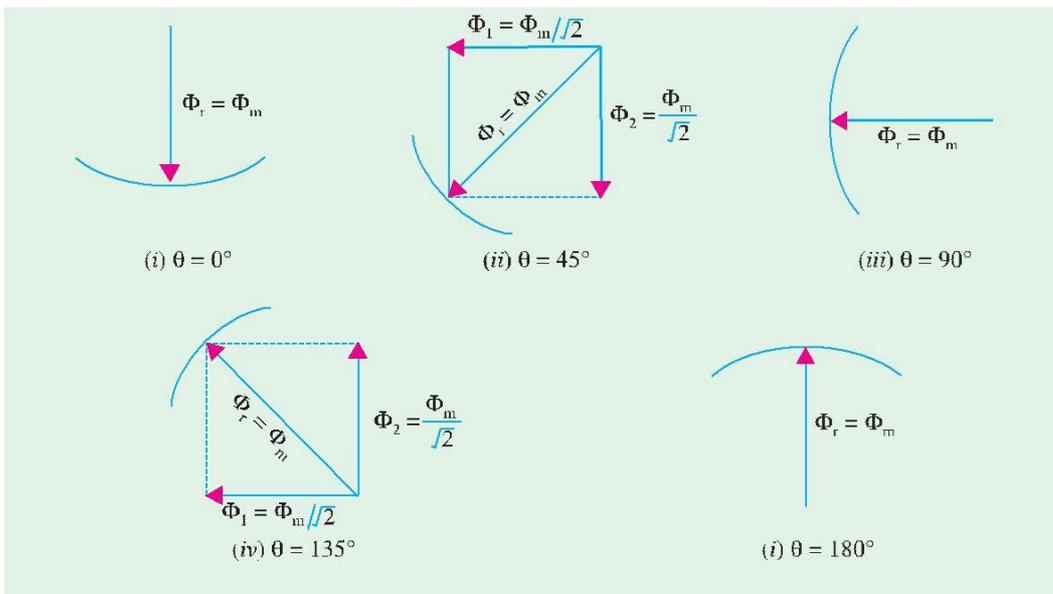
## 1.7. Production of Rotating Field

It will now be shown that when stationary coils, wound for two or three phases, are supplied by two or three-phase supply respectively, a uniformly-rotating (or revolving) magnetic flux of constant value is produced. Two-phase Supply The principle of a 2- $\phi$ , 2-pole stator having two identical windings, 90 space degrees apart, is illustrated in Fig.

The flux due to the current flowing in each phase winding is assumed sinusoidal and is represented in Fig. The assumed positive directions of fluxes are those shown in Fig. 34.8. Let  $\Phi_1$  and  $\Phi_2$  be the instantaneous values of the fluxes set up by the two windings. The resultant flux  $\Phi_r$  at any time is the vector sum of these two fluxes ( $\Phi_1$  and  $\Phi_2$ ) at that time. We will consider conditions at intervals of 1/8th of a time period i.e. at intervals corresponding to angles of  $0^\circ$ ,  $45^\circ$ ,  $90^\circ$ ,  $135^\circ$  and  $180^\circ$ . It will be shown that resultant flux  $\Phi_r$  is constant in magnitude i.e. equal to  $\Phi_m$  -the maximum flux due to either phase and is making one revolution/cycle. In other words, it means that the resultant flux rotates synchronously. (a) When  $\theta = 0^\circ$  i.e. corresponding to point 0 in Fig.  $\Phi_1 = 0$ , but  $\Phi_2$  is maximum i.e. equal to  $\Phi_m$  and negative. Hence, resultant flux  $\Phi_r = \Phi_m$  and, being negative, is shown by a vector pointing downwards (b) When  $\theta = 45^\circ$  i.e. corresponding to point 1 in Fig. 34.9. At this instant,  $\Phi_1 = \Phi_m / 2$  and is positive;  $\Phi_2 = \Phi_m / 2$  but is still negative. Their resultant, as shown in Fig., is  $\Phi_r = 2 \cdot 2 \left[ \left( \frac{\Phi_m}{2} \right) \left( \frac{\Phi_m}{2} \right) \right]^{1/2} = \Phi_m$  although this resultant has shifted  $45^\circ$  clockwise. (c) When  $\theta = 90^\circ$  i.e. corresponding to point 2 in Fig. 34.9. Here  $\Phi_2 = 0$ , but  $\Phi_1 = \Phi_m$  and is positive. Hence,  $\Phi_r = \Phi_m$  and has further shifted by an angle of  $45^\circ$  from its position in (b) or by  $90^\circ$  from its original position in (a). (d) When  $\theta = 135^\circ$  i.e. corresponding to point 3 in Fig. 34.9. Here,  $\Phi_1 = \Phi_m / 2$  and is positive,  $\Phi_2 = \Phi_m / 2$  and is also positive. The resultant  $\Phi_r = \Phi_m$  and has further shifted clockwise by another  $45^\circ$ , as shown in Fig. 34.10 (iv)..



(e) When  $\theta = 180^\circ$  i.e. corresponding to point 4 in Fig. 34.9. Here,  $\Phi_1 = 0$ ,  $\Phi_2 = \Phi_m$  and is positive. Hence,  $\Phi_r = \Phi_m$  and has shifted clockwise by another  $45^\circ$  or has rotated through an angle of  $180^\circ$  from its position at the beginning. This is shown in Fig. 34.10(v).



Hence, we conclude

1. that the magnitude of the resultant flux is constant and is equal to  $\Phi_m$  — the maximum flux due to either phase.
2. that the resultant flux rotates at synchronous speed given by  $N_s = 120 f/P$  rpm.

However, it should be clearly understood that in this revolving field, there is no actual revolution of the flux. The flux due to each phase changes periodically, according to the changes in the phase current, but the magnetic flux itself does not move around the stator. It is only the *seat* of the resultant flux which keeps on shifting synchronously around the stator.

### Mathematical Proof

Let  $\Phi_1 = \Phi_m \sin \omega t$  and  $\Phi_2 = \Phi_m \sin (\omega t - 90^\circ)$

$$\therefore \Phi_r^2 = \Phi_1^2 + \Phi_2^2$$

$$\Phi_r^2 = (\Phi_m \sin \omega t)^2 + [\Phi_m \sin (\omega t - 90^\circ)]^2 = \Phi_m^2 (\sin^2 \omega t + \cos^2 \omega t) = \Phi_m^2$$

$$\therefore \Phi_r = \Phi_m$$

It shows that the flux is of constant value and does not change with time.

### Three-phase Supply

It will now be shown that when three-phase windings displaced in space by  $120^\circ$ , are fed by three-phase currents, displaced in time by  $120^\circ$ , they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

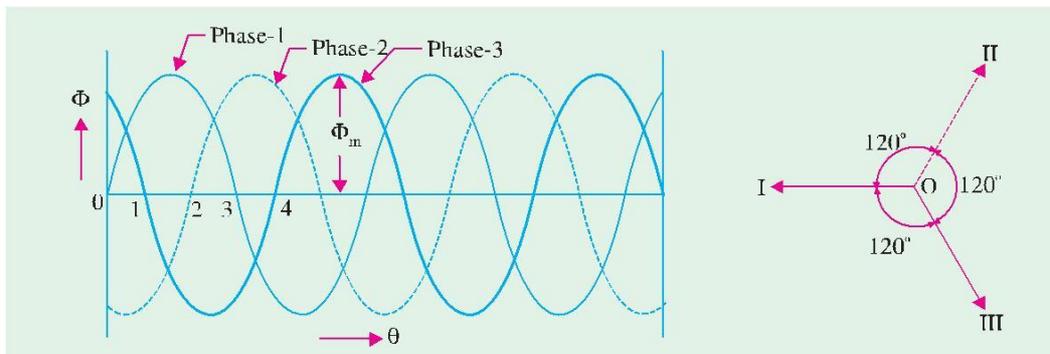
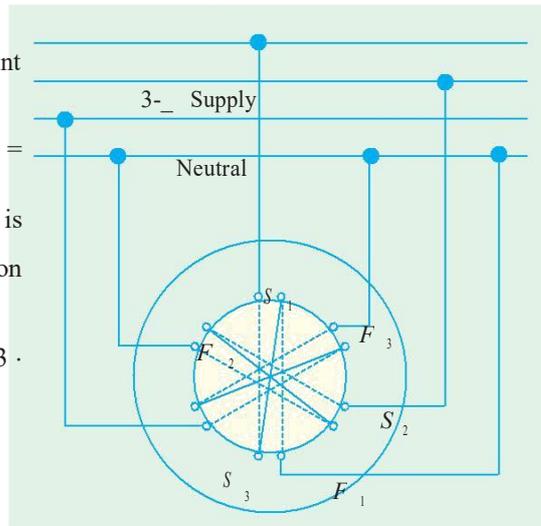
The principle of a 3-phase, two-pole stator having three identical windings placed  $120^\circ$  space degrees apart is shown in Fig. The flux (assumed sinusoidal) due to three-phase windings is shown in Fig .

The assumed positive directions of the fluxes are shown in Fig. Let the maximum value of flux due to any one of the three phases be  $\Phi_m$ . The resultant flux  $\Phi_r$ , at any instant, is given by the vector sum of the individual fluxes,  $\Phi_1$ ,  $\Phi_2$  and  $\Phi_3$  due to three phases. We will consider values of  $\Phi_r$  at four instants  $1/6$ th time-period apart corresponding to points marked 0, 1, 2 and 3 in Fig.

(i) When  $\theta = 0^\circ$  i.e. corresponding to point 0 in Fig. 34.12.

Here  $\Phi_1 = 0, \Phi_2 = -\frac{3}{2}\Phi_m, \Phi_3 = \frac{3}{2}\Phi_m$ . The vector for  $\Phi_2$  in Fig. 34.14 (i) is drawn in a direction opposite to the direction assumed positive in Fig. 34.13.

$$\therefore \Phi_r = 2 \cdot \frac{3}{2} \Phi_m \cos \frac{60^\circ}{2} = 3 \cdot \frac{3}{2} \Phi_m = \frac{9}{2} \Phi_m$$



Here  $\Phi_1 = \frac{3}{2}\Phi_m$

$\Phi_2 = -\frac{3}{2}\Phi_m$

$\Phi_3 = 0$

$$\therefore \Phi_r = 2 \cdot \frac{3}{2} \Phi_m \cos 30^\circ = 3 \Phi_m$$

It is found that the resultant flux is again  $\frac{3}{2}\Phi_m$  but has rotated clockwise through an angle of  $60^\circ$ .

(iii) When  $\theta = 120^\circ$  i.e. corresponding to point 2 in Fig. 34.12.

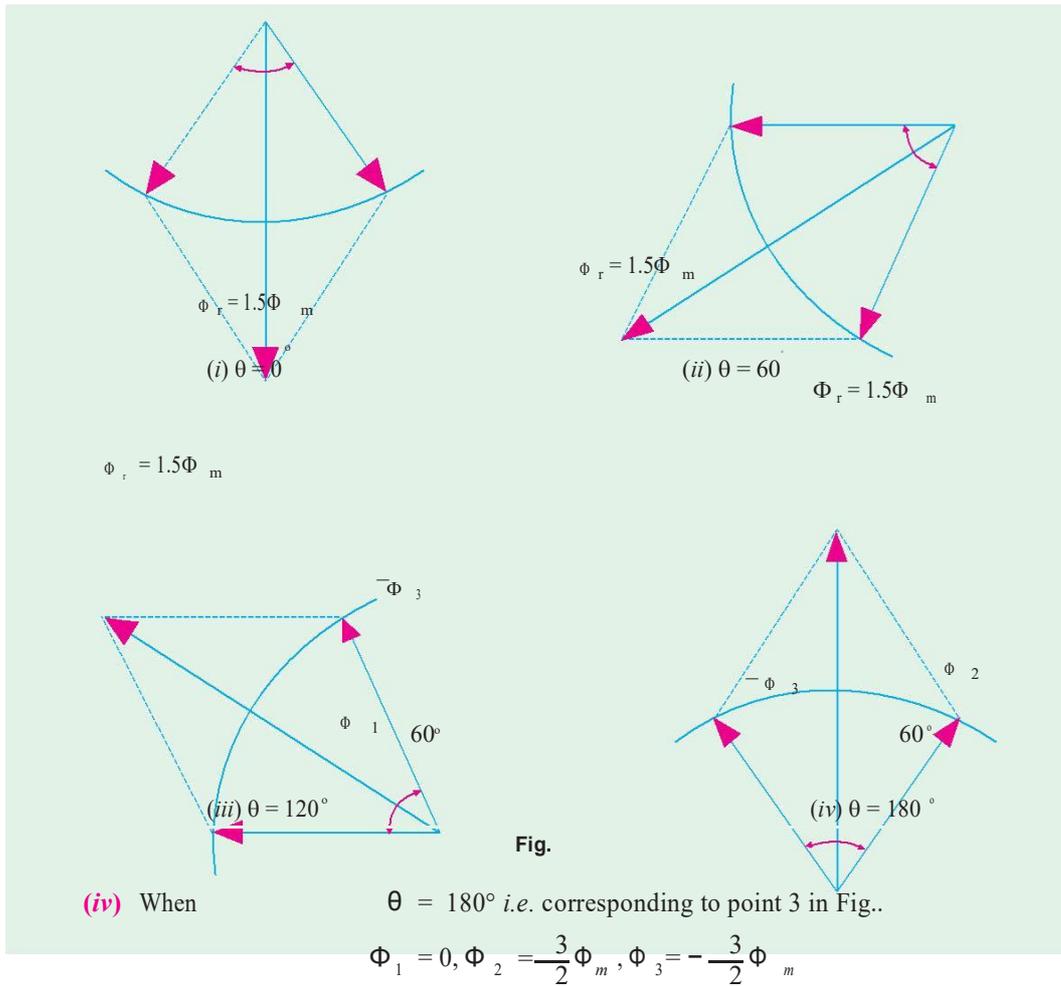
Here,  $\Phi_1 = \frac{3}{2}\Phi_m, \Phi_2 = 0, \Phi_3 = -\frac{3}{2}\Phi_m$

It can be again proved that  $\Phi_r = \frac{3}{2}\Phi_m$ .

...drawn parallel to  $OI$  of Fig. as shown in Fig (ii)

...drawn in opposition to  $OII$  of Fig. 34.13.

[Fig.]



The resultant is  $\frac{3}{2}\Phi_m$  and has rotated clockwise through an additional angle  $60^\circ$  or through an angle of  $180^\circ$  from the start.

Hence, we conclude that

1. the resultant flux is of constant value =  $\frac{3}{2}\Phi_m$  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 given by  $N_s = 120 f/P$ .**

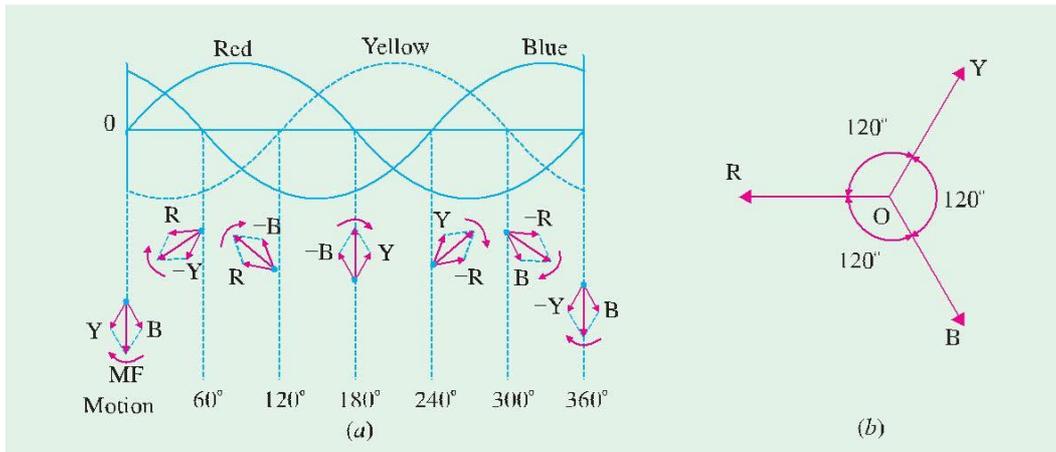


Fig. (a) shows the graph of the rotating flux in a simple way. As before, the positive directions of the flux phasors have been shown separately in Fig. 34.15 (b). Arrows on these flux phasors are reversed when each phase passes through zero and becomes negative.

### Slip

In practice, the rotor never succeeds in ‘catching up’ with the stator field. If it really did so, then there would be no relative speed between the two, hence no rotor e.m.f., no rotor current and so no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference in speeds depends upon the load on the motor.\*

The difference between the synchronous speed  $N_s$  and the actual speed  $N$  of the rotor is known as *slip*. Though it may be expressed in so many revolutions/second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term ‘*slip*’ is descriptive of the way in which the rotor ‘slips back’ from synchronism.

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

Sometimes,  $N_s - N$  is called the *slip speed*.

Obviously, rotor (or motor) speed is  $N = N_s (1 - s)$ .

It may be kept in mind that revolving flux is rotating synchronously, relative to the stator (*i.e.* stationary space) but at slip speed relative to the rotor.

### 1.7. Frequency of Rotor Current

When the rotor is stationary, the frequency of rotor current is *the same as the supply frequency*. But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip-speed. Let at any slip-speed, the frequency of the rotor current be  $f'$ . Then

$$N_s - N = \frac{120f'}{P} \quad \text{Also, } N_s = \frac{120f}{P}$$

$$\frac{f'}{N_s - N} = \frac{N_s - N}{N_s} = s \quad \therefore f' = sf$$

Dividing one by the other, we get,  $f$

As seen, rotor currents have a frequency of  $f' = sf$  and when flowing through the individual phases of rotor winding, give rise to rotor magnetic fields. These individual rotor magnetic fields produce a combined rotating magnetic field, whose speed relative to rotor is

$$= \frac{120f'}{P} = \frac{120sf}{P} = sN_s$$

However, the rotor itself is running at speed  $N$  with respect to space. Hence, speed of rotor field in *space* = speed of rotor magnetic field relative to rotor + speed of rotor relative to space

$$= sN_s + N = sN_s + N_s(1-s) = N_s$$

It means that no matter what the value of slip, rotor currents and stator currents each produce a sinusoidally distributed magnetic field of constant magnitude and constant space speed of  $N_s$ . In other words, both the rotor and stator fields rotate synchronously, which means that they are stationary with respect to each other. These two synchronously rotating magnetic fields, in fact, superimpose on each other and give rise to the actually existing rotating field, which corresponds to the magnetising current of the stator winding.

**Example 34.1.** A slip-ring induction motor runs at 290 r.p.m. at full load, when connected to 50-Hz supply. Determine the number of poles and slip.

(Utilisation of Electric Power AMIE Sec. B 1991)

**Solution.** Since  $N$  is 290 rpm;  $N_s$  has to be somewhere near it, say 300 rpm. If  $N_s$  is assumed as 300 rpm, then  $300 = 120 \cdot 50/P$ . Hence,  $P = 20$ .  $\therefore s = (300 - 290)/300 = 3.33\%$

**Example 34.2.** The stator of a 3- $\phi$  induction motor has 3 slots per pole per phase. If supply frequency is 50 Hz, calculate

- (i) number of stator poles produced and total number of slots on the stator  
 (ii) speed of the rotating stator flux (or magnetic field).

**Solution. (i)**  $P = 2n = 2 \cdot 3 = 6$  poles  
 Total No. of slots  $= 3 \text{ slots/pole/phase} \cdot 6 \text{ poles} \cdot 3 \text{ phases} = 54$

(ii)  $N_s = 120 f/P = 120 \cdot 50/6 = 1000$  r.p.m.

**Example 34.3.** A 4-pole, 3-phase induction motor operates from a supply whose frequency is 50 Hz. Calculate :

- (i) the speed at which the magnetic field of the stator is rotating.  
 (ii) the speed of the rotor when the slip is 0.04.  
 (iii) the frequency of the rotor currents when the slip is 0.03.  
 (iv) the frequency of the rotor currents at standstill.

(Electrical Machinery II, Bangalore Univ. 1991)

**Solution. (i)** Stator field revolves at synchronous speed, given by

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

(ii) rotor (or motor) speed,  $N = N_s (1 - s) = 1500(1 - 0.04) = 1440$  r.p.m.

(iii) frequency of rotor current,  $f' = sf = 0.03 \cdot 50 = 1.5$  r.p.s = 90 r.p.m  
 $= 1, f' = sf = 1 \cdot f = f = 50\text{Hz}$

(iv) Since at standstill,  $s = 1$

**Example 34.4.** A 3- $\phi$  induction motor is wound for 4 poles and is supplied from 50-Hz system. Calculate (i) the synchronous speed (ii) the rotor speed, when slip is 4% and (iii) rotor frequency when rotor runs at 600 rpm.

(Electrical Engineering-I, Pune Univ. 1991)

**Solution. (i)**  $N_s = 120 f/P = 120 \cdot 50/4 = 1500$  rpm

(ii) rotor speed,  $N = N_s (1 - s) = 1500 (1 - 0.04) = 1440$  rpm

(iii) when rotor speed is 600 rpm, slip is

$$s = (N_s - N)/N_s = (1500 - 600)/1500 = 0.6$$

rotor current frequency,  $f' = sf = 0.6 \cdot 50 = 30$  Hz

**Example 34.5.** A 12-pole, 3-phase alternator driven at a speed of 500 r.p.m. supplies power to an 8-pole, 3-phase induction motor. If the slip of the motor, at full-load is 3%, calculate the full-load speed of the motor.

**Solution.** Let  $N$  = actual motor speed; Supply frequency,  $f = 12 \cdot 500/120 = 50$  Hz. Synchronous speed  $N_s = 120 \cdot 50/8 = 750$  r.p.m.

$$\% \text{ slip } s = \frac{N_s - N}{N_s} \cdot 100 ; 3 = \frac{750 - N}{750} \cdot 100 \quad \therefore N = 727.5 \text{ r.p.m.}$$

**Note.** Since slip is 3%, actual speed  $N$  is less than  $N_s$  by 3% of  $N_s$  i.e. by  $3 \cdot 750/100 = 22.5$  r.p.m.

### 1.8. Relation Between Torque and Rotor Power Factor

it has been shown that in the case of a d.c. motor, the torque  $T_a$  is proportional to the product of armature current and flux per pole i.e.  $T_a \propto \phi I_a$ . Similarly, in the case of an induction motor, the torque is also 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.

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

$$\text{or} \quad \phi_2$$

$T = k I_2 \sin \theta$   
 = rotor current at  
 where  $I_2$  standstill  
 $\theta$  = angle between rotor  
 $E_2$  e.m.f. and  
 rotor  
 current  
 $k =$  a constant

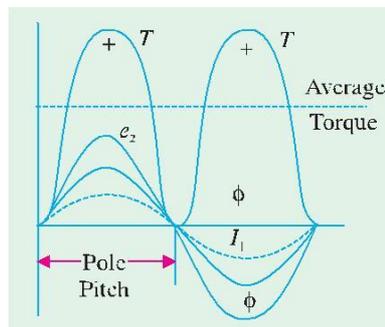
Denoting rotor e.m.f. at *standstill* by  $E_2$ , we have that

$$E_2 \propto \phi \therefore T \propto E_2 I_2 \cos \phi_2$$

$$T = k_1 E_2 I_2 \cos \phi_2$$

where  $k_1$  is another constant.

The effect of rotor power factor on rotor torque is illustrated in Fig. 34.17 and Fig. 34.18 for various values of  $\phi_2$ . From the above expression for torque, it is clear that as  $\phi_2$  increases (and hence,  $\cos \phi_2$  decreases) the torque decreases and *vice versa*



**(i) Rotor Assumed Non-inductive (or  $\phi_2 = 0$ )**

In this case, the rotor current  $I_2$  is in phase with the e.m.f.  $E_2$  induced in the rotor (Fig. 34.17). The instantaneous value of the torque acting on each rotor conductor is given by the product of instantaneous value of the flux and the rotor current ( $\mathbf{C} F \propto B I_2 l$ ). Hence, torque curve is obtained by plotting the products of flux  $\phi$  (or flux density  $B$ ) and  $I_2$ . It is seen that the torque is always positive *i.e.* unidirectional.

**(ii) Rotor Assumed Inductive**

This case is shown in Fig. 34.18. Here,  $I_2$  lags behind  $E_2$  by an angle  $\phi_2 = \tan^{-1} X_2/R_2$  where  $R_2$  = rotor resistance/phase;  $X_2$  = rotor reactance/phase at **standstill**.

It is seen that for a portion 'ab' of the pole pitch, the torque is negative *i.e.* reversed. Hence, the total torque which is the difference of the forward and the backward torques, is considerably reduced. If  $\phi_2 = 90^\circ$ , then the total torque is zero because in that case the backward and the forward torques become equal and opposite.

**1.9.Starting Torque**

The torque developed by the motor at the instant of starting is called starting torque. In some cases, it is greater than the normal running torque, whereas in some other cases it is somewhat less.

$$\begin{aligned} \text{Let} \quad E_2 &= \text{rotor e.m.f. per phase at } \mathbf{standstill}; \\ R_2 &= \text{rotor resistance/phase} \\ X_2 &= \text{rotor reactance/phase at } \mathbf{standstill} \\ \therefore Z_2 &= \sqrt{R_2^2 + X_2^2} = \text{rotor impedance/phase at } \mathbf{standstill} \\ \text{Then,} \quad I_2 &= \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}; \quad \cos \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}} \end{aligned}$$

$$\text{Standstill or starting torque } T_{st} = k_1 E_2 I_2 \cos \phi_2$$

$$\text{or} \quad T_{st} = k_1 E_2 \cdot \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + X_2^2}} = \frac{k E_2^2 R_2}{R_2^2 + X_2^2} \quad \dots(i)$$

If supply voltage  $V$  is constant, then the flux  $\Phi$  and hence,  $E_2$  both are constant.

$$\therefore T_{st} = k_2 \frac{R_2}{R_2^2 + X_2^2} = k_2 \frac{R_2}{Z_2^2} \text{ where } k_2 \text{ is some other constant.}$$

$$\text{Now,} \quad k_1 = \frac{3}{2\pi N_s}, \quad \therefore T_{st} = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

**1.10.Starting Torque of a Squirrel-cage Motor**

The resistance of a squirrel-cage motor is fixed and small as compared to its reactance which is very large especially at the start because at standstill, the 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 a very large angle behind  $E_2$ , with the result that the starting torque per ampere is very poor. It is roughly 1.5 times the full-load torque, although the starting current is 5 to 7 times the full-load current. Hence, such motors are not useful where the motor has to start against heavy loads.

**1.11.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 resistance 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 and so the torque starts decreasing.

**Condition for Maximum Starting Torque**

It can be proved that starting torque is maximum when rotor resistance equals rotor reactance.

Now 
$$T_{st} = \frac{k R_2}{R_2^2 + X_2^2} \quad \therefore \frac{dT_{st}}{dR_2} = k \frac{1}{2R_2^2 + X_2^2} - \frac{R_2 (2R_2)}{(R_2^2 + X_2^2)^2} = 0$$

or 
$$R_2 + X_2^2 = 2R_2^2 \quad \therefore R_2 = X_2^2$$

**1.12. Effect of Change in Supply Voltage on Starting Torque**

We have seen in Art. 34.13 that  $T_{st} = \frac{k E_2^2 R_2}{R_2^2 + X_2^2}$ . Now  $E_2 \propto$  supply voltage  $V$

$$\therefore T_{st} = \frac{k V^2 R_2}{R_2^2 + X_2^2} = \frac{k V^2 R_2}{Z_2^2}$$
 where  $k$  is yet another constant. Hence  $T_{st} \propto V^2$ .

Clearly, the torque is very sensitive to any changes in the supply voltage. A change of 5 per cent in supply voltage, for example, will produce a change of approximately 10% in the rotor torque. This fact is of importance in star-delta and auto transformer starters

**Example .** A 3-6 induction motor having a star-connected rotor has an induced e.m.f. of 80 volts between slip-rings at standstill on open-circuit. The rotor has a resistance and reactance per phase of  $1 \Omega$  and  $4 \Omega$  respectively. Calculate current/phase and power factor when (a) slip-rings are short-circuited (b) slip-rings are connected to a star-connected rheostat of  $3 \Omega$  per phase.

(Electrical Technology, Bombay Univ. 1987, and similar example: Rajiv Gandhi Techn. Univ. Bhopal, Dec. 2000)

**Solution.** Standstill e.m.f./rotor phase =  $80/\sqrt{3} = 46.2 \text{ V}$

$$\begin{aligned} \text{(a) Rotor impedance/phase} &= \sqrt{(1^2 + 4^2)} = 4.12 \Omega \\ \text{Rotor current/phase} &= 46.2/4.12 = \mathbf{11.2 \text{ A}} \\ \text{Power factor} &= \cos \phi = 1/4.12 = \mathbf{0.243} \end{aligned}$$

As p.f. is low, the starting torque is also low.

$$\begin{aligned} \text{(b) Rotor resistance/phase} &= 3 + 1 = 4 \Omega \\ \text{Rotor impedance/phase} &= \sqrt{(4^2 + 4^2)} = 5.66 \Omega \\ \therefore \text{ Rotor current/phase} &= 46.2/5.66 = \mathbf{8.16 \text{ A}}; \cos \phi = 4/5.66 = \mathbf{0.707}. \end{aligned}$$

Hence, the starting torque is increased due to the improvement in the power factor. It will also be noted that improvement in p.f. is much more than the decrease in current due to increased impedance.

**Example.** A 1100-V, 50-Hz delta-connected induction motor has a star-connected slip-ring rotor with a phase transformation ratio of 3.8. The rotor resistance and standstill leakage reactance are 0.012 ohm and 0.25 ohm per phase respectively. Neglecting stator impedance and magnetising current determine.

- (i) the rotor current at start with slip-rings shorted
- (ii) the rotor power factor at start with slip-rings shorted
- (iii) the rotor current at 4% slip with slip-rings shorted
- (iv) the rotor power factor at 4% slip with slip-rings shorted
- (v) the external rotor resistance per phase required to obtain a starting current of 100 A in the stator supply lines. (Elect. Machines AMIE Sec. B 1992)

**Solution.** It should be noted that in a  $\Delta/Y$  connection, primary phase voltage is the same as the line voltage. The rotor phase voltage can be found by using the phase transformation ratio of 3.8 i.e.  $K = 1/3.8$ .

$$\text{Rotor phase voltage at standstill} = 1100 \cdot 1/3.8 = 289.5 \text{ V}$$

- (i) Rotor impedance/phase =  $\sqrt{0.012^2 + 0.25^2} = 0.2503 \Omega$   
Rotor phase current at start =  $289.5/0.2503 = \mathbf{1157 \text{ A}}$
- (ii)  $p.f. = R_2/Z_2 = 0.012/0.2503 = \mathbf{0.048 \text{ lag}}$
- (iii) at 4% slip,  $X_r = sX_2 = 0.04 \cdot 0.25 = 0.01 \Omega$   
 $\therefore Z_r = \sqrt{0.012^2 + 0.01^2} = \mathbf{0.0156 \Omega}$   
 $E_r = sE_2 = 0.04 \cdot 289.5 = 11.58 \text{ V}; I_2 = 11.58/0.0156 = \mathbf{742.3 \text{ A}}$
- (iv)  $p.f. = 0.012/0.0156 = \mathbf{0.77}$
- (v)  $I_2 = I_1/K = 100 \cdot 3.8 = 380 \text{ A}; E_2 \text{ at standstill} = 289.5 \text{ V}$   
 $Z_2 = 289.5/380 = 0.7618 \Omega; R_2 = \sqrt{Z_2^2 - X_2^2} = \sqrt{0.7618^2 - 0.25^2} = 0.7196 \Omega$   
 $\therefore \text{ External resistance reqd./phase} = 0.7196 - 0.012 = \mathbf{0.707 \Omega}$

### Tutorial Problem

1. In the case of an 8-pole induction motor, the supply frequency was 50-Hz and the shaft speed was

735 r.p.m. What were the magnitudes of *(Nagpur Univ.,  
Summer 2000)*  
the following:

- |                       |                      |
|-----------------------|----------------------|
| (i) synchronous speed | (ii) speed of slip   |
| (iii) per unit slip   | (iv) percentage slip |

2. An 8-pole alternator runs at 750. r.p.m. and supplies power to a 6-pole induction motor which has at full-load a slip of 3%. Find the full-load speed of the induction motor and the frequency of its rotor e.m.f. **[970 r.p.m. ; 1.5 Hz]**

3. A 3-phase, 50-Hz induction motor with its rotor star-connected gives 500 V (r.m.s.) at standstill between the slip-rings on open-circuit. Calculate the current and power factor at standstill when the rotor winding is joined to a star-connected external circuit, each phase of which has a resistance of 10  $\Omega$  and an inductance of 0.04 H. The resistance per phase of the rotor winding is 0.2  $\Omega$  and its inductance is 0.04 H.

Also, calculate the current and power factor when the slip-rings are short-circuited and the motor is running with a slip of 5 per cent. Assume the flux to remain constant.

**[10.67 A; 0.376; 21.95  
A; 0.303]**

4. Obtain an expression for the condition of maximum torque of an induction motor. Sketch the torque-slip curves for several values of rotor circuit resistance and indicate the condition for maximum torque to be obtained at starting.

If the motor has a rotor resistance of 0.02  $\Omega$  and a standstill reactance of 0.1  $\Omega$ , what must be the value of the total resistance of a starter for the rotor circuit for maximum torque to be exerted at starting ? **[0.08  $\Omega$ ] (City and Guilds, London)**

5. The rotor of a 6-pole, 50-Hz induction motor is rotated by some means at 1000 r.p.m. Compute (i) rotor voltage (ii) rotor frequency (iii) rotor slip and (iv) torque developed. Can the rotor rotate at this speed by itself ? **[(i) 0 (ii) 0 (iii) 0 (iv) 0; No] (Elect. Engg. Grad I.E.T.E. June 1985)**

6. The rotor resistances per phase of a 4-pole, 50-Hz, 3-phase induction motor are 0.024 ohm and 0.12 ohm respectively. Find the speed at maximum torque. Also find the value of the additional rotor resistance per phase required to develop 80% of maximum torque at starting.

**[1200 r.p.m. 0.036  $\Omega$ ] (*Elect. Machines, A.M.I.E. Sec. B, 1990*)**

7. The resistance and reactance per phase of the rotor of a 3-phase induction motor are 0.6 ohm and 5 ohms respectively. The induction motor has a star-connected rotor and when the stator is connected to a supply of normal voltage, the induced e.m.f. between the slip rings at standstill is 80 V. Calculate the current in each phase and the power factor at starting when (i) the slip-rings are shorted, (ii) slip-rings are connected to a star-connected resistance of 4 ohm per phase.

### 1.13. Rotor E.M.F. and Reactance Under Running Conditions

Let  $E_2$  = *standstill* rotor induced e.m.f./phase

$X_2$  = *standstill* rotor reactance/phase,  $f_2$  = rotor current frequency at *standstill*

When rotor is stationary *i.e.*  $s = 1$ , the frequency of rotor e.m.f. is the same as that of the stator supply frequency. The value of e.m.f. induced in the rotor at standstill is maximum because the relative speed between the rotor and the revolving stator flux is maximum. In fact, the motor is equivalent to a 3-phase transformer with a short-circuited rotating secondary.

When rotor starts running, the relative speed between it and the rotating stator flux is decreased. Hence, the rotor induced e.m.f. which is directly proportional to this relative speed, is also decreased (and may disappear altogether if rotor speed were to become equal to the speed of stator flux). Hence, for a slip  $s$ , the rotor induced e.m.f. will be  $s$  times the induced e.m.f. at standstill.

Therefore, under *running conditions*  $E_r = sE_2$

The frequency of the induced e.m.f. will likewise become  $f_r = sf_2$

Due to decrease in frequency of the rotor e.m.f., the rotor reactance will also decrease.

∴

$$X_r = sX_2$$

where  $E_r$  and  $X_r$  are rotor e.m.f. and reactance under *running* conditions.

### Torque Under Running Conditions

$$T \propto E_r I_r \cos \phi_2 \text{ or } T \propto \Phi I_r \cos \phi_2$$

where  $E_r$  = rotor e.m.f./phase under *running conditions*

$I_r$  = rotor current/phase under *running conditions*

Now  $E_r = sE_2$

$$\therefore I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\cos \phi_2 = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad \text{—Fig. 34.20}$$

$$\therefore T \propto \frac{s \Phi E_2 R_2}{R_2^2 + (sX_2)^2} = \frac{k \Phi \cdot s \cdot E_2 R_2}{R_2^2 + (sX_2)^2}$$

$$\text{Also } T = \frac{k \cdot s E_2^2 R_2}{R_2^2 + (sX_2)^2} \quad (3E_2 \propto \Phi)$$

### 1.14. Condition for Maximum Torque Under Running Conditions

The torque of a rotor under **running** conditions is

$$T = \frac{k \Phi s E R_2}{R_2^2 + (sX_2)^2} = k_1 \frac{s E_2 R_2}{R_2^2 + (sX_2)^2} \quad \dots(i)$$

The condition for maximum torque may be obtained by differentiating the above expression with respect to slip  $s$  and then putting it equal to zero. However, it is simpler to put  $Y = T^{-1}$  and then differentiate it.

$$\begin{aligned} \therefore Y &= \frac{R_2^2 + (sX_2)^2}{k \Phi s E_2 R_2} = \frac{R_2}{k \Phi s E_2} + \frac{sX_2^2}{k \Phi E_2 R_2}; \frac{dY}{ds} = \frac{-R_2}{k \Phi s^2 E_2} + \frac{X_2^2}{k \Phi E_2 R_2} = 0 \\ \therefore \frac{R_2}{k \Phi s^2 E_2} &= \frac{X_2^2}{k \Phi E_2 R_2} \quad \text{or } R_2^2 = s^2 X_2^2 \quad \text{or } R_2 = sX_2 \end{aligned}$$

Hence, torque under **running condition** is maximum at that value of the slip  $s$  which makes rotor reactance per phase equal to rotor resistance per phase. This slip is sometimes written as  $s_b$  and the maximum torque as  $T_b$ .

Slip corresponding to maximum torque is  $s = R_2/X_2$

Putting  $R_2 = sX_2$  in the above equation for the torque, we get

$$I_{\max} = \frac{k \Phi s^2 E X_2}{2 s X_2} \quad \text{or} \quad \frac{k \Phi s E R_2}{2 R_2} \quad \text{or} \quad I_{\max} = \frac{k \Phi E}{2 X_2} \quad \text{or} \quad \frac{k \Phi s E}{2 R_2} \quad \dots(ii)$$

Substituting value of  $s = R_2/X_2$  in the other equation given in (i) above, we get

$$I_{\max} = k_1 \frac{(R_2/X_2) \cdot E_2 \cdot R_2}{R_2^2 + (R_2/X_2)^2 \cdot X_2^2} = k_1 \frac{E_2^2}{2 X_2}$$

Since,  $k_1 = 3/2\pi N_s$ , we have  $T_{\max} = \frac{3}{2\pi N_s} \cdot \frac{E_2^2}{2 X_2}$  N-m

From the above, it is found

1. that the maximum torque is independent of rotor resistance as such.

however, the speed or slip at which maximum torque occurs is determined by the rotor where  $k_1$  is another constant. Its value can be proved to be equal to  $3/2 \pi N_s$

Hence, in that case, expression for torque becomes

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

At standstill when  $s = 1$ , obviously

$$I_{st} = \frac{k_1 E_2 R_2}{R^2 + X^2} \text{ or } = \frac{3}{2\pi N_s} \cdot \frac{E_2 R_2}{R^2 + X^2}$$

2. maximum torque varies inversely as standstill reactance. Hence, it should be kept as small as possible.

3. maximum torque varies directly as the square of the applied voltage.

4. for obtaining maximum torque at starting ( $s = 1$ ), rotor resistance must be equal to rotor reactance.

## UNIT – II

### Characteristics of Induction Motors & Speed Control

#### Methods

##### 2.1.EQUIVALENT CIRCUIT

The induction motor consists of a two magnetically connected systems namely, stator and rotor. This is similar to a transformer that also has two magnetically connected systems namely primary and secondary windings. Also, the induction motor operates on the same principle as the transformer. Hence, the induction motor is also called as **rotating transformer**

The stator is supplied by a balanced three-phase voltage that drives a three-phase current through the winding. This current induces a voltage in the rotor. The applied voltage ( $V_1$ ) across phase A is equal to the sum of the

–induced voltage ( $E_1$ ).

–voltage drop across the stator resistance ( $I_1 R_1$ ).

–voltage drop across the stator leakage reactance ( $I_1 j X_1$ ).

Let

$I_1$  = stator current/phase

$R_1$  = stator winding resistance/phase

$X_1$  = stator winding reactance/phase

$R_R$  = rotor winding resistance/phase

$X_R$  = rotor winding reactance/phase

$I_R$  = rotor current

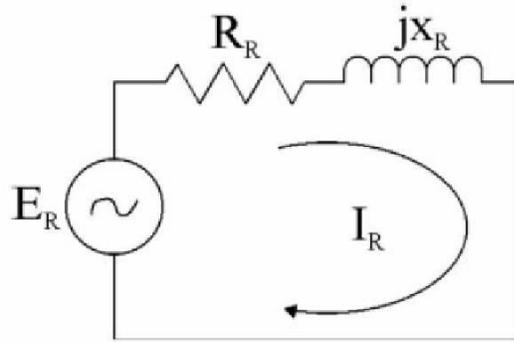
$V_1$  = applied voltage to the stator/phase

$I_o = I_c + I_m$  ( $I_m$ -magnetising component,  $I_c$ -core loss component)

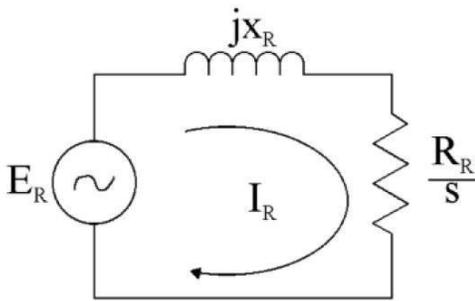
Rotor circuit alone

$$I_R = \frac{E_R}{R_R + jX_R} = \frac{s \cdot E_{R_0}}{R_R + s \cdot jX_{R_0}}$$

$$I_R = \frac{E_{R_0}}{\frac{R_R}{s} + jX_{R_0}}$$



The rotor circuit can be represented as



So, the induction motor can be represented as

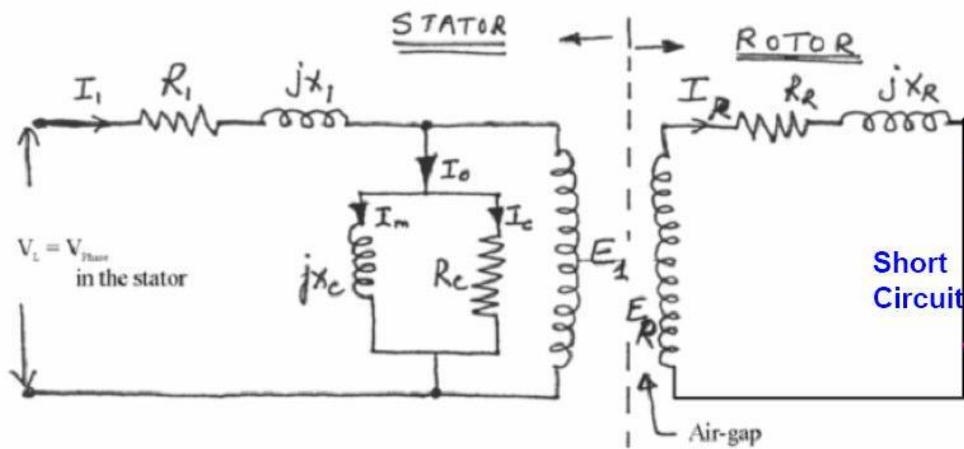


Figure. Equivalent circuit of one phase out of 3 phase of an induction motor

Transformation is done using the effective turns ratio,  $a_{eff}$  for currents.

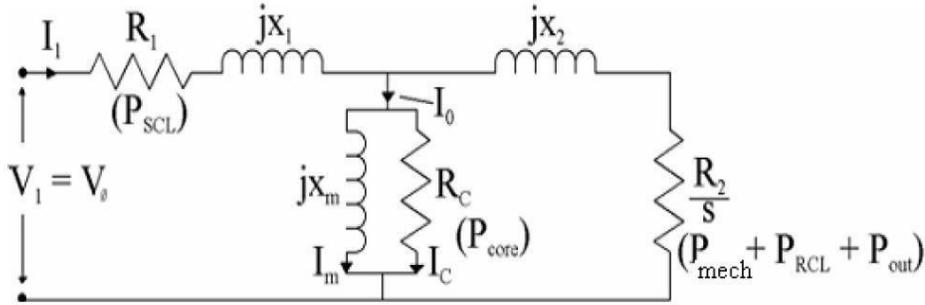
$$I_2 = \frac{I_R}{a_{eff}}$$

Impedance transfer is made using the ratio  $a_{eff}^2$ ; where  $R_2$  and  $X_2$  are transferred values.

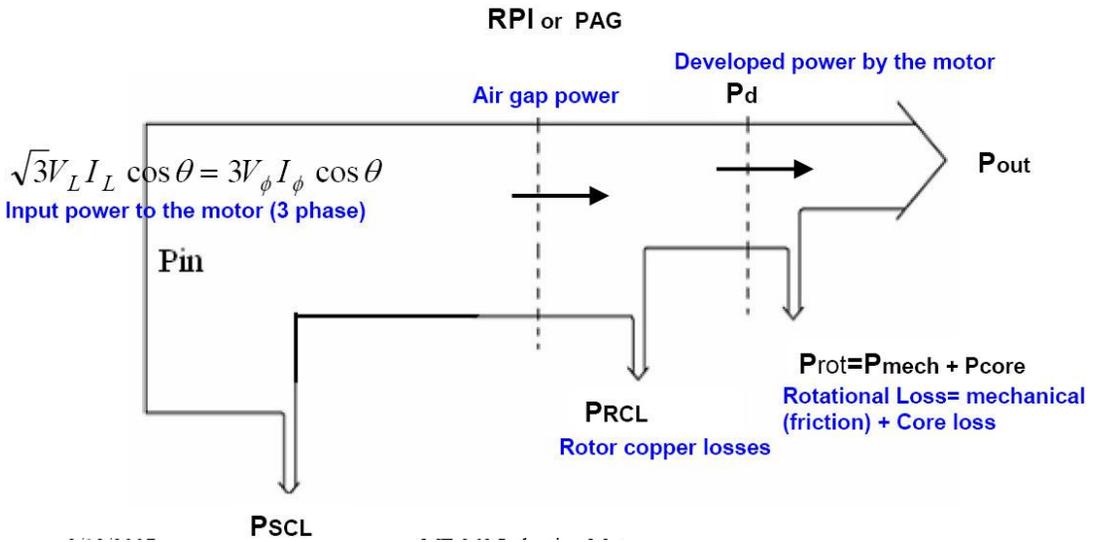
$$R_2 = a_{eff}^2 R_R$$

$$X_2 = a_{eff}^2 X_R$$

Equivalent circuit referred to stator is



**POWER FLOW**



where

$P_{SCL}$  – stator copper losses

$P_{RCL}$  – rotor copper losses

$RPI$  – rotor power input

The concept of the total air gap power can be introduced where:

The mechanical power however is only developed across the new variable resistance, hence  $P_{mech}$  is:

$$\begin{aligned} P_{mech} &= I_2^2 \cdot \frac{R_2}{s} (1-s) \\ &= (1-s) \cdot P_{ag} \\ &= \frac{1-s}{s} \cdot P_2 \end{aligned}$$

As the rotor copper loss is  $P_2 = I_2^2 R_2 = sP_g$  then a ratio of powers can be defined:

$$P_{ag} : P_2 : P_{mech} = 1 : s : (1-s)$$

The motor torque is given by

$$T_{mech} = \frac{P_{mech}}{\omega_{mech}} = \frac{I_2^2 \cdot \frac{R_2}{s} \cdot (1-s)}{\omega_{synch} \cdot (1-s)} = \frac{1}{\omega_{synch}} \cdot I_2^2 \cdot \frac{R_2}{s}$$

The ideal efficiency can be determined by firstly assuming that the power transferred across the air gap equals the input power.

$$\begin{aligned} P_{ag} &= P_{in} \\ P_2 &= s \cdot P_{ag} \\ P_{out} &= P_{mech} = P_{ag} \cdot (1-s) \end{aligned}$$

Therefore efficiency is given by

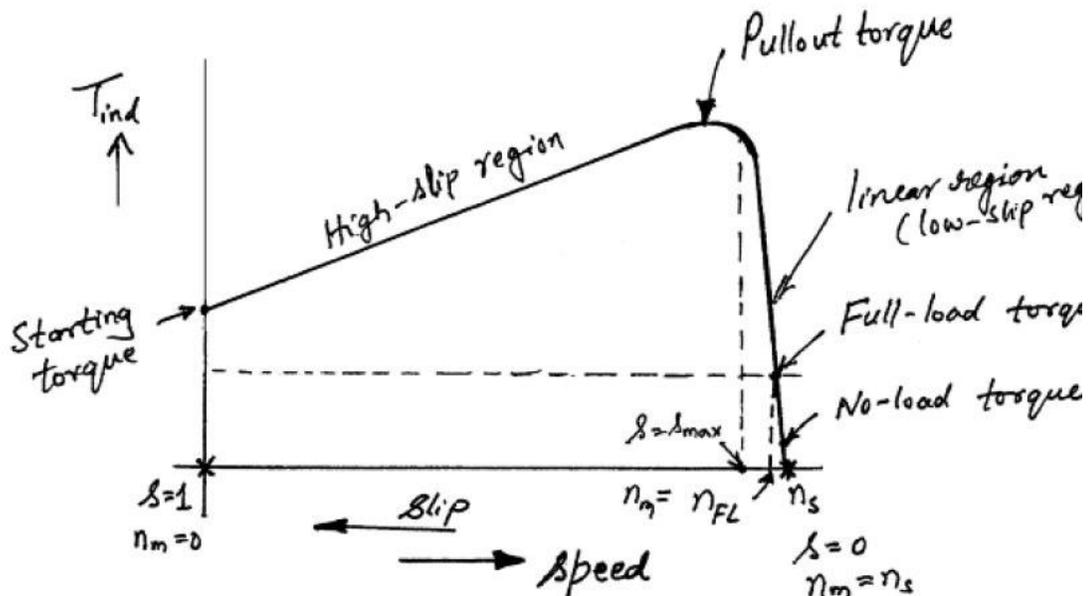
$$Eff_{ideal} = \frac{P_{out}}{P_{in}} = \frac{P_{ag} \cdot (1-s)}{P_{ag}} = (1-s)$$

The efficiency increases as the speed increases, hence an induction machine should always be operated at low values of slip to ensure efficient (and high power factor) operation

## 2.2 TORQUE – SPEED CHARACTERISTICS

For small values of slip  $s$ , the torque is directly proportional to  $s$ .

For large values of slip  $s$ , the torque is inversely proportional to  $s$ .



### Example 2

A 480 V, 50 hp, three phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW and the rotor copper losses are 700 W. The friction loss is 600 W and the core losses are 1800 W, find:

- The air gap power.
- The converted power.
- The output power.
- The efficiency of the motor.

### Solution

$$\begin{aligned}
 \text{a) } P_{in} &= \sqrt{3} V_T I_L \cos(\theta) \\
 P_{in} &= \sqrt{3} (480)(60)(0.85) = 42.4 \text{ kW} \\
 P_{AG} &= P_{in} - P_{SCL} = 42.4 - 2 = 40.4 \text{ kW} \\
 \text{b) } P_d &= P_{AG} - P_{RCL} = 40.4 - 0.7 = 39.7 \text{ kW} \\
 \text{c) } P_{out} &= P_d - P_{rot} = 39.7 - 2.4 = 37.3 \text{ kW} \\
 \text{d) } \eta &= \frac{P_{out}}{P_{in}} = \frac{37.3}{42.4} = 88\%
 \end{aligned}$$

**Example 3**

A 460 V, 25 hp, 60 Hz, four pole, Y-connected induction motor has the following impedances:

$$R_1 = 0.641 \Omega \quad R_2 = 0.332 \Omega$$

$$X_1 = 1.106 \Omega \quad X_2 = 0.464 \Omega \quad X_m = 26.3 \Omega$$

Mechanical loss is 100 W and core loss is 1 kW for a slip = 2.2%, find:

- (a) The speed.
- (b) The stator current.
- (c) Power factor
- (d) The developed and output power
- (e) The developed and output torque
- (f) Efficiency

**Solution:**

$$a) n_s = \frac{120f}{P} = \frac{(120)(60)}{4} = 1800 \text{ rpm}$$

$$n_m = (1-s)n_s = (1-.022)(1800) = 1760 \text{ rpm}$$

$$b) Z_{total} = \left\{ \left( \frac{R_2}{s} + jX_2 \right) \parallel (jX_m) \right\} + (R_1 + jX_1) = 14.0$$

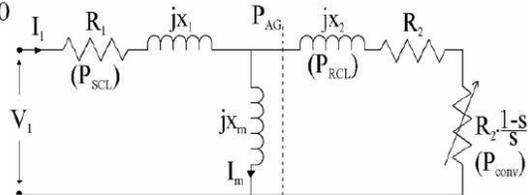
$$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88 \angle -33.6$$

$$c) p.f. = \cos(33.6) = 0.833 \text{ lagging}$$

$$d) P_{in} = \sqrt{3}(480)(18.88)(0.833) = 12.53 \text{ kW}$$

$$P_{SCL} = 3I_1^2 R_1 = 3(18.88)^2 (0.641) = 685 \text{ W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12,530 - 685 = 11.845 \text{ kW}$$



**2.3 STARTING OF 3-PHASE INDUCTION MOTORS**

There are two important factors to be considered in starting of induction motors:

1. The starting current drawn from the supply, and
2. The starting torque.

The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

At synchronous speed,  $s = 0$ , and therefore,  $R_2/s = \infty$ . so  $I_2' = 0$ .

The stator current therefore comprises only the magnetising current i.e.  $I_1 = I_\phi$  and is quite therefore quite small.

At low speeds,  $\frac{R_2'}{s} + jX_2 = \infty$  is small, and therefore  $I_2'$  is quite high and consequently  $I_1$  is quite large.

Actually the typical starting currents for an induction machine are ~ 5 to 8 times the normal running current.

Hence the starting currents should be reduced. The most usual methods of starting 3-phase induction motors are:

### For slip-ring motors

Rotor resistance starting

### For squirrel-cage motors

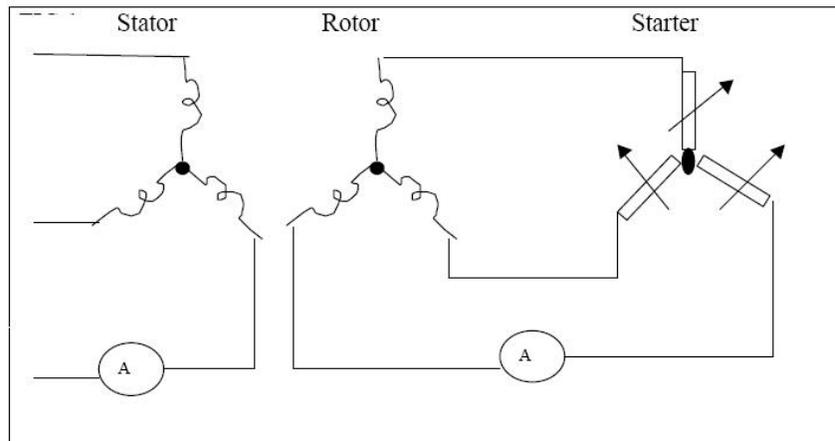
Direct-on -line starting

Star-delta starting

Autotransformer starting.

### 1. Rotor resistance starting

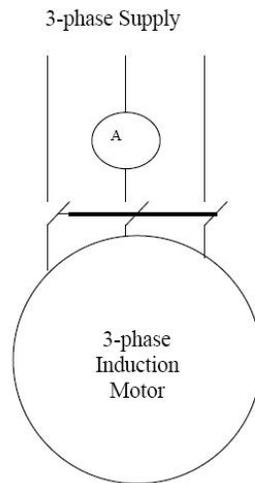
By adding external resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.



### 2. Direct-on-line starting

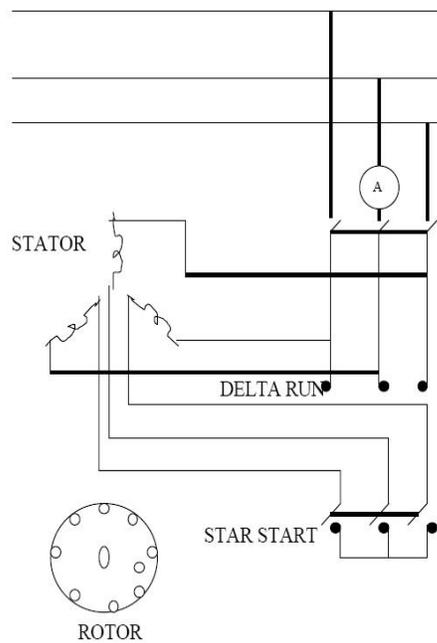
This is the most simple and inexpensive method of starting a squirrel cage induction motor. The motor is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque. To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors.

To decrease the starting current cage motors of medium and larger sizes are started at a reduced supply voltage. The reduced supply voltage starting is applied in the next two methods.



### 3. Star-Delta starting

This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change-over switch.

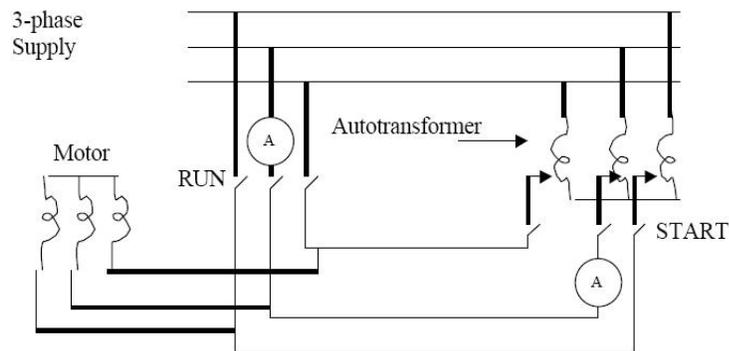


For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation. The phase voltages & the phase currents of the motor in star connection are reduced to  $1/\sqrt{3}$  of the direct-on-line values in delta. The line current is  $1/3$  of the value in delta.

A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to  $1/3$  of its delta value.

#### 4. Auto-transformer starting

This method also reduces the initial voltage applied to the motor and therefore the starting current and torque. The motor, which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped auto-transformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position. The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjusted to the required value, by taking the correct tapping on the autotransformer. This method is more expensive because of the additional autotransformer.



#### 2.4.SPEED CONTROL OF INDUCTION MACHINES

We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque at synchronous speed to the stall torque at a value of slip  $s = \hat{s}$ . Normally  $\hat{s}$  may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite stiff with respect to load changes. The entire speed variation is only in the range  $n_s$  to  $(1 - s)n_s$ ,  $n_s$  being dependent on supply frequency and number of poles.

The foregoing discussion shows that the induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

### 1.Speed control by changing applied voltage

From the torque equation of the induction machine, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in figure below. These curves show that the slip at maximum torque remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

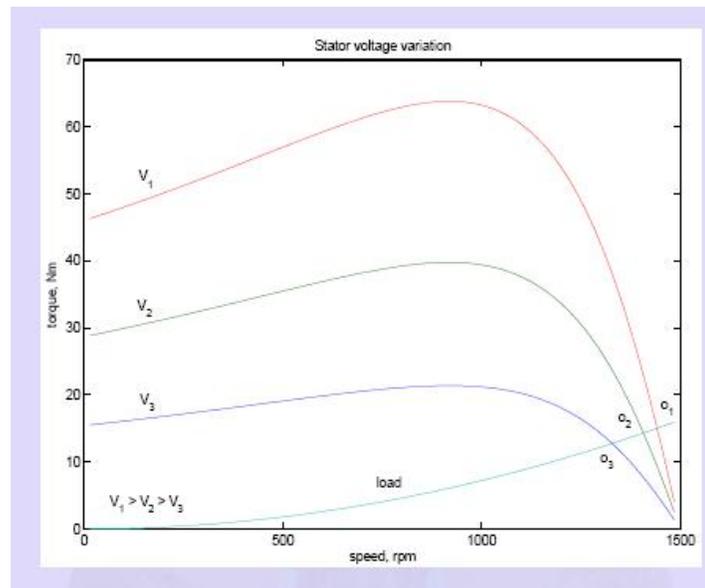


Figure. Speed-torque curves: voltage variation

The figure above also shows a load torque characteristic, one that is typical of a fan type of load. In a fan (blower) type of load, the variation of torque with speed is such that  $T \propto \omega^2$ . Here one can see that it may be possible to run the motor to lower speeds within the range  $n_s$  to  $(1 - s)n_s$ . Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads. One may note that if the applied voltage is reduced, the voltage across the magnetizing branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production, which is primarily the explanation for figure.

If, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such conditions, reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved. Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper. Another use of voltage control is in the so-called 'soft-start' of the machine. This is discussed in the section on starting methods.

## 2. Rotor resistance control

From the expression for the torque of the induction machine, torque is dependent on the rotor resistance. The maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Figure below shows a family of torque-speed characteristic obtained by changing the rotor resistance.

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines,

there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

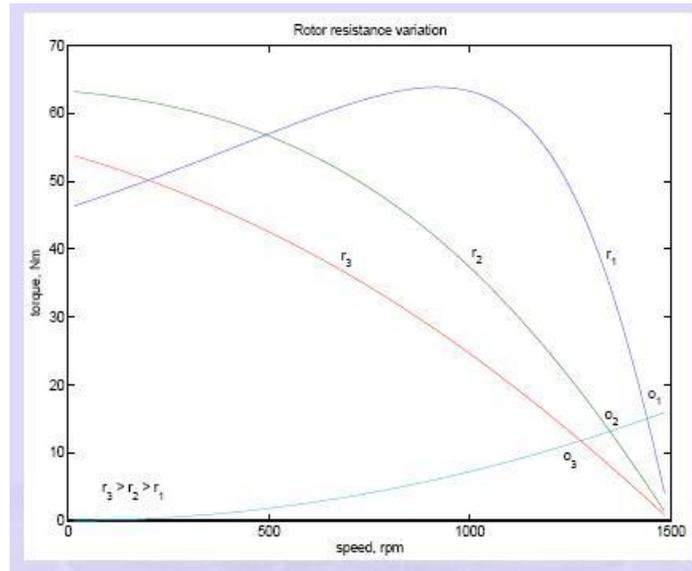


Figure. Speed-torque curves: rotor resistance variation

The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A ‘solid-state’ alternative to a rheostat is a chopper controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine.

### 3. Pole changing schemes

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by  $n_s = f_s/p$  (in rev./s) where  $p$  is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps.

If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four pole faces A, B, C, D as shown in figure below.

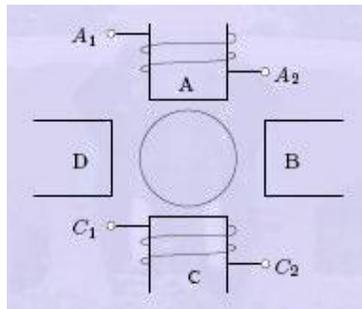
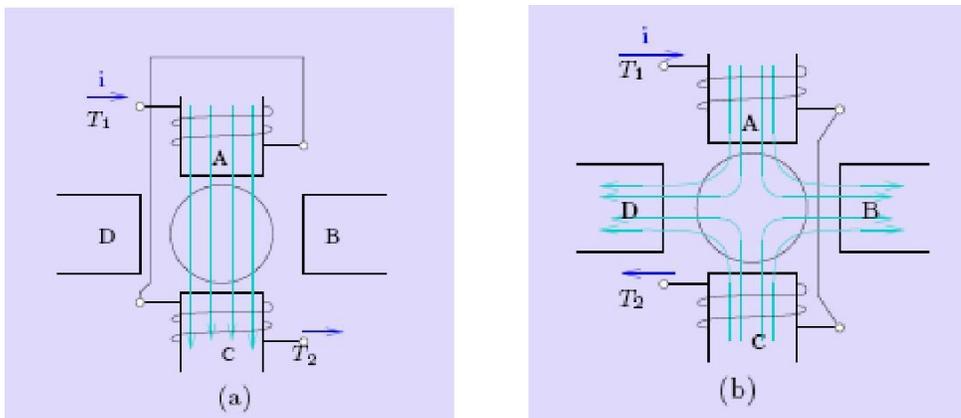


Figure. Pole arrangement

Coils are wound on A & C in the directions shown. The two coils on A & C may be connected in series in two different ways — A<sub>2</sub> may be connected to C<sub>1</sub> or C<sub>2</sub>. A<sub>1</sub> with the other terminal at C then form the terminals of the overall combination. Thus two connections result as shown in figure (a) & (b) below.



Now, for a given direction of current flow at terminal A<sub>1</sub>, say into terminal A<sub>1</sub>, the flux directions within the poles are shown in the figures. In case (a), the flux lines are out of the pole A (seen from the rotor) for and into pole C, thus establishing a two-pole structure. In case (b) however, the flux lines are out of the poles in A & C. The flux lines will be then have to complete the circuit by flowing into the pole structures on the sides. If, when seen from the rotor, the pole emanating flux lines is considered as north pole and the pole into which they enter is termed as south, then the pole configurations produced by these connections is a two-pole arrangement in fig. 31(a) and a four-pole arrangement in fig. 31(b). Thus by changing the terminal connections we get either a two pole air-gap field or a four-pole field. In an induction machine this would correspond to a synchronous speed reduction in half from case (a) to case (b).

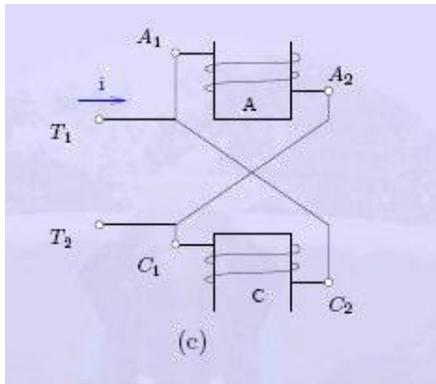


Figure: Pole Changing: Various connections

Further note that irrespective of the connection, the applied voltage is balanced by the series addition of induced emfs in two coils. Therefore the air-gap flux in both cases is the same. Cases (a) and (b) therefore form a pair of constant torque connections.

Consider, on the other hand a connection as shown in the figure(c). The terminals  $T_1$  and  $T_2$  are where the input excitation is given. Note that current direction in the coils now resembles that of case (b), and hence this would result in a four-pole structure. However, in figure(c), there is only one coil induced emf to balance the applied voltage. Therefore flux in case (c) would therefore be halved compared to that of case (b) (or case (a), for that matter). Cases (a) and (c) therefore form a pair of constant horse-power connections. It is important to note that in generating a different pole numbers, the current through one coil (out of two, coil C in this case) is reversed.

#### 4. Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters which convert dc to ac of desired frequency. Depending on the type of control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine.

$$V = 4.44N\phi_m f$$

where  $N$  is the number of the turns per phase,  $\phi_m$  is the peak flux in the air gap and  $f$  is the frequency. Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the

machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque capability.

Actually, it is the voltage across the magnetizing branch of the exact equivalent circuit that must be maintained constant, for it is that which determines the induced emf. Under conditions where the stator voltage drop is negligible compared the applied voltage, the above equation is valid.

In this mode of operation, the voltage across the magnetizing inductance in the 'exact' equivalent circuit reduces in amplitude with reduction in frequency and so does the inductive reactance. This implies that the current through the inductance and the flux in the machine remains constant. The speed torque characteristics at any frequency may be estimated as before. There is one curve for every excitation frequency considered corresponding to every value of synchronous speed. The curves are shown below. It may be seen that the maximum torque remains constant.

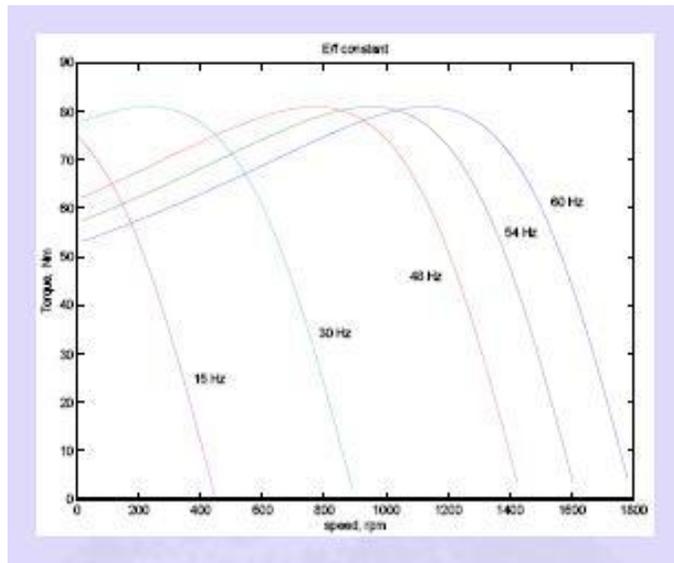


Figure. Torque-speed curves with  $E/f$  held constant

With this kind of control, it is possible to get a good starting torque and steady state performance. However, under dynamic conditions, this control is insufficient. Advanced control techniques such as field- oriented control (vector control) or direct torque control (DTC) are necessary.

## UNIT-III

# CONSTRUCTION, PRINCIPLE OF OPERATION, CHARACTERISTICS & REGULATION OF SYNCHRONOUS GENERATOR

### 3.1.INTRODUCTION

Synchronous machines are principally used as alternating current generators. They supply the electric power used by all sectors of modern society. Synchronous machine is an important electromechanical energy converter. Synchronous generators usually operate in parallel forming a large power system supplying electrical power to consumers or loads. For these applications the synchronous generators are built in large units, their rating ranging from tens to hundreds of Megawatts. These synchronous machines can also be run as synchronous motors.

Synchronous machines are AC machines that have a field circuit supplied by an external DC source. Synchronous machines are having two major parts namely stationary part stator and a rotating field system called rotor.

In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then driven by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

### 3.2.Types of synchronous machines

According to the arrangement of armature and field winding, the synchronous machines are classified as rotating armature type or rotating field type.

In rotating armature type the armature winding is on the rotor and the field winding is on the stator. The generated emf or current is brought to the load via the slip rings. These type of generators are built only in small units. In case of rotating field type generators field windings are on the rotor and the armature windings are on the stator. Here the field current is supplied through a pair of slip rings and the induced emf or current is supplied to the load via the stationary terminals.

Based on the type of the prime movers employed the synchronous generators are classified as

7. Hydrogenerators : The generators which are driven by hydraulic turbines are called hydrogenerators. These are run at lower speeds less than 1000 rpm.

8. Turbogenerators: These are the generators driven by steam turbines. These generators are run at very high speed of 1500rpm or above.
9. Engine driven Generators: These are driven by IC engines. These are run at speed less than 1500 rpm.

### **3.3.Construction of synchronous machines**

3. Salient pole Machines: These type of machines have salient pole or projecting poles with concentrated field windings. This type of construction is for the machines which are driven by hydraulic turbines or Diesel engines.
4. Nonsalient pole or Cylindrical rotor or Round rotor Machines: These machines are having cylindrical smooth rotor construction with distributed field winding in slots. This type of rotor construction is employed for the machine driven by steam turbines.

#### **Stator core:**

The stator is the outer stationary part of the machine, which consists of

3. The outer cylindrical frame called yoke, which is made either of welded sheet steel, cast iron.
4. The magnetic path, which comprises a set of slotted steel laminations called stator core pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, reducing losses and heating. CRGO laminations of 0.5 mm thickness are used to reduce the iron losses.

A set of insulated electrical windings are placed inside the slots of the laminated stator. The cross-sectional area of these windings must be large enough for the power rating of the machine. For a 3-phase generator, 3 sets of windings are required, one for each phase connected in star. Fig. 1 shows one stator lamination of a synchronous generator. In case of generators where the diameter is too large stator lamination can not be punched in on circular piece. In such cases the laminations are punched in segments. A number of segments are assembled together to form one circular laminations. All the laminations are insulated from each other by a thin layer of varnish.

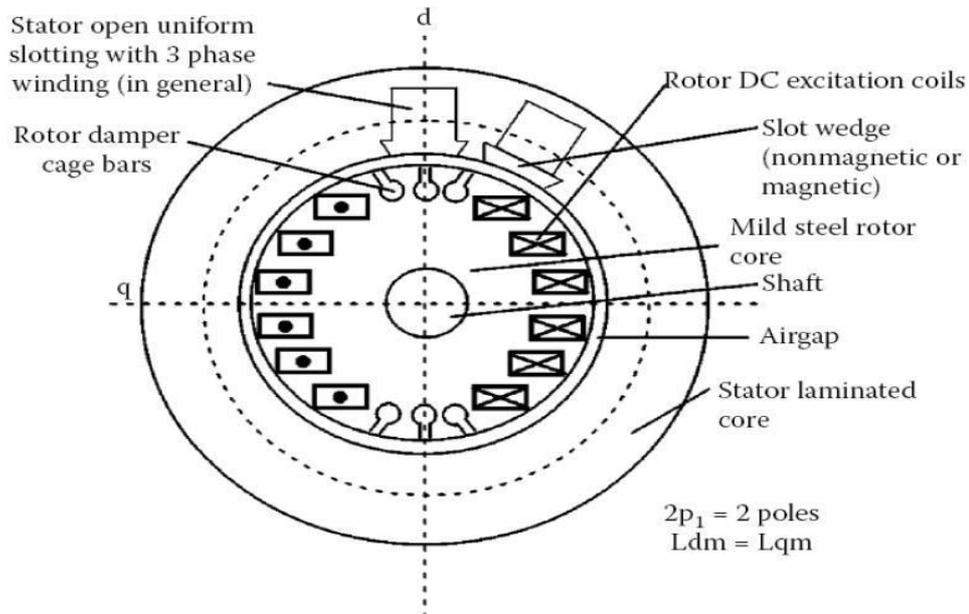


Figure 1.1. Non Salient pole generator

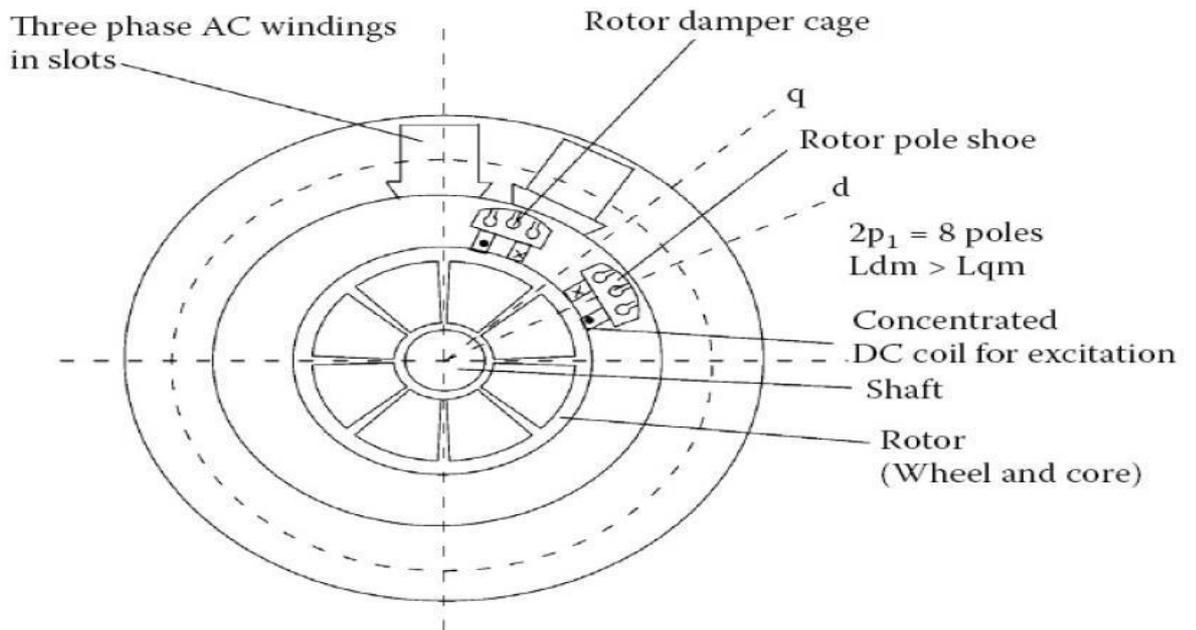


Figure: 1.2. Salient pole generator.

Rotor of water wheel generator consists of salient poles. Poles are built with thin silicon steel

laminations of 0.5mm to 0.8 mm thickness to reduce eddy current laminations. The laminations are clamped by heavy end plates and secured by studs or rivets. For low speed rotors poles have the bolted on construction for the machines with little higher peripheral speed poles have dove tailed construction as shown in Figs. Generally

rectangular or round pole constructions are used for such type of alternators. However the round poles have the advantages over rectangular poles.

Generators driven by water wheel turbines are of either horizontal or vertical shaft type. Generators with fairly higher speeds are built with horizontal shaft and the generators with higher power ratings and low speeds are built with vertical shaft design. Vertical shaft generators are of two types of designs (i) Umbrella type where in the bearing is mounted below the rotor. (ii) Suspended type where in the bearing is mounted above the rotor.

In case of turbo alternator the rotors are manufactured from solid steel forging. The rotor is slotted to accommodate the field winding. Normally two third of the rotor periphery is slotted to accommodate the winding and the remaining one third unslotted portion acts as the pole. Rectangular slots with tapering teeth are milled in the rotor. Generally rectangular aluminum or copper strips are employed for filed windings. The field windings and the overhangs of the field windings are secured in place by steel retaining rings to protect against high centrifugal forces. Hard composition insulation materials are used in the slots which can with stand high forces, stresses and temperatures. Perfect balancing of the rotor is done for such type of rotors.

Damper windings are provided in the pole faces of salient pole alternators. Damper windings are nothing but the copper or aluminium bars housed in the slots of the pole faces. The ends of the damper bars are short circuited at the ends by short circuiting rings similar to end rings as in the case of squirrel cage rotors. These damper windings are serving the function of providing mechanical balance; provide damping effect, reduce the effect of over voltages and damp out hunting in case of alternators. In case of synchronous motors they act as rotor bars and help in self starting of the motor.

### **Relation between Speed and Frequency:**

In the previous course on induction motors it is established that the relation between speed and frequency and number of poles is given by

$$\text{Frequency } f = P \times N / 120 \text{ Hz}$$

**3.4.Windings in Alternators:** In case of three phase alternators the following types of windings are employed.

- Lap winding,
- wave winding and
- Mush winding.

Based on pitch of the coil

- full pitched

short pitched windings

Based on number of layers

- 3. Single layer
- 4. Double layer

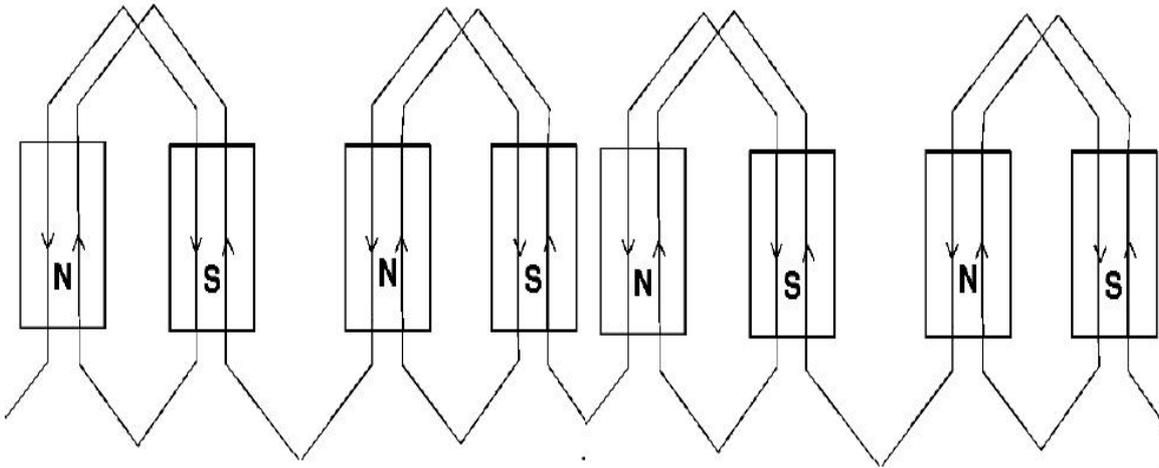


Figure: 1.3. Single layer winding

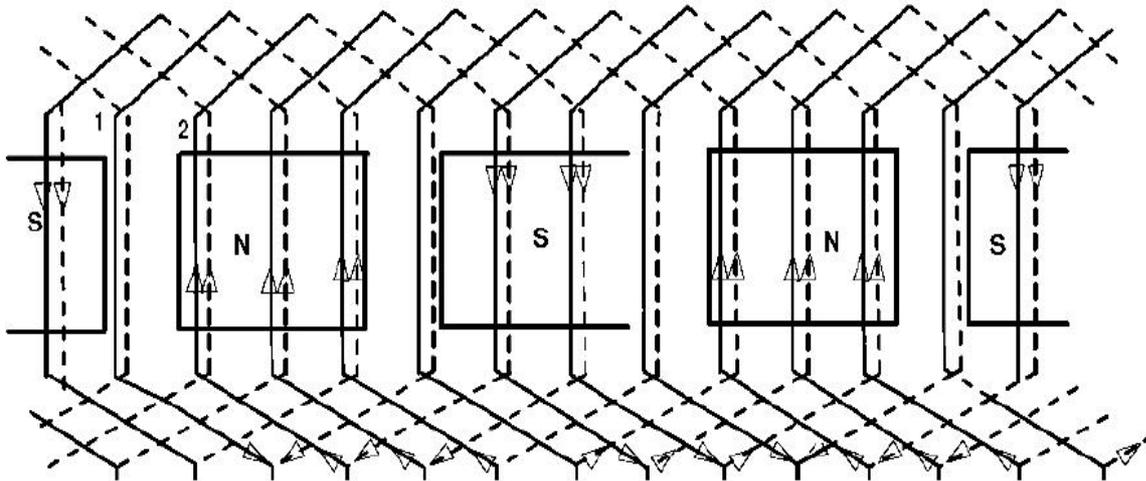


Figure: 1.4. Double layer winding

**3.5.EMF Equation of an alternator:**

Consider the following  $\Phi$  = flux per pole in wb

P = Number of poles

Ns = Synchronous speed in rpm

## ELECTRICAL MACHINES-II

$f$  = frequency of induced emf in Hz

$Z$  = total number of stator conductors

$Z_{ph}$  = conductors per phase connected

in series  $T_{ph}$  = Number of turns per phase

Assuming concentrated winding, considering one conductor placed in a slot

According to Faradays Law electromagnetic induction,

The average value of emf induced per conductor in one revolution

$e_{avg} = \frac{d\phi}{dt}$   $e_{avg}$  = Change of Flux in one revolution/ Time taken for one revolution

Change of Flux in one revolution =  $p \times \phi$

Time taken for one revolution =  $\frac{60}{Ns}$  seconds

Hence  $e_{avg} = \frac{p \times \phi}{\frac{60}{Ns}} = p \times \phi \times \frac{Ns}{60}$

We know  $f = \frac{PNs}{120}$

hence  $\frac{PNs}{60} = 2f$

Hence  $e_{avg} = 2 \phi f$  volts

Hence average emf per turn =  $2 \times 2 \phi f$  volts =  $4 \phi f$  volts

If there are  $T_{ph}$ , number of turns per phase connected in series, then average emf induced in

$T_{ph}$  turns is  $E_{ph, avg} = T_{ph} \times e_{avg} = 4 \phi f T_{ph}$  volts

Hence RMS value of emf induced  $E = 1.11 \times E_{ph, avg}$

$$= 1.11 \times 4 \phi f T_{ph}$$

$$\text{volts} = 4.44 \phi f T_{ph}$$

$$T_{ph} \text{ volts}$$

This is the general emf equation for the machine having concentrated and full pitched winding. In practice, alternators will have short pitched winding and hence coil span will not be  $180^\circ$ , but on or two slots short than the full pitch.

### **Pitch Factor:**

Pitch factor  $K_p = \frac{\text{emf induced in a short pitched coil}}{\text{emf induced in a full pitched coil}} =$

$$\frac{(2E \cos \alpha/2)}{2E}$$

$$K_p = \cos \alpha/2$$

where  $\alpha$  is called chording angle.

**Distribution Factor:** Even though we assumed concentrated winding in deriving emf equation, in practice an attempt is made to distribute the winding in all the slots coming under a pole. Such a winding is called distributed winding.

In concentrated winding the emf induced in all the coil sides will be same in

ELECTRICAL MACHINES-II

magnitude and in phase with each other. In case of distributed winding the magnitude of emf will be same but the emfs induced in each coil side will not be in phase with each other as they are distributed in the slots under a pole. Hence the total emf will not be same as that in concentrated winding but will be equal to the vector sum of the emfs induced. Hence it will be less than that in the concentrated winding. Now the factor by which the emf induced in a distributed winding gets reduced is called distribution factor and defined as the ratio of emf induced in a distributed winding to emf induced in a concentrated winding.

Distribution factor  $K_d = \frac{\text{emf induced in a distributed winding}}{\text{emf induced in a concentrated winding}} = \frac{\text{vector sum of the emf}}{\text{arithmetic sum of the emf}}$  Let

$E =$  emf induced per coil side

$m =$  number of slots per pole per

phase,  $n =$  number of slots per pole

$\beta =$  slot angle  $= 180/n$

The emf induced in concentrated winding with  $m$  slots per pole per phase  $= mE$  volts.

Fig below shows the method of calculating the vector sum of the voltages in a distributed winding having a mutual phase difference of  $\beta$ . When  $m$  is large curve ACEN will form the arc of a circle of radius  $r$ .

From the figure below  $AC = 2 \times r \times \sin \beta/2$

Hence arithmetic sum  $= m \times 2r \sin \beta/2$

Now the vector sum of the emfs is AN as shown in figure below  $= 2 \times r \times \sin m\beta/2$

Hence the distribution factor  $K_d = \frac{\text{vector sum of the emf}}{\text{arithmetic sum of the emf}} = \frac{(2r \sin m\beta/2)}{(m \times 2r \sin \beta/2)}$

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

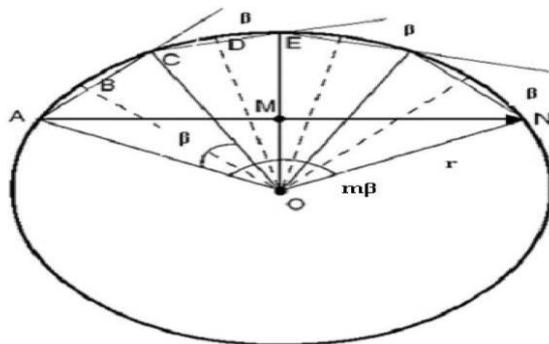


Figure: 1.5. Calculation of vector sum

In practical machines the windings will be generally short pitched and distributed over the periphery of the machine. Hence in deducing the emf equation both pitch factor and distribution factor has to be considered. Hence the general emf equation including pitch factor and distribution factor can be given as EMF induced per phase =  $4.44 f T_{ph} \times K_p K_d$  volts  
 $E_{ph} = 4.44 K_p K_d f T_{ph}$  volts

Hence the line Voltage  $E_L = \sqrt{3} \times \text{phase voltage} = \sqrt{3} E_{ph}$

**Harmonics:** When the uniformly sinusoidal distributed air gap flux is cut by either the stationary or rotating armature sinusoidal emf is induced in the alternator. Hence the nature of the waveform of induced emf and current is sinusoidal. But when the alternator is loaded waveform will not continue to be sinusoidal or becomes non sinusoidal. Such non sinusoidal wave form is called complex wave form. By using Fourier series representation it is possible to represent complex non sinusoidal waveform in terms of series of sinusoidal components called harmonics, whose frequencies are integral multiples of fundamental wave. The fundamental wave form is one which is having the frequency same as that of complex wave. The waveform, which is of the frequency twice that of the fundamental is called second harmonic. The one which is having the frequency three times that of the fundamental is called third harmonic and so on. These harmonic components can be represented as follows.

Fundamental:

$$e_1 = E_{m1} \sin(\omega t \pm \theta_1)$$

$$\text{Harmonic } e_2 = E_{m2} \sin(2\omega t \pm$$

$$\theta_2)$$

$$\text{3rd Harmonic } e_3 = E_{m3} \sin(3\omega t \pm \theta_3)$$

$$\text{5th Harmonic } e_5 = E_{m5} \sin(5\omega t \pm \theta_5) \text{ etc.}$$

In case of alternators as the field system and the stator coils are symmetrical the induced emf will also be symmetrical and hence the generated emf in an alternator will not contain any even harmonics.

**3.6.Slot Harmonics:** As the armature or stator of an alternator is slotted, some harmonics are induced into the emf which is called slot harmonics. The presence of slot in the stator makes the air gap reluctance at the surface of the stator non uniform. Since in case of alternators the poles are moving or there is a relative motion between the stator and rotor, the slots and the teeth alternately occupy any point in the air gap. Due to this the reluctance or the air gap will be continuously varying. Due to this variation of reluctance ripples will be formed in the air gap between the rotor and stator slots and teeth. This ripple formed in the air gap will induce ripple emf called slot harmonics.

**Minimization of Harmonics:** To minimize the harmonics in the induced waveforms following methods are employed:

Distribution of stator winding.

Short Chording

Fractional slot winding

Skewing

Larger air gap length.

### **Effect of Harmonics on induced emf:**

The harmonics will affect both pitch factor and distribution factor and hence the induced emf. In a well designed alternator the air gap flux density distribution will be symmetrical and hence can be represented in Fourier series as follows.

$$B = B_{m1} \sin \omega t + B_{m3} \sin 3\omega t + B_{m5} \sin 5\omega t + \dots$$

The emf induced by the above flux density distribution is given by

$$e = E_{m1} \sin \omega t + E_{m3} \sin 3\omega t + E_{m5} \sin 5\omega t + \dots$$

The RMS value of the resultant voltage induced can be given as

$$E_{ph} = \sqrt{[(E_1)^2 + (E_3)^2 + (E_5)^2 + \dots + (E_n)^2]}$$

$$\text{And line voltage } E_{Line} = \sqrt{3} \times E_{ph}$$

### **Effect of Harmonics of pitch and distribution Factor:**

The pitch factor is given by  $K_p = \cos \alpha/2$ , where  $\alpha$  is the chording angle.

For any harmonic say  $n^{\text{th}}$  harmonic the pitch factor is given by  $K_{pn} = \cos n\alpha/2$

The distribution factor is given by  $K_d = (\sin m\beta/2) / (m \sin \beta/2)$

For any harmonic say  $n^{\text{th}}$  harmonic the distribution factor is given by  $K_{dn} = (\sin m n\beta/2) / (m \sin n\beta/2)$

### **Operation of Alternators:**

Similar to the case of DC generator, the behavior of a Synchronous generator connected to an external load is different than that at no-load. In order to understand the performance of the Synchronous generator when it is loaded, consider the flux distributions in the machine when the armature also carries a current. Unlike in the DC machine in alternators the emf peak and the current peak will not occur in the same coil due to the effect of the power factor of the load. The current and the induced emf will be at their peaks in the same coil only for upf loads. For zero power factor lagging loads, the current reaches its peak in a coil which falls behind that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. Likewise for zero power factor leading loads, the current reaches its peak in a coil which is ahead of that coil wherein the induced emf is at its peak by 90

electrical degrees or half a pole-pitch. For simplicity, assume the resistance and leakage reactance of the stator windings to be negligible. Also assume the magnetic circuit to be linear i.e. the flux in the magnetic circuit is deemed to be proportional to the resultant ampere-turns - in other words the machine is operating in the linear portion of the magnetization characteristics. Thus the emf induced is the same as the terminal voltage, and the phase-angle between current and emf is determined only by the power factor (pf) of the external load connected to the synchronous generator.

### 3.7. Armature Reaction:

#### Magnetic fluxes in alternators

There are three main fluxes associated with an alternator:

Main useful flux linked with both field & armature winding.

Leakage flux linked only with armature winding.

Leakage flux linked only with field winding.

The useful flux which links with both windings is due to combined mmf of the armature winding and field winding. When the armature winding of an alternator carries current then an mmf sets in armature. This armature mmf reacts with field mmf producing the resultant flux, which differs from flux of field winding alone. The effect of armature reaction depends on nature of load (power factor of load). At no load condition, the armature has no reaction due to absence of armature flux. When armature delivers current at unity power factor load, then the resultant flux is displaced along the air gap towards the trailing pole tip. Under this condition, armature reaction has distorting effect on mmf wave as shown in Figure. At zero lagging power factor loads the armature current is lagging by  $90^\circ$  with armature voltage. Under this condition, the position of armature conductor when inducing maximum emf is the centre line of field mmf. Since there is no distortion but the two mmf are in opposition, the armature reaction is now purely demagnetizing as shown in Figure. Now at zero power factors leading, the armature current leads armature voltage by  $90^\circ$ . Under this condition, the mmf of armature as well as the field winding is in same phase and additive. The armature mmf has magnetizing effect due to leading armature current as shown in Figure.

#### (a) Unity Power Factor

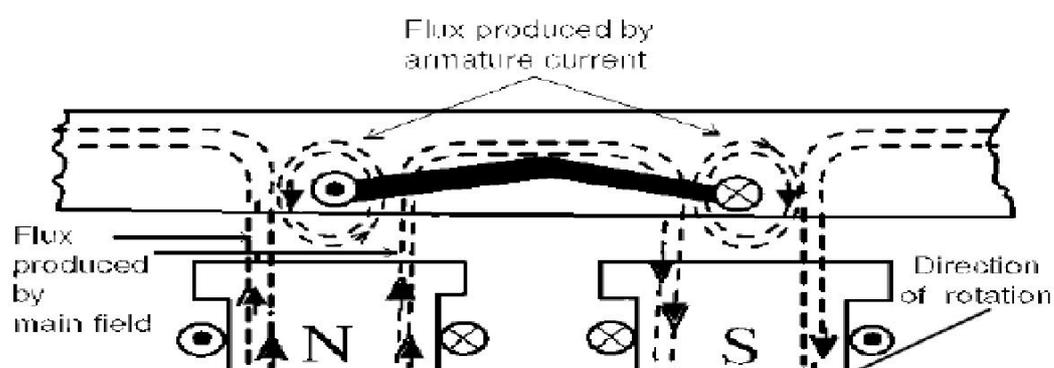


Figure: 1.6. Distorting effect of armature reaction

(b) Zero Power Factor Lagging

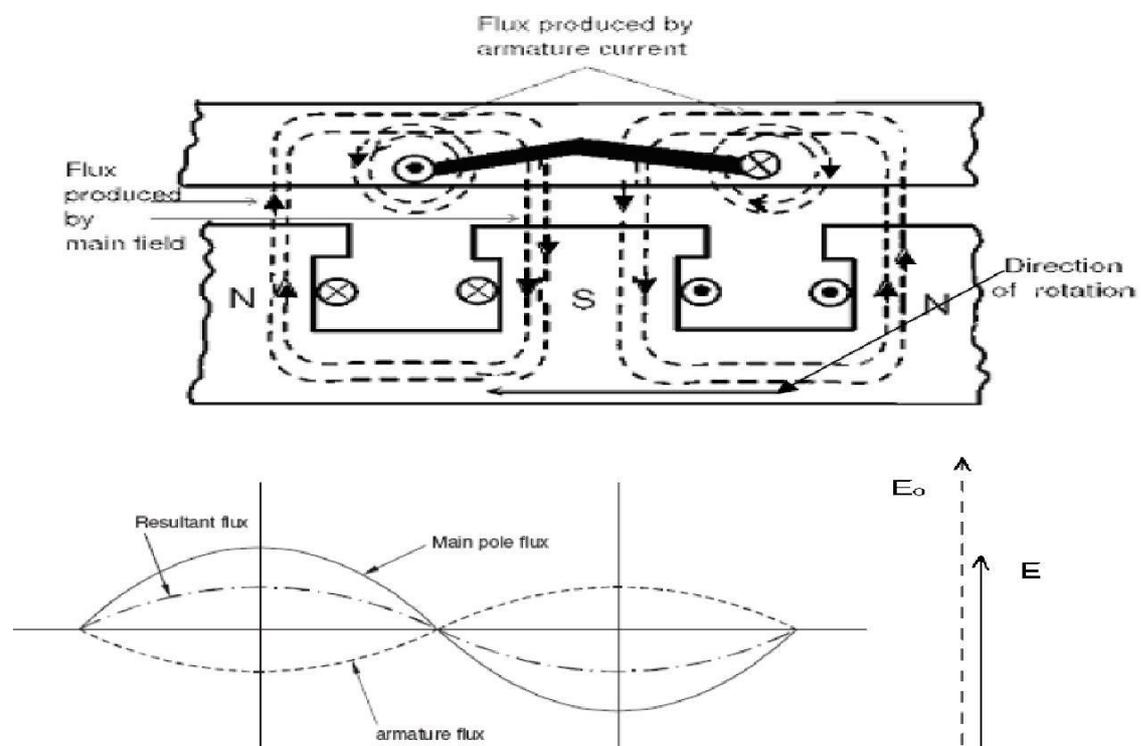


Figure 1.7. Demagnetizing effect of armature reaction

(c) Zero Power Factor Leading

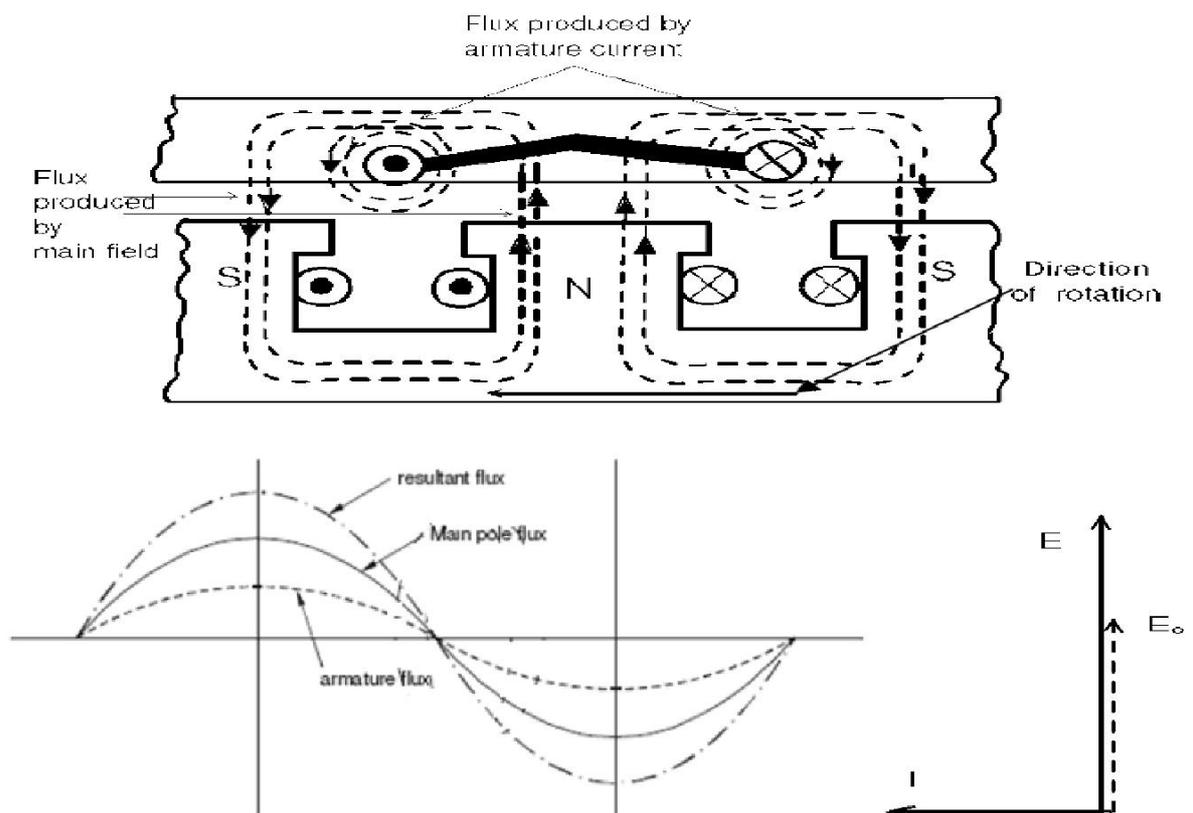


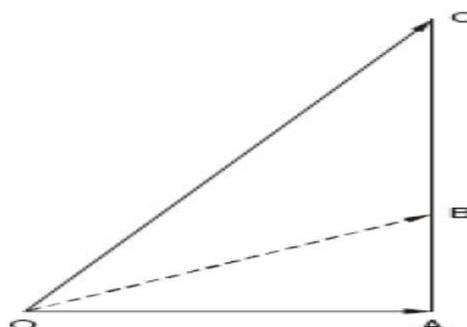
Figure 1.8. Magnetizing effect of armature reaction

When the rotor is run, a voltage  $E$  is induced in the stator windings. If a load is connected to the terminals of the generator, a current flows. The 3-phase stator current flow will produce a magnetic field of its own. This stator magnetic field will distort the original rotor magnetic field, changing the resulting phase voltage. This effect is called armature reaction because the armature (stator) current affects the magnetic field.

From the phasor diagrams of the armature reaction it can be seen that  $E_0$  is the emf induced under no load condition and  $E$  can be considered as the emf under loaded condition. It can also be understood that the  $E_0$  is the emf induced due to the field winding acting alone and  $E$  is the emf induced when both field winding and stator winding are acting in combination. Hence emf  $E$  can be considered as sum of  $E_0$  and another fictitious emf  $E_a$  proportional to the stator current. From the figures it can be seen that the emf  $E_a$  is always in quadrature with current. This resembles the emf induced in an inductive reactance. Hence the effect of armature reaction is exactly same as if the stator has an additional reactance  $x_a = E_a/I$ . This is called the armature reaction reactance. The leakage reactance is the true reactance and the armature reaction reactance is a fictitious reactance.

### 3.8. Synchronous Reactance and Synchronous Impedance

The synchronous reactance is an equivalent reactance the effects of which are supposed to reproduce the combined effects of both the armature leakage reactance and the armature reaction. The alternator is supposed to have no armature reaction at all, but is supposed to possess an armature reactance in excess of its true leakage reactance. When the synchronous reactance is combined vectorially with the armature resistance, a quantity called the synchronous impedance is obtained as shown in figure.



$OA =$  Armature Resistance

$AB =$  Leakage Reactance

$BC =$  Equivalent Reactance of Armature

Reaction  $AC =$  Synchronous Reactance

$OC =$  Synchronous Impedance

The armature winding has one more reactance called armature reaction reactance in addition to leakage reactance and resistance. Considering all the three parameters the equivalent circuit of a synchronous generator can be written as shown below. The sum of leakage reactance and armature reaction reactance is called synchronous reactance  $X_s$ . Under this condition impedance of the armature winding is called the synchronous impedance  $Z_s$ .

Hence synchronous reactance  $\mathbf{X_s = X_l + X_a}$

per phase and synchronous impedance  $\mathbf{Z_s =}$

$\mathbf{R_a + j X_s}$  per phase

As the armature reaction reactance is dependent on armature current so is synchronous reactance and hence synchronous impedance is dependent on armature current or load current.

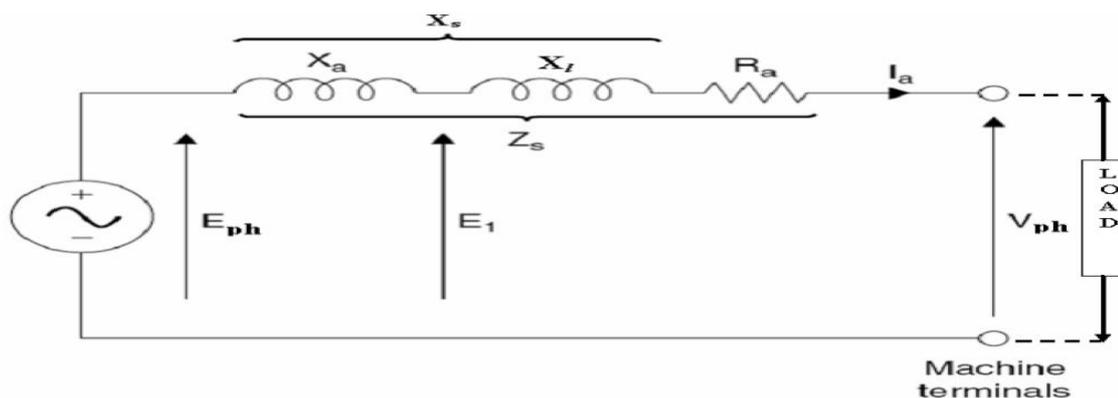


Figure: 1.9. Equivalent circuit of alternator

**3.9. Phasor diagram**

In the phasor diagrams E is the induced emf /phase =  $E_{ph}$  and V is the terminal voltage /phase =  $V_{ph}$ . From each of the phasor diagrams the expression for the induced emf  $E_{ph}$  can be expressed in terms of  $V_{ph}$ , armature current, resistance, reactances and impedance of the machine as follows.

1. Unity power factor load

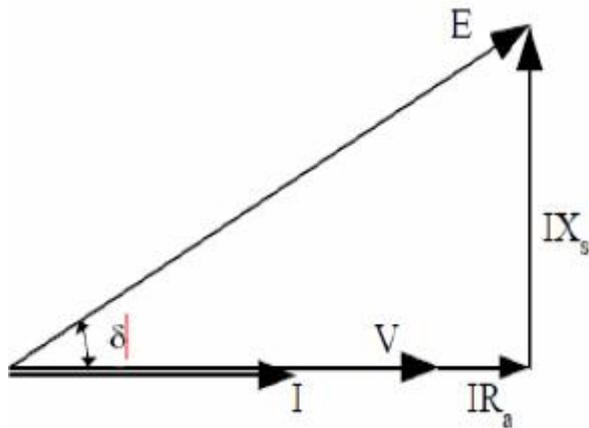


Figure: 1.10. Phasor diagram at Unity power factor load

Under unity power factor load:  $E_{ph} = (V + IR_a) + j (IX_S)$

$$E_{ph} = \sqrt{ (V + IR_a)^2 + (IX_S)^2 }$$

1. Zero power factor lagging

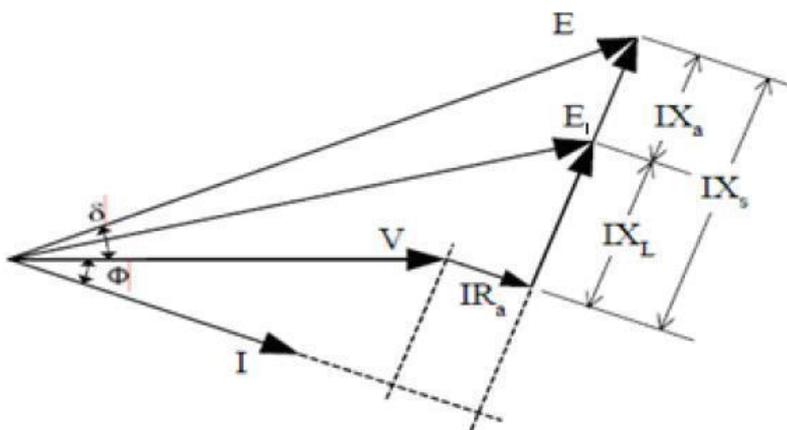


Figure: 1.11. Phasor diagram at zero power factor lagging

Under zero power factor lagging:  $E_{ph} = V + (IR_a + j IX_S) = V + I(R_a + j X_S)$

The above expression can also be written as  $E_{ph} = \sqrt{[(V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2]}$

### 5. Zero power factor leading

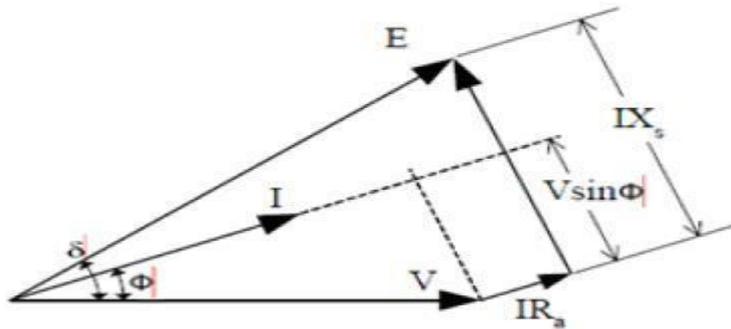


Figure: 1.12. Phasor diagram at zero power factor leading.

## 3.10. REGULATION OF SYNCHRONOUS GENERATOR

### Voltage Regulation

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the load on the machine starts increasing and hence it will always be different than the induced emf. Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation. Or The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage. Hence regulation can be expressed as

$$\% \text{ Regulation} = (E_{ph} - V_{ph} / V_{ph}) \times 100$$

where  $E_{ph}$  = induced emf /phase,  $V_{ph}$  = rated terminal voltage/phase

Methods of finding Voltage Regulation: The voltage regulation of an alternator can be determined by different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it cannot be determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

## ELECTRICAL MACHINES-II

1. Direct loading
2. EMF method or Synchronous impedance method
3. MMF method or Ampere turns method
4. ASA modified MMF method
5. ZPF method or Potier triangle method

All the above methods other than direct loading are valid for non salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

**3.11.EMF method:** This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following informations are to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

### OC & SC test on alternator

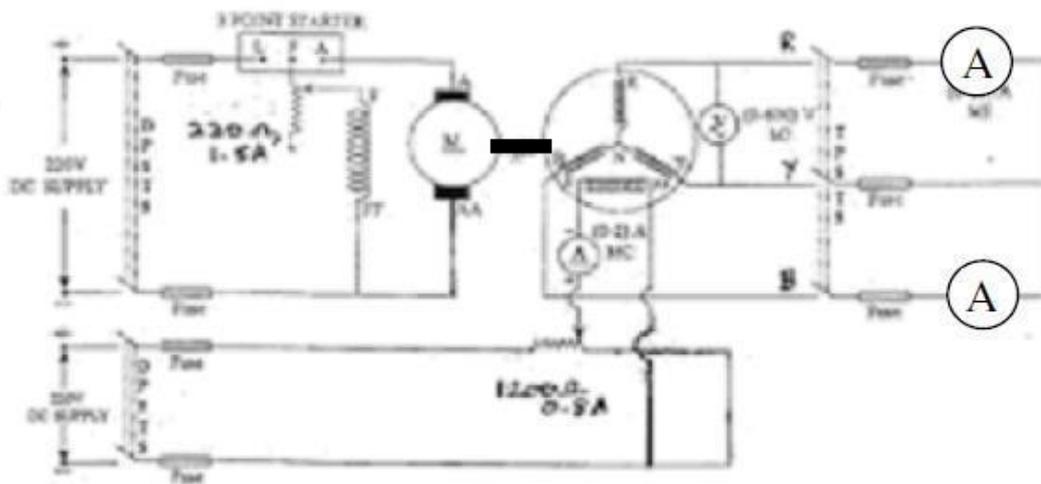


Figure: 2.1. OC & SC test on alternator

### Open Circuit Characteristic (O.C.C.)

The open-circuit characteristic or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator. Indeed, in large turbo-alternators, where the air gap is relatively long, the curve shows a gradual bend. It is determined by inserting resistance in the field circuit and measuring corresponding value of terminal voltage and field current.

Two voltmeters are connected across the armature terminals. The machine is run at rated speed and field current is increased gradually to  $I_{f1}$  till armature voltage reaches rated value or even 25% more than the rated voltage. Figure 32 illustrates a typical circuit for OC and SC test and figure 33 illustrates OC and SC curve. The major portion of the exciting ampere-turns is required to force the flux across the air gap, the reluctance of which is assumed to be constant. A straight line called the air gap line can therefore be drawn as shown, dividing the excitation for any voltage into two portions, (a) that required to force the flux across the air gap, and (b) that required to force it through the remainder of the magnetic circuit. The shorter the air gap, the steeper is the air gap line.

Procedure to conduct OC test:

1. Start the prime mover and adjust the speed to the synchronous speed of the alternator.
2. Keep the field circuit rheostat in cut in position and switch on DC supply.
3. Keep the TPST switch of the stator circuit in open position.
4. Vary the field current from minimum in steps and take the readings of field current and stator terminal voltage, till the voltage read by the voltmeter reaches up to 110% of rated voltage. Reduce the field current and stop the machine. Plot of terminal voltage/ phase vs field current gives the OC curve.

### **Short Circuit Characteristic (S.C.C.)**

The short-circuit characteristic, as its name implies, refers to the behaviour of the alternator when its armature is short-circuited. In a single-phase machine the armature terminals are short-circuited through an ammeter, but in a three-phase machine all three phases must be short-circuited. An ammeter is connected in series with each armature terminal, the three remaining ammeter terminals being short-circuited. The machine is run at rated speed and field current is increased gradually to  $I_{f2}$  till armature current reaches rated value. The armature short-circuit current and the field current are found to be proportional to each other over a wide range, as shown in Figure 33, so that the short-circuit characteristic is a straight line. Under short-circuit conditions the armature current is almost  $90^\circ$  out of phase with the voltage, and the armature mmf has a direct demagnetizing action on the field. The resultant ampere – turns inducing the armature emf are, therefore, very small and is equal to the difference between the field and the armature ampere – turns. This results in low mmf in the magnetic circuit, which remains in unsaturated condition and hence the small value of induced emf increases linearly with field current. This small induced armature emf is equal to the voltage drop in the winding itself, since the terminal voltage is zero by assumption. It is the voltage required to circulate the short-circuit current through the armature windings. The armature resistance is usually small compared with the reactance.

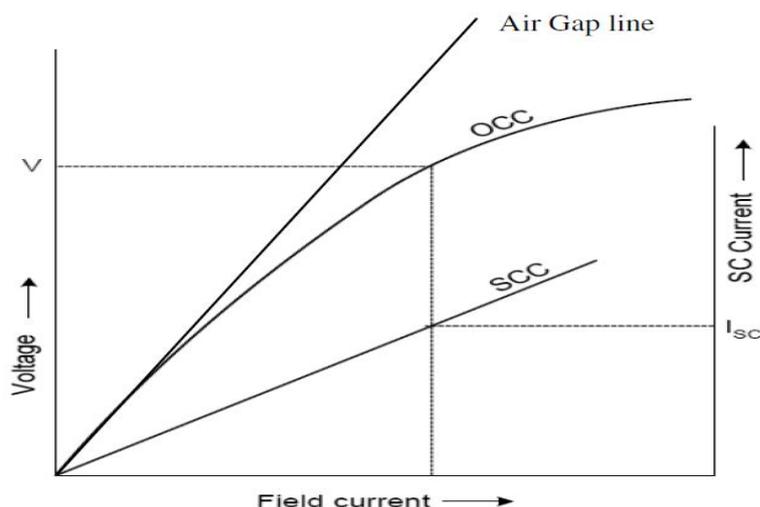


Figure: 2.2 OCC &amp; SCC of an alternator

### Short-Circuit Ratio:

The short-circuit ratio is defined as the ratio of the field current required to produce rated volts on open circuit to field current required to circulate full-load current with the armature short-circuited.

Short-circuit ratio =  $I_{f1}/I_{f2}$

### Determination of synchronous impedance $Z_s$ :

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated from the oc and sc characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

synchronous impedance  $Z_s = (\text{open circuit voltage per phase})/(\text{short circuit current per phase})$   
for same  $I_f$

Hence  $Z_s = (V_{oc}) / (I_{sc})$  for same  $I_f$

From figure 33 synchronous impedance  $Z_s = V/I_{sc}$

Armature resistance  $R_a$  of the stator can be measured using Voltmeter – Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.

$Z_s \sqrt{(R_a)^2 + (X_s)^2}$  and Synchronous reactance  $X_s = \sqrt{(Z_s)^2 - (R_a)^2}$

Hence induced emf per phase can be found as  $E_{ph} = \sqrt{[ (V \cos + IR_a)^2 + (V \sin \pm IX_s)^2 ]}$   
 where  $V$  = phase voltage per phase =  $V_{ph}$  ,  $I$  = load current per phase in the above expression  
 in second term + sign is for lagging pwr factor ans – sign is for leading power factor.

$$\% \text{ Regulation} = [(E_{ph} - V_{ph} / V_{ph} )] \times 100$$

where  $E_{ph}$  = induced emf /phase,  $V_{ph}$  = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence this method is called pessimistic method. The complete phasor diagram for the emf method is shown in figure

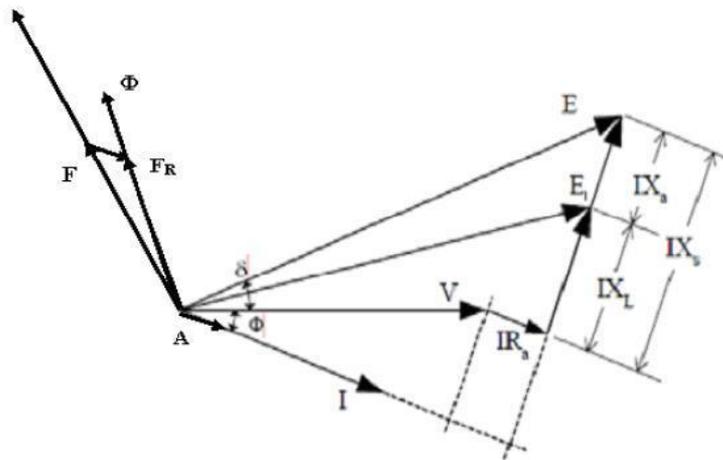


Figure: 2.3. Phasor diagram of alternator.

### 3.12.MMF method

This method is also known as amp - turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence

ELECTRICAL MACHINES-II

called mmf method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Figure 35 shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. The details are shown in figure 36. Using the details it is possible to determine the regulation at different power factors

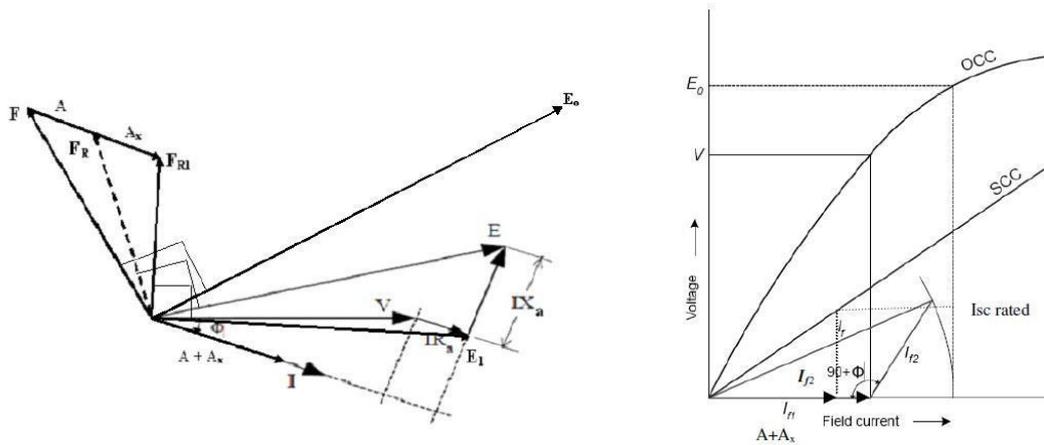


Figure: 2.4. Phasor diagram for MMF method and characteristics.

From the phasor diagram it can be seen that the mmf required to produce the emf  $E_1 = (V + IR_a)$  is  $F_{R1}$ . In large machines resistance drop may be neglected.

The mmf required to overcome the reactance drops is  $(A + A_x)$  as shown in phasor diagram. The mmf  $(A + A_x)$  can be found from SC characteristic as under SC condition both reactance drops will be present. Following procedure can be used for determination of regulation by mmf method.

5. By conducting OC and SC test plot OCC and SCC as shown in figure 36.
6. From the OCC find the field current  $I_{f1}$  required to produce the voltage,  $E_1 = (V + IR_a)$ .
7. From SCC find the magnitude of field current  $I_{f2}$  ( $\approx A + A_x$ ) to produce the required armature current.  $A + A_x$  can also be found from ZPF characteristics.
8. Draw  $I_{f2}$  at angle  $(90^\circ + \Phi)$  from  $I_{f1}$ , where  $\Phi$  is the phase angle of current w. r. t voltage. If current is leading, take the angle of  $I_{f2}$  as  $(90^\circ - \Phi)$  as shown in figure 36.
9. Determine the resultant field current,  $I_f$  and mark its magnitude on the field current axis.
10. From OCC. find the voltage corresponding to  $I_f$ , which will be  $E_0$  and hence find the Regulation.

Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

### 3.13 ASA Modified MMF Method

Because of the unrealistic assumption of unsaturated magnetic circuit neither the emf method nor the mmf method are giving the realistic value of regulation. In spite of these shortcomings these methods are being used because of their simplicity. Hence ASA has modified mmf method for calculation of regulation. With reference to the phasor diagram of mmf method it can be seen that  $F = F_{R1} - (A + A_x)$ . In the mmf method the total mmf  $F$  computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount  $F_{F2}$  which can be computed from occ, scc and air gap lines as explained below referring to figure

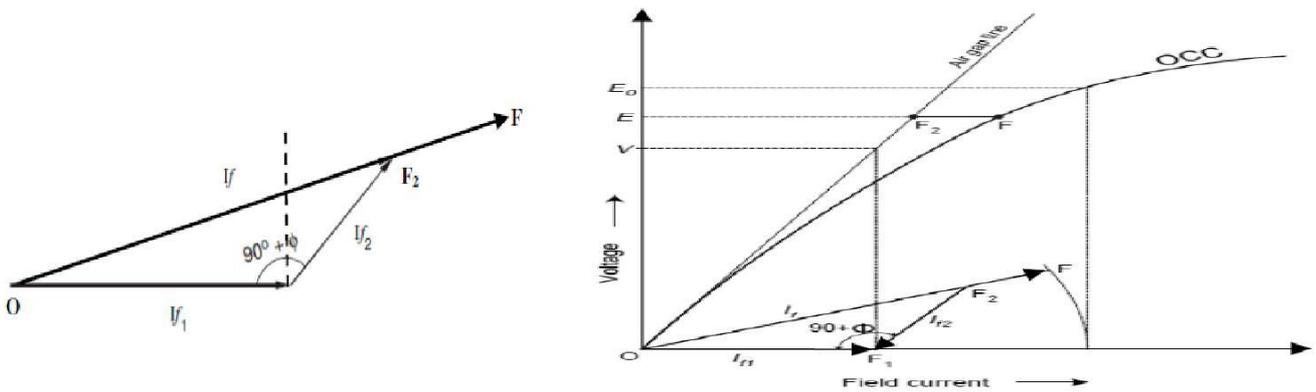


Figure: 2.5. Phasor diagram for ASA method and characteristics

$I_{f1}$  is the field current required to induce the rated voltage on open circuit. Draw  $I_{f2}$  with length equal to field current required to circulate rated current during short circuit condition at an angle  $(90^\circ + \Phi)$  from  $I_{f1}$ . The resultant of  $I_{f1}$  and  $I_{f2}$  gives  $I_f$  (OF2 in figure). Extend OF2 upto F so that F2F accounts for the additional field current required for accounting the effect of partial saturation of magnetic circuit. F2F is found for voltage E (refer to phasor diagram of mmf method) as shown in figure 41. Project total field current OF to the field current axis and find corresponding voltage  $E_0$  using OCC. Hence regulation can be found by ASA method which is more realistic.

### Zero Power Factor ( ZPF) method Potier Triangle Method

During the operation of the alternator, resistance voltage drop  $I_a R_a$  and armature leakage reactance drop  $I_a X_L$  are actually emf quantities and the armature reaction reactance is a mmf quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. As explained earlier oc and sc tests are conducted and OCC and SCC are drawn. ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like OCC but shifted by a factor  $I X_L$  vertically and horizontally by armature reaction mmf as shown below in figure. Following are the steps to draw ZPF characteristics.

By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop  $IXL$  and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from  $V$ ,  $IRa$ ,  $IXL$  and  $\Phi$ . Use the expression  $E = \sqrt{(V \cos\Phi + IRa)^2 + (V \sin\Phi + IXL)^2}$  to compute E. Find field current corresponding to E. Draw

FG with magnitude equal to BE at angle  $(90+\Psi)$  from field current axis, where  $\Psi$  is the phase angle of current from voltage vector E (internal phase angle).

The resultant field current is given by OG. Mark this length on field current axis.

From OCC find the corresponding EO. Find the regulation.

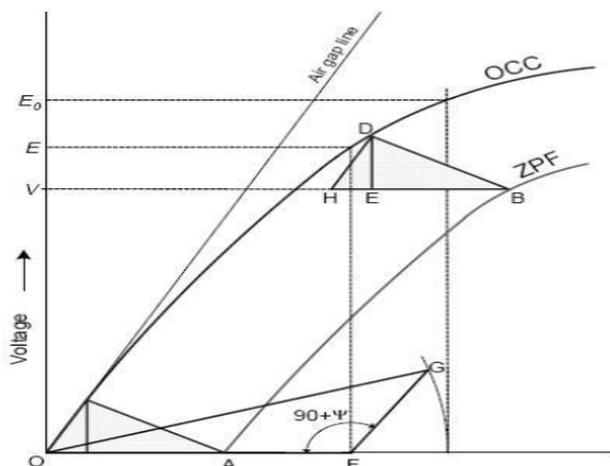


Figure: 2.6 ZPF method characteristics

### 3.14. Salient pole alternators and Blondel's Two reaction Theory

The details of synchronous generators developed so far is applicable to only round rotor or non salient pole alternators. In such machines the air gap is uniform throughout and hence the effect of mmf will be same whether it acts along the pole axis or the inter polar axis. Hence reactance of the stator is same throughout and hence it is called synchronous reactance. But in case salient pole machines the air gap is non uniform and it is smaller along pole axis and is larger along the inter polar axis. These axes are called direct axis or d-axis and quadrature axis or q-axis. Hence the effect of mmf when acting along direct axis will be different than that when it is acting along quadrature axis. Hence the reactance of the stator cannot be same when the mmf is acting along d – axis and q- axis. As the length of the air

gap is small along direct axis reluctance of the magnetic circuit is less and the air gap along the q – axis is larger and hence the along the quadrature axis will be comparatively higher. Hence along d-axis more flux is produced than q-axis. Therefore the reactance due to armature reaction will be different along d-axis and q-axis. These reactances are

$X_{ad}$  = direct axis reactance;  $X_{aq}$  = quadrature axis reactance

Hence the effect of armature reaction in the case of a salient pole synchronous machine can be taken as two components - one acting along the direct axis (coinciding with the main field pole axis) and the other acting along the quadrature axis (inter-polar region or magnetic neutral axis) - and as such the mmf components of armature-reaction in a salient-pole machine cannot be considered as acting on the same magnetic circuit. Hence the effect of the armature reaction cannot be taken into account by considering only the synchronous reactance, in the case of a salient pole synchronous machine.

In fact, the direct-axis component  $F_{ad}$  acts over a magnetic circuit identical with that of the main field system and produces a comparable effect while the quadrature-axis component  $F_{aq}$  acts along the inter polar axis, resulting in an altogether smaller effect and, in addition, a flux distribution totally different from that of  $F_{ad}$  or the main field m.m.f. This explains why the application of cylindrical-rotor theory to salient-pole machines for predicting the performance gives results not conforming to the performance obtained from an actual test.

Blondel's two-reaction theory considers the effects of the quadrature and direct-axis components of the armature reaction separately. Neglecting saturation, their different effects are considered by assigning to each an appropriate value of armature-reaction "reactance," respectively  $x_{ad}$  and  $x_{aq}$ . The effects of armature resistance and true leakage reactance ( $X_L$ ) may be treated separately, or may be added to the armature reaction coefficients on the assumption that they are the same, for either the direct-axis or quadrature-axis components of the armature current (which is almost true). Thus the combined reactance values can be expressed as :  $X_{sd} = x_{ad} + x_l$  and  $X_{sq} = x_{aq} + x_l$  for the direct- and cross-reaction axes respectively.

In a salient-pole machine,  $x_{aq}$ , the quadrature-axis reactance is smaller than  $x_{ad}$ , the direct-axis reactance, since the flux produced by a given current component in that axis is smaller as the reluctance of the magnetic path consists mostly of the interpolar spaces. It is essential to clearly note the difference between the quadrature and direct-axis components  $I_{aq}$ , and  $I_{ad}$  of the armature current  $I_a$ , and the reactive and active components  $I_{aa}$  and  $I_{ar}$ . Although both pairs are represented by phasors in phase quadrature, the former are related to the induced emf  $E_t$  while the latter are referred to the terminal voltage  $V$ .

These phasors are clearly indicated with reference to the phasor diagram of a (salient pole)

synchronous generator supplying a lagging power factor (pf) load, shown in Fig

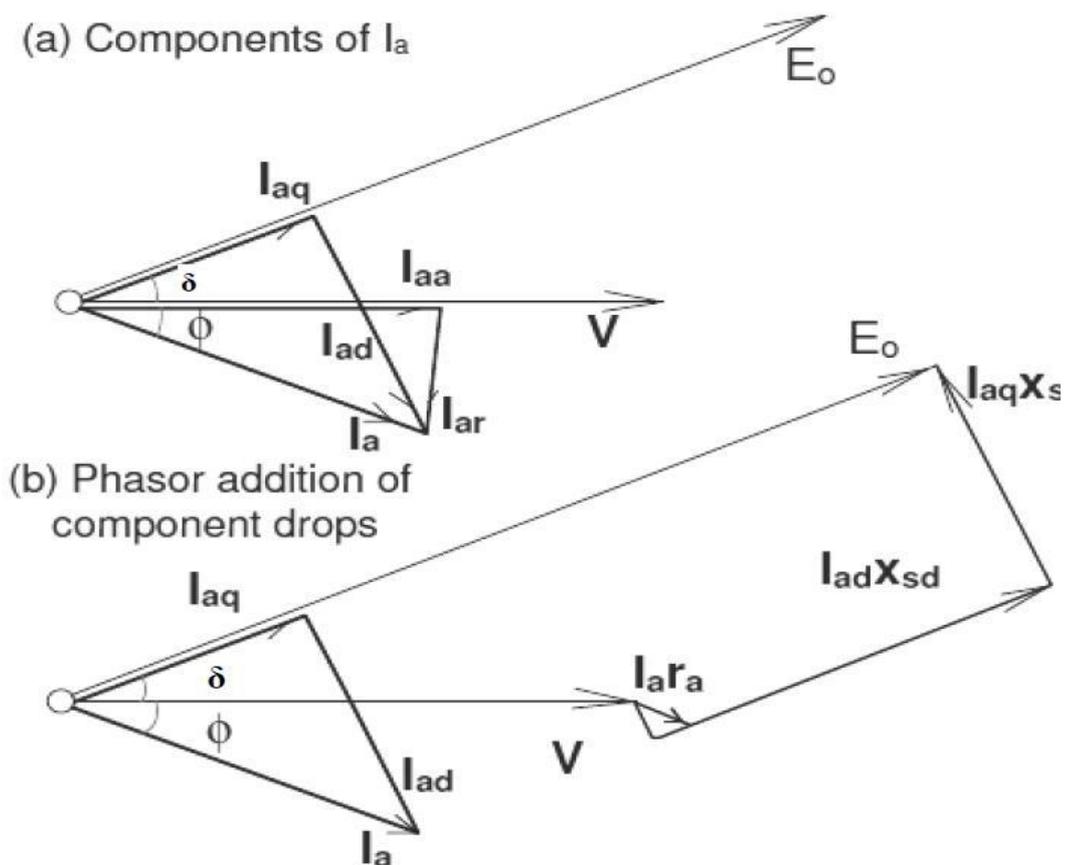


Figure: 2.7. Phasor diagram of salient pole alternator

$$I_{aq} = I_a \cos(\delta + \phi); \quad I_{ad} = I_a \sin(\delta + \phi); \quad \text{and} \quad I_a = \sqrt{(I_{aq})^2 + (I_{ad})^2}$$

$$I_{aa} = I_a \cos \phi; \quad I_{ar} = I_a \sin \phi; \quad \text{and} \quad I_a = \sqrt{(I_{aa})^2 + (I_{ar})^2}$$

where  $\delta$  = torque or power angle and  $\phi$  = the p.f. angle of the load.

The phasor diagram shows the two reactance voltage components  $I_{aq} * X_{sq}$  and  $I_{ad} * X_{sd}$  which are in quadrature with their respective components of the armature current. The resistance drop  $I_a \times R_a$  is added in phase with  $I_a$  although we could take it as  $I_{aq} \times R_a$  and  $I_{ad} \times R_a$  separately, which is unnecessary as  $I_a = I_{ad} + jI_{aq}$ .

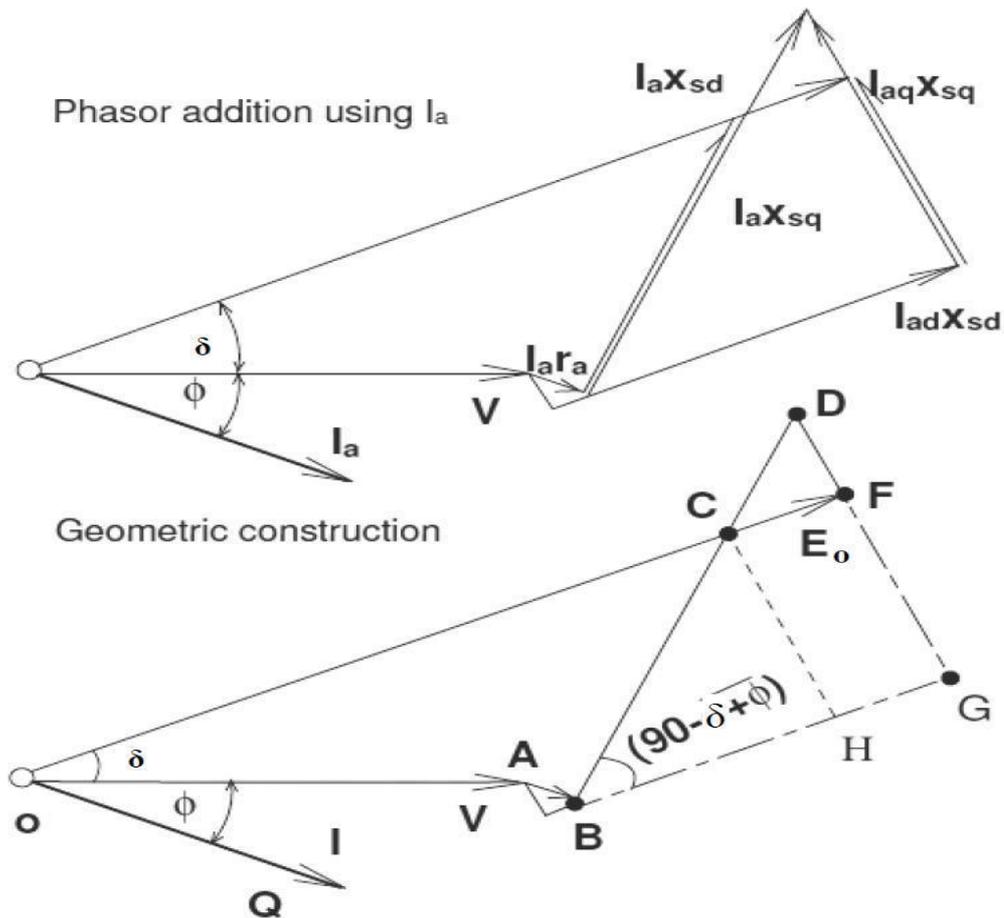


Figure: 2.8. Phasor diagram of salient pole alternator.

### 3.15. Power output of a Salient Pole Synchronous Machine

Neglecting the armature winding resistance, the power output of the generator is given by:  $P = V \times I_a \times \cos \phi$

This can be expressed in terms of  $\delta$ , by noting that

$$I_a \cos \phi = I_{aq} \cos \delta + I_{ad} \sin \delta$$

$$V \cos \delta = E_o - I_{ad} * X_{sd} \text{ and } V \sin \delta = I_{aq} * X_{sq}$$

Substituting the above expressions for power we get

$$P = V [(V \sin \delta / X_{sd}) * \cos \delta + (E_o - V \cos \delta) / X_{sd} * \sin \delta]$$

ELECTRICAL MACHINES-II  
On simplification we get

$$P = (V * E_0 / X_{sd}) \sin \delta + V^2 * (X_{sd} - X_{sq}) / (2 * X_{sq} * X_{sq}) * \sin 2 \delta$$

The above expression for power can also be written as

$$P = (E_0 * V * \sin \delta / X_d) + V^2 * (X_d - X_q) * \sin 2 \delta / (2 * X_q * X_q)$$

The above expression for power consists of two terms first is called electromagnetic power and the second is called reluctance power.

It is clear from the above expression that the power is a little more than that for a cylindrical rotor synchronous machine, as the first term alone represents the power for a cylindrical rotor synchronous machine. A term in  $(\sin 2\delta)$  is added into the power – angle characteristic of a non-salient pole synchronous machine. This also shows that it is possible to generate an emf even if the excitation  $E_0$  is zero. However this magnitude is quite less compared with that obtained with a finite  $E_0$ . Likewise it can be shown that the machine develops a torque - called the reluctance torque - as this torque is developed due to the variation of the reluctance in the magnetic circuit even if the excitation  $E_0$  is zero.

### 3.16.Determination of $X_d$ and $X_q$ by slip test:

The direct and quadrature axis reactances  $X_d$  and  $X_q$  can be of a synchronous machine can be experimentally determined by a simple test known as slip test. Basic circuit diagram for conducting this test is shown in figure. Here the armature terminals are supplied with a subnormal voltage of rated frequency with field circuit left open. The generator is driven by a prime mover at a slip speed which is slightly more or less than the synchronous speed. This is equivalent to the condition in which the armature mmf remains stationary and rotor rotates at a slip speed with respect to the armature mmf. As the rotor poles slip through the armature mmf the armature mmf will be in line with direct axis and quadrature axis alternately. When it is in line with the direct axis the armature mmf directly acts on the magnetic circuit and at this instant the voltage applied divided by armature current gives the direct axis synchronous reactance. When the armature mmf coincides with the quadrature axis then the voltage impressed divided by armature current gives the quadrature axis synchronous reactance. Since  $X_d > X_q$  the pointers of the ammeter reading the armature current will oscillate from a minimum to a maximum. Similarly the terminal voltage will also oscillate between the minimum and maximum.

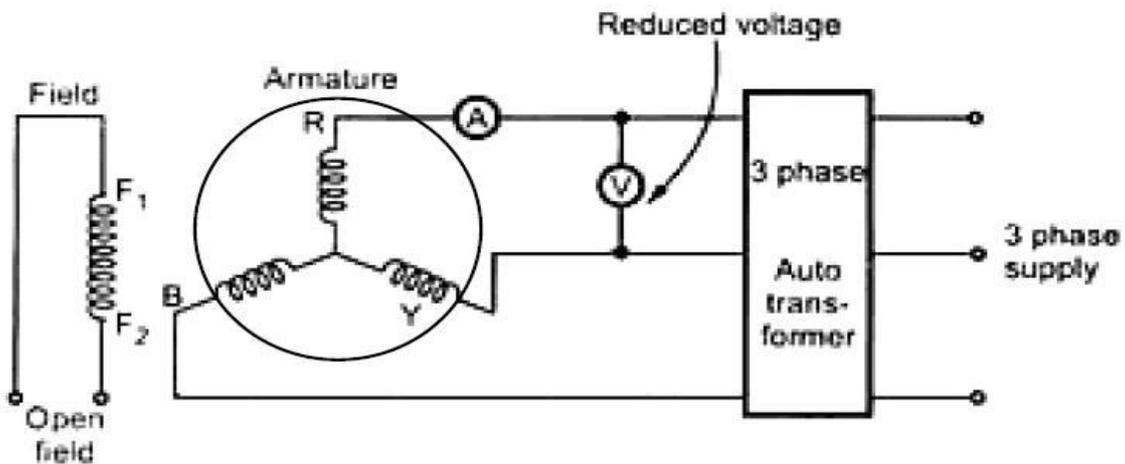


Figure: 2.9. Slip test

$$\therefore X_d = \text{Maximum voltage} / \text{minimum current}$$

$$X_q = \text{Minimum voltage} / \text{maximum current.}$$

## UNIT-IV

## PARALLEL OPERATION OF SYNCHRONOUS GENERATORS & SYNCHRONOUS MOTORS

### 4.1.Synchronizing of alternators:

#### Synchronizing

The operation of connecting two alternators in parallel is known as synchronizing. Certain conditions must be fulfilled before this can be effected. The incoming machine must have its voltage and frequency equal to that of the bus bars and, should be in same phase with bus bar voltage. The instruments or apparatus for determining when these conditions are fulfilled are called synchrosopes. Synchronizing can be done with the help of (i) dark lamp method or (ii) by using synchroscope.

Reasons for operating in parallel:

10. Handling larger loads.
11. Maintenance can be done without power disruption.
12. Increasing system reliability.
13. Increased efficiency.

Conditions required for Paralleling:

The figure below shows a synchronous generator G1 supplying power to a load, with another generator G2 about to be paralleled with G1 by closing switch S1. What conditions must be met before the switch can be closed and the 2 generators connected in parallel?

Paralleling 2 or more generators must be done carefully as to avoid generator or other system component damage. Conditions to be satisfied are as follows:

5. RMS line voltages must be equal.
6. The generators to be paralleled must have the same phase sequence.
7. The oncoming generator (the new generator) must have the same operating frequency as compared to the system frequency.

General Procedure for Paralleling Generators:

Consider the figure shown below. Suppose that generator G2 is to be connected to the running system as shown below:

11. Using Voltmeters, the field current of the oncoming generator should be adjusted until its terminal voltage is equal to the line voltage of the running system.
12. Check and verify phase sequence to be identical to the system phase sequence. There are 2 methods to do this:

One way is using the 3 lamp method, where the lamps are stretched across the open terminals of the switch connecting the generator to the system (as shown in the figure below). As the phase changes between the 2 systems, the lamps first get bright (large phase difference) and then get dim (small phase difference). If all 3 lamps get bright and dark together, then the systems have the same phase sequence. If the lamps brighten in succession, then the systems have the opposite phase sequence, and one of the sequences must be reversed.

Using a Synchroscope – a meter that measures the difference in phase angles (it does not check phase sequences only phase angles).

13. Check and verify generator frequency is same as that of the system frequency. This is done by watching a frequency of brightening and dimming of the lamps until the frequencies are close by making them to change very slowly.
14. Once the frequencies are nearly equal, the voltages in the 2 systems will change phase with respect to each other very slowly. The phase changes are observed, and when the phase angles are equal, the switch connecting the 2 systems is closed.

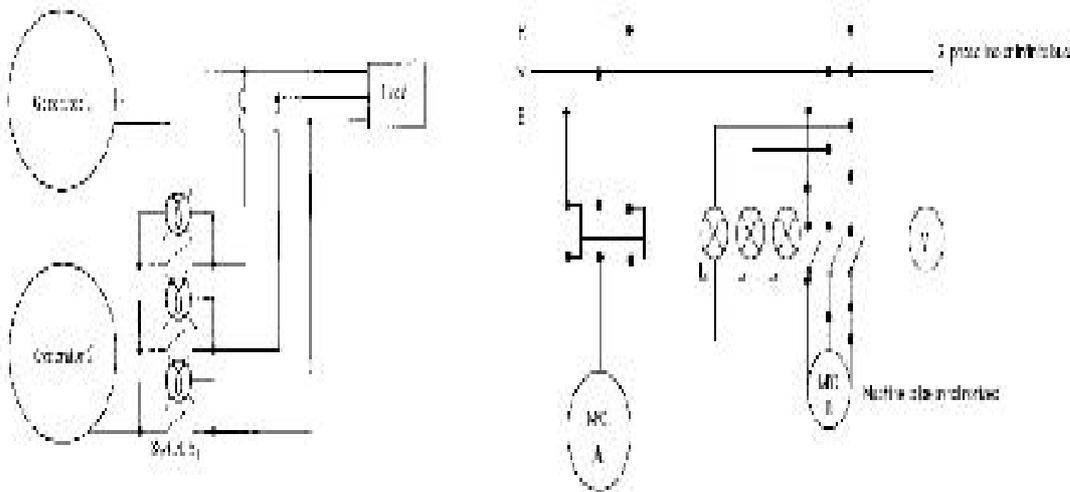


Figure: 3.1. Synchronization of alternators.

#### 4.2.Synchronizing Current

If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1, i.e.  $E_1$  is equal to and in phase opposition to emf of alternator 2, i.e.  $E_2$  as shown in the Figure .There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by an

angle  $\theta$ .

The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current  $I_s$  is very nearly in quadrature with the resultant emf  $E_r$  acting on the circuit. Figure represents a single phase case, where  $E_1$  and  $E_2$  represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf,  $E_r$ , is almost in quadrature with both the emfs, and gives rise to a current,  $I_s$ , lagging behind  $E_r$  by an angle approximating to a right angle. It is, thus, seen that  $E_1$  and  $I_s$  are almost in phase. The first alternator is generating a power  $E_1 I_s \cos \Phi_1$ , which is positive, while the second one is generating a power  $E_2 I_s \cos \Phi_2$ , which is negative, since  $\cos \Phi_2$  is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current  $I_s$  flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it till such a time that  $E_1$  and  $E_2$  are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current,  $I_s$ , is called the synchronizing current.

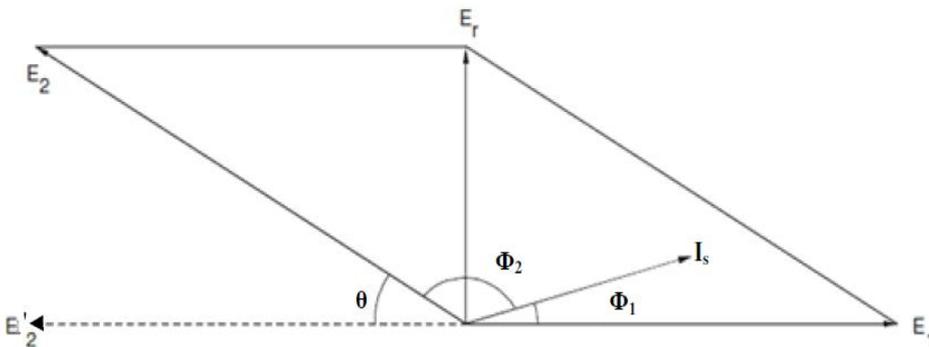


Figure: 3.2. Phasor diagram for synchronizing current.

#### 4.3.Synchronizing Power

Suppose that one alternator has fallen behind its ideal position by an electrical angle  $\theta$ , measured in radians. Since  $E_1$  and  $E_2$  are assumed equal and  $\theta$  is very small  $E_r$  is very nearly equal to  $\theta E_1$ . Moreover, since  $E_r$  is practically in quadrature with  $E_1$  and  $I_s$  may be assumed to be in phase with  $E_1$  as a first approximation. The synchronizing power may, therefore, be taken as,

$$P_s = E_1 I_s \text{ and } I_s = E_r / 2Z_s \text{ and } E_r = \theta E_1$$

$$P_s = \theta^2 E_1^2 / 2Z_s \text{ or } P_s = \theta^2 E_1^2 / 2X_s$$

Where  $Z_s$  is the synchronous impedance,  $Z_s = X_s$  when the resistance is neglected.

When one alternator is considered as running on a set of bus bars the power capacity of which is very large compared with its own, the combined reactance of the other sets connected to the bus bars is negligible, so that, in this case  $Z_s = X_s$  is the synchronous reactance of the one alternator under consideration.

$$P_{sy} = 3 E_1^2 / 2Z_s \text{ or}$$

$$P_{sy} = 3 E_1^2 / 2X_s$$

$$\text{Total synchronizing power } P_{sy} = 3 E_1^2 / 2Z_s \text{ or}$$

$$P_{sy} = 3 E_1^2 / 2X_s$$

When the machine is connected to an infinite bus bar the synchronizing power is given by

$$P_{sy} = 3 E_1^2 / Z_s \text{ or}$$

$$P_{sy} = 3 E_1^2 / X_s$$

And synchronizing torque  $T_{sy} = P_{sy} \times 60 / 2 \pi N_s$

Alternators with a large ratio of reactance to resistance are superior from a synchronizing point of view to those which have a smaller ratio, as then the synchronizing current  $I_s$  cannot be considered as being in phase with  $E_1$ . Thus, while reactance is bad from a regulation point of view, it is good for synchronizing purposes. It is also good from the point of view of self-protection in the event of a fault.

#### 4.4. Effect of Change of Excitation

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output. Let two similar alternators of the same rating be operating in parallel, receiving equal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same. When delivering a total load of  $I$  amperes at a power-factor of  $\cos \phi$ , each alternator delivers half the total

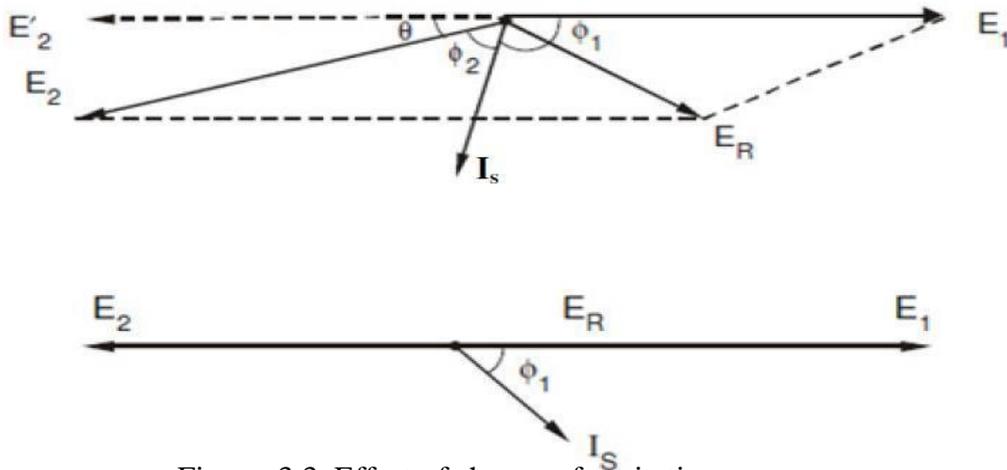


Figure: 3.3. Effect of change of excitation

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current,  $I_s$ , is zero. Since the armature resistance is neglected, the vector difference between  $E_1 = E_2$  and  $V$  is equal to  $I_1 X_{s1} - I_2 X_{s2}$ , this vector leading the current  $I$  where  $X_{s1}$  and  $X_{s2}$  are the synchronous reactances of the two alternators respectively.

Now consider the effect of reducing the excitation of the second alternator.  $E_2$  is therefore reduced as shown in Figure. This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased so as to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current  $I_2$  is changed due to the change in  $E_2$ , but the active components of both  $I_1$  and  $I_2$  remain unaltered. It can be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator. It can also be observed that  $I_1 + I_2 = I$ , the total load current.

#### 4.5. Effect of Change of Input Torque

The amount of power output delivered by an alternator running in parallel with others is governed solely by the power input received from its prime mover. If two alternators only are operating in parallel the increase in power input may be accompanied by a minute

## ELECTRICAL MACHINES-II

increase in their speeds, causing a proportional rise in frequency. This can be corrected by reducing the power input to the other alternator, until the frequency is brought back to its original value. In practice, when load is transferred from one alternator to another, the power input to the alternator required to take additional load is increased, the power input to the other alternator being simultaneously decreased. In this way, the change in power output can be effected without measurable change in the frequency. The effect of increasing the input to one prime mover is, thus, seen to make its alternator take an increased share of the load, the other being relieved to a corresponding extent. The final power-factors are also altered, since the ratio of the reactive components of the load has also been changed. The power-factors of the two alternators can be brought back to their original values, if desired, by adjusting the excitations of alternators.

### 4.6. Load Sharing

When several alternators are required to run in parallel, it probably happens that their rated outputs differ. In such cases it is usual to divide the total load between them in such a way that each alternator takes the load in the same proportion of its rated load in total rated outputs. The total load is not divided equally. Alternatively, it may be desired to run one large alternator permanently on full load, the fluctuations in load being borne by one or more of the others.

If the alternators are sharing the load equally the power triangles are as shown in figure below.

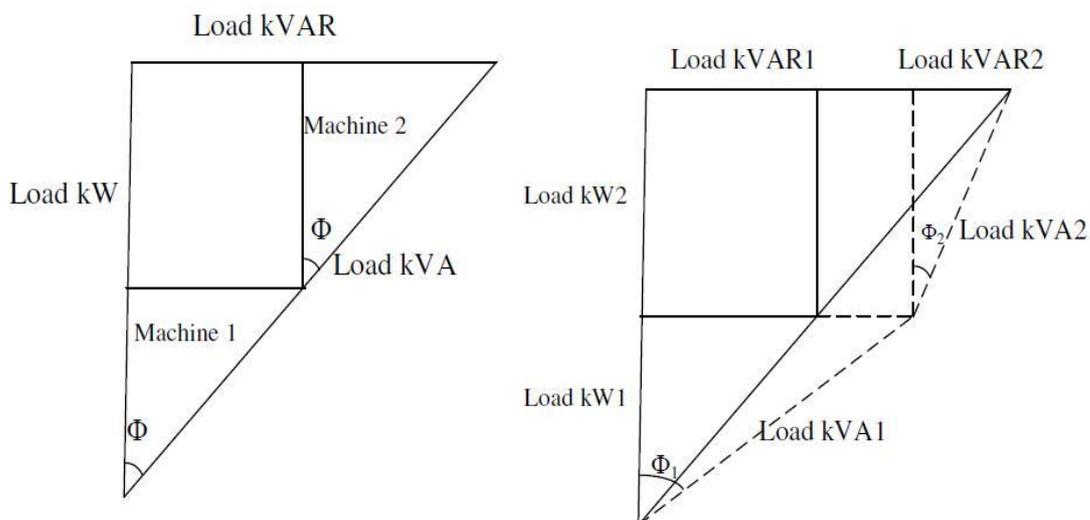


Figure: 3.4. Load sharing of alternators.

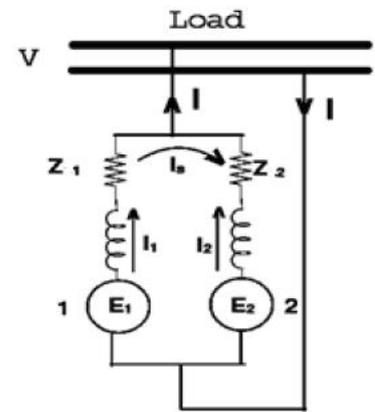
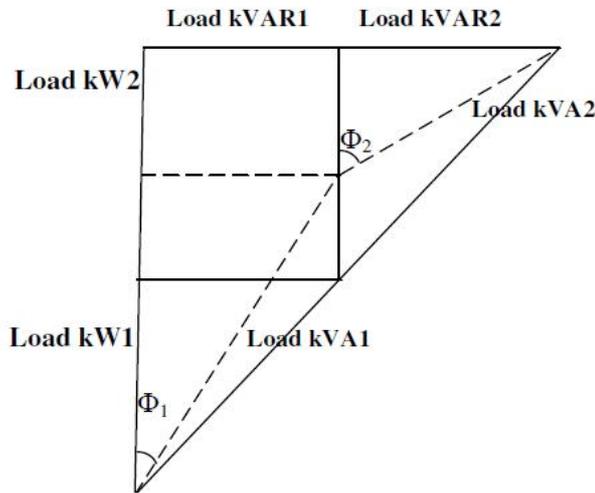


Figure: 3.5. Load sharing of alternators.

#### 4.7. Sharing of load when two alternators are in parallel

Consider two alternators with identical speed load characteristics connected in parallel as shown in figure above.

Let  $E_1, E_2$  be the induced emf per phase,

$Z_1, Z_2$  be the impedances per phase ,

$I_1, I_2$  be the current supplied by each

machine per phase  $Z$  be the load impedance

per phase,  $V$  be the terminal voltage per

phase

From the circuit we have  $V = E_1 - I_1 Z_1 = E_2 - I_2 Z_2$  and hence

$$I_1 = E_1 - V/Z_1 \text{ and } I_2 = E_2 - V/Z_2$$

and also  $V = (I_1 + I_2) Z = IZ$  solving above equations

$$I_1 = [(E_1 - E_2) Z + E_1 Z_2] / [Z(Z_1 + Z_2) + Z_1 Z_2]$$

$$I_2 = [(E_2 - E_1) Z + E_2 Z_1] / [Z(Z_1 + Z_2) + Z_1 Z_2]$$

The total current  $I = I_1 + I_2 = [E_1 Z_2 + E_2 Z_1] / [Z(Z_1 + Z_2) + Z_1 Z_2]$

And the circulating current or synchronizing current  $I_s = (E_1 - E_2) / (Z_1 + Z_2)$

## 4.8.SYNCHRONOUS MOTORS

### Principle of operation

In order to understand the principle of operation of a synchronous motor, assume that the armature winding (laid out in the stator) of a 3-phase synchronous machine is connected to a suitable balanced 3-phase source and the field winding to a D.C source of rated voltage. The current flowing through the field coils will set up stationary magnetic poles of alternate North and South. On the other hand, the 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. In other words there will be moving North and South poles established in the stator due to the 3-phase currents i.e. at any location in the stator there will be a North Pole at some instant of time and it will become a South Pole after a time period corresponding to half a cycle. (After a time =  $1/2f$ , where  $f$  = frequency of the supply). Assume that the stationary South pole in the rotor is aligned with the North pole in the stator moving in clockwise direction at a particular instant of time, as shown in Figure below. These two poles get attracted and try to maintain this alignment (as per Lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions are suitable for the production of torque in the clockwise direction. However, the rotor cannot move instantaneously due to its mechanical inertia, and so it needs some time to move.

In the mean time, the stator pole would quickly (a time duration corresponding to half a cycle) change its polarity and becomes a South Pole. So the force of attraction will no longer be present and instead the like poles experience a force of Repulsion as shown in Figure below. In other words, the conditions are now suitable for the production of torque in the anticlockwise direction. Even this condition will not last longer as the stator pole.

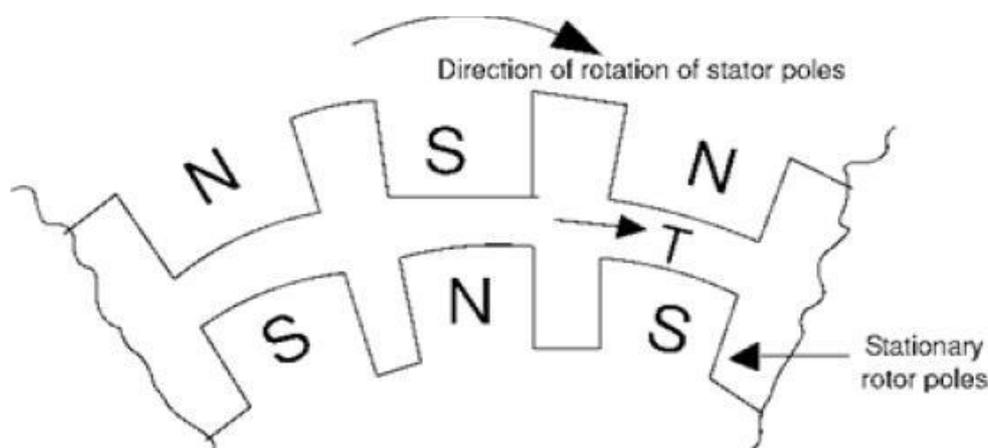


Figure: 4.1. Force of attraction between stator poles and rotor poles - resulting in production of torque in clockwise direction.

Would again change to North pole after a time of  $1/2f$ . Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to  $1/2f$  seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

On the contrary if the rotor is brought to near synchronous speed by some external device say a small motor mounted on the same shaft as that of the rotor, the rotor poles get locked to the unlike poles in the stator and the rotor continues to run at the synchronous speed even if the supply to the motor is disconnected. Thus the synchronous rotor cannot start rotating on its own when the rotor and stator are supplied with rated voltage and frequency and hence the synchronous motor has no starting torque. So, some special provision has to be made either inside the machine or outside of the machine so that the rotor is brought to near about its synchronous speed. At that time, if the armature is supplied with electrical power, the rotor can pull into step and continue to run at its synchronous speed. Some of the commonly used methods for starting synchronous rotor are described in the following paragraph.

Would again change to North Pole after a time of  $1/2f$ . Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to  $1/2f$  seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

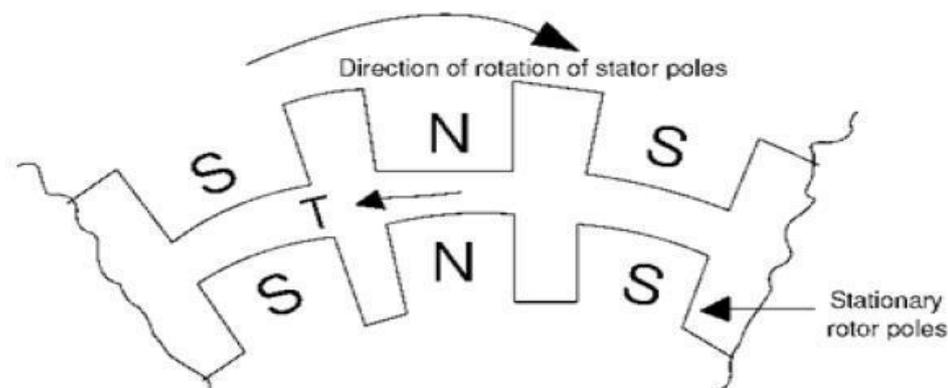


Figure: 4.2. Force of repulsion between stator poles and rotor poles - resulting in production of torque in anticlockwise direction

#### 4.9. Methods of starting synchronous motor

Basically there are three methods that are used to start a synchronous motor:

To reduce the speed of the rotating magnetic field of the stator to a low enough value that the rotor can easily accelerate and lock in with it during one half-cycle of the rotating magnetic field's rotation. This is done by reducing the frequency of the applied electric power. This method is usually followed in the case of inverter-fed synchronous motor operating under variable speed drive applications.

To use an external prime mover to accelerate the rotor of synchronous motor near to its synchronous speed and then supply the rotor as well as stator. Of course care should be taken to ensure that the directions of rotation of the rotor as well as that of the rotating magnetic field of the stator are the same. This method is usually followed in the laboratory- the synchronous machine is started as a generator and is then connected to the supply mains by following the synchronization or paralleling procedure. Then the power supply to the prime mover is disconnected so that the synchronous machine will continue to operate as a motor.

To use damper windings if these are provided in the machine. The damper windings are provided in most of the large synchronous motors in order to nullify the oscillations of the rotor whenever the synchronous machine is subjected to a periodically varying load.

### Behaviour of a synchronous motor

The behaviour of a synchronous motor can be predicted by considering its equivalent circuit on similar lines to that of a synchronous generator as described below.

#### 4.10. Equivalent circuit model and phasor diagram of a synchronous motor

The equivalent-circuit model for one armature phase of a cylindrical rotor three phase synchronous motor is shown in Figure below exactly similar to that of a synchronous generator except that the current flows in to the armature from the supply. Applying Kirchhoff's voltage law to Figure below

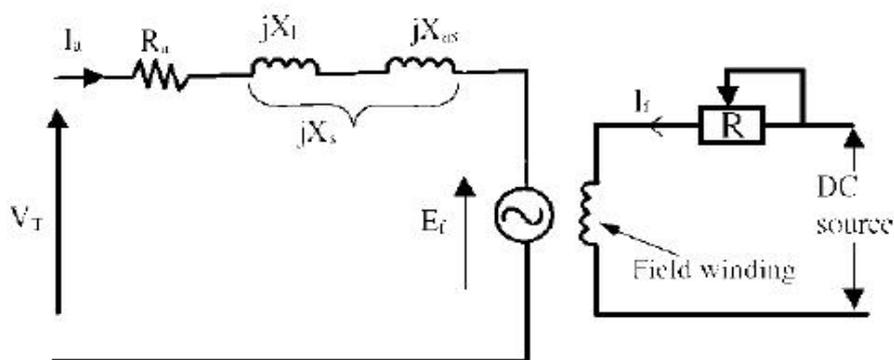


Figure: 4.3. Equivalent circuit model for one phase of a synchronous motor armature

$$V_T = I_a R_a + jI_a X_l + jI_a X_{as} + E_f$$

Combining reactances,  $X_s = X_l + X_{as}$

$$V_T = E_f + I_a(R_a + jX_s) \text{ or } V_T = E_f + I_a Z_s$$

where:

$R_a$  = armature resistance (/phase)

$X_l$  = armature leakage reactance (/phase)  $X_s$  = synchronous reactance (/phase)

$Z_s$  = synchronous impedance (/phase)  $V_T$  = applied voltage/phase (V)

$I_a$  = armature current/phase (A)

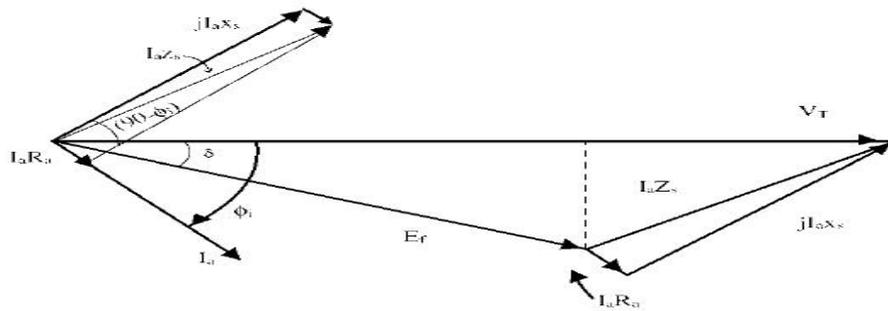


Figure: 4.4. Phasor diagram corresponding to the equivalent-circuit model

A phasor diagram shown in Figure above, illustrates the method of determining the counter EMF which is obtained from the phasor equation;

$$E_f = V_T - I_a Z_s$$

The phase angle  $\delta$  between the terminal voltage  $V_T$  and the excitation voltage  $E_f$  in Figure above is usually termed the torque angle. The torque angle is also called the load angle or power angle.

**4.11.Effect of changes in load on,  $I_a$ ,  $\delta$ , and p. f. of synchronous motor**

The effects of changes in mechanical or shaft load on armature current, power angle, and power factor can be seen from the phasor diagram shown in Figure below; As already stated, the applied stator voltage, frequency, and field excitation are assumed, constant. The initial load conditions are represented by the thick lines. The effect of increasing the shaft load to twice its initial value is represented by the light lines indicating the new steady state conditions. While drawing the phasor diagrams to show new steady-state conditions, the line of action of the new  $jI_a X_s$  phasor must be perpendicular to the new  $I_a$  phasor. Furthermore, as shown in figure if the excitation is not changed, increasing the shaft load causes the locus of the  $E_f$  phasor to follow a circular arc, thereby increasing its phase angle with increasing shaft load. Note also that an increase in shaft load is also accompanied by a decrease in  $\Phi_i$ ; resulting in an increase in power factor.

As additional load is placed on the machine, the rotor continues to increase its angle of lag relative to the rotating magnetic field, thereby increasing both the angle of lag of the counter EMF phasor and the magnitude of the stator current. It is interesting to note that during all this load variation; however, except for the duration of transient conditions whereby the rotor assumes a new position in relation to the rotating magnetic field, the average speed of the machine does not change. As the load is being increased, a final point is reached at which a further increase in  $\delta$  fails to cause a corresponding increase in motor torque, and the rotor pulls out of synchronism. In fact as stated earlier, the rotor poles at this point, will fall behind the stator poles such that they now come under the influence of like poles and the force of attraction no longer exists. Thus, the point of maximum torque occurs at a power angle of approximately  $90^\circ$  for a cylindrical-rotor machine. This maximum value of torque that causes a synchronous motor to pull out of synchronism is called the pull-out torque. In actual practice, the motor will never be operated at power angles close to  $90^\circ$  as armature current will be many times its rated value at this load

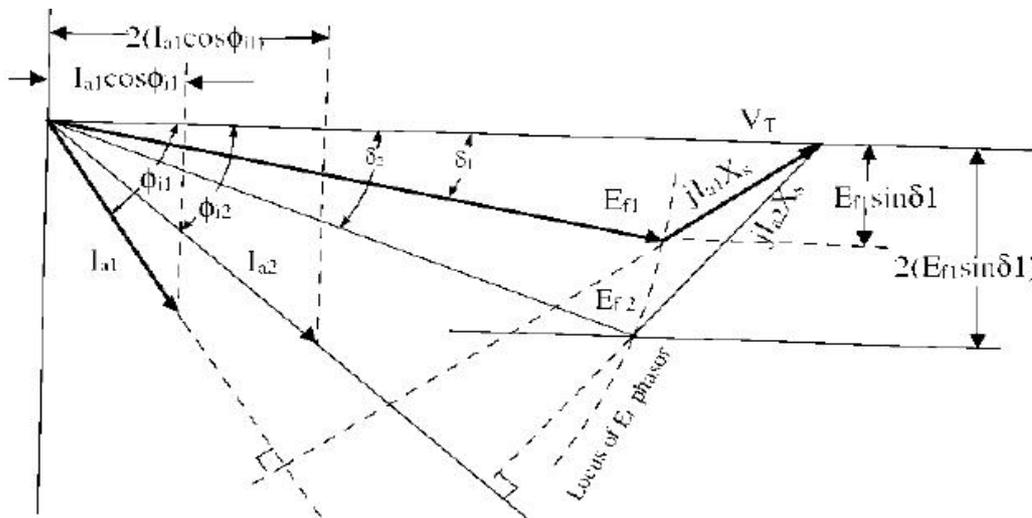


Figure: 4.5. Effect of changes in load on,  $I_a$ ,  $\delta$ , and p. f.

#### 4.12. Effect of changes in excitation on the performance synchronous motor

Increasing the strength of the magnets will increase the magnetic attraction, and thereby cause the rotor magnets to have a closer alignment with the corresponding opposite poles of the rotating magnetic poles of the stator. This will obviously result in a smaller power angle. This fact can also be seen from power angle equation. When the shaft load is assumed to be constant, the steady -state value of  $E_f \sin\delta$  must also be constant. An increase in  $E_f$  will cause a transient increase in  $E_f \sin\delta$ , and the rotor will accelerate. As the rotor changes its angular position,  $\delta$  decreases until  $E_f \sin\delta$  has the same steady -state value as before, at which time the rotor is again operating at synchronous speed, as it should run only

at the synchronous speed. This change in angular position of the rotor magnets relative to the poles of rotating magnetic field of the stator occurs in a fraction of a second. The effect of changes in field excitation on armature current, power angle, and power factor of a synchronous motor operating with a constant shaft load, from a constant voltage, constant frequency supply, is illustrated in figure below.

$$E_{f1} \sin \delta_1 = E_{f2} \sin \delta_2 = E_{f3} \sin \delta_3 = E_f \sin \delta$$

This is shown in Figure below, where the locus of the tip of the  $E_f$  phasor is a straight line parallel to the VT phasor.

Similarly,

$$I_{a1} \cos \Phi_{i1} = I_{a2} \cos \Phi_{i2} = I_{a3} \cos \Phi_{i3} = I_a \cos \Phi_i$$

This is also shown in Figure below, where the locus of the tip of the  $I_a$  phasor is a line perpendicular to the phasor VT.

Note that increasing the excitation from  $E_{f1}$  to  $E_{f3}$  caused the phase angle of the current phasor with respect to the terminal voltage VT (and hence the power factor) to go from lagging to leading. The value of field excitation that results in unity power factor is called normal excitation. Excitation greater than normal is called over excitation, and excitation less than normal is called under excitation.

Further, as indicated in Figure, when operating in the overexcited mode,  $|E_f| > |V_T|$ . A synchronous motor operating under over excited condition is called a synchronous condenser.

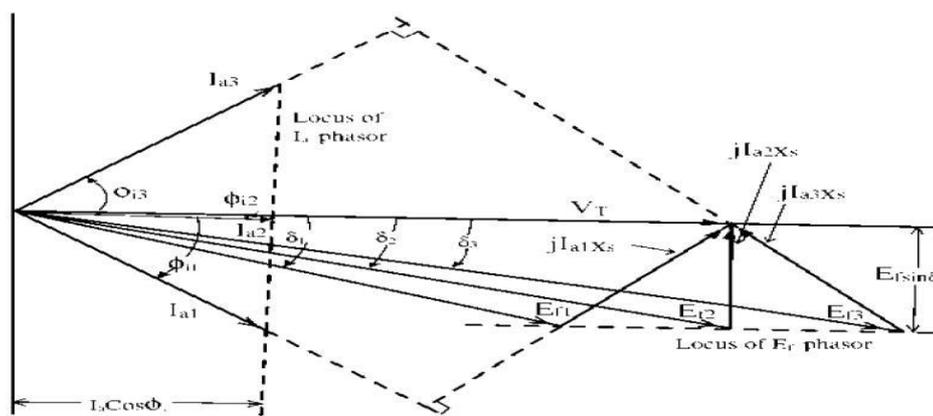


Figure: 4.6. Phasor diagram showing effect of changes in field excitation on armature current, power angle and power factor of a synchronous motor

### 4.13.V and inverted V curve of synchronous motor

Graphs of armature current vs. field current of synchronous motors are called V curves and are shown in Figure below for typical values of synchronous motor loads. The curves are related to the phasor diagram shown in figure below, and illustrate the effect of the variation of field excitation on armature current and power factor. It can be easily noted from these curves that an increase in shaft loads require an increase in field excitation in order to maintain the power factor at unity.

The points marked *a*, *b*, and *c* on the upper curve corresponds to the operating conditions of the phasor diagrams shown. Note that for  $P = 0$ , the lagging power factor operation is electrically equivalent to an inductor and the leading power factor operation is electrically equivalent to a capacitor. Leading power factor operation with  $P = 0$  is sometimes referred to as synchronous condenser or synchronous capacitor operation. Typically, the synchronous machine V-curves are provided by the manufacturer so that the user can determine the resulting operation under a given set of conditions.

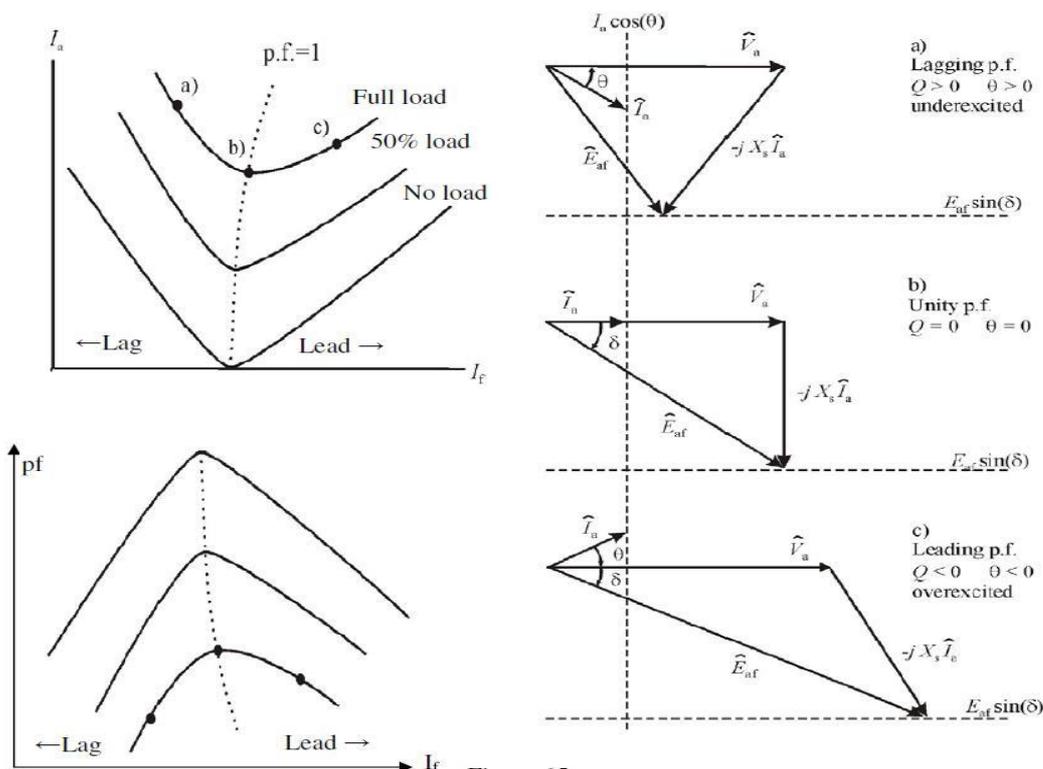


Figure: 4.7. Plots of power factor vs. field current of synchronous motors are called inverted V curves and are shown in Figure above for different values of synchronous motor loads.

### 4.14. Flow in Synchronous Motor

The figure below gives the details regarding the power flow in synchronous motor.

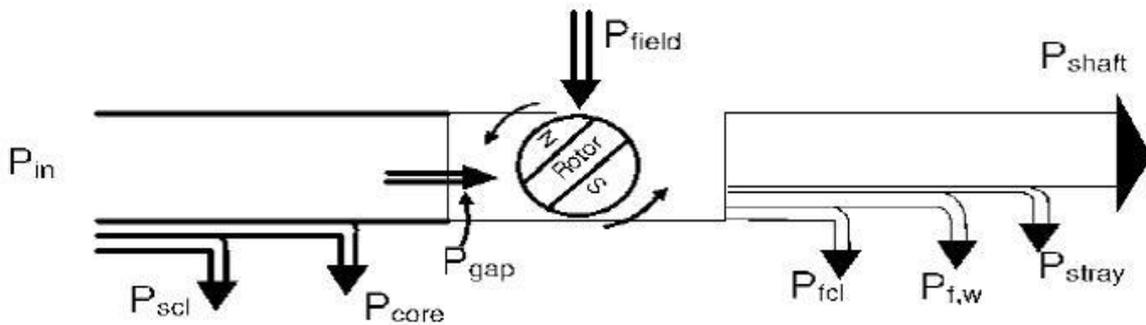


Figure: 4.8. Power stages in synchronous moto

Where

$P_{in}$  = Power input to the motor  $P_{sc1}$  = Power loss as stator copper loss  $P_{core}$  = Power loss as core loss  $P_{gap}$  = Power in the air gap

$P_{fc1}$  = Power loss as field copper loss  $P_{fw}$  = Power loss as friction and windage loss  $P_{stray}$  = Power loss as stray loss  $P_{shaft}$  = Shaft output of the machine

Power input to a synchronous motor is given by  $P = 3V_{ph}I_{ph}\cos\Phi = \sqrt{3}VLIL\cos\Phi$ . In stator as per the diagram there will be core loss and copper losses taking place. The remaining power will be converted to gross mechanical power.

Hence  $P_m = \text{Power input to the motor} - \text{Total losses in stator}$ .

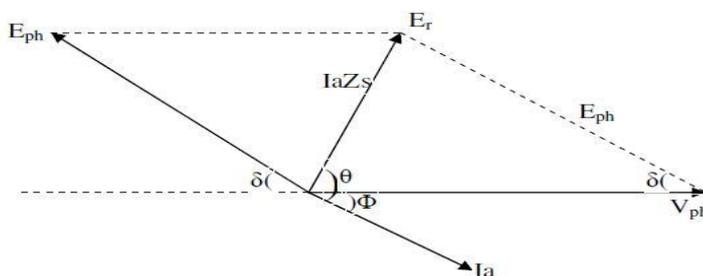


Figure: 4.9. Phasor diagram

From the phasor diagram we can write Power input /phase  $P_i = V_{ph} I_{ph} \cos \Phi$  Mechanical power developed by the motor  $P_m = E_b I_a \cos \alpha$  &  $I_a = E_b I_a \cos(\delta - \Phi)$

Assuming iron losses as negligible stator  $c_u$  losses =  $P_i - P_m$

Power output /phase =  $P_m - (\text{field } c_u \text{ loss} + \text{friction \& windage loss} + \text{stray loss})$

### **Torque developed in Motor**

Mechanical power is given by  $P_m = 2\pi N_s T_g / 60$  where  $N_s$  is the synchronous speed and the  $T_g$  is the gross torque developed.

$$P_m = 2\pi N_s T_g / 60$$

$$\text{Hence } T_g = \frac{P_m}{2\pi N_s}$$

$$T_g = \frac{P_m}{2\pi N_s}$$

$$T_g = 9.55 \frac{P_m}{N_s} \text{ N-m}$$

$$\text{Shaft output torque } T_{sh} = 60 \times \frac{P_{out}}{2\pi N_s}$$

$$T_{sh} = 9.55 \frac{P_{out}}{N_s} \text{ N-m}$$

## **4.15. Hunting and Damper Winding**

### **Hunting**

Sudden changes of load on synchronous motors may sometimes set up oscillations that are superimposed upon the normal rotation, resulting in periodic variations of a very low frequency in speed. This effect is known as hunting or phase-swinging. Occasionally, the trouble is aggravated by the motor having a natural period of oscillation approximately equal to the hunting period. When the synchronous motor phase-swings into the unstable region, the motor may fall out of synchronism.

### **Damper winding**

The tendency of hunting can be minimized by the use of a damper winding. Damper windings are placed in the pole faces. No emfs are induced in the damper bars and no current flows in the damper winding, which is not operative. Whenever any irregularity takes place in the speed of rotation, however, the polar flux moves from side to side of the pole, this movement causing the flux to move backwards and forwards across the damper bars. Emfs are induced in the damper bars forwards across the damper winding. These tend to damp out the superimposed oscillatory motion by absorbing its energy. The damper winding, thus, has no effect upon the normal average speed, it merely tends to damp out the oscillations in the speed, acting as a kind of electrical flywheel. In the case of a three-phase synchronous motor the stator currents set up a rotating mmf rotating at uniform speed and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars.

#### 4.16. Synchronous Condenser

An over excited synchronous motor operates at unity or leading power factor. Generally, in large industrial plants the load power factor will be lagging. The specially designed synchronous motor running at zero load, in parallel with inductive loads to improve power factor, it is known as synchronous condenser. Compared to static capacitor the power factor can improve easily by variation of field excitation of motor. Phasor diagram of a synchronous condenser connected in parallel with an inductive load is given below.

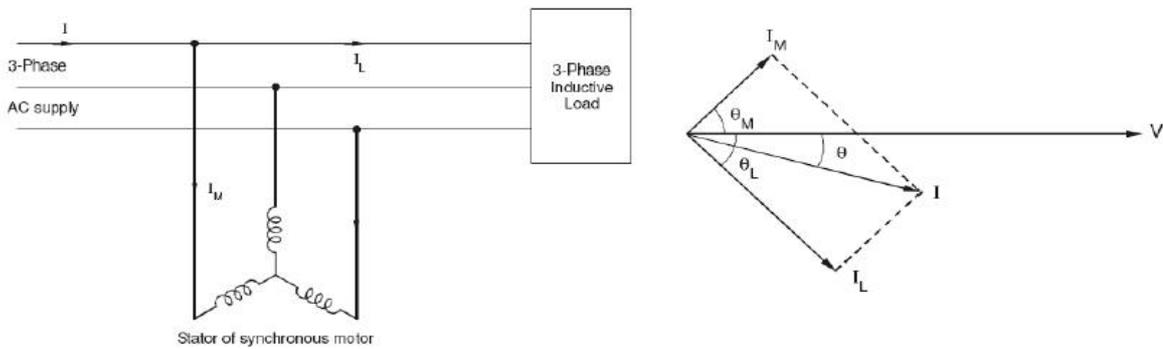


Figure: 4.10. Synchronous condenser and phasor diagram

## UNIT-V

### SINGLE PHASE MOTORS & SPECIAL MACHINES

#### 5.1.Introduction

The characteristics of single phase induction motors are identical to 3-phase induction motors except that single phase induction motor has no inherent starting torque and some special arrangements have to be made for making itself starting. It follows that during starting period the single phase induction motor must be converted to a type which is not a single phase induction motor in the sense in which the term is ordinarily used and it becomes a true single phase induction motor when it is running and after the speed and torque have been raised to a point beyond which the additional device may be dispensed with. For these reasons, it is necessary to distinguish clearly between the starting period when the motor is not a single phase induction motor and the normal running condition when it is a single phase induction motor. The starting device adds to the cost of the motor and also requires more space. For the same output a 1-phase motor is about 30% larger than a corresponding 3-phase motor.

The single phase induction motor in its simplest form is structurally the same as a poly- phase induction motor having a squirrel cage rotor, the only difference is that the single phase induction motor has single winding on the stator which produces mmf stationary in space but alternating in time, a poly phase stator winding carrying balanced currents produces mmf rotating in space around the air gap and constant in time with respect to an observer moving with the mmf. The stator winding of the single phase motor is disposed in slots around the inner periphery of a laminated ring similar to the 3-phase motor.

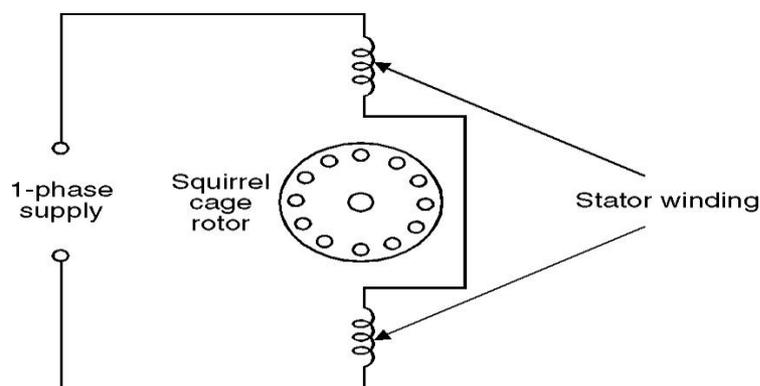


Figure: 5.1. Elementary single phase induction motor

An induction motor with a cage rotor and single phase stator winding is shown schematically in Fig. 5.1. The actual stator winding as mentioned earlier is distributed in slots so as to produce an approximately sinusoidal space distribution of mmf.

### 5.2.Principle of Operation

Suppose the rotor is at rest and 1-phase supply is given to stator winding. The current flowing in the stator winding gives rise to an mmf whose axis is along the winding and it is a pulsating mmf, stationary in space and varying in magnitude, as a function of time, varying from positive maximum to zero to negative maximum and this pulsating mmf induces currents in the short-circuited rotor of the motor which gives rise to an mmf. The currents in the rotor are induced due to transformer action and the direction of the currents is such that the mmf so developed opposes the stator mmf. The axis of the rotor mmf is same as that of the stator mmf. Since the torque developed is proportional to sine of the angle between the two mmf and since the angle is zero, the net torque acting on the rotor is zero and hence the rotor remains stationary.

For analytical purposes a pulsating field can be resolved into two revolving fields of constant magnitude and rotating in opposite directions as shown in Fig. 5.2 and each field has a magnitude equal to half the maximum length of the original pulsating phasor.

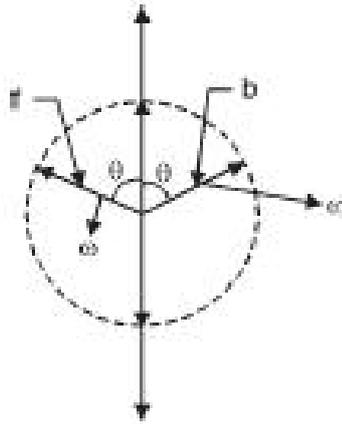


Figure: 5.2. Representation of the pulsating field by space phasors.

These component waves rotate in opposite direction at synchronous speed. The forward (anticlockwise) and backward-rotating (clockwise) mmf waves  $f$  and  $b$  are shown in Fig. 5.2. In case of 3-phase induction motor there is only one forward rotating magnetic field and hence torque is developed and the motor is self-starting. However, in single phase induction motor each of this component mmf waves produces induction motor action but the corresponding torques are in opposite direction. With the rotor at rest the forward and backward field produce equal torques but opposite in direction and hence no net torque is developed on the motor and the motor remains stationary. If the forward and backward air gap fields remained equal when the rotor is revolving, each of the component fields would produce a torque-speed characteristic similar to that of a Poly phase induction motor with negligible leakage impedance as shown by the dashed curves  $f$  and  $b$  in Fig. 5.3.

The resultant torque-speed characteristic which is the algebraic sum of the two component curves shows that if the motor were started by auxiliary means it would produce torque in what- ever direction it was started.

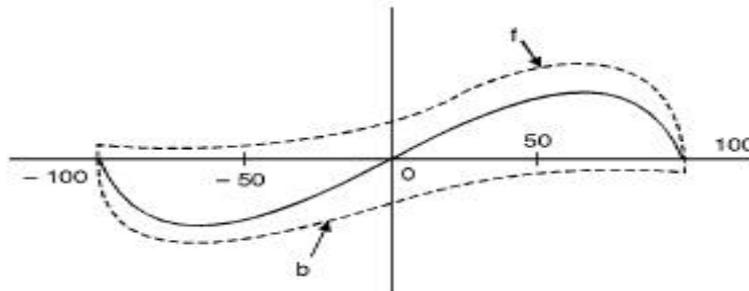


Figure: 5.3. Torque-speed characteristic of a 1-phase induction motor based on constant forward and backward flux waves.

In reality the two fields, forward and backward do not remain constant in the air gap and also the effect of stator leakage impedance can't be ignored. In the above qualitative analysis the effects of induced rotor currents have not been properly accounted for.

When single phase supply is connected to the stator and the rotor is given a push along the forward rotating field, the relative speed between the rotor and the forward rotating magnetic field goes on decreasing and hence the magnitude of induced currents also decreases and hence the mmf due to the induced current in the rotor decreases and its opposing effect to the forward rotating field decreases which means the forward rotating field becomes stronger as the rotor speeds up. However for the backward rotating field the relative speed between the rotor and the backward field increases as the rotor rotates and hence the rotor emf increases and hence the mmf due to this component of current increases and its opposing effect to the backward rotating field increases and the net backward rotating field weakens as the rotor rotates along the forward rotating field. However, the sum of the two fields remains constant since it must induce the stator counter emf which is approximately constant if the stator leakage impedance drop is negligible. Hence, with the rotor in motion the torque of the forward field is greater and that of the backward field is less than what is shown in Fig. 5.3. The true situation being as is shown in Fig. 5.4.

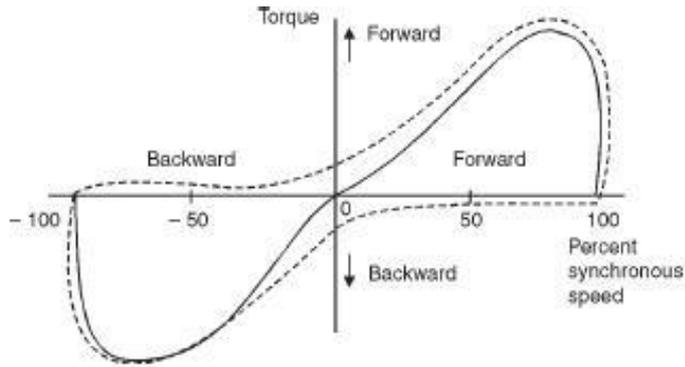


Figure: 5.4. Torque-speed characteristic of a 1-phase induction motor taking into account changes in the flux waves.

In the normal running region at a few per cent slip the forward field is several times stronger than the backward field and the flux wave does not differ materially from the constant

Amplitude revolving field in the air gap of a balanced poly phase motor. Therefore, in the normal running range of the motor, the torque-speed characteristic of a single phase motor is not very much different from that of a poly phase motor having the same rotor and operating with the same maximum air gap flux density.

In addition to the torque shown in Fig. 5.4, double-stator frequency torque pulsation are produced by the interaction of the oppositely rotating flux and mmf waves which move past each other at twice synchronous speed. These double frequency torques produce no average torque as these pulsations are sinusoidal and over the complete cycle the average torque is zero. However, sometimes these are additive to the main torque and for another half a cycle these are subtractive and therefore a variable torque acts on the shaft of the motor which makes the motor noisier as compared to a poly phase induction motor where the total torque is constant. Such torque pulsations are unavoidable in single phase circuits. Mathematically

$$\begin{aligned}
 T &\propto I^2 \cos 2\omega t \\
 T &= K I_m^2 \cos 2\omega t \\
 &= K I_m^2 (1 - \cos 4\omega t) / 2
 \end{aligned}$$

### 5.3.Starting Of Single Phase Induction Motors

The single phase induction motors are classified based on the method of starting method and in fact are known by the same name descriptive of the method. Appropriate selection of these motors depends upon the starting and running torque requirements of the load, the duty cycle and limitations on starting and running current drawn from the supply by these motors. The cost of single phase induction motor increases with the size of the motor and with the performance such as starting torque to current ratio (higher ratio is desirable), hence, the user will like to go in for a smaller size (hp) motor with minimum cost, of course, meeting all the operational requirements. However, if a very large no. of fractional horsepower motors are required, a specific design can always be worked out which might give minimum cost for a given performance requirements. Following are the starting methods.

(a) Split-phase induction motor. The stator of a split phase induction motor has two windings, the main winding and the auxiliary winding. These windings are displaced in space by 90 electrical degrees as shown in Fig. 9.5 (a). The auxiliary winding is made of thin wire (super enamel copper wire) so that it has a high R/X ratio as compared to the main winding which has thick super enamel copper wire. Since the two windings are connected across the supply the

Torque is developed and the motor becomes a self-starting motor. After the motor starts, the auxiliary winding is disconnected usually by means of centrifugal switch that operates at about 75 per cent of synchronous speed. Finally the motor runs because of the main winding. Since this being single phase some level of humming noise is always associated with the motor during Running. A typical torque speed characteristic is shown. It is to be noted that the direction of rotation of the motor can be reversed by reversing the connection to either the main winding or the auxiliary windings. Current  $I_m$  and  $I_a$  in the main winding and auxiliary winding lag behind the supply voltage  $V$ ,  $I_a$  leading the current  $I_m$ . This means the current through auxiliary winding reaches maximum value first and the mmf or flux due to  $I_a$  lies along the axis of the auxiliary winding and after some time ( $t = \pi/\omega$ ) the current  $I_m$  reaches maximum value and the mmf or flux due to  $I_m$  lies along the main winding axis. Thus the motor becomes a 2-phase unbalanced motor. It is unbalanced since the two currents are not exactly 90 degrees apart. Because of these two fields a starting

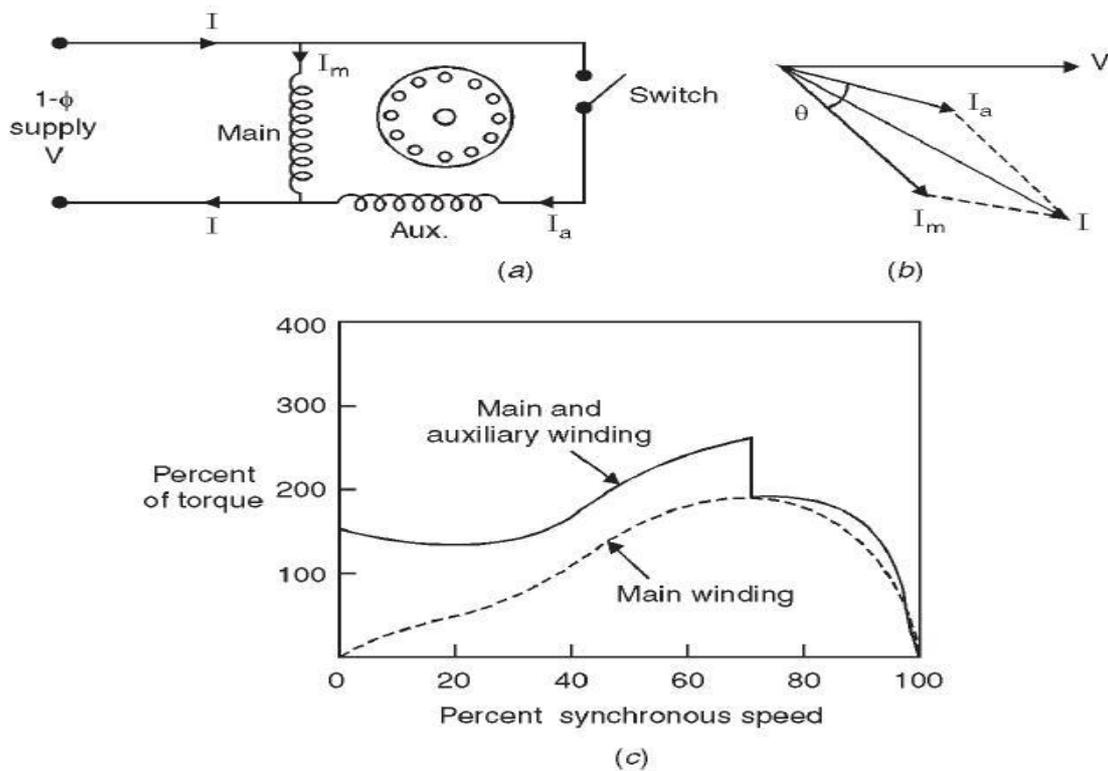


Figure: 5.5. Split phase induction motor (a) Connection

Phasor diagram at starting (c) typical torque-speed characteristic.

**5.4.Capacitor starts induction motor:** Capacitors are used to improve the starting and running performance of the single phase inductions motors. The capacitor start induction motor is also a split phase motor. The capacitor of suitable value is connected in series with the auxiliary coil through a switch such that  $I_a$  the current in the auxiliary coil leads the current  $I_m$  in the main coil by 90 electrical degrees in time phase so that the starting torque is maximum for certain values of  $I_a$  and  $I_m$ . This becomes a balanced 2- phase motor if the magnitude of  $I_a$  and  $I_m$  are equal and are displaced in time phase by 90° electrical degrees. Since the two windings are displaced in space by 90 electrical degrees as shown in Fig. 9.6 maximum torque is developed at start. However, the auxiliary winding and capacitor are disconnected after the motor has picked up t5 per cent of the synchronous speed. The motor will start without any humming noise. However, after the auxiliary winding is disconnected, there will be some humming noise.

Since the auxiliary winding and capacitor are to be used intermittently, these can be designed for minimum cost. However, it is found that the best compromise among the factors of starting torque, starting current and costs results with a phase angle somewhat less than  $90^\circ$  between  $I_m$  and  $I_a$ . A typical torque-speed characteristic is shown in Fig. 5.6 (c) high starting torque being an outstanding feature.

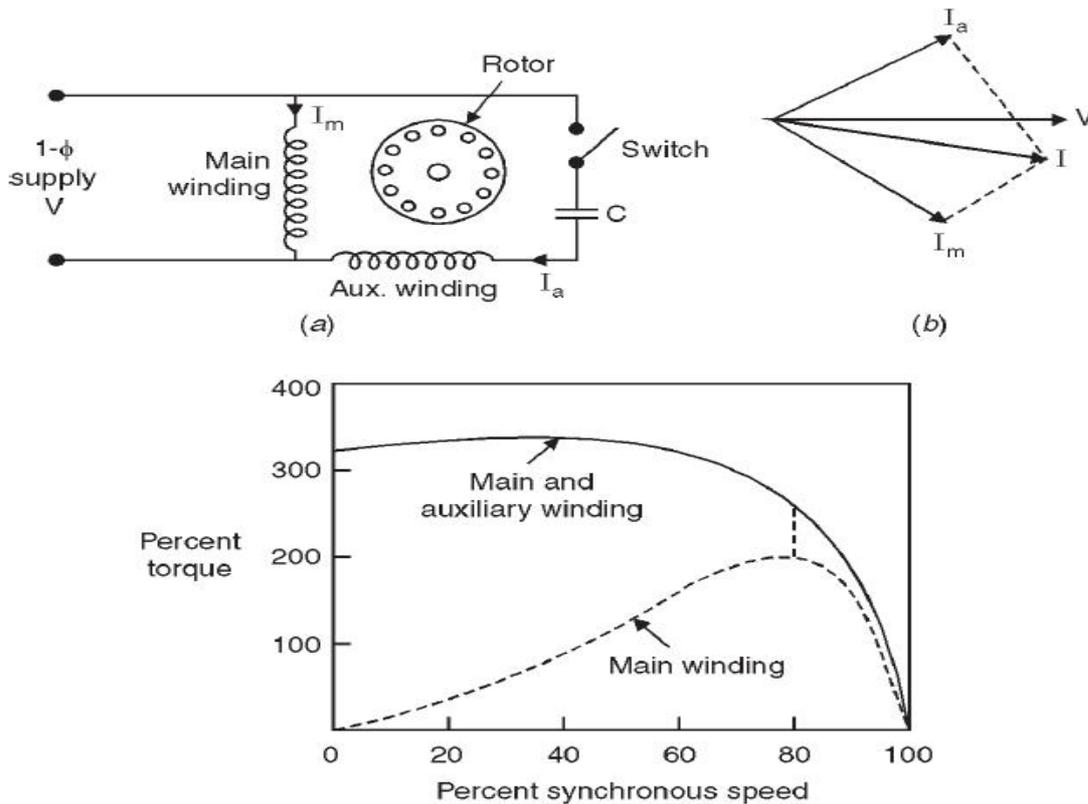


Figure: 5.6. Capacitor start motor (a) Connection

(b) Phasor diagram at start (c) Speed torque curve.

Permanent-split capacitor motor. In this motor the auxiliary winding and capacitor are not disconnected from the motor after starting, thus the construction is simplified by the omission of the switch as shown in Fig. 5.7(a).

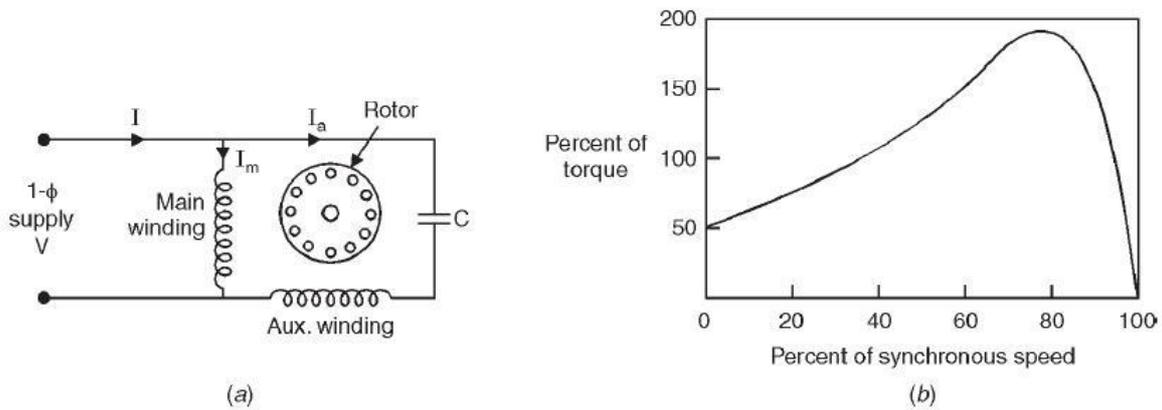


Figure: 5.7. Permanent split capacitor motor (a) Connection (b) Torque-speed characteristic.

Here the auxiliary winding and capacitor could be so designed that the motor works as a perfect 2-phase motor at anyone desired load. With this the backward rotating magnetic field would be completely eliminated. The double stator frequency torque pulsations would also be eliminated, thereby the motor starts and runs as a noise free motor. With this there is improvement in p.f. and efficiency of the motor. However, the starting torque must be sacrificed as the capacitance is necessarily a compromise between the best starting and running characteristics. The torque-speed characteristic of the motor is shown in Fig. 9.7 (b).

(c) Capacitor start capacitor run motor. If two capacitors are used with the auxiliary winding as shown in Fig. 5.8 (a), one for starting and other during the start and run, theoretically optimum starting and running performance can both be achieved.

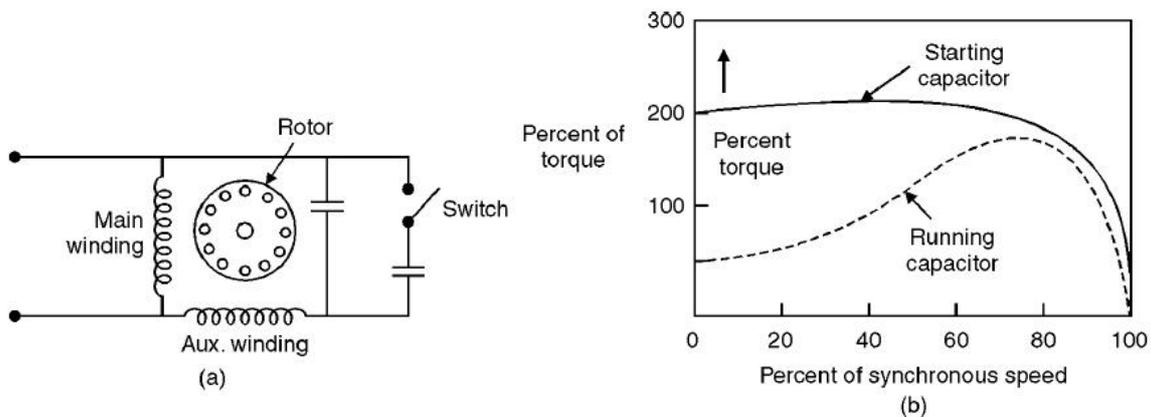


Fig. 5.8. (a) Capacitor start capacitor run motor (b) Torque-speed characteristic.

The small value capacitor required for optimum running conditions is permanently connected in series with the auxiliary winding and the much larger value required for starting is obtained by a capacitor connected in parallel with the running capacitor. The starting capacitor is disconnected after the motor starts.

The value of the capacitor for a capacitor start motor is about  $300 \mu\text{F}$  for  $1/2 \text{ hp}$  motor Since

This capacitor must carry current for a short starting period; the capacitor is a special compact ac Electrolytic type made for motor starting duty. However, the capacitor permanently connected has a typical rating of  $40 \mu\text{F}$  ; since it is connected permanently, the capacitor is an ac paper, foil and oil type. The cost of the motor is related to the performance; the permanent capacitor motor is the lowest cost, the capacitor start motor next and the capacitor start capacitor run has the highest cost.

(c) Shaded pole induction motor. Fig. 5.9 (a) shows schematic diagram of shaded pole induction motor. The stator has salient poles with one portion of each pole surrounded by a short-circuited turn of copper called a shading coil. Induced currents in the shading coil (acts as an inductor) cause the flux in the shaded portion of the pole to lag the flux in the other portion. Hence the flux under the un shaded pole leads the flux under the shaded pole which results in a rotating field moving in the direction from un shaded to the shaded portion of the pole and a low starting torque is produced which rotates the rotor in the direction from un shaded to the shaded pole. A typical torque speed characteristic is shown in Fig. 5.9 (b). The efficiency is low. These motors are the least expensive type of fractional horse power motor and are built up to about  $1/20 \text{ hp}$ . Since the rotation of the motor is in the direction from un shaded towards the shaded part of the pole, a shaded pole motor can be reversed only by providing two sets of shading coils which may be opened and closed or it may be reversed permanently by inverting the core.

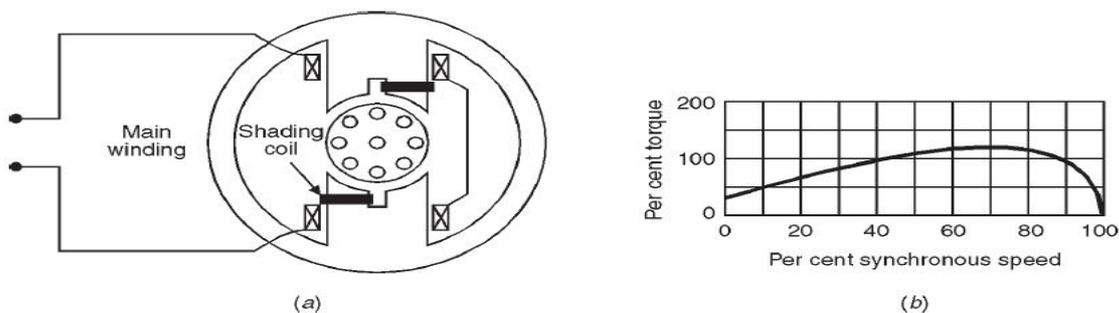


Figure: 5.9. Shaded-pole motor and typical torque-speed characteristic.

### 5.5. Universal Motor

We know that single phase motors are not self starting. We have to provide additional features to make itself starting. The other solution to the single phase problem is to design a d.c. motor so that it will run on a.c. as well. The direction of rotation of a d.c. machine depends upon the polarities of the armature circuit and the field circuit. If a d.c. machine is designed so that (i) when line current reverses direction the field and armature currents reverse simultaneously and (ii) the core loss with alternating flux is relatively low, then a successful single phase machine results.

The first criterion is met by connecting armature and field windings in series. The second is achieved by using a laminated core. A d.c. shunt motor on the other hand cannot be used on a.c. because of high inductance of the field winding as compared to armature winding which causes the field pole reversals to be out of phase with the current reversals in the armature and the result is that the torque is backward during part of each half cycle lowering average torque and reducing the efficiency.

A d.c. series motor designed to operate also on a.c. is called a universal motor as it will run efficiently on any frequency from d.c. upto its design frequency. Fig. 5.10 shows the principle of operation of the motor.

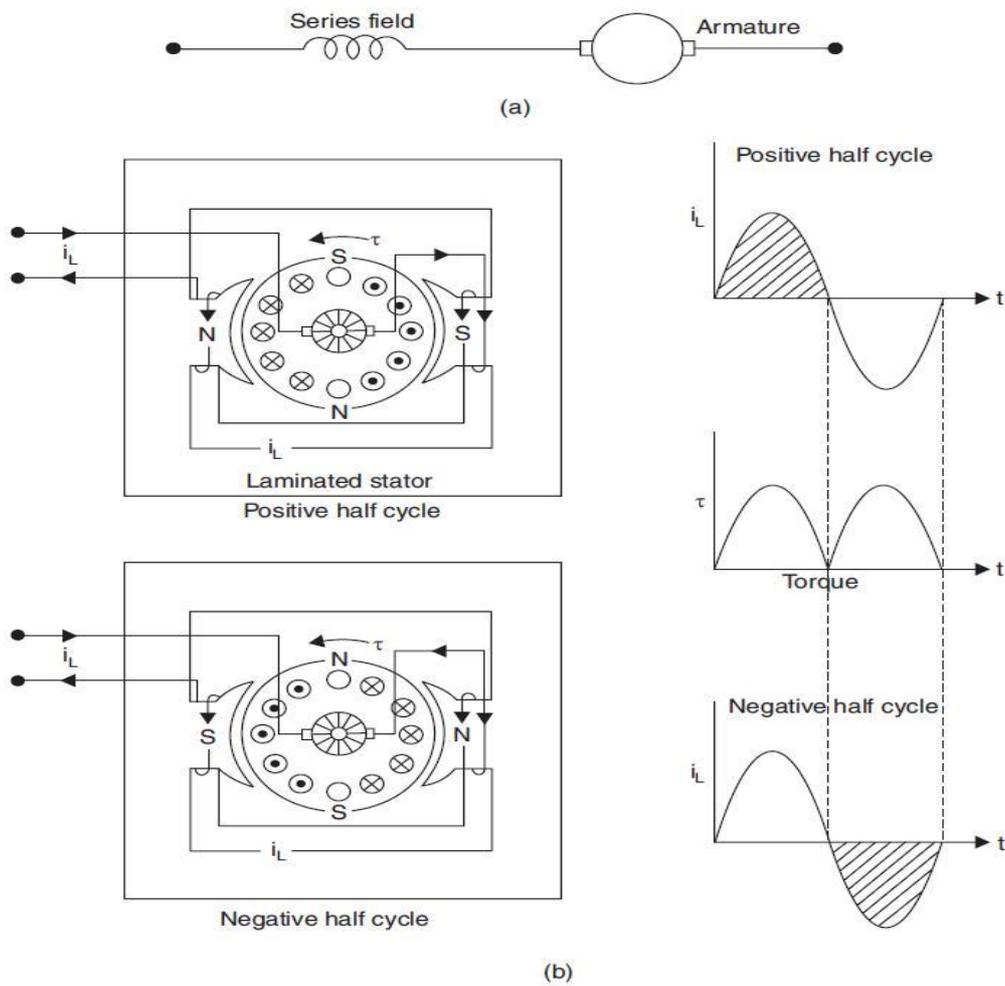


Figure 5.10 The universal motor. (a) Circuit diagram. (b) Principle of operation.

Universal motors are designed for voltages ranging from 32 to 250 volts, frequencies zero to 60Hz and ratings upto 3/4 hp. The average speed is high in the range of 1000 rpm at normal load. The torque/speed characteristic of the motor is shown in Fig. 5.11 No load speed is quite high often in the range of 20,000 rpm. It is limited by windage and friction. Having high speed capability, universal motor of a given horse power rating is significantly smaller than other kinds of a.c. motors operating at the same frequency. Their starting torque is relatively high. These characteristics make universal motors ideal for devices such as hand drills, hand grinders, food mixers, vacuum cleaners and the like which require compact motors operating at speeds greater than 3000/3600 rpm. Universal motors must be designed with weak magnetic fields to minimize commutation difficulties. High resistance carbon brushes are used to limit the circulating current due to the transformer voltage in the short circuited coils.

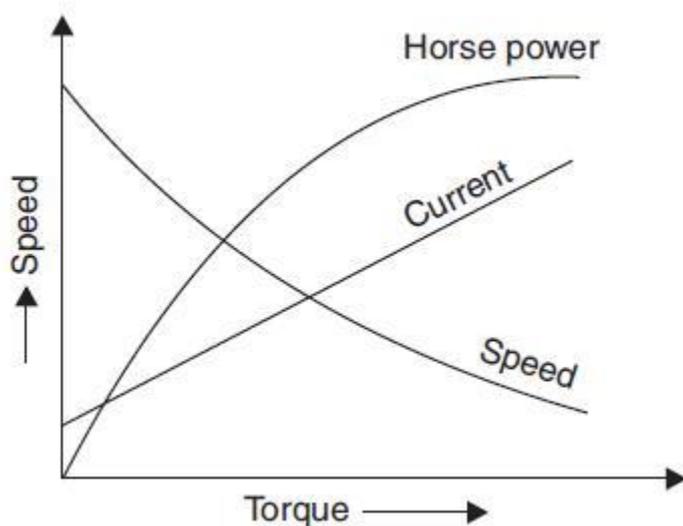


Figure: 5.11 Characteristics of universal motors

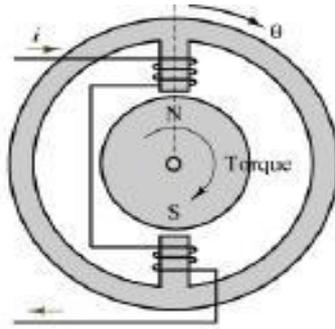
### 5.6. Stepper motors

A special type of synchronous motor which is designed to rotate a specific number of degrees for every electric pulse received by its control unit. Typical steps are  $7.5$  or  $15^\circ$  per pulse. It is a motor that can rotate in both directions, move in precise angular increments, sustain a holding torque at zero speed, and be controlled with digital circuits. It moves in accurate angular increments known as steps, in response to the application of digital pulses to the electric drive circuit.

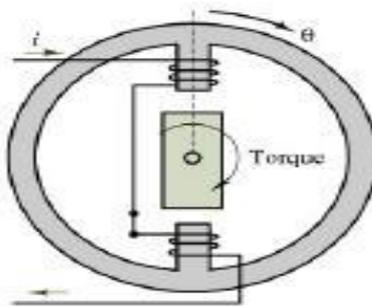
Generally, such motors are manufactured with steps per revolution. Step motors are either bipolar, requiring two power sources or uni polar requiring only one power source.

$$\Theta_m = 2/p * \theta_e$$

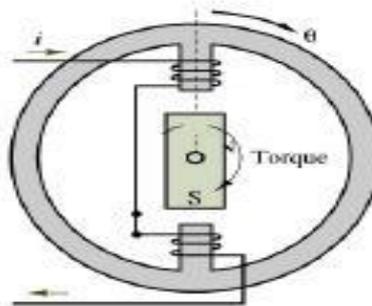
$$\omega_m = 2/p * \omega_e$$



(a) Permanent-magnet stepping motor



(b) Variable-reluctance stepping motor



(c) Hybrid stepping motor

## UNIT WISE QUESTION BANK

### UNIT I: POLY PHASE INDUCTION MOTORS

1	What do you mean by AC three-phase induction motor?
2	On what principle does the induction motor work?
3	What are the types of induction motors?
4	What are the main parts of AC three-phase induction motor?
5	The starting torque of a three-phase induction motor can be increased by increasing what?
6	In a poly phase squirrel-cage induction motor, increased starting torque can be obtained by
7	The ratio among rotor input, rotor output and rotor $Cu$ losses are?
8	How a rotor rotates in an Induction motor? Explain.
9	Discuss about slip in an Induction motor.

#### LONG ANSWER QUESTIONS

1	Describe the principle construction and operation of Induction motor.
2	Discuss the various losses taking place in IM. Explain the effect of slip on the Performance of IM.
3	Derive the torque equation of an induction motor. Mention the condition for maximum torque.
4	Describe how rotating magnetic field is developed in induction motor.
5	Discuss the following (a) How torque is developed in the rotor of a induction motor. (b) Why in some induction motors double cages are provided?
6	Why the rotor of a poly phase induction motor can never attain synchronous speed? Discuss.
7	Describe the constructional features of both slip ring and squirrel cage induction motor. Discuss the merits of one over the other.
8	With neat diagram describe the equivalent circuit of 3phase Double Cage IM.
9	Draw the phasor diagram of an Induction motor and explain.
10	With a neat sketch discuss the principle of operation of double cage Induction motor Briefly explain the torque slip characteristics of an Induction motor.

#### ANALYTICAL QUESTIONS

1	The frequency of stator EMF is 50 Hz for an 8-pole induction motor. If the rotor frequency is 2.5 hz, calculate the slip and the actual speed of rotor.
2	An 8 pole, 3phase alternator is coupled to a prime mover running at 750 rpm. It supplies an induction motor which has a full load speed of 960 rpm. Find the number of poles of IM and slip
3	In case of an 8-pole induction motor the supply frequency was 50 Hz and the shaft speed was 735 rpm. Compute (i) Synchronous speed (ii) Slip speed per unit slip (iii) Percentage slip.
4	A 3- $\phi$ induction motor is wound for 4 poles and is supplied from 50Hz system. Calculate i) Synchronous speed ii) Rotor speed, when slip is 4% iii) Rotor frequency when rotor runs at 60 rpm.

**UNIT – II**  
**CHARACTERISTICS OF INDUCTION MOTORS & SPEED CONTROL**  
**METHODS**

**SHORT ANSWER TYPE QUESTIONS**

1	What are the advantages of auto transformer starting?
2	What are the advantages of slip ring IM over squirrel cage IM?
3	What is meant by cascade operation?
4	Discuss about direct online starting of an IM?
5	How do changes in supply voltages and frequency affect the performance of an IM?
6	Why no-load current of an Induction motor is much higher than that of an equivalent transformer?
7	In what ratio line current and starting torque is reduced with star-starting? <span style="float: right;">delta</span>
8	On what factors does the speed of an Induction motor depends?
9	Why the induction generator is often called as asynchronous generator?
10	What is the application for Induction generators?

**LONG ANSWER QUESTIONS**

1	With neat diagram discuss the various tests to be conducted on 3phase IM to plot the circle diagram.
2	Compare DOL starter, Auto transformer starter & Rotor resistance starter with relate to the following: (i) starting current (ii) starting torque

8	Two 50 Hz, 3 phase Induction motors having six and four poles respectively are cumulatively cascaded, the 6 pole motor being connected to the main supply. Determine the frequency of the rotor currents and the slips referred to each stator field if the set has a slip of 2%.
9	A 50 KVA, 400V, 3 phase, 50 Hz squirrel cage Induction motor has full load slip of 5%. Its standstill impedance is 0.866 ohms per phase. It is started using a tapped auto transformer. If the maximum allowable supply current at the time of starting is 100A, calculate the tap position and the ratio of starting torque to full load.
10	A three-phase delta-connected cage type induction, motor when connected directly to a 400 V, 50Hz supply, takes a starting current of 100 A, in each stator phase. Calculate i) The line current for direct-on-line starting.

S.No	QUESTION	BLOOMS TAXONOMY LEVEL
<b>UNIT-III</b> <b>CONSTRUCTION, PRINCIPLE OF OPERATION</b> <b>CHARACTERISTICS &amp; REGULATION OF SYNCHRONOUS GENERATOR</b> <b>SHORT ANSWER QUESTION</b>		
1	State different type of synchronous generators used in hydro electrical power station.	Evaluate
2	What are the main parts of synchronous generator	Remember
3	Write the EMF equation of an Alternator.	Remember
4	What is the speed of a 4 pole 50Hz Synchronous machine?	Remember
5	Define Synchronous speed.	Remember
6	How can a DC generator be converted into an alternator?	Remember
7	Discuss about armature reaction in synchronous generator	Understand
8	Define distribution factor.	Understand
9	Define pitch factor.	Remember
10	Define winding factor.	Remember
11	Define the following a) Short pitch winding b) Full pitch winding	Understand
12	Define the following a) Concentrated winding b) Distributed winding	Understand

13	Define the following a) Single layer winding b) Double layer winding	Understand
14	Explain effect of changing the power factor on terminal voltage by keeping the Load current, Field current and Speed constant	Understand
15	Draw the equivalent circuit for three phase alternator	Remember

**LONG ANSWERS QUESTIONS**

1	Deduce the relation between the number of poles, the frequency and the speed of the synchronous generator	Apply
2	What are the causes of harmonics in the voltage waveform of an alternator?	Understand
3	What is an armature reaction? Explain its effect on the terminal voltage of an alternator at unity power factor load.	Understand
4	In brief, derive an expression for the winding factor of an alternator	Apply
5	Derive EMF equation of an alternator	Apply
6	Discuss about the determination of synchronous reactance of an alternator	Understand
7	Draw the load characteristics of synchronous generator and describe the same	Apply
8	What is the difference between integral slot and fractional slot windings	Understand
9	With phasor diagram, discuss about the leakage reactance of synchronous generator	Apply
10	Compute the distribution factor for a 36-slot, 4-pole, single-layer 3-Phase winding.	Apply
11	Compute the distribution factor for a 60-slot, 12-pole, single-layer 3-Phase winding.	Apply
12	Derive EMF equation and describe how the induced 'emf' in armature winding is affected by (a) form factor (b) pitch factor and (iii) distribution factor	Apply
13	Explain the alternator on load for different power factors	Understand
14	Explain the harmonic suppression techniques	Understand
15	Explain slot and space harmonics in alternator	Understand

**ANALYTICAL QUESTIONS**

1	Calculate the speed and open-circuit line and phase voltages of a 4-pole, 3-phase, 50Hz star-connected alternator with 36 slots and 30 slots 30 conductors per slot. The flux per pole is 0.05wb.	Evaluate
2	A 4-pole, 50Hz star-connected alternator has a flux per pole of 0.12wb. it has 4 slots per pole per phase, conductors per slot being 4. if the winding coil span is $150^\circ$ , find the emf.	Apply

3	A 3-phase,8-pole,750rpm star-connected alternator has 72 slots on the armature. Each slot has 12 conductors and winding is short-pitched by 2 slots. Find the induced emf between lines, given the flux per pole is 0.06wb	Apply
4	An 8-pole,3-phase,60 <sup>0</sup> spread, double layer winding has 72 coils in 72 slots. The coils are short-pitched by two slots. Calculate the winding factor for the fundamental and third harmonic.	Evaluate
5	The stator of a 3-phase, 20-pole alternator has 120 slots and there are 4 conductors per slot accommodated in two layers. If the speed of the alternator is 300rpm, calculate the emf induced per phase. Resultant flux in the air-gap is 0.05 wb per pole. Assume the coil span as 160 <sup>0</sup> electrical.	Evaluate
6	A star-connected, 3-phase,6-pole alternator has a stator with 90 slots and 8 conductors per slot. The rotor revolves at 1000rpm. The flux per pole is $4 \times 10^{-2}$ wb. Calculate the emf generated if all the conductors in each phase are in series. Assume sinusoidal flux distribution and full-pitched coils.	Evaluate
7	A 16 pole, 3-phase alternator has a star-connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.03wb distributed sinusoidal and the speed is 375 rpm. Find the line voltage, if the coil span is 150 <sup>0</sup> elec.	Apply
8	A 3-phase, 16-pole alternator has the following data: number of slots=192, conductors per slot=8, coil span 10 slots; speed of alternator=375rpm; flux per pole =55mwb.calculate the phase and line voltage.	Evaluate
9	For a 3-Ø winding with 4 slots per pole phase and with the coil span of 10 slot pitch, calculate the values of the distribution factor and coil span factor.	Evaluate
10	An 8-pole ac generator is running at 750rpm. What is the frequency? At what speed must the generator be run so that frequency shall be 25hz?	Apply
11	A 6-pole, 50hz star-connected alternator has a flux per pole of 0.15wb. It has 6 slots per pole per phase, conductors per slot being 4.if the winding coil span is 150 <sup>0</sup> , find the emf.	Apply
12	The stator of a 3-phase, 24-pole alternator has 120 slots and there are 4 conductors per slot accommodated in two layers. If the speed of the alternator is 500rpm, calculate the emf induced per phase. Resultant flux in the air-gap is 0.06 wb per pole. Assume the coil span as 140 <sup>0</sup> electrical.	Evaluate
13	A star-connected, 3-phase, 6-pole alternator has a stator with 90 slots and 6 conductors per slot. The rotor revolves at 1200rpm. The flux per pole is $4 \times 10^{-5}$ wb. Calculate the emf generated if all the conductors in each phase are in series. Assume sinusoidal flux distribution and full-pitched coils.	Evaluate
14	A 16 pole, 3-phase alternator has a star-connected winding with 144 slots and 8 conductors per slot. The flux per pole is 0.03wb distributed sinusoidal and the speed is 500 rpm. Find the line voltage, if the coil span is 145 <sup>0</sup> elec.	Apply
15	A 3-phase, 16-pole alternator has the following data: number of slots=192, conductors per slot=6, coil span 10 slots; speed of alternator=475rpm; flux per pole =45mwb.calculate the phase and line voltage.	Evaluate

### REGULATION OF SYNCHRONOUS GENERATOR

#### SHORT ANSWER QUESTION

1	Write different methods for determining the voltage regulation of synchronous generator.	Remember
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2	Define regulation of Alternator.	Remember
3	What are the components of synchronous impedance?	Remember
4	Discuss the importance of synchronous impedance method	Remember
5	Discuss two reaction analysis	Remember
6	Define $X_d$ and $X_q$	Remember
7	Why voltage regulation calculated by Potier's method is somewhat lower?	Remember
8	What are the parameters can be determined from slip test	Understand
9	What are the differences between MMF and EMF methods	Understand
10	Distinguish between salient pole and cylindrical rotor synchronous generators?	Remember
11	Advantages of EMF method	Remember
12	Advantages of MMF method	Remember
13	Advantages of Potier triangle method	Remember
14	Explain about leakage reactance	Understand
15	Advantages of ASA method	Remember

**LONG ANSWERS QUESTIONS**

1	Discuss in brief, how voltage regulation can be computed by synchronous impedance method	Understand
2	Discuss in brief about the two-reaction analysis of a salient-pole synchronous machine	Understand
3	With relevant waveforms and connection diagram, describe the slip test of synchronous machine	Apply
4	What is the significance of zero power-factor characteristics of an alternator? Discuss in brief to obtain the same	Apply
5	Describe why, synchronous impedance method of computing the voltage regulation, leads to a pessimistic value at lagging power factor loads	Understand
6	Describe how, open-circuit and short-circuit tests are conducted on a synchronous machine	Understand
7	Discuss in brief, how voltage regulation can be computed by MMF method.	Understand
8	Discuss in brief, how voltage regulation can be computed by ASA method.	Understand
9	Discuss in brief, how voltage regulation can be computed for salient pole alternators.	Understand

10	A synchronous generator has $X_d=0.75$ pu and $X_q=0.5$ pu. It is supplying full-load at rated voltage at 0.8 lagging power factor. Draw the phasor diagram and compute the excitation emf	Apply
11	Discuss in brief, how voltage regulation can be computed by EMF method.	Understand
12	A 3-phase, star-connected alternator is rated at 1300kva, 14500v. The armature resistance and synchronous reactance are $1.56 \Omega$ and $35\Omega$ respectively per phase. Calculate the percentage regulation for a load of 1380kw at 0.86leading power factor	Evaluate
13	A 3-phase, star-connected alternator is rated at 1400kva, 15500v. The armature resistance and synchronous reactance are $1.58 \Omega$ and $36\Omega$ respectively per phase. Calculate the percentage regulation for a load of 1180kw at 0.9leading power factor	Evaluate
14	A synchronous generator has $X_d=0.7$ pu and $X_q=0.4$ pu. It is supplying full-load at rated voltage at 0.85 lagging power factor. Draw the phasor diagram and compute the excitation emf	Apply
15	A 3-phase, star-connected alternator is rated at 1200kva, 14500v. The armature resistance and synchronous reactance are $1.49 \Omega$ and $20\Omega$ respectively per phase. Calculate the percentage regulation for a load of 1380kw at 0.95leading power factor	Evaluate
<b>ANALYTICAL QUESTIONS</b>		
1	A 3-phase star-connected synchronous generator is rated at 1.4MVA, 11KV. The armature effective resistance and synchronous reactance are $1.2 \Omega$ and $25\Omega$ respectively per phase. Calculate the percentage voltage regulation for a load of 1.4375MVA at (i) 0.8pf lagging and (ii) 0.8pf leading. Also find out the pf at which the regulation becomes zero.	Evaluate
2	A 3-phase, star-connected alternator is rated at 1600kva, 13500v. The armature resistance and synchronous reactance are $1.5 \Omega$ and $30\Omega$ respectively per phase. Calculate the percentage regulation for a load of 1280kw at 0.8leading power factor.	Evaluate
3	From the following test results, determine the regulation of a 2 KV single phase alternator, delivering a current of 100 A at 0.8 p.f. leading test results; full load current of 100 A is produced on short circuit by a field excitation of 2.5 A. An emf of 500 V is produced on open circuit by the same field current. The armature resistance is 0.8 ohms.	Apply
4	A three phase star connected 1000 KVA, 11000 V alternator has rated current of 52.5 A the ac resistance of the winding per phase is 0.45 Ohms. The test results are given below; OC test : field current = 12.5 A, voltage between lines = 422 V. SC test: field current = 12.5 A , line current = 52.5 A determine the full load voltage regulation of the alternator a) 0.8 p.f. lagging b) 0.8 p.f. leading	Evaluate
5	A)A three phase star connected, 5KVA, 400 V, 50 Hz, 4-pole alternator has the following test data at rated speed i) exciting current      0.5   1                      1.5   2   2.5   3   3.5   4   4.5   5   6   8 Per phase OC Volts 75 140 173 202 224 270 250 257 260 263 266 271 ii) exciting current      1   2                      3 SC line current              3.6 7.2 10.8 iii) Armature resistance per phase is 2 ohms Draw OC and SC characteristics on a graph paper and then determine unsaturated value of synchronous reactance per phase and in per unit. B) For the same synchronous machine, a) determine percentage voltage regulation at rated load at 0.8 p.f. lag and lead by synchronous impedance method under unsaturated condition. Draw relevant phasor diagrams.	Apply

6	<p>A 3-phase star-connected, 1000kva, 2000v, 50hz alternator gave the following open-circuit and short circuit test readings:                  Field current(amp):                   10 20   25 30   40 50                  Open-circuit voltage(v):           800 1500 1760 2000 2350 2600                  Short-circuit current(amp):- 200       250   300 - -                  Draw the characteristic curves and estimate the full-load percentage regulation at i) 0.8 p.f. lagging and (ii) 0.8 p.f. leading. the armature resistance per phase may be taken as 0.2Ω.use mmf method</p>	Apply
7	<p>A 3-phase synchronous generator has per phase a direct axis synchronous reactance of 1.0p.u. And a quadrature axis synchronous reactance of 0.65 pu. Draw a phasor diagram of the machine when operating at full-load at a pf 0.8 lagging and estimate from there (i) the load angle and (ii)pu no-load emf. Neglect armature resistance.</p>	Apply
8	<p>A 3.5 MVA, slow speed,3-phase synchronous generator rated at 6.6kv has 62 poles. It's direct and quadrature axis synchronous reactance as measured by the slip test is 9.6 and 6 Ω respectively. Neglect armature resistance ; determine the regulation and excitation emf needed to maintain 6.6kv at the terminals when supplying a load of 2.5MW at 0.8pf lagging. What maximum power can generator supply at the rated terminal voltage, if the field becomes open-circuited?</p>	Evaluate
9	<p>A 10kva, 380v, 50hz, 3-phase, star-connected salient pole alternator has direct axis and quadrature axis reactance of 12Ω and 8Ω respectively. The armature has a resistance of 1Ω per phase. The generator delivers rated load at 0.8pf lagging with the terminal voltage being maintained at rated value. If the load angle is 16.15°, determine (i) the direct axis and quadrature axis components of armature current (ii) exciting voltage of the generator.</p>	Apply
10	<p>The following data pertains to a 15000 kva,11kv,3-phase,50hz,star-connected turbo-alternator:                  OC line kv                               :4.9 8.4   10.1   11.5 12.8 13.3   13.65                  Field AT in 10<sup>3</sup>                       :10   18   24       30   40   45   50                  Zero p.f. full-load line kv : -       0 - -       -   10.2 -                  Determine: (i) armature reaction (ii) armature reactance (iii) synchronous reactance (iv) percentage regulation for full-load at 0.8 p.f. lagging.</p>	Apply
11	<p>A three phase star connected 1200 KVA, 12000 V alternator has rated current of 52.5 A the ac resistance of the winding per phase is 0.45 Ohms. The test results are given below; OC test : field current = 12.56 A, voltage between lines = 532 V. SC test: field current = 12.56 A , line current = 52.55 A determine the full load voltage regulation of the alternator a) 0.8 p.f. lagging b) 0.8 p.f. leading</p>	Evaluate
12	<p>A)A three phase star connected, 5KVA, 400 V, 50 Hz, 4-pole alternator has the following test data at rated speed                  i) exciting current                   0.55 1           1.5 2 2.5   3 3.5 4   4.5 5 6 8                  Per phase OC Volts 75 130 173 202 224 270 252 257 260 263 266 270                  ii) exciting current                   1   2   3                  SC line current                       3.65 7.210.8                  iii) Armature resistance per phase is 2 ohms                  Draw OC and SC characteristics on a graph paper and then determine unsaturated value of synchronous reactance per phase and in per unit.                  B) For the same synchronous machine, a) determine percentage voltage regulation at rated load at 0.86 p.f. lag and lead by synchronous impedance method under unsaturated condition. Draw relevant phasor diagrams.</p>	Apply

13	A 5 MVA, slow speed, 3-phase synchronous generator rated at 6.5kv has 62 poles. It's direct and quadrature axis synchronous reactance as measured by the slip test is 10 and 5 $\Omega$ respectively. Neglect armature resistance; determine the regulation and excitation emf needed to maintain 6.6kv at the terminals when supplying a load of 2.55MW at 0.8pf lagging. What maximum power can generator supply at the rated terminal voltage, if the field becomes open-circuited?	Evaluate
14	A 15kva, 480v, 50hz, 3-phase, star-connected salient pole alternator has direct axis and quadrature axis reactance of 22 $\Omega$ and 9 $\Omega$ respectively. The armature has a resistance of 1 $\Omega$ per phase. The generator delivers rated load at 0.85pf lagging with the terminal voltage being maintained at rated value. If the load angle is 16.25 <sup>o</sup> , determine (i) the direct axis and quadrature axis components of armature current (ii) exciting voltage of the generator.	Apply
15	A 6 MVA, slow speed, 3-phase synchronous generator rated at 3.3kv has 62 poles. It's direct and quadrature axis synchronous reactance as measured by the slip test is 10 and 8 $\Omega$ respectively. Neglect armature resistance; determine the regulation and excitation emf needed to maintain 3.3v at the terminals when supplying a load of 2.8MW at 0.89pf lagging. What maximum power can generator supply at the rated terminal voltage, if the field becomes open-circuited?	Evaluate

**UNIT-IV**  
**PARALLEL OPERATION OF SYNCHRONOUS GENERATOR**  
**SYNCHRONOUS MOTORS**

**SHORT ANSWER QUESTION**

1	Write synchronous power equation for cylindrical pole rotor machine.	Understand
2	What are the conditions for parallel operation of alternators?	Understand
3	What is Power angle of an alternator?	Remember
4	What is an infinite bus?	Remember
5	A machine with large air-gap has a higher synchronizing power, why?	Remember
6	Define sub-transient of AC generators.	Remember
7	What is the effect of varying excitation of an alternator running in parallel with other alternator	Understand
8	How will the power angle and power factor of a 3-phase alternator supplying power to an infinite bus at constant excitation change if the steam input is reduces?	Remember

9	At what power angle a synchronous generator will develop maximum power?	Remember
10		
11	Write synchronous power equation for salient pole rotor machine.	Understand
12	What is the synchronizing power?	Remember
13	Define transient of AC generators.	Remember
14	Define steady-state reactances of AC generators.	Remember
15	What is an infinite bus? Mention three conditions to be satisfied prior to synchronizing an alternator to an infinite bus.	Remember

**LONG ANSWERS QUESTIONS**

1	Derive expression for synchronizing power when two alternators are connected in parallel.	Apply
2	Describe the factors which affect the sharing of load between two alternators operating in parallel. .	Understand
3	Why bright lamp method is preferred over dark lamp method for synchronizing of alternators.	Understand
4	Discuss in brief about the short-circuit transient in synchronous machine	Understand
5	Describe the factors which affect the sharing of load between two alternators operating in parallel.	Understand
6	Derive expressions for synchronizing power and synchronizing torque when two AC generators are connected in parallel	Apply
7	Describe with relevant diagram, dark lamp method of synchronizing two 3-phase alternators	Understand
8	Describe with relevant diagram, bright lamp method of synchronizing two 3-phase alternators	Understand
9	Discuss the use of Synchro scope in the parallel operation of alternators.	Understand

10	Two single-phase generators operate in parallel on a load impedance of $Z$ ohms. Their emfs are $E_1$ and $E_2$ and their synchronous impedances $Z_1$ and $Z_2$ . Deduce the terminal voltage in terms of these and admittances $Y, Y_1$ and $Y_2$	Understand
11	Derive expression for synchronizing torque when two alternators are connected in parallel.	Apply
12	How do you calculate the time constants in case of an alternator?	Apply
13	Show that the behavior of a synchronous machine on infinite bus is quite different from its isolated operation.	Understand
14	What is an infinite bus? State the characteristics of an infinite bus. What are the operating characteristics of an alternator connected to an infinite bus?	Understand
15	Discuss the load shearing between two alternators.	Understand
1	Two identical 2MVA alternators operate in parallel. The governor of first machine is such that the frequency droops uniformly from 50hz on no-load to 47.5 Hz on full-load.the corresponding uniform speed droop of the second machine is 50hz to 48hz. How will they share a load of 3MW?	Evaluate
2	Two identical 3-phase alternators work in parallel and supply a total load of 1600kw at 11000v at a power factor of 0.92. Each machine supplies half the total power. The synchronous reactance of each is 50 ohm per phase and resistance is 2.5 ohm per phase. The field excitation of the first machine is adjusted so that armature current is 50A lagging. Determine the armature current of the second alternator, the power factor at which each is working and generated voltage of the first alternator?	Evaluate
3	A 2000KVA, 3-phase,8-pole alternator runs at 750rpm in parallel with other machines on 6000v bus-bars. Find synchronizing power on full load 0.8 pf lagging per mechanical degree of displacement and the corresponding synchronizing torque. The synchronous reactance is 6 ohms per phase.	Evaluate
4	Two identical 2 MVA alternators operate in parallel. The governor of first machine is such that the frequency drops uniformly from 50 Hz on no-load to 47.5 Hz on full-load. The corresponding uniform speed drop of the second machine is 50 Hz to 48 Hz. How will they share a load of 3 MW?	Evaluate
5	A 3 MVA, 6-pole alternator runs at 1000rpm on 3.3kv bus-bars.the synchronous reactance is 25%.calculate the synchronous power and torque per mechanical degree of displacement when the alternator is supplying full-load at 0.8 pf lag.	Apply
6	A 2000kva, 3-phase,8-pole alternator runs at 750rpm in parallel with other machines on 6000v bus-bars. Find synchronous power on full-load 0.8 pf lagging per mechanical degree of displacement and the corresponding synchronizing torque. The synchronous reactance is 6 ohms per phase.	Apply

7	A 2-pole, 50hz, 3-phase, turbo-alternator is excited to generate the bus-bar voltage of 11kv on no-load. Calculate the synchronizing power per degree of mechanical displacement of the rotor and the corresponding synchronizing torque. The machine is star-connected and the short- circuit current for this excitation is 1200 amperes.	Apply
8	Two identical 3-phase alternators work in parallel and supply a total load of 1600kw at 11000V at a power factor of 0.92. Each machine supplies half the total power. The synchronous reactance of each is 50 ohms/phase and resistance is 2.5 ohms/phase. The field excitation of the first machine is adjusted so that armature current is 50A lagging. Determine the armature current of the second alternator, the power factor at which each machine is working and generated voltage of the first alternator.	Evaluate
9	A 10mva, 10 kv, 3-phase, 50hz, 1500 rpm alternator is parallel with others of much greater capacity. The moment of inertia of the rotor is $2 \times 10^3 \text{ kg-m}^2$ and the synchronous reactance of the machines is 40%. Calculate the frequency of oscillation of the rotor.	Apply
10	A 100 MVA, 22 KV, 50 Hz synchronous generator is operating open circuited and is excited to give rated terminal voltage. A 3-phase short circuit develops at its terminals. Neglecting DC and double frequency components of current	Apply
11	A 3000KVA, 3-phase, 8-pole alternator runs at 850rpm in parallel with other machines on 8000v bus-bars. Find synchronizing power on full load 0.86 pf lagging per mechanical degree of displacement and the corresponding synchronizing torque. The synchronous reactance is 8 ohms per phase.	Evaluate
12	Two identical 2 MVA alternators operate in parallel. The governor of first machine is such that the frequency drops uniformly from 50 Hz on no-load to 47.5 Hz on full-load. The corresponding uniform speed drop of the second machine is 50 Hz to 48 Hz. How will they share a load of 4 MW?	Evaluate
13	A 3 MVA, 6-pole alternator runs at 1000rpm on 3.3kv bus-bars.the synchronous reactance is 28%.calculate the synchronous power and torque per mechanical degree of displacement when the alternator is supplying full-load at 0.85 pf lag.	Apply
14	A 2000kva, 3-phase, 8-pole alternator runs at 950rpm in parallel with other machines on 6000v bus-bars. Find synchronous power on full-load 0.82 pf lagging per mechanical degree of displacement and the corresponding synchronizing torque. The synchronous reactance is 7 ohms per phase.	Apply
15	Two identical 3-phase alternators work in parallel and supply a total load of 1200kw at 12000V at a power factor of 0.95. Each machine supplies half the total power. The synchronous reactance of each is 55 ohms/phase and resistance is 2.55 ohms/phase. The field excitation of the first machine is adjusted so that armature current is 52A lagging. Determine the armature current of the second alternator, the power factor at which each machine is working and generated voltage of the first alternator.	Evaluate

**SYNCHRONOUS MOTORS AND POWER CIRCLES**

**SHORT ANSWER QUESTION**

1	What are the main parts of synchronous motor?	Remember
2	Discuss why synchronous motor has no starting torque.	Understand

3	What is synchronous capacitor?	Remember
4	Synchronous motor always runs at synchronous speed why?	Remember
5	What is hunting?	Remember
6	What are V-Curves and inverted V curves?	Remember
7	What are the uses of damper windings in a synchronous motor?	Remember
8	How do you operate the synchronous motor at any desired pf?	Understand
9	What will be the pf when the synchronous motor is operated at under excited conditions?	Remember
10	What are the different methods of starting synchronous motor?	Remember
11	Why Synchronous motors are not self starting? Explain.	Understand
12	What are the uses of damper winding in a synchronous motor?	Remember
13	What is a synchronous condenser? What is the use of synchronous condenser?	Understand
14	Why it is necessary to increase the excitation to obtain minimum current with application of load?	Understand
15	What are the applications of synchronous motor?	Understand

**LONG ANSWERS QUESTIONS**

1	Describe in brief the principle of operation of synchronous motor	Understand
2	Draw and discuss the phasor diagrams of a 3-phase synchronous motor for lagging, leading and unity power factor conditions. Name all the phasors.	understand
3	What do you mean by constant power circle for synchronous motor? How it is derived?	Apply

4	Name different methods of starting a synchronous motor, explain any one in detailed.	Remember
5	Derive an expression of mechanical power developed for a synchronous motor in terms of E & V	Understand
6	Mention the various applications of synchronous motor and describe the functions of a damper winding in a synchronous motor	Apply
7	What could be the reasons if a 3-phase synchronous motor fails to start?	Understand
8	Write a short note on synchronous induction motor	Remember
9	Derive the expression for power developed in a synchronous motor, various conditions for maximum power developed	Apply
10	Describe how a synchronous motor can be operated as a synchronous condenser.	Understand
11	Find an expression for power in terms of load angle, for a salient pole synchronous motor working at a lagging pf. Armature resistance may be neglected.	Understand
12	Show that the current locus of a synchronous motor developing constant power is a circle. Determine its center and radius.	Apply
13	What are the advantages and disadvantages of the Synchronous motor?	Remember
14	Explain the power circle diagram of the synchronous motor.	Understand
15	Explain the characteristic features of a synchronous motor.	Understand

**ANALYTICAL QUESTIONS**

1	A 2.3 kV, 3-phase, star-connected synchronous motor has $Z_s=(0.2+j2.2)$ $\Omega$ /phase. The motor is operating at 0.5 power factor leading with a line current of 200 A. Determine the generated emf per phase	Apply
2	A 3-phase, 415V, 6-pole, 50Hz, star-connected synchronous motor has emf of 520V(L-L). the stator winding has a synchronous reactance of 2ohms per phase and the motor develops a torque of 220N-m. the motor is operating at 415V, 50Hz bus (a) calculate the current drawn from the supply and it's power factor (b) draw the phasor diagram showing all the relevant quantities.	Apply

3	A 500v,6-pole,3-phase,50hz,star-connected synchronous motor has a resistance and synchronous reactance of $0.3\Omega$ and $3\Omega$ per phase respectively. The open-circuit voltage is 600v. If the friction and core losses total 1kw,calculate the line current and power factor when the motor output is 100hp.	Evaluate
4	A 50hz,4-pole,3- $\bar{O}$ ,star-connected synchronous motor has a synchronous reactance of $12.0\Omega$ /phase and negligible armature resistance. The excitation is such as to give an open-circuit voltage of 13.2kv.the motor is connected to 11.5kv, 50hz supply. What maximum load can the motor supply before losing synchronism? What is the corresponding motor torque, line current and power factor?	Evaluate
5	The excitation of a 415v,3-phase,mesh connected synchronous motor is such that the induced emf is 520v.the impedance per phase is $(0.5+j4.0)\Omega$ . if the friction and iron losses are constant at 1000watts,calculate the power output, line current, power factor and efficiency for maximum power output?	Apply
6	A 75 kw 3phase Y connected, 50Hz,440V cylindrical rotor synchronous motor operates at rated condition with 0.8pf leading. The motor efficiency excluding field and stator losses, is 95% and $X_s=2.5\bar{U}$ calculate (i) mechanical power developed (ii) armature current (iii) back emf (iv) power angle and (v)max or pull out toque of the motor.	Evaluate
7	A 3 phase 150kw 2300v 50Hz 1000rpm salient pole synchronous motor has $X_d=32\text{ohms/ph}$ and $X_q=20\text{ohm/ph}$ . Neglecting losses ,calculate the torque developed by the motor if field excitation is so adjusted as to make the back emf twice the applied voltage and $\alpha=60^\circ$ .	Evaluate
8	A 3300v, 1.5 Mw, 3 phase, Y connected synchronous motor has $X_d=4\text{ohm/ph}$ and $X_q=3\text{ohm/ph}$ . Neglecting losses, calculate the excitation emf when motor supplies rated load at upf. Calculate the maximum mechanical power which the motor would develop for this field excitation.	Evaluate
9	The input to an 11000V, 3 phase star connected synchronous motor is 60A. The effective resistance and synchronous reactance per phase are respectively 1 ohm and 30ohms. Find (i) the power supplied to the motor (ii) mechanical power developed and (iii) induced emf for a power factor of 0.8 leading	Apply
10	A synchronous motor having 40% reactance and a negligible resistance is to be operated at rated load at (i) upf (ii) 0.8 pf lag (iii) 0.8pf lead. What are the values of induced emf? Indicate assumptions made if any.	Apply
11	A 500V, 6-pole, 3-phase, 50hz, star-connected synchronous motor has a resistance and synchronous reactance of $0.29\Omega$ and $3.5\Omega$ per phase respectively. The open-circuit voltage is 650V. If the friction and core losses total 1kw,calculate the line current and power factor when the motor output is 110HP.	Evaluate
12	A 50hz, 6-pole, 3- $\bar{O}$ , and star-connected synchronous motor has a synchronous reactance of $12.2\Omega$ /phase and negligible armature resistance. The excitation is such as to give an open-circuit voltage of 13.4kv.the motor is connected to 11.9kv, 50hz supply. What maximum load can the motor supply before losing synchronism? What is the corresponding motor torque, line current and power factor?	Evaluate

13	The excitation of a 415v, 3-phase, and mesh connected synchronous motor is such that the induced emf is 520v. the impedance per phase is $(0.5+j4.0) \Omega$ . If the friction and iron losses are constant at 1000watts, calculate the power output, line current, power factor and efficiency for maximum power output?	Apply
14	A 76 kw 3phase Y connected, 50Hz, 415V cylindrical rotor synchronous motor operates at rated condition with 0.8pf leading. The motor efficiency excluding field and stator losses, is 96% and $X_s=2.55\hat{U}$ calculate (i) mechanical power developed (ii) armature current (iii) back emf (iv) power angle and (v) max or pull out torque of the motor.	Evaluate
15	A 3 phase 155kw 2400v 50Hz 1200rpm salient pole synchronous motor has $X_d=32\text{ohms/ph}$ and $X_q=20\text{ohm/ph}$ . Neglecting losses, calculate the torque developed by the motor if field excitation is so adjusted as to make the back emf twice the applied voltage and $\alpha=65^\circ$ .	Evaluate

### UNIT-V

### SINGLE PHASE MOTORS & SPECIAL MACHINES

#### SHORT ANSWER QUESTION

1	What are the applications of AC series motor?	Remember
2	What is stepper motor?	Remember
3	What is the function of capacitor in a single phase induction motor?	Remember
4	In which direction does a shaded pole induction motor run?	Remember
5	Write the classification of stepper motor?	Remember
6	Why single phase induction motor has low power factor?	Remember
7	What is meant by split phase motor?	Remember
8	What are the advantages of universal motor?	Remember
9	What are the applications of universal motor?	Remember
10	What are the applications of stepper motor	Remember

11	Why starting torque in capacitor start induction motor is more than resistance split phase induction motor?	Remember
12	Compare the constructional features of a.c series motor with d.c. series motor.	Remember
13	Explain the operating characteristics of ac series motor	Understand
14	Explain the function of compensating winding in ac series motor.	Understand
15	How rotor tooth pitch is defined?	Remember

**LONG ANSWERS QUESTIONS**

1	Discuss in detail about the split-phase motors	Understand
2	Discuss about the principle and performance of AC series motor	Understand
3	Describe the phase control of 1-phase induction motor	Remember
4	Write a short notes on double revolving field theory	Remember
5	Discuss about Torque-Speed curve of single-phase induction motor	Apply
6	Show that the starting torque of a single phase induction motor is zero	Apply
7	With a neat sketch, discuss about the operation of shaded pole motor with squirrel cage rotor	Understand
8	What type of operating characteristics does an ac series motor give?	Understand
9	What is the principle of operation of universal motor?	Understand
10	What is the principle of operation of stepper motor?	Understand

11	Neatly draw and explain the vector diagram of universal motor. Give your observations.	Understand
12	Compare the performance characteristics of ac series motor when it is connected across i) AC supply and ii) D.C Supply	Apply
13	What is conductively compensated and inductively compensated ac series motor?	Apply
14	Explain the operation of variable reluctance motor.	Understand
15	Write a note on hysteresis motor and its applications.	Understand

### ANALYTICAL QUESTIONS

1	A 2-winding single-phase motor has the main auxiliary winding currents $I_m=15$ A and $I_a=7.5$ A at stand-still. The auxiliary winding current leads the main winding current by $\alpha=45^\circ$ electrical. The two winding are in space quadrature and the effective number of turns are $N_m=80$ and $N_a=100$ . Compute the amplitudes of the forward and backward stator <i>mmf</i> waves. Also determine the magnitude of the auxiliary current and its phase angle difference $\alpha$ with the main winding current if only the backward field is to be present.	Evaluate
2	A stepper motor driven by a bipolar drive circuit has the following parameters: winding inductance = 30 mH, rated current = 3A, DC supply = 45V, total resistance in each phase = 15 $\Omega$ . When the transistors are turned off, determine 14. the time taken by the phase current to decay to zero and (ii) the proportion of the stored inductive energy returned to the supply.	Evaluate
3	A stepper motor has a step angle of $3^\circ$ . Determine (a) resolution (b) number of steps required for the shaft to make 25 revolutions and (c) shaft speed, if the stepping frequency is 3600 pps.	Apply
4	A stepper motor has a steep angle of $1.8^\circ$ . What number should be loaded into the encoder of its drive system if it is desired to turn on the shaft ten complete revolutions?	Evaluate
5	What is the motor torque $T_m$ required to accelerate an initial load of $3 \times 10^{-4}$ kg $m^2$ from $f_1 = 1000$ Hz to $f_2 = 2000$ Hz during 100 ms. The frictional torque $T_f$ is 0.05 N-m and the step angle is $1.8^\circ$ .	Apply
6	A 250W single phase 50hz 220v universal motor runs at 2000rpm and takes 1 A when supplied from a 220V dc supply. If the motor is connected to 220V ac supply and takes 1A(r m s), calculate the speed, torque and power factor, assume $R_a=20\Omega$ and $L_a=0.4H$	Evaluate
7	A universal series motor has a resistance of $30\Omega$ and an inductance of 0.5H. When connected to a 250V DC supply and loaded to take 0.8A, it runs at 2000rpm. Estimate its speed and power factor when connected to a 250V, 50hz ac supply and loaded to take the same current.	Evaluate

8	Find the mechanical power output of 185kw, 4 pole, 110V, 50Hz single phase induction motor, whose constants are given below at a slip of 0.05. $R_1=1.86\Omega$ , $X_1=2.56\Omega$ , $X_\phi=53.5\Omega$ , $R_2=3.56\Omega$ , $X_2=2.56\Omega$ core loss 3.5w, friction and wind age loss 13.5w	Evaluate
9	A 250w, 230V, 50Hz capacitor start motor has the following constants for the main and auxiliary windings: main winding, $Z_m=(4.5+3.7i)\Omega$ . Auxiliary winding $Z_a=(9.5+3.5i)\Omega$ . Determine the value of the starting capacitor that will place the main and auxiliary winding currents in quadrature at starting.	Apply
10	A single phase induction motor has stator windings in space quadrature and is supplied with a single phase voltage of 200V at 50Hz. The standstill impedance of the main winding is $(5.2+10.1i)$ and the auxiliary winding is $(19.7+14.2i)$ . Find the value of capacitance to be inserted in the auxiliary winding for maximum starting torque.	Apply
11	A stepper motor has a step angle of $4^\circ$ . Determine (a) resolution (b) number of steps required for the shaft to make 26 revolutions and (c) shaft speed, if the stepping frequency is 3800 pps.	Apply
12	A stepper motor has a steep angle of $1.9^\circ$ . What number should be loaded into the encoder of its drive system if it is desired to turn on the shaft ten complete revolutions?	Evaluate
13	What is the motor torque $T_m$ required to accelerate an initial load of $3 \times 10^{-4}$ kg $m^2$ from $f_1 = 1500$ Hz to $f_2 = 2500$ Hz during 100 ms. The frictional torque $T_f$ is 0.05 N-m and the step angle is $1.7^\circ$ .	Apply
14	A 250W single phase 50hz 220v universal motor runs at 1500rpm and takes 1 A when supplied from a 220V dc supply. If the motor is connected to 220V ac supply and takes 1A(r m s), calculate the speed, torque and power factor, assume $R_a=25\Omega$ and $L_a=0.45H$	Evaluate
15	A universal series motor has a resistance of $30\Omega$ and an inductance of 0.5H. When connected to a 250V DC supply and loaded to take 0.85A, it runs at 1800rpm. Estimate its speed and power factor when connected to a 250V, 50hz ac supply and loaded to take the same current.	Evaluate

