8

Synchronous Machines

8.1 Introduction

It is known that the electric supply used, now a days for commercial as well as domestic purposes, is of alternating type.

Similar to d.c. machines, the a.c. machines associated with alternating voltages, are also classified as generators and motors.

The machines generating a.c. e.m.f. are called **alternators** or **synchronous generators**. While the machines accepting input from a.c. supply to produce mechanical output are called **synchronous motors**. Both these machines work at a specific constant speed called **synchronous speed** and hence in general called **synchronous machines**.

8.2 Difference between D.C. Generator and Alternator

It is seen that in case of a d.c. generator, basically the nature of the induced e.m.f. in the armature conductors is of alternating type. By using commutator and brush assembly it is converted to d.c. and made available to the external circuit. If commutator is dropped from a d.c. generator and induced e.m.f. is tapped outside from an armature directly, the nature of such e.m.f. will be alternating. Such a machine without commutator, providing an a.c. e.m.f. to the external circuit is called an **alternator**. The obvious question is how is it possible to collect an e.m.f. from the rotating armature without commutator ?

Key Point : *So the arrangement which is used to collect an induced e.m.f. from the* ***rotating armature*** *and make it available to the* ***stationary circuit*** *is called* ***slip ring and brush assembly****.*

8.2.1 Concept of Slip Rings and Brush Assembly

Whenever there is a need of developing a contact between rotating element and the stationary circuit without conversion of an e.m.f. from a.c. to d.c., the slip rings and brush assembly can be used.

In case of three phase alternators, the armature consist of three phase winding and an a.c. e.m.f. gets induced in these windings. After connecting windings in star or delta, the three ends of the windings are brought out. Across these terminals three phase supply is ranging from 125 r.p.m. to 500 r.p.m. The prime movers used to drive such rotor are generally water turbines and I.C. engines.

8.6.2 Smooth Cylindrical Type Rotor

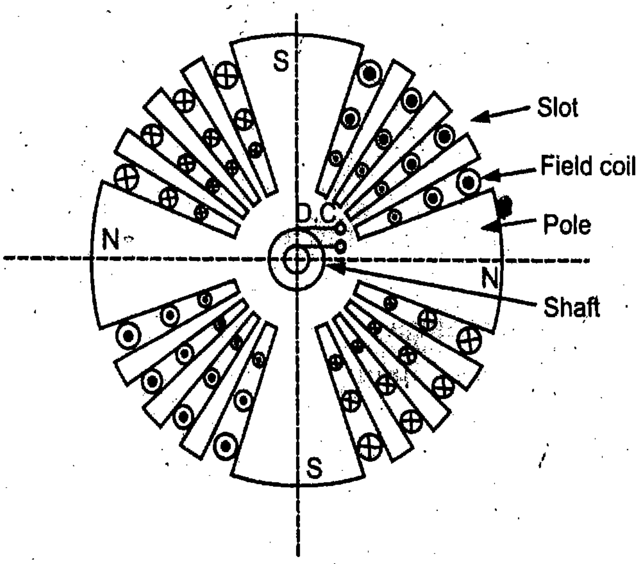


Fig. 8.4 Smooth cylindrical rotor

This is also called **non salient type** or **non-projected pole type of rotor.**

The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coil. The slots are covered at the top with the help of steel or manganese wedges. The unslotted portions of the cylinder itself act as the poles. The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor. These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits. The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging between 1500 to 3000 r.p.m. Such high speed alternators are called '**turboalternators**'. The prime movers used to drive such type of rotors are generally steam turbines, electric motors.

The Fig. 8.4 shows smooth cylindrical type of rotor.

Let us list down the differences between the two types in tabular form.

8.6.3 Difference between Salient and Cylindrical Type of Rotor

Sr. No.	Salient Pole Type	Smooth Cylindrical Type
1.	Poles are projecting out from the surface.	Unslotted portion of the cylinder acts as poles hence poles are non projecting.
2.	Air gap is non uniform.	Air gap is uniform due to smooth cylindrical periphery.
3.	Diameter is high and axial length is small.	Small diameter and large axial length is the feature.
4.	Mechanically weak.	Mechanically robust.
5.	Preferred for low speed alternators.	Preferred for high speed alternators i.e. for turboalternators.
6.	Prime mover used are water turbines, I.C. engines.	Prime movers used are steam turbines, electric motors.

7.	For same size, the rating is smaller than cylindrical type.	For same size, rating is higher than salient pole type.
8.	Separate damper winding is provided.	Separate damper winding is not necessary.

8.7 Working Principle

The alternators work on the principle of **electromagnetic induction**. When there is a relative motion between the conductors and the flux, e.m.f. gets induced in the conductors. The d.c. generators also work on the same principle. The only difference in practical alternator and a d.c. generator is that in an alternator the conductors are stationary and field is rotating. But for understanding purpose we can always consider relative motion of conductors with respect to the flux produced by the field winding.

Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles. The magnetic axis of the two poles produced by field is vertical, shown dotted in the Fig. 8.5.

Let conductor starts rotating from position 1. At this instant, the entire velocity component is **parallel** to the flux lines. Hence there is no cutting of flux lines by the conductor. So $\frac{d\phi}{dt}$ at this instant is zero and hence induced e.m.f. in the conductor is also zero.

As the conductor moves from position 1 towards position 2, the part of the velocity component becomes perpendicular to the flux lines and proportional to that, e.m.f. gets induced in the conductor. The magnitude of such an induced e.m.f. increases as the conductor moves from position 1 towards 2.

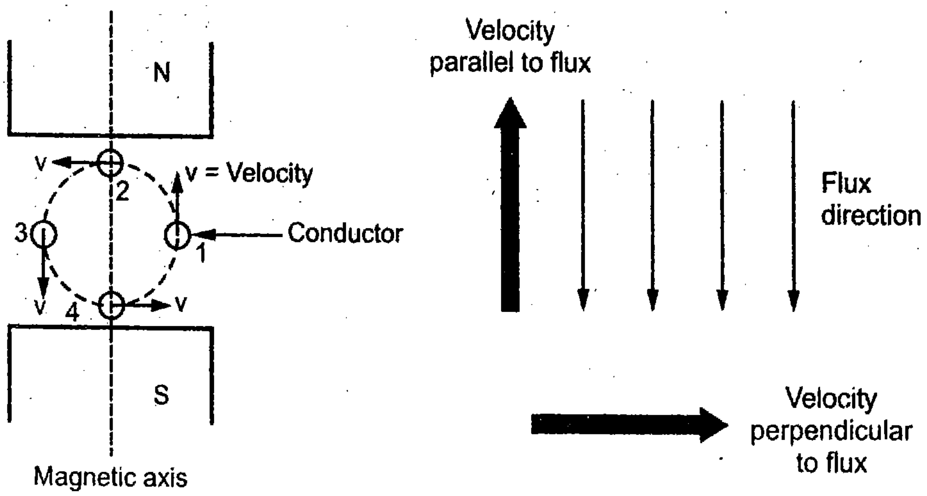


Fig. 8.5 Two pole alternator

At position 2, the entire velocity component is **perpendicular** to the flux lines. Hence there exists maximum cutting of the flux lines. And at this instant, the induced e.m.f. in the conductor is at its maximum.

As the position of conductor changes from 2 towards 3, the velocity component perpendicular to the flux starts decreasing and hence induced e.m.f. magnitude also starts decreasing. At position 3, again the entire velocity component is parallel to the flux lines and hence at this instant induced e.m.f. in the conductor is zero.

As the conductor moves from position 3 towards 4, the velocity component perpendicular to the flux lines again starts increasing. But the direction of velocity component now is opposite to the direction of velocity component exsisting during the movement of the conductor from position 1 to 2. Hence an induced e.m.f. in the conductor increases but in the opposite direction.

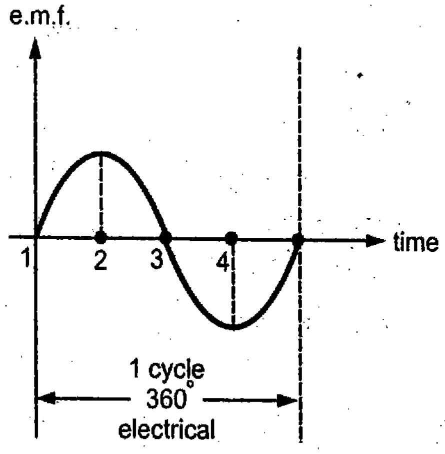


Fig. 8.6 Alternating nature of the induced e.m.f.

At position 4, it achieves maxima in the opposite direction, as the entire velocity component becomes **perpendicular** to the flux lines.

Again from position 4 to 1, induced e.m.f. decreases and finally at position 1, again becomes zero. This cycle continues as conductor rotates at a certain speed.

So if we plot the magnitudes of the induced e.m.f. against the time, we get an alternating nature of the induced e.m.f. as shown in the Fig. 8.6.

This is the working principle of an alternator.

8.7.1 Mechanical and Electrical Angle

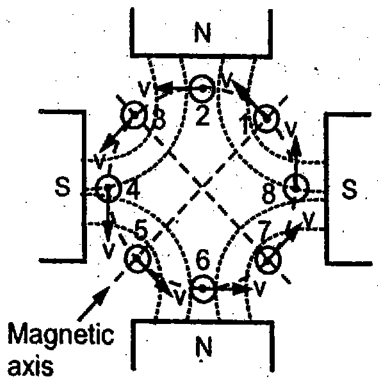


Fig. 8.7 (a) 4 Pole alternator

We have seen that for 2 pole alternator, one mechanical revolution corresponds to one electrical cycle of an induced e.m.f. Now consider 4 pole alternator i.e. the field winding is designed to produce 4 poles. Due to 4 poles, the magnetic axis exists diagonally shown dotted in the Fig. 8.7.

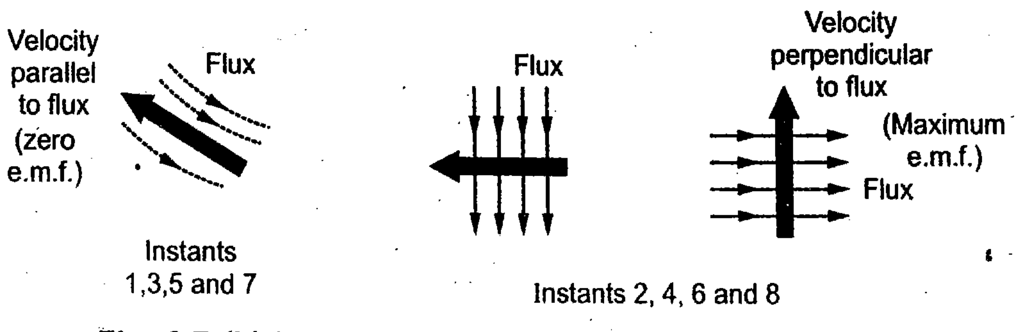


Fig. 8.7 (b) Veclocity components at different instants

5.1 Introduction

An electric motor is a device which converts an electrical energy into a mechanical energy. This mechanical energy then can be supplied to various types of loads. The motors can operate on d.c. as well as single and three phase a.c. supply. The motors operating on d.c. supply are called d.c. motors while motors operating on a.c. supply are called a.c. motors. As a.c. supply is commonly available, the a.c. motors are very popularly used in practice. The a.c. motors are classified as single and three phase induction motors, synchronous motors and some special purpose motors. Out of all these types, three phase induction motors are widely used for various industrial applications. Hence this chapter gives the emphasis on the working principle, types and features of three phase induction motors. The important advantages of three phase induction motors over other types are self starting property, no need of starting device, higher power factor, good speed regulation and robust construction. The working principle of three phase induction motors is based on the production of **rotating magnetic field**. Hence before beginning the actual discussion of three phase induction motors, let us discuss the production of rotating magnetic field from a three phase a.c. supply.

5.2 Rotating Magnetic Field (R.M.F.) JNTU : Nov.-04, 06, 12, March-06, May-08

The rotating magnetic field can be defined as the field or flux having constant amplitude but whose axis is continuously rotating in a plane with a certain speed. So if the arrangement is made to rotate a permanent magnet, then the resulting field is a rotating magnetic field. But in this method, it is necessary to rotate a magnet physically to produce rotating magnetic field.

But in three phase induction motors such a rotating magnetic field is produced by supplying currents to a set of **stationary** windings, with the help of three phase a.c. supply. The current carrying windings produce the magnetic field or flux. And due to interaction of three fluxes produced due to three phase supply, resultant flux has a constant magnitude and its axis rotating in space, without physically rotating the windings. This type of field is nothing but rotating magnetic field. Let us study how it happens ?

5.2.1 Production of R.M.F.

A three phase induction motor consists of three phase winding as its stationary part called **stator**. The three phase stator winding is connected in star or delta. The three phase windings are displaced from each other by 120°. The windings are supplied by a balanced three phase a.c. supply. This is shown in the Fig. 5.2.1. The three phase windings are denoted as R-R′, Y-Y′ and B-B′.

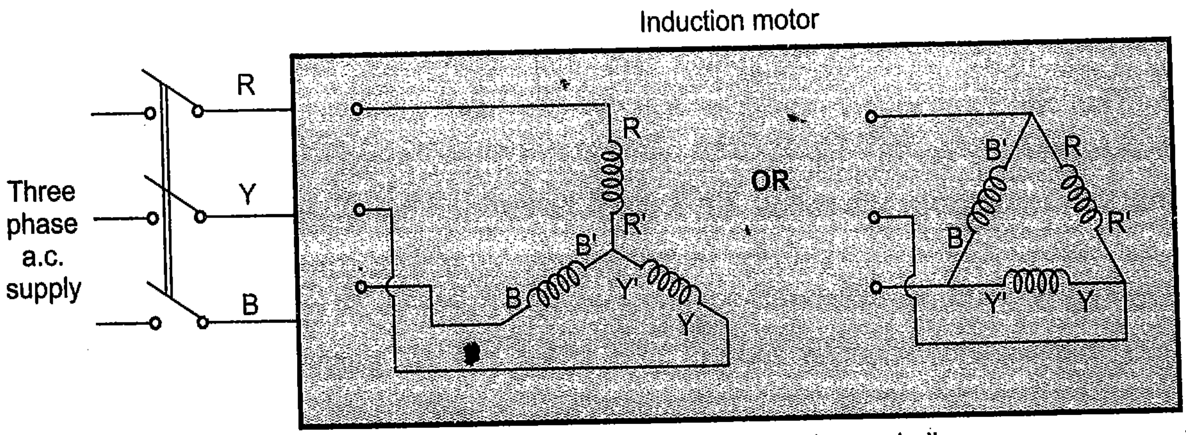


Fig. 5.2.1

The three phase currents flow simultaneously through the windings and are displaced from each other by 120° electrical. Each alternating phase current produces its own flux which is sinusoidal. So all three fluxes are sinusoidal and are separated from each other by 120°. If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes ϕ_R, ϕ_Y and ϕ_B can be written as,

$$\phi_R = \phi_m \sin(\omega t) = \phi_m \sin\theta \quad \text{... (5.2.1)}$$

$$\phi_Y = \phi_m \sin(\omega t - 120^\circ) = \phi_m \sin(\theta - 120^\circ) \quad \text{... (5.2.2)}$$

$$\phi_B = \phi_m \sin(\omega t - 240^\circ) = \phi_m \sin(\theta - 240^\circ) \quad \text{... (5.2.3)}$$

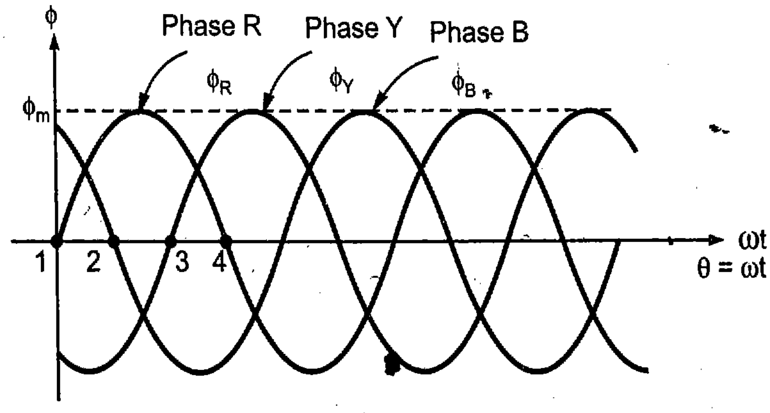
As windings are identical and supply is balanced, the magnitude of each flux is ϕ_m. Due to phase sequence R-Y-B, flux ϕ_Y lags behind ϕ_R by 120° and ϕ_B lags ϕ_Y by 120°. So ϕ_B ultimately lags ϕ_R by 240°. The flux ϕ_R is taken as reference while writing the equations.

The Fig. 5.2.2 (a) shows the waveforms of three fluxes in space. The Fig. 5.2.2 (b) shows the phasor diagram which clearly shows the **assumed positive directions** of each flux. Assumed positive direction means whenever the flux is positive it must be represented along the direction shown and whenever the flux is negative it must be represented along the opposite direction to the assumed positive direction.

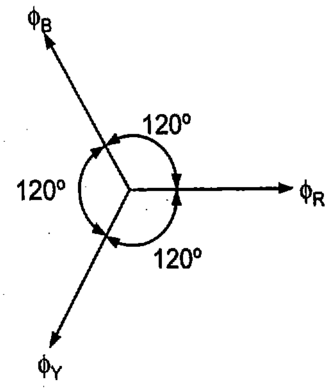
Let ϕ_R, ϕ_Y and ϕ_B be the instantaneous values of three fluxes. The resultant flux ϕ_T is the phasor addition of ϕ_R, ϕ_Y and ϕ_B.

$$\therefore \quad \bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B$$

Let us find ϕ_T at the instants 1, 2, 3 and 4 as shown in the Fig. 5.2.2 (a) which represents the values of θ as 0°, 60°, 120° and 180° respectively. The phasor addition can be performed by obtaining the values of ϕ_R, ϕ_Y and ϕ_B by substituting values of θ in the equations (5.2.1), (5.2.2) and (5.2.3).



(a) Waveforms of three fluxes



(b) Assumed positive directions

Fig. 5.2.2

Case 1 : $\theta = 0°$

Substituting in the equations (5.2.1), (5.2.2) and (5.2.3) we get,

$$\phi_R = \phi_m \sin 0° = 0$$

$$\phi_Y = \phi_m \sin(-120°) = -0.866\,\phi_m$$

$$\phi_B = \phi_m \sin(-240°) = +0.866\,\phi_m$$

The phasor addition is shown in the Fig. 5.2.3 (a). The positive values are shown in assumed positive directions while negative values are shown in opposite direction to the assumed positive directions of the respective fluxes. Refer to assumed positive directions shown in the Fig. 5.2.2 (b).

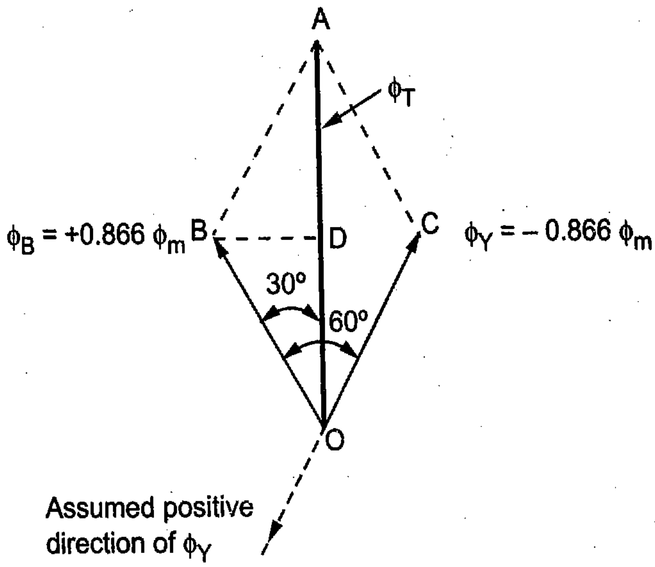


Fig. 5.2.3 (a) Vector diagram for θ = 0°

BD is drawn perpendicular from B on ϕ_T. It bisects ϕ_T.

$$\therefore \quad OD = DA = \frac{\phi_T}{2}$$

In triangle OBD, $\angle BOD = 30°$

$$\therefore \quad \cos 30° = \frac{OD}{OB} = \frac{\phi_T/2}{0.866\phi_m}$$

$$\therefore \quad \phi_T = 2 \times 0.866\phi_m \times \cos 30°$$

$$= 1.5\,\phi_m$$

So magnitude of ϕ_T is 1.5 ϕ_m and its position is vertically upwards at $\theta = 0°$.

Case 2 : $\theta = 60°$

Equations (5.2.1), (5.2.2) and (5.2.3) give us,

$$\phi_R = \phi_m \sin 60° = +0.866\,\phi_m$$

$$\phi_Y = \phi_m \sin(-60°) = -0.866\,\phi_m$$

$$\phi_B = \phi_m \sin(-180°) = 0$$

So ϕ_R is positive and ϕ_Y is negative and hence drawing in appropriate directions we get phasor diagram as shown in the Fig. 5.2.3 (b).

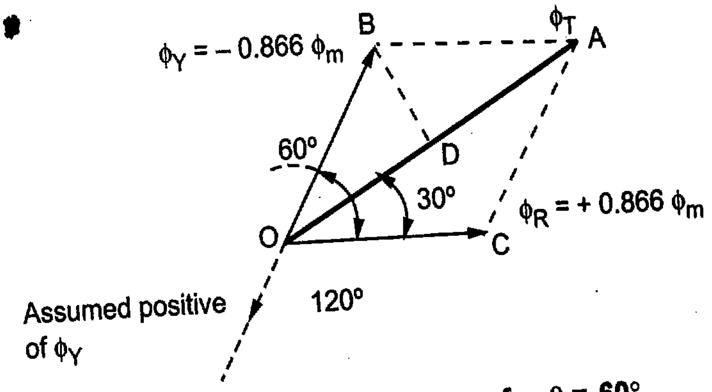


Fig. 5.2.3 (b) Vector diagram for $\theta = 60°$

Doing the same construction, drawing perpendicular from B on ϕ_T at D we get the same result as,

$$\phi_T = 1.5\,\phi_m$$

But it can be seen that **though its magnitude is 1.5 ϕ_m it has rotated through 60° in space, in clockwise direction, from its previous position.**

Case 3 : $\theta = 120°$

Equations (5.2.1), (5.2.2) and (5.2.3) give us,

$$\phi_R = \phi_m \sin 120 = +0.866\,\phi_m$$

$$\phi_Y = \phi_m \sin 0 = 0$$

$$\phi_B = \phi_m \sin(-120) = -0.866\,\phi_m$$

So ϕ_R is positive and ϕ_B is negative. Showing ϕ_R and ϕ_B in the appropriate directions, we get the phasor diagram as shown in the Fig. 5.2.3 (c).

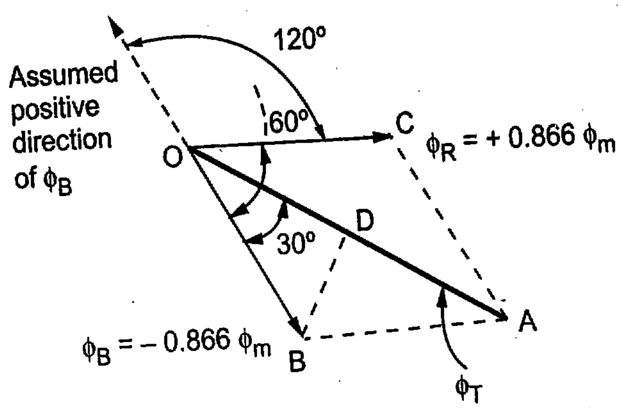


Fig. 5.2.3 (c) Vector diagram for $\theta = 120°$

After doing the construction same as before i.e. drawing perpendicular from B on ϕ_T, it can be proved again that,

$$\phi_T = 1.5\,\phi_m$$

But the position of ϕ_T is such that it has rotated further through 60° from its previous position, in clockwise direction. **And from its position at $\theta = 0°$, it has rotated through 120° in space, in clockwise direction.**

Case 4 : $\theta = 180°$

From the equations (5.2.1), (5.2.2) and (5.2.3),

$$\phi_R = \phi_m \sin(180°) = 0$$

$$\phi_Y = \phi_m \sin(60°) = +0.866\,\phi_m$$

$$\phi_B = \phi_m \sin(-60°) = -0.866\,\phi_m$$

So $\phi_R = 0$, ϕ_Y is positive and ϕ_B is negative. Drawing ϕ_Y and ϕ_B in the appropriate directions, we get the phasor diagram as shown in the Fig. 5.2.3 (d).

From phasor diagram, it can be easily proved that,

$$\phi_T = 1.5\,\phi_m$$

Thus the magnitude of ϕ_T once again remains same. But it can be seen that it has further rotated through 60° from its previous position in clockwise direction.

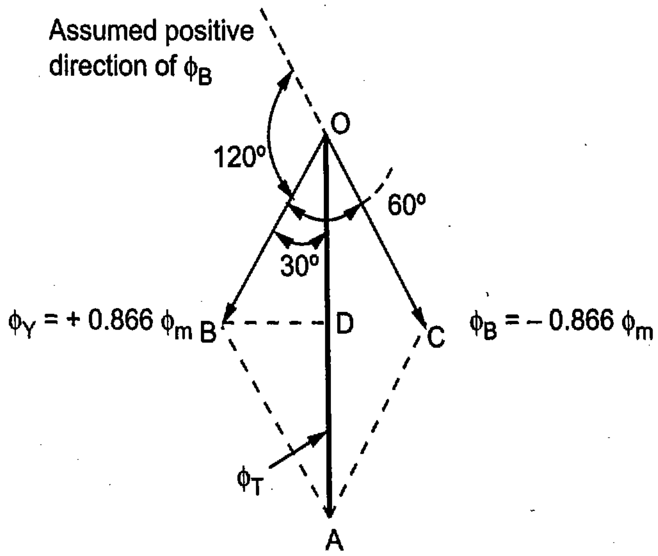


Fig. 5.2.3 (d) Vector diagram for θ = 180°

So for an electrical half cycle of 180°, the resultant ϕ_T has also rotated through 180°. This is applicable for the windings wound for 2 poles.

From the above discussion we have following conclusions :

a) The resultant of the three alternating fluxes, separated from each other by 120°, has a constant amplitude of 1.5 ϕ_m where ϕ_m is maximum amplitude of an individual flux due to any phase.

b) The resultant always keeps on rotating with a certain speed in space.

Key Point *This shows that when a three phase stationary windings are excited by balanced three phase a.c. supply then the resulting field produced is* ***rotating magnetic field****. Though nothing is physically rotating, the field produced is rotating in space having constant amplitude.*

5.2.2 Speed of R.M.F.

There exists a fixed relation between frequency f of a.c. supply to the windings, the number of poles P for which winding is wound and speed N r.p.m. of rotating magnetic

5.5 Working Principle

JNTU : Nov.-03, 04, 06, 08, May-04, 05, 13

Induction motor works on the principle of electromagnetic induction.

When a three phase supply is given to the three phase stator winding, a rotating magnetic field of constant magnitude is produced as discussed earlier. The speed of this rotating magnetic field is synchronous speed, N_s r.p.m.

$$N_s = \frac{120\,f}{P} = \text{Speed of rotating magnetic field}$$

where f = Supply frequency

P = Number of poles for which stator winding is wound.

This rotating field produces an effect of rotating poles around a rotor. Let direction of rotation of this rotating magnetic field is **clockwise** as shown in the Fig. 5.5.1 (a).

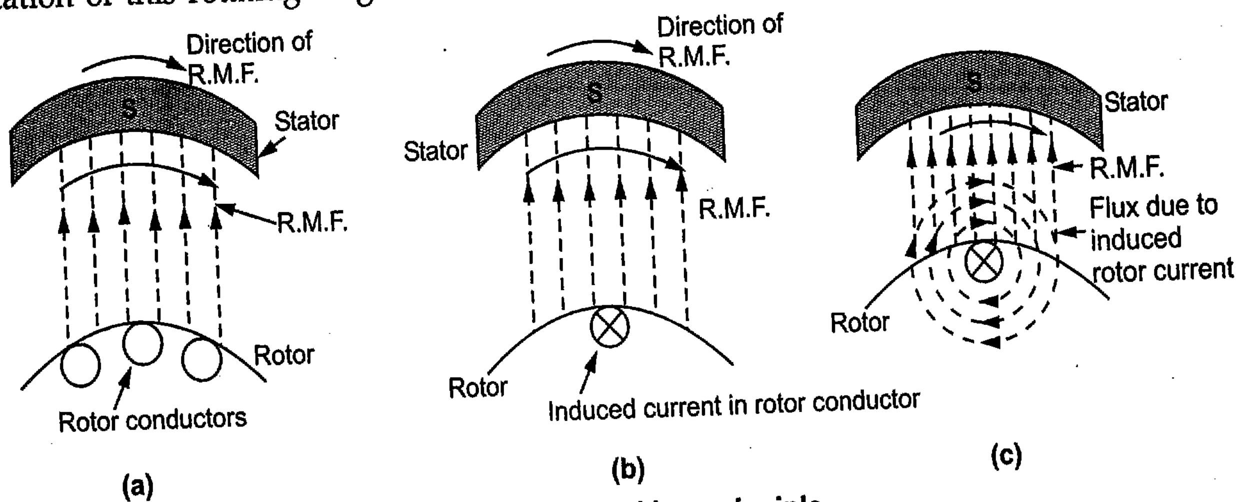


Fig. 5.5.1 Working principle

Now at this instant rotor is **stationary** and stator flux R.M.F. is **rotating**. So its obvious that there exists a relative motion between the R.M.F. and rotor conductors. Now the R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever conductor cuts the flux, e.m.f. gets induced in it. So e.m.f. gets induced in the rotor conductors called **rotor induced e.m.f.** This is electro-magnetic induction. As rotor forms closed circuit, induced e.m.f. circulates current through rotor called **rotor current** as shown in the Fig. 5.5.1 (b). Let direction of this current is going into the paper denoted by a cross as shown in the Fig. 5.5.1 (b).

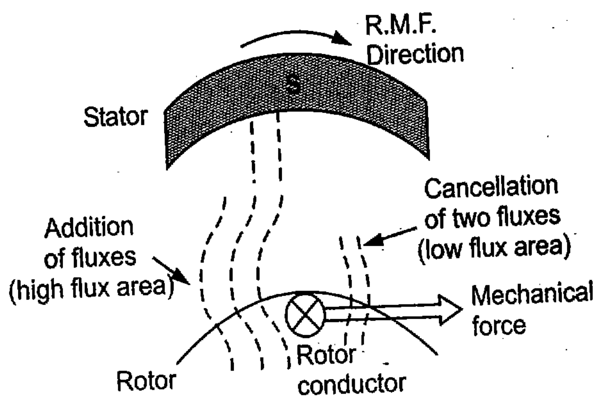


Fig. 5.5.1 (d) Interaction of fluxes

Any current carrying conductor produces its own flux. So rotor produces its flux called **rotor flux**. For assumed direction of rotor current, the direction of rotor flux is clockwise as shown in the Fig. 5.5.1 (c). This direction can be easily determined using right hand thumb rule. Now there are two fluxes, one R.M.F. and other rotor flux. Both the fluxes interact with each as shown in the Fig. 5.5.1 (d). On left of rotor conductor, two fluxes are in same direction hence add up to get high flux area. On right side, two fluxes cancel each other to produce low flux area. As flux lines act as stretched rubber band, high flux density area exerts a push on rotor conductor towards low flux density area. So rotor conductor experiences a force from left to right in this case, as shown in the Fig. 5.5.1 (d), due to **interaction of the two fluxes**.

As all the rotor conductors experience a force, the overall rotor experiences a torque and starts rotating. So **interaction of the two fluxes is very essential for a motoring action.** As seen from the Fig. 5.5.1 (d), the direction of force experienced is same as that of rotating magnetic field. Hence rotor starts rotating in the same direction as that of rotating magnetic field.

Alternatively this can be explained as : According to Lenz's law the direction of induced current in the rotor is so as oppose the cause producing it. The cause of rotor current is the induced e.m.f. which is induced because of relative motion present between the rotating magnetic field and the rotor conductors. Hence to oppose the relative motion i.e. to reduce the relative speed, the rotor experiences a torque in the same direction as that of R.M.F. and tries to catch up the speed of rotating magnetic field.

So, N_S = Speed of rotating magnetic field in r.p.m.

N = Speed of rotor i.e. motor in r.p.m.

$N_S - N$ = Relative speed between the two, rotating magnetic field and the rotor conductors.

Thus rotor always rotates in same direction as that of R.M.F.

5.5.1 Can $N = N_S$?

When rotor starts rotating, it tries to catch the speed of rotating magnetic field.

If it catches the speed of the rotating magnetic field, the relative motion between rotor and the rotating magnetic field will vanish ($N_S - N = 0$). In fact the relative motion is the main cause for the induced e.m.f. in the rotor. So induced e.m.f. will vanish and hence there cannot be rotor current and the rotor flux which is essential to produce the torque on the rotor. Eventually motor will stop. But immediately there will exist a relative motion between rotor and rotating magnetic field and it will start. But due to inertia of rotor, this does not happen in practice and rotor continues to rotate with a speed slightly less than the synchronous speed of the rotating magnetic field in the steady state. The **induction motor never rotates at synchronous speed**. The speed at which it rotates is hence called **subsynchronous speed** and motor sometimes called **asynchronous motor**.

$$\therefore \quad N < N_s$$

So it can be said that rotor slips behind the rotating magnetic field produced by stator. The difference between the two is called **slip speed** of the motor.

$$N_s - N = \text{Slip speed of the motor in r.p.m.}$$

This speed decides the magnitude of the induced e.m.f. and the rotor current, which in turn decide the torque produced. The torque produced is as per the requirements of overcoming the friction and iron losses of the motor along with the torque demanded by the load on the motor.

Review Questions

1. *Can induction motor rotate at synchronous speed ? Why ?*
   JNTU : Nov.-03, 04, May-04, 05, Marks 6
2. *Explain the principle of operation of a 3-phase induction motor.*
   JNTU : Nov.-04, 06, 08, May-13, Marks 8

5.6 Slip of Induction Motor

JNTU : May-13

We have seen that rotor rotates in the same direction as that of R.M.F. but in steady state attains a speed less than the synchronous speed. The difference between the two speeds i.e. synchronous speed of R.M.F. (N_s) and rotor speed (N) is called slip speed. This slip speed is generally expressed as the percentage of the synchronous speed.

So slip of the induction motor is defined as the difference between the synchronous speed (N_s) and actual speed of rotor i.e. motor (N) expressed as a fraction of the synchronous speed (N_s). This is also called absolute slip or fractional slip and is denoted as 's'.

Thus

$$s = \frac{N_s - N}{N_s} \quad \text{... (Absolute slip)}$$

The percentage slip is expressed as,

$$\% s = \frac{N_s - N}{N_s} \times 100 \quad \text{... (Percentage slip)}$$

In terms of slip, the actual speed of motor (N) can be expressed as,

$$N = N_s (1 - s) \quad \text{... (From the expression of slip)}$$

At start, motor is at rest and hence its speed N is zero.

$$\therefore \quad s = 1 \text{ at start}$$

This is maximum value of slip s possible for induction motor which occurs at start. While s = 0 gives us $N = N_s$ which is not possible for an induction motor. So **slip of induction motor cannot be zero** under any circumstances.

Practically motor operates in the slip range of 0.01 to 0.05 i.e. 1 % to 5 %. The slip corresponding to full load speed of the motor is called **full load slip.**

Example 5.6.1 *A 4 pole, 3 phase induction motor is supplied from 50 Hz supply. Determine its synchronous speed. On full load, its speed is observed to be 1410 r.p.m. Calculate its full load slip.*

Solution : Given values are,

$$P = 4, \quad f = 50 \text{ Hz}, \quad N = 1410 \text{ r.p.m.}$$

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

Full load absolute slip is given by,

$$s = \frac{N_s - N}{N_s} = \frac{1500 - 1410}{1500} = 0.06$$

$$\therefore \quad \%\, s = 0.06 \times 100 = \mathbf{6\ \%}$$

Example 5.6.2 *A 4 pole, 3 phase, 50 Hz, star connected induction motor has a full load slip of 4 %. Calculate full load speed of the motor.*

Solution : Given values are,

$$P = 4, \quad f = 50 \text{ Hz}, \quad \%\, s_{fl} = 4\,\%$$

$$s_{fl} = \text{Full load absolute slip} = 0.04$$

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

$$s_{fl} = \frac{N_s - N_{fl}}{N_s} \quad \text{where } N_{fl} = \text{Full load speed of motor}$$

$$\therefore \quad 0.04 = \frac{1500 - N_{fl}}{1500}$$

$$\therefore \quad N_{fl} = \mathbf{1440 \text{ r.p.m.}}$$

This is the full load speed of the motor.

2. *A 3-phase induction motor has a 4-pole, star connected stator winding. The motor runs on a 50 Hz supply with 200 V between lines. The rotor resistance and standstill rotor reactance per phase are 0.1 Ω and 0.9 Ω respectively. The ratio of rotor to stator turns in 0.67. Calculate :*
   i) Total torque at 4 % slip *ii) Maximum torque developed*
   iii) Speed at maximum torque *iv) Maximum mechanical power*
   Neglect stator impedance. **[Ans. : 40.4786 Nm, 63.5065 Nm, 1333.333 r.p.m., 8867.1801 W]**

3. *A 3-phase induction motor has a 4-pole, star connected stator winding. The motor runs on a 50 Hz supply with 200 V between lines. The rotor resistance and standstill rotor reactance per phase are 0.1 Ω and 0.9 Ω respectively. The ratio of rotor to stator turns in 0.67. Calculate :*
   i) Total torque at 4 % slip *ii) Maximum torque developed*
   iii) Speed at maximum torque *iv) Maximum mechanical power*
   Neglect stator impedance.
   [Ans. : i) 40.47 Nm, ii) 63.50 Nm, iii) 1333.33 r.p.m. iv) $P_m = T_m \times \omega_m$ = 8.867 kW]

5.11 Torque-Slip Characteristics

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As the induction motor is loaded from no load to full load, its speed decreases hence slip increases. Due to the increased load, motor has to produce more torque to satisfy load demand. The torque ultimately depends on slip as explained earlier. The behaviour of motor can be easily judged by sketching a curve obtained by plotting torque produced against slip of induction motor. The curve obtained by plotting torque against slip from s = 1 (at start) to s = 0 (at synchronous speed) is called **torque-slip characteristics** of the induction motor. It is very interesting to study the nature of torque-slip characteristics.

We have seen that for a constant supply voltage, E_2 is also constant. So we can write torque equation as,

$$T \propto \frac{s R_2}{R_2^2 + (s X_2)^2}$$

Now to judge the nature of torque-slip characteristics let us divide the slip range (s = 0 to s = 1) into two parts and analyze them independently.

i) Low slip region :

In low slip region, 's' is very very small. Due to this, the term $(s X_2)^2$ is so small as compared to R_2^2 that it can be neglected.

$$\therefore \quad T \propto \frac{s R_2}{R_2^2} \propto s \qquad \text{... As } R_2 \text{ is constant.}$$

Hence in **low slip region torque is directly proportional to slip**. So as load increases, speed decreases, increasing the slip. This increases the torque which satisfies the load demand.

Hence the graph is straight line in nature.

At $N = N_s$, $s = 0$ hence $T = 0$. As no torque is generated at $N = N_s$, motor stops if it tries to achieve the synchronous speed. Torque increases linearly in this region, of low slip values.

ii) High slip region :

In this region, slip is high i.e. slip value is approaching to 1. Here it can be assumed that the term R_2^2 is very very small as compared to $(s X_2)^2$. Hence neglecting R_2^2 from the denominator, we get

$$T \propto \frac{s R_2}{(sX_2)^2} \propto \frac{1}{s}$$

where R_2 and X_2 are constants.

So in high slip region torque is inversely proportional to the slip. Hence its nature is like rectangular hyperbola.

Now when load increases, load demand increases but speed decreases. As speed decreases, slip increases. In high slip region as $T \propto 1/s$, torque decreases as slip increases. But torque must increase to satisfy the load demand. As torque decreases, due to extra loading effect, speed further decreases and slip further increases. Again torque decreases as $T \propto 1/s$ hence same load acts as an extra load due to reduction in torque produced. Hence speed further drops. Eventually motor comes to standstill condition. The **motor cannot continue to rotate at any point in this high slip region**. Hence this region is called **unstable region** of operation.

So torque - slip characteristics has two parts,

1. Straight line called **stable region of operation.**

2. Rectangular hyperbola called **unstable region of operation.**

Now the obvious question is upto which value of slip, torque-slip characteristic represents stable operation ?

In low slip region, as load increases, slip increases and torque also increases linearly. Every motor has its own limit to produce a torque. The maximum torque, the motor can produce as load increases is T_m which occurs at $s = s_m$. So linear behaviour continues till $s = s_m$.

If load is increased beyond this limit, motor slip acts dominantly pushing motor into high slip region. Due to unstable conditions, motor comes to standstill condition at such a load. Hence T_m i.e. maximum torque which motor can produce is also called

breakdown torque or **pull out torque**. So range s = 0 to s = s_m is called low slip region, known as stable region of operation. Motor always operates at a point in this region. And range s = s_m to s = 1 is called high slip region which is rectangular hyperbola, called unstable region of operation. Motor cannot continue to rotate at any point in this region.

At s = 1, N = 0 i.e. at start, motor produces a torque called **starting torque** denoted as T_{st}.

The entire torque-slip characteristics is shown in the Fig. 5.11.1.

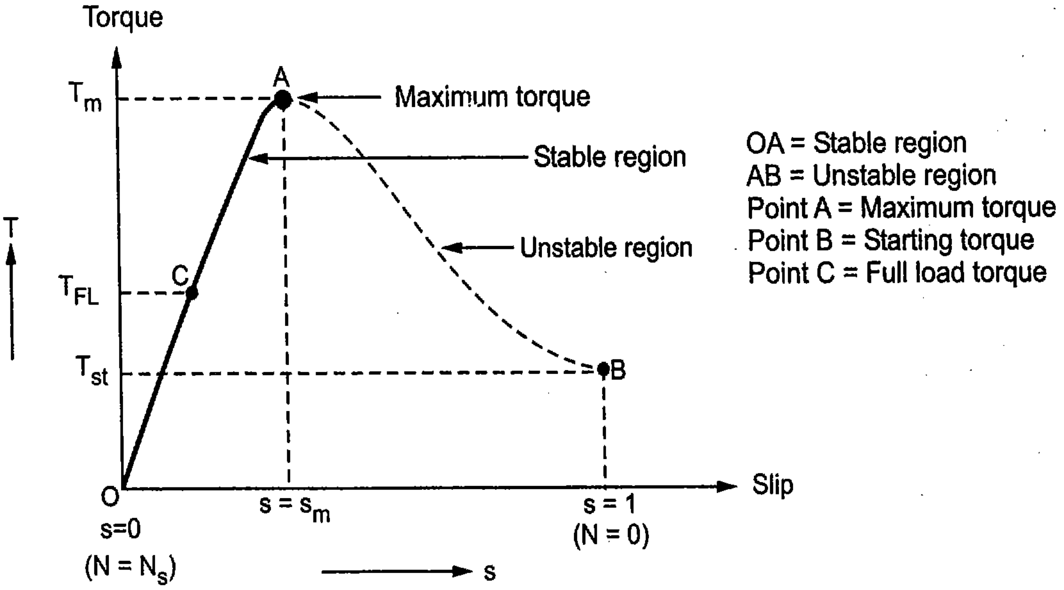

Fig. 5.11.1 Torque-slip characteristics

5.11.1 Full Load Torque

When the load on the motor increases, the torque produced increases as speed decreases and slip increases. The increased torque demand is satisfied by drawing more current from the supply.

The load which motor can drive safely while operating continuously and due to such load, the current drawn is also within safe limits is called **full load condition** of motor. When current increases, due to heat produced the temperature rises. The safe limit of current is that which when drawn for continuous operation of motor, produces a temperature rise well within the limits. Such a full load point is shown on the torque-slip characteristics as point C in the Fig. 5.11.1 and corresponding torque as $T_{F.L.}$.

The interesting thing is that the load on the motor can be increased beyond point C till maximum torque condition. But due to high current and hence high temperature rise there is possibility of damage of winding insulation, **if motor is operated for longer time** duration in this region i.e. from point C to B. But motor can be used to drive loads more than full load, producing torque upto maximum torque for short duration of time. Generally full load torque is less than the maximum torque.