Module-5

Synchronous motor: *Principle of operation, phasor diagrams, torque and torque angle, Blondel diagram, effect of change in load, effect of change in excitation, V and inverted V curves. Synchronous condenser, hunting and damping. Methods of starting synchronous motors*.

Other motors: *Construction and operation of Universal motor, AC servomotor, Linear induction motor and stepper motors.*

1. Introduction

If a three-phase supply is given to the stator of a three-phase alternator, it can work as a motor. As is driven at synchronous speed, it is called a synchronous generator. So if the alternator is run as a motor. It will rotate at a synchronous speed. Such a device that converts electrical energy into mechanical energy running at synchronous speed is called a synchronous motor. Synchronous motor works only at synchronous speed and cannot work at a speed other than the synchronous speed. Its speed is constant irrespective of load, no doubt, its speed changes for an instant at the time of loading.

Types

The two types of synchronous motors are,

1. Three-phase synchronous motors
2. Single-phase synchronous motor

The single-phase synchronous motors are further classified as reluctance motors and hysteresis motor. The three-phase synchronous motor works on the concept of a rotating magnetic field. The field produced by stationary three-phase winding, which rotates in space is called a rotating magnetic field. Its speed is always synchronous and given by,

$N_s = 120f/P$

Where P = Number of poles for which winding is wound

f = Frequency of the supply.

2. Principle of Working of 3-Phase Synchronous Motor:

Synchronous motor works on the principle of magnetic locking. When two unlike poles are brought near each other, if the magnets are strong, there exists a tremendous force of attraction between those two poles. In such condition, the two magnets are said to be magnetically locked. If one of the two magnets is rotated, the other also rotates in the same direction, with the same speed due to the force of attraction i.e. due to the magnetic locking condition. The principle is shown schematically in the Fig.1.

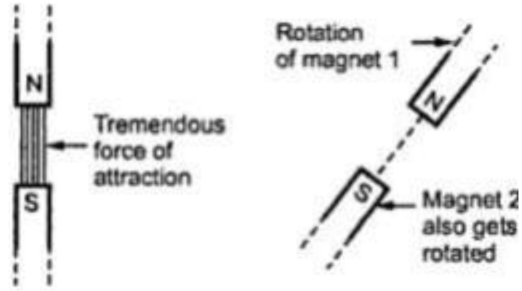


Fig. 1 Principle of magnetic locking

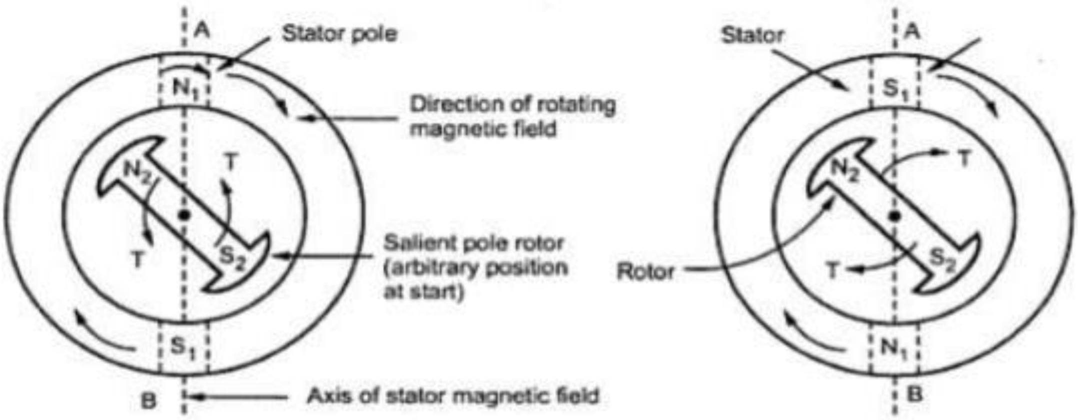
The two magnetic fields are produced in the synchronous motor by exciting both the windings, stator and rotor with three phase a.c. supply and d.c. supply respectively.

When three phase winding is excited by a three phase a.c. supply the flux produced by the three phase winding is always of rotating type, which is already discussed in the previous post. Such a magnetic flux rotates in space at a speed called synchronous speed. This magnetic field is called rotating magnetic field. The speed of the rotating magnetic field is synchronous given by,

$$Ns = 120f/P \text{ r.p.m.}$$

When the field winding on the rotor is excited by a d.c. supply, it also produces two poles, assuming rotor construction to be two poles, salient type. Let these poles be N2 and S2. Now one magnet is rotating at Ns having poles N1 and S1 while at start rotor is stationary i.e. second magnet is stationary having poles N2 and S2. If somehow the unlike poles N1 and S2 or S1 and N2 are brought near each other, the magnetic locking may get established between the stator and rotor poles. As stator poles are rotating due to magnetic locking rotor will also rotate in the same direction as that of stator poles i.e. in the direction of the rotating magnetic field, with the same speed i.e. Ns. Hence synchronous motor rotates at one and only one speed i.e. synchronous speed. But this all depends on the existence of magnetic locking between the stator and rotor poles. Practically it is not possible for stator poles to pull the rotor poles from their stationary position into a magnetic locking condition.

3. Why synchronous Motor is not self-starting?



(a) Action of synchronous motor **(b) Action of synchronous motor**

Consider the rotating magnetic field as equivalent to the physical rotation of two stator poles N1 and

S1.

Consider an instant when two poles are at such a position where the stator magnetic axis is vertical, along A-B as shown in Fig (a).

At this instant, the rotor is stationary and unlike poles will try to attract each other. Due to this rotor will be subjected to an instantaneous torque in an anticlockwise direction as shown in Fig. (a). Now stator poles are rotating very fast i.e. at a speed Ns r.p.m. Due to inertia, before the rotor hardly rotates in the direction of anticlockwise torque, to which it is subjected, the stator poles change their positions. Consider an instant half a period later where stator poles are exactly reversed but due to inertia rotor is unable to rotate from its initial position. This is shown in the Fig.(b).

At this instant, due to the unlike poles trying to attract each other, the rotor will be subjected to a torque in the clockwise direction. This will tend to rotate the rotor in the direction of a rotating magnetic field.

But before this happens, stator poles again change their position reversing the direction of the torque exerted on the rotor.

Blondel Diagram { Constant Power Circle):

The Blondel diagram of a synchronous motor is an extension of a simple phasor diagram of a synchronous motor.

For a synchronous motor, the power input to the motor per phase is given by,

$P_{in} = V_{ph} I_{ph} \cos\Phi$ .... per phase

The gross mechanical power developed per phase will be equal to the difference between Pin per phase and the per phase copper losses of the winding.

Copper loss per phase = $(I_{aph})^2 R_a$

$\therefore \quad P_m = V_{ph} I_{ph} \cos\Phi - (I_{aph})^2 R_a$ ....per phase

For mathematical convenience let $V_{ph} = V$ and $I_{aph} = I$,

$\therefore \quad P_m = VI \cos - I^2 R_a$

$\therefore \quad I^2 R_a - VI \cos + P_m = 0$

$$\therefore \quad I^2 - \frac{VI\cos\phi}{R_a} + \frac{P_m}{R_a} = 0 \qquad ...(1)$$

Now consider the phasor diagram as shown in the Fig.

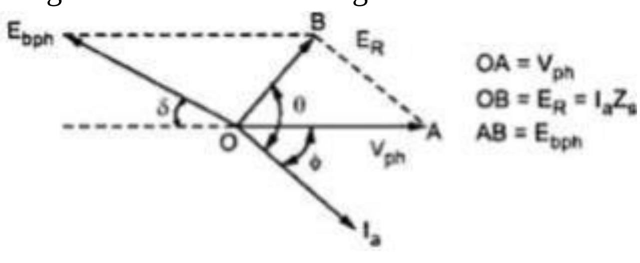


Fig. 1

The equation (1) represents polar equation to a circle. To obtain this circle in a phasor diagram, draw a line OY at an angle θ with respect to OA.

$\therefore \quad \angle YOA = \theta$

$\therefore \quad \angle YOB = \phi$

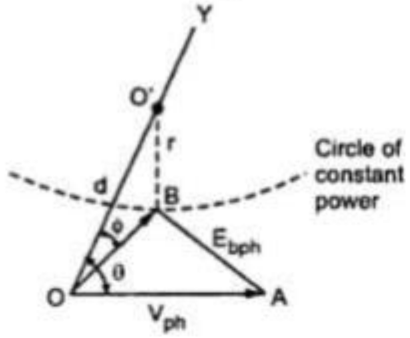


Fig. 2 Blondel diagram

The circle represented by equation (1) has a centre at some point O' on the line OY. The circle drawn with centre as O' and radius as O'B represents circle of constant power. This is called Blondel diagram, shown in the Fig. 2.

Thus if excitation is varied while the power is kept constant, then working point B while move along the circle of constant power.

Let O'B = Radius of circle = r

OO' = Distant d

Applying cosine rule to triangle OBO',

$$r^2 = (OB)^2 + (OO')^2 - 2\,(OB)\,(OO')\cos(OB \hat{\ } OO') \qquad \dots (2)$$

Now OB represents resultant ER which is Ia Zs. Thus OB is proportional to current and when referred to OY represents the current in both magnitude and phase.

OB = Ia = I say

Substituting various values in equation (2) we get,

$$r^2 = I^2 + d^2 - 2dI\cos\Phi$$

$$\therefore \quad I^2 - 2d\,I\cos\phi + (d^2 - r^2) = 0 \qquad \dots (3)$$

Comparing equations (1) and (3) we get,

$$OO' = d = \frac{V}{2R_a} \qquad \dots (4)$$

Thus the point O' is independent of power Pm and is a constant for a give motor operating at a fixed applied voltage V.

Comparing last term of equations (1) and (3),

$$d^2 - r^2 = \frac{P_m}{R_a}$$

$$\therefore \quad r^2 = \left(d^2 - \frac{P_m}{R_a}\right)$$

$$\therefore \quad r = \sqrt{d^2 - \frac{P_m}{R_a}}$$

$$= \sqrt{\left(\frac{V}{2R_a}\right)^2 - \frac{P_m}{R_a}}$$

$$\therefore \quad \boxed{r = \frac{1}{2R_a}\sqrt{V^2 - 4P_m R_a}} \quad \ldots (5)$$

The equation shows that as power Pm must be real, then 4Pm Ra ≥ V^2 . The maximum possible power per phase is,

$$4(P_m)_{max} R_a = V^2$$

$$\therefore \quad \boxed{(P_m)_{max} = \frac{V^2}{4R_a}} \quad \ldots (6)$$

And the radius of the circle for maximum power is zero. Thus at the time of maximum power, the circles becomes a point O'.

While when the power Pm = O, then

r = V/2Ra = OO'

This shows that the circle of zero power passes through the points O and A. The radius for any power Pm is given by,

$$r = \frac{V}{2R_a}\sqrt{1 - \frac{4P_m R_a}{V^2}}$$

but $(P_m)_{max} = \frac{V^2}{4R_a}$, substituting above

$$r = \frac{V}{2R_a}\sqrt{1 - \frac{P_m}{(P_m)_{max}}}$$

$$\therefore \quad r = \frac{V}{2R_a}\sqrt{1 - m}$$

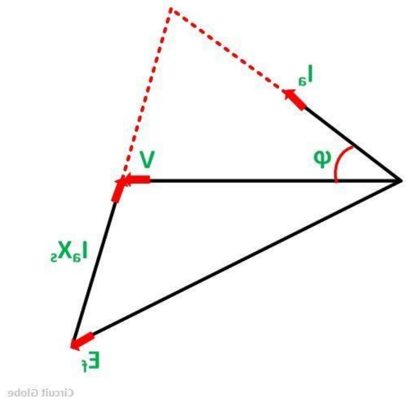
where $m = \frac{P_m}{(P_m)_{max}}$

We know, $OO' = d = \frac{V}{2R_a}$

$$\therefore \quad r = d\sqrt{1 - m} \quad \ldots (7)$$

4. Effect of change in load constant excitation:

A synchronous motor runs at constant synchronous speed, regardless of the load. Let us see the effect of the load change on the motor. Consider a synchronous motor operating initially with a leading power factor. The phasor diagram for the leading power factor is shown below:



The load on the shaft is increased. The rotor slows down momentarily, as it required some time to take increased power from the line. In another word, it can be said that even if the rotor is rotating at synchronous speed, the rotor slips back in space because of the increase in the load. In this process, the torque angle δ becomes larger, and, as a result, the induced torque increases.
The induced torque equation is given as:

$$T_{ind} = \frac{V\,E_f \sin\delta}{\omega\,X_s}$$

Then increased torque increases the rotor speed, and the motor again regains the synchronous speed, but with the larger torque angle. The excitation voltage Ef is proportional to ϕω, it depends upon the field current and the speed of the motor. Since the motor is moving at a synchronous speed, and the field current is also constant. Hence, the magnitude of the Voltage |Ef| remains constant. We have,

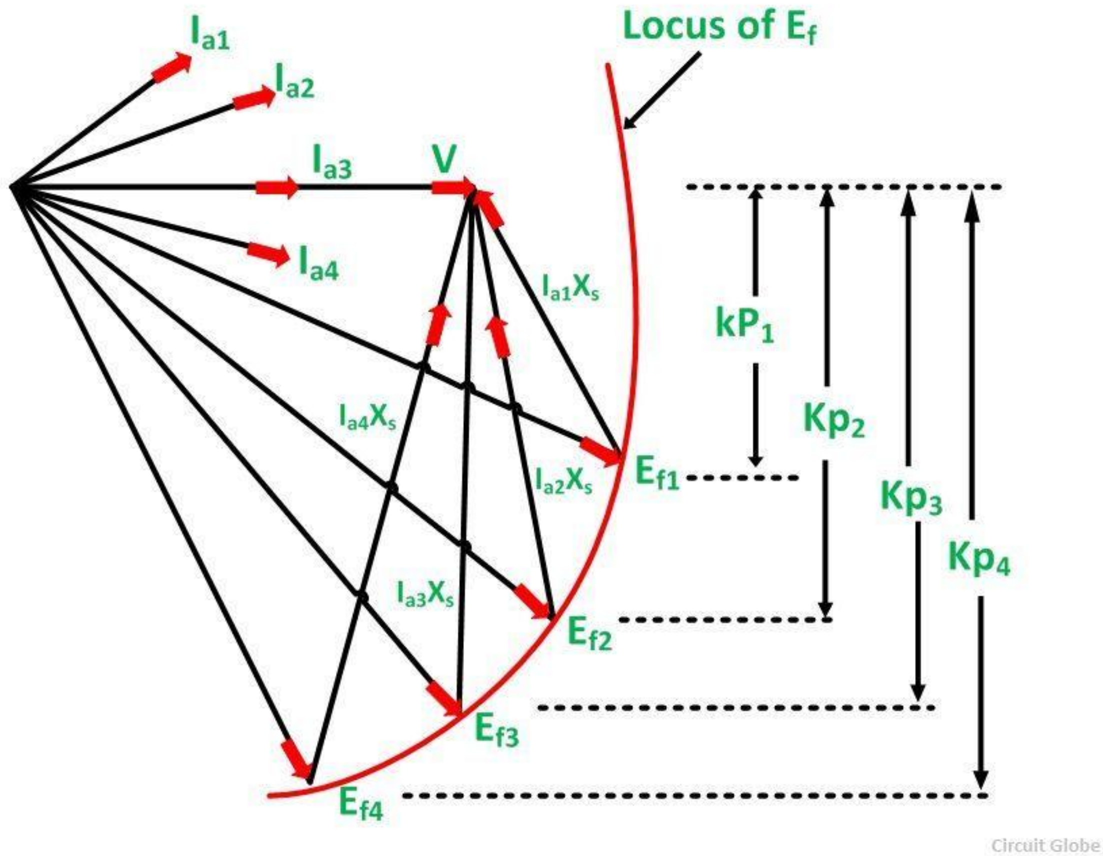
$$P = \frac{V\,E_f \sin\delta}{X_s} = V\,I_a \cos\varphi$$

Therefore,

$$E_f \sin\delta = \frac{X_s}{V} P = KP \quad \text{where} \quad K = \frac{X_s}{V} = \text{constant}$$

From the above equations, it is clear, that if P is increased the value of Ef sinδ and Ia cosϕ also increases.

The figure below shows the effect of an increase in load on the operation of a synchronous motor.



It is seen from the above figure that with the increase in load, the quantity jIaXs goes on increasing and the relation V = Ef + jIaXs is satisfied. The armature current is also increased. The power factor angle also changes with the change in load. It becomes less and less leading and then becomes more and more lagging as shown in the figure above.

5. Effect of change in excitation constant load:

If excitation i.e. field current is changed keeping load constant, the synchronous motor reacts by changing its power factor of operation.

Consider a synchronous motor operating at a certain load. The corresponding load angle is δ

Normal Excitation(E_b = V): At start, consider normal behaviour of the synchronous motor, where excitation is adjusted to get Eb = V i.e. induced e.m.f. is equal to applied voltage. Such an excitation is called Normal Excitation of the motor. Motor is drawing certain current from the supply and power input to the motor is say Pin. The power factor of the motor is lagging in nature as shown in the Fig. 1(a).

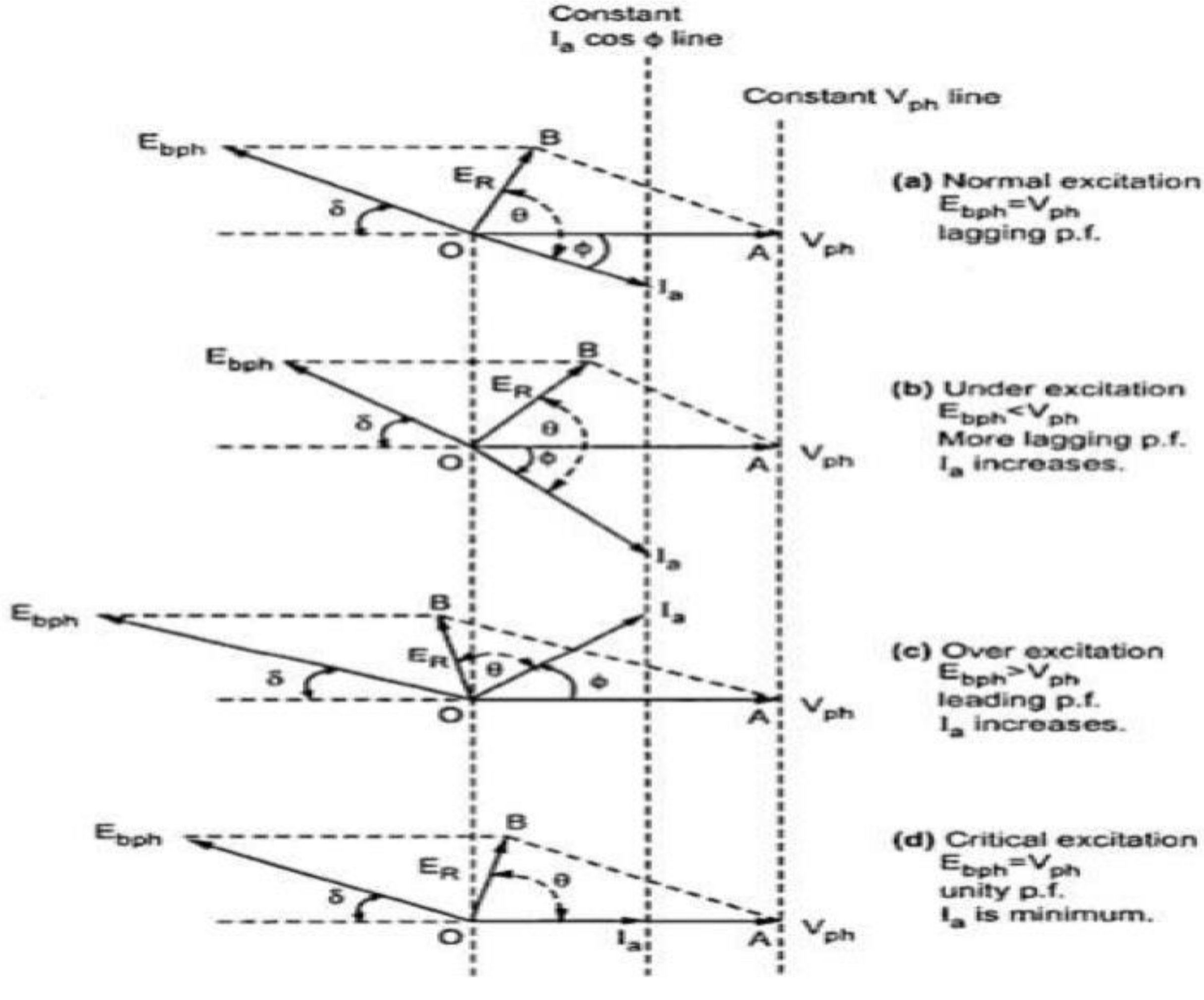
Now when excitation is changed, changes but there is hardly any change in the losses of the motor. So the power input also remains same for constant load demanding same power output.

Now Pin = √3 VL IL cos Φ = 3 (Vph Iph cos Φ)

Under Excitation (E_b < V): E_R increases in magnitude. This means for constant Zs, current drawn by the motor increases. But ER phase shifts in such a way that, phasor Ia also shifts (as E_R ^ Ia = θ) to keep Ia cos Φ component constant. This is shown in the Fig. 1(b). So in under excited conditions, current drawn by the motor increases. The p.f. cos Φ decreases and becomes more and more lagging in nature.

Over Excitation (Eb < V): Due to the increased magnitude of Eb, ER also increases in magnitude. But the phase of ER also changes. Now = E_R ^ Ia = θ is constant, hence Ia also changes its phase. So Φ changes. The Ia increases to keep Ia cos Φ constant as shown in Fig.1(c). The phase of E_R changes so that Ia becomes leading with respect to Vph in over-excited condition. So the power factor of the motor becomes leading in nature. So overexcited synchronous motor works on the leading power factor. So power factor decreases as over-excitation increases but it becomes more and more leading in nature.

Critical Excitation: When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity (cos Φ = 1) is called critical excitation. Then Iaph is in phase with Vph. Now Ia cos Φ must be constant, cos Φ = 1 is at its maximum hence motor has to draw minimum current from supply for unity power factor condition. So for critical excitation, cos Φ = 1 and current drawn by the motor is minimum compared to current drawn by the motor for various excitation conditions. This is shown in the Fig. 1(d).



6. V-Curves and Inverted V-Curves:

If excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the Fig. 1.

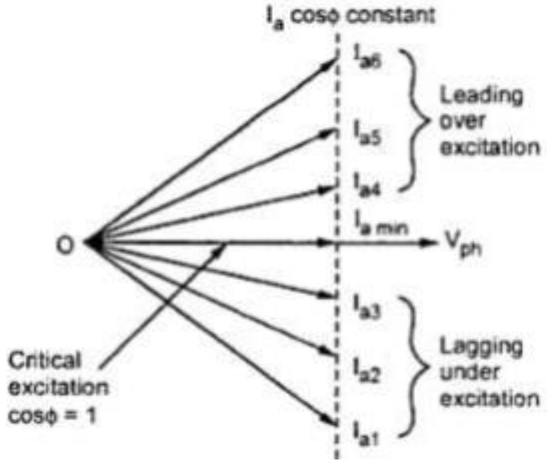


Fig. 1

Excitation can be increased by increasing the field current passing through the field winding of the synchronous motor. If the graph of armature current drawn by the motor (Ia) against field current (I_f) is plotted, then its shape looks like an English alphabet V. If such graphs are obtained at various load conditions we get a family of curves, all looking like V. Such curves are called V curves of synchronous motor. These are shown in Fig. 2a).

As against this, if the power factor (cos Φ) is plotted against field current (If), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in Fig. 2(b).

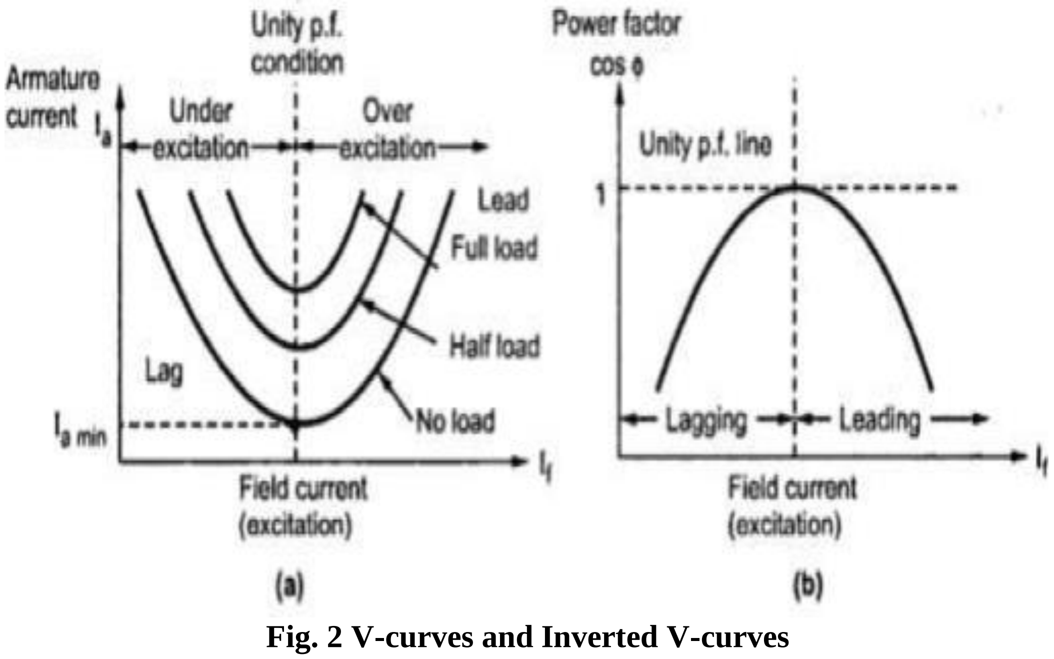


Fig. 2 V-curves and Inverted V-curves

7. Synchronous Condensers:

When the synchronous motor is over excited it takes leading p.f. current. If the synchronous motor is on no load, where load angle δ is very small and it is over excited (Eb > V) then the power factor angle increases almost up to 90°. And motor runs with almost zero leading power factor condition. This is shown in the phasor diagram Fig. 1

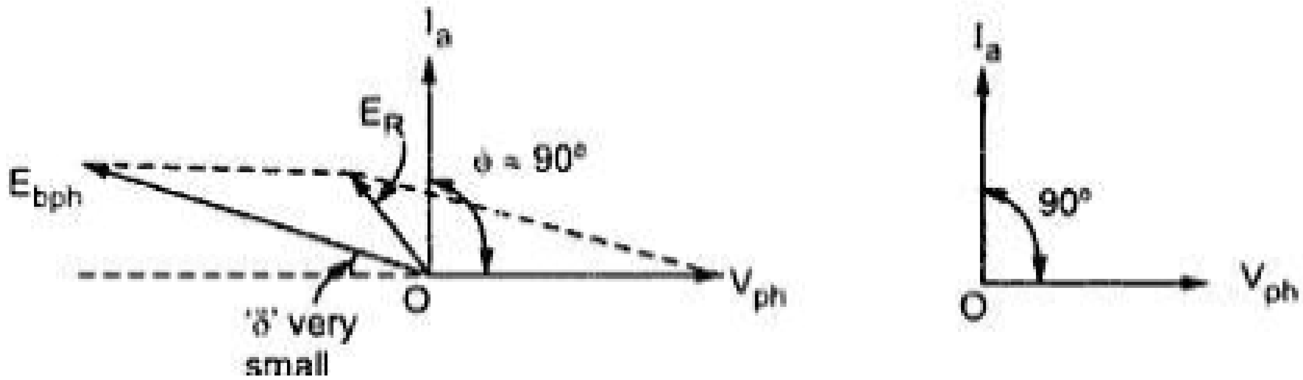


Fig. 1 Synchronous condenser

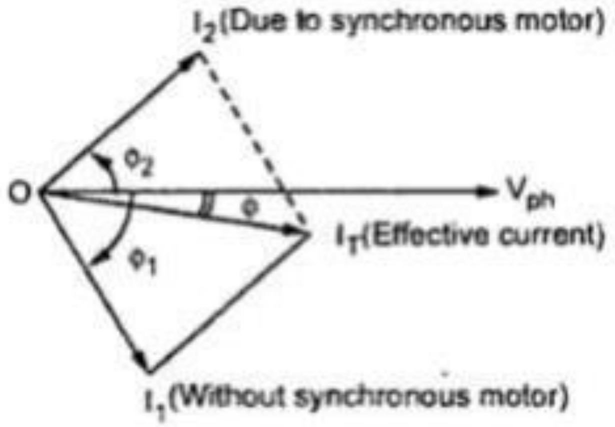
This characteristic is similar to a normal capacitor which takes leading power factor current. Hence over excited synchronous motor operating on no load condition is called as synchronous condenser or synchronous capacitor. This is the property due to which a synchronous motor is used as a phase advancer or as a power improvement device.

9. Use of Synchronous Condenser in Power Factor Improvement:

The low power factor increases the cost of generation, distribution and transmission of the electrical energy. Hence such a low power factor needs to be corrected. Such power factor correction is possible by connecting a synchronous motor across the supply and operating it on no load with over-excitation.

Now let Vph is the voltage applied and I1ph is the current lagging Vph by angle Φ1. This power factor Φ1 is very low, lagging.

The synchronous motor acting as a synchronous condenser is now connected across the same supply. This draws a leading current of I2ph. The total current drawn from the supply is now phasor of I_{ph} and I_{2ph}. This total current I_T now lags Vph by smaller angle Φ due to which effective power factor gets improved. This is shown in Fig.



Power factor correction by synchronous condenser

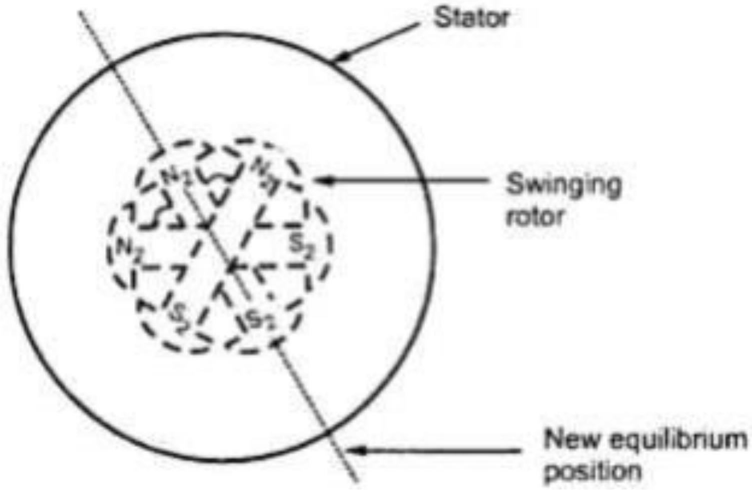
8. Hunting in Synchronous Motor:

When a synchronous motor is on no load, the stator and rotor pole axes almost coincide with each other.

When the motor is loaded, the rotor axis falls back with respect to the stator. The angle by which the rotor retards is called the load angle or angle of retardation δ.

If the load connected to the motor is suddenly changed by a large amount, then the rotor tries to retard to take its new equilibrium position.

However, due to the inertia of the rotor, it cannot achieve its final position instantaneously. While achieving its new position due to inertia it passes beyond its final position corresponding to a new load. This will produce more torque than what is demanded. This will try to reduce the load angle and the rotor swings in another direction. So there is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load. Such a swing is shown in the Fig.

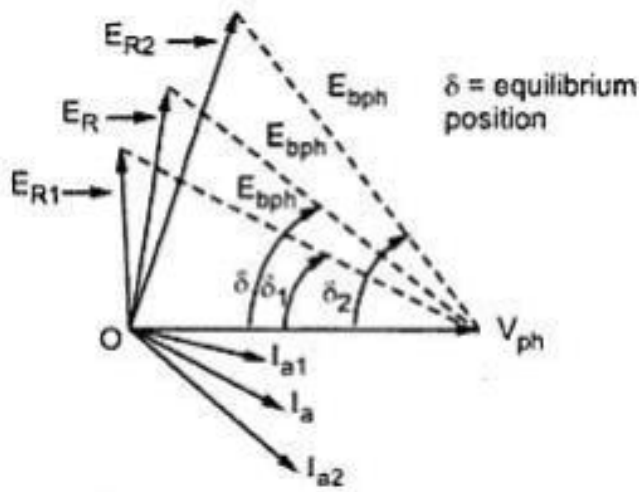


Hunting in a synchronous motor

Such oscillations of the rotor about its new equilibrium position, due to the sudden application or removal of load is called swinging or hunting in a synchronous motor.

Due to such hunting, the load angle changes its value about its final value δ. As changes, for the same excitation i.e. Ebph the current drawn by the motor also changes. Hence during hunting, there are changes in the current drawn by the motor which may cause problems to the other appliances.

connected to the same line. The changes in armature current due to hunting are shown in Fig.



If such oscillations continue for a longer period, there are large fluctuations in the current. If such variations are synchronous with the natural period of oscillation of the rotor, the amplitude of the swing may become so great that the motor may come out of synchronism. At this instant mechanical stresses on the rotor are severe and the current drawn by the motor is also very large. So

the motor gets subjected to large mechanical and electrical stresses.

9. Use of Damper Winding to Prevent Hunting:

It is mentioned earlier that in the slots provided in the pole faces, a short-circuited winding is placed. This is called damper winding.

When the rotor starts oscillating i.e. when hunting starts a relative motion between damper winding and the rotating magnetic field is created. Due to this relative motion, e.m.f. gets induced in the damper winding. According to Lenz's law, the direction of induced e.m.f. is always so as to oppose the cause producing it. The cause is hunting. So such induced e.m.f. oppose the hunting. The induced e.m.f. tries to dampen the oscillations as quickly as possible. Thus hunting is minimized due to damper winding.
The time required by the rotor to take its final equilibrium position after hunting is called as setting time of the rotor. If the load angle is plotted against time, the schematic representation of hunting can be obtained as shown in Fig It is shown in the diagram that due to damper winding the setting time of the rotor reduces considerably.

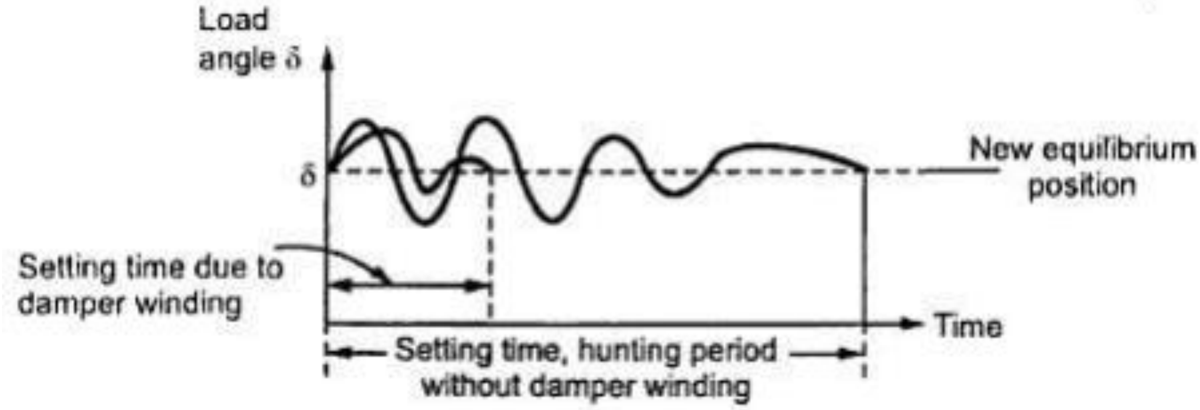


Fig. Effect of damper winding on hunting

10. Methods of Starting Synchronous Motors:

As seen earlier, the synchronous motor is not self-starting. It is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible by various methods in practice. The various methods to start the synchronous motor are,

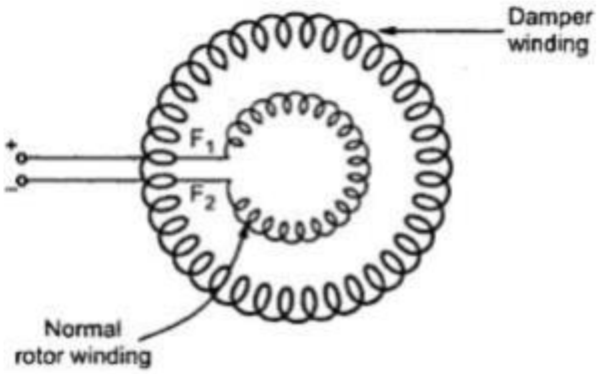
1. Using pony motors
2. Using damper winding
3. As a slip-ring induction motor
4. Using small d.c. machine coupled to it.

1. Using pony motors

In this method, the rotor is brought to the synchronous speed with the help of some external device like a small induction motor. Such an external device is called a 'pony motor'.
Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as a synchronous motor.

2. Using Damper Winding

In a synchronous motor, in addition to the normal field winding, the additional winding consists of copper bars placed in the slots in the pole faces. The bars are short-circuited with the help of end rings. Such an additional winding on the rotor is called damper winding. This winding as short-circuited, acts as a squirrel cage rotor winding of an induction motor. The schematic representation of such damper winding is shown in the Fig.

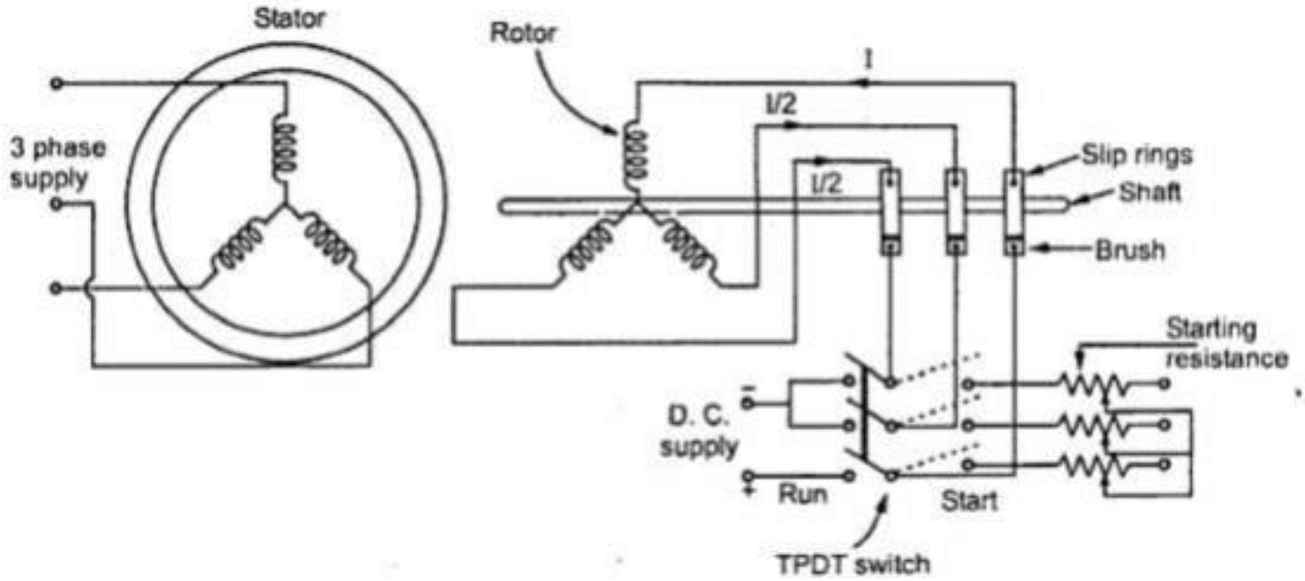


Starting as a squirrel cage I.M.

Once the rotor is excited by a three-phase supply, the motors starts rotating as an induction motor at sub-synchronous speed. Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed. As the rotor rotates at synchronous speed, the relative motion between the damper winding and the rotating magnetic field is zero. Hence when motor is running as a synchronous motor, there cannot be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards, it is out of the circuit. As the damper winding is short circuited and motor gets started as an induction motor, it draws a high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

3. As a Slip Ring Induction Motor

The above method of starting a synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper winding, it is designed to form a three-phase star or delta-connected winding. The three ends of this winding are brought out through slip rings. An external rheostat then can be introduced in series with the rotor circuit. So when the stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque. The resistance is then gradually cut off, as the motor gathers speed. When the motor attains speed near synchronous. d.c. excitation is provided to the rotor, then motors gets pulled into synchronism ans starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a motor resistance starter. The synchronous motor started by this method is called a slip ring induction motor is shown in Fig.



Starting as a slip ring I.M

4. Using Small D.C. Machine

Many a times, a large synchronous motor are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.

11. Torque and Torque angle:

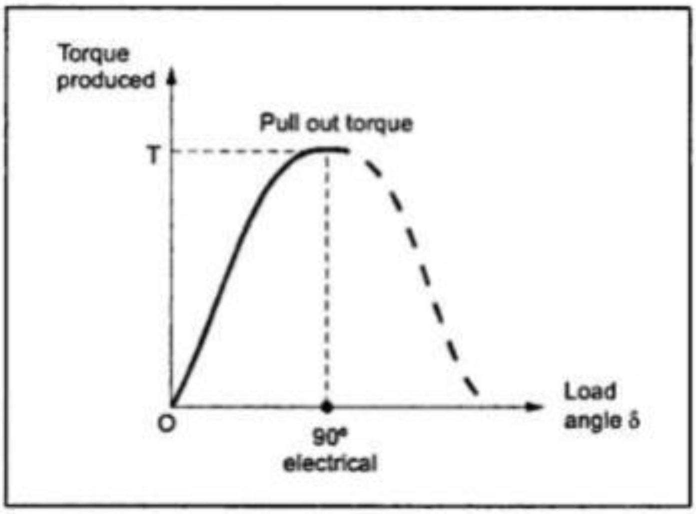
1. Starting Torque: Torque developed by the synchronous motor at starting when rated voltage is applied. It is also called breakaway talk it is necessary to overcome friction and inertia.

2. Running Torque: Torque developed by the motor under running conditions. It is decided by the output rating of the motor and the speed of the driven machine.

3. Pull-in Torque: Initially $N_s > N$. When speed is near to synchronous, excitation is switched on and the motor gets pulled into synchronism and starts rotating at N_s. The amount of torque developed by the motor at the time of pulling into synchronism is Pull-in torque.

4. Pull–out torque: When the motor is loaded, the rotor falls back with respect to the stator by an angle called load angle δ. As δ increases, the magnetic locking between the stator and rotor decreases. At $\delta = 90^0$, the torque developed is maximum by the motor and magnetic locking is very weak. Any further increases in the load pull the motor out of synchronism and the motor stops. Thus the maximum torque developed by the motor without pulling out of synchronism is called pullout torque.

5. Torque angle: The torque produced in the synchronous motor depends on the load angle 'δ' for small values of and to be precise depends on 'sinδ'. The load angle 'δ' is measured in degrees electrical. As angle δ increases, the magnetic flux lines producing the force of attraction between the two get more and more stretched. This weakens the force maintaining the magnetic locking, though torque produced by the motor increases. As δ reaches up to 90^o electrical i.e. half a pole pitch, the stretched flux lines get broken and hence magnetic locking between the stator and rotor no longer exists. The motor comes out of synchronism. So torque produced at δ equal to 90^0 electrical is the maximum torque, a synchronous motor can produce, maintaining magnetic locking i.e. synchronism. Such torque is called pull-out torque. The relationship between the torque produced and the load angle is shown in Fig



Torque angle characteristic

12. Universal Motor:

There are small capacity series motors which can be operated on d.c. supply or single-phase alternating supply of same voltage with same characteristics, called universal motors. Most of the universal motors are meant to operate at speeds as high as 3500 RPM.

Operation of Universal Motor

When fed with a DC supply

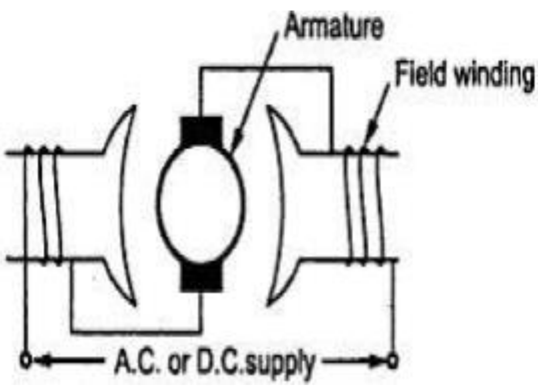
When the universal motor is fed with a DC supply, it works as a DC series motor. In this case, when the current flows in the field winding, it produces an electromagnetic field. The same current also flows in the armature conductors. When a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. This mechanical force causes the rotor to rotate. Fleming’s Left-hand rule gives us the direction of this force.

When fed with an AC supply

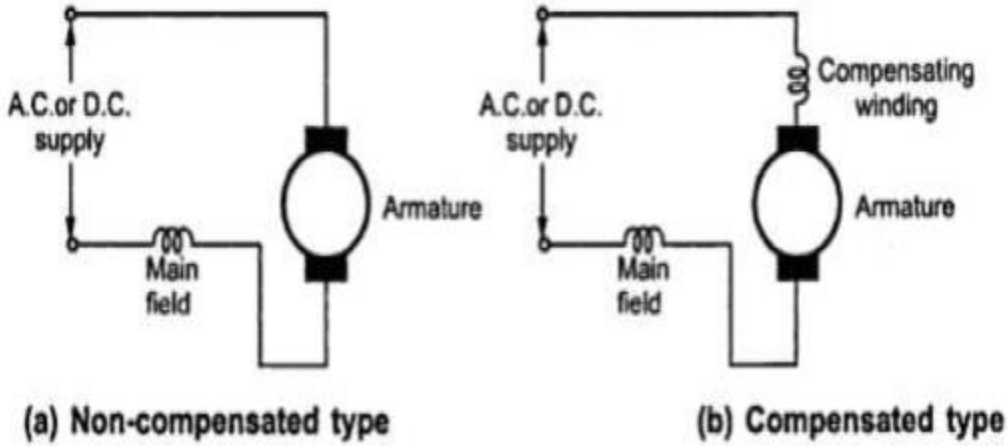
A unidirectional torque is produced when the universal motor is supplied with AC power. This is because the armature winding and the field winding are connected in series and are in the same phase. Therefore, whenever the polarity of the AC changes, the direction of the current in the armature and the field winding changes simultaneously. The direction of the magnetic field and the direction of armature current reverse so that the direction of force experienced by armature conductors remains the same. Thus, regardless of AC or DC supply, universal motors work on the same principle that DC series motors work on.

i) Non compensated, low h.p ii) Compensated type, high h.p.

Non compensated type pole has 2 poles, having entire magnetic path as laminated. Armature is wound type similar to the normal d.c. motor. Such non compensated construction is shown in the Fig. 1.



Cross-section of non-compensated universal motor

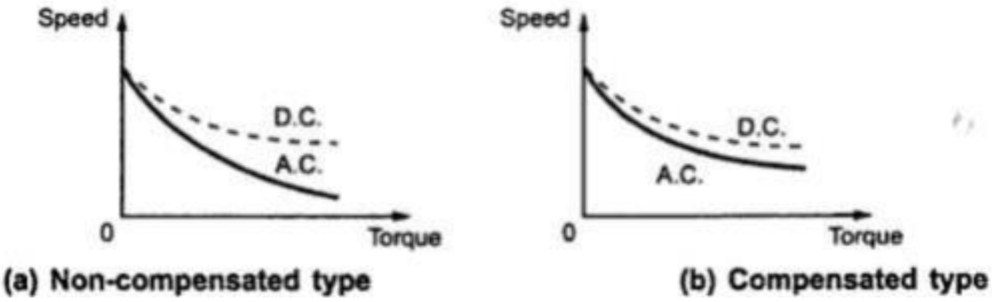


Connection diagrams for a universal motor

Non-compensated type pole has 2 poles, having an entire magnetic path as laminated. Armature is a wound type similar to the normal d.c. motor. In the compensated type, the motor has distributed field winding consisting of the main field and compensating winding. This is somewhat similar to the stator of split-phase single-phase induction motor type construction.

Speed torque characteristics:

The speed-torque characteristics for both types of universal motor are shown in the Fig.



Speed-torque characteristic of universal motor

The compensated type universal motor has better speed-torque characteristics i.e. the characteristics are the same for the operation of the motor on a.c. or d.c. supply. The motors are generally designed for full load operation speeds ranging between 3000 to 20000 r.p.m.

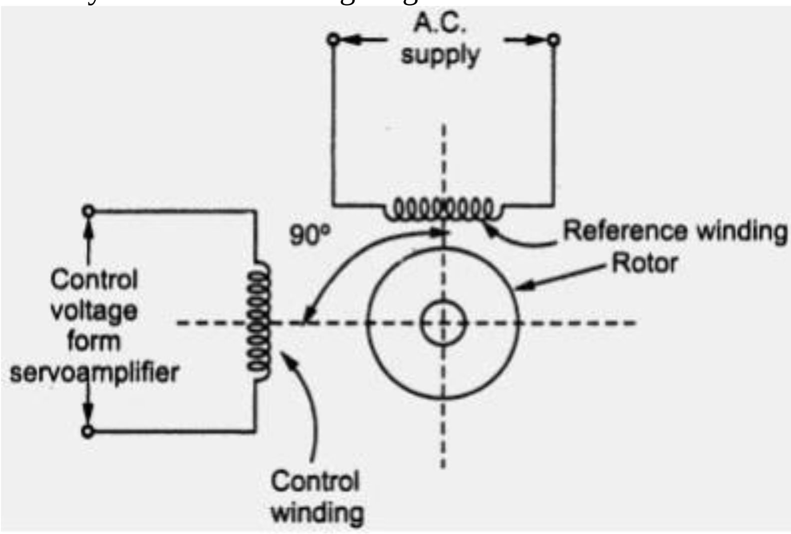
Applications: Though compensated type characteristics are better, the non-compensated type is more preferred for low h.p. applications. While the compensated type of universal motors is preferred for h.p. applications. High starting torque is an important feature of universal motors. The universal motors are used for domestic applications like vacuum cleaners, food processors and mixers, hair dryers, coffee grinders, electric shavers, etc. Their other applications are blowers, portable tools like drilling machines, and small drivers.

13. A.C. Servomotor:

Most of the servomotors used in the low power servomechanism are a.c. servomotors. The a.c. servomotor is basically a phase induction motor. The output power of a.c. servomotor varies from a fraction of watts to a few hundred watts. The operating frequency is 50 Hz to 400 Hz.

Construction:

The a.c. servomotor is basically consists of a stator and a rotor. The stator carries two windings, uniformly distributed and displaced by 90^0 in space, from each other. On winding is called as main winding or fixed winding or reference winding. The reference winding is excited by a constant voltage a.c. supply. The other winding is called as control winding. It is excited by variable control voltage, which is obtained from a servo amplifier. The winding are 90^0 away from each other and control voltage is 90^0out of phase with respect to the voltage applied to the reference winding. This is necessary to obtain a rotating magnetic field.



Stator of a.c. servomotor

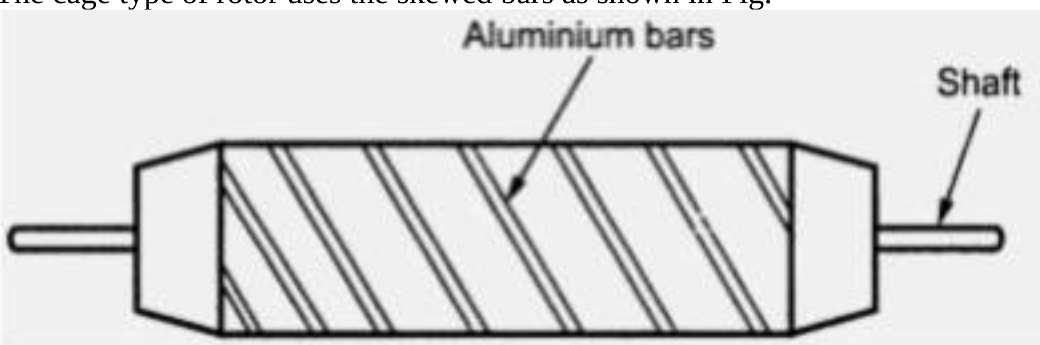
Rotor

The rotor is generally of two types. The two types of rotors are,
1. Squirrel cage rotor
2. Drag cup-type rotor

Squirrel Cage Rotor

The usual squirrel cage rotor has aluminum bars that are shorted at the ends with the help of the end rings. The overall construction looks like a cage. The construction is like the squirrel cage rotor used for the three-phase induction motors.

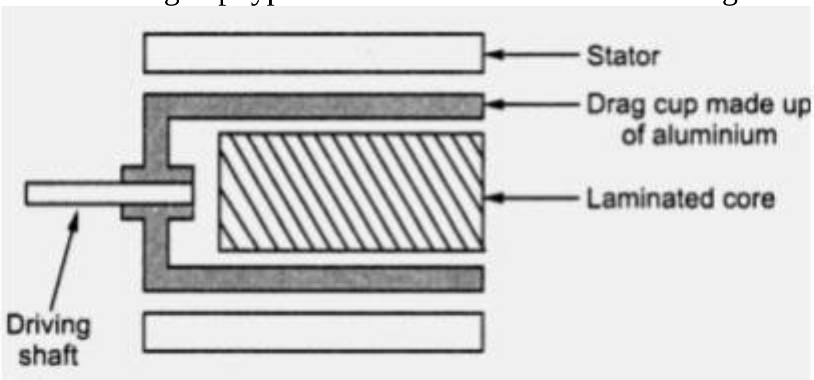
This has a small diameter and large length. This is because it reduces the inertia. Aluminum conductors are used to keep weight small. Its resistance is high to keep torque-speed characteristics as linear as possible. An air gap is kept very small which reduces the magnetism current. The cage type of rotor uses the skewed bars as shown in Fig.



Cage-type rotor construction

Drag cup type rotor

To reduce the inertia further, a drag cup type of rotor construction is used. There are two air gaps in this construction. The drag cup is made up of nonmagnetic material like copper, aluminum or an alloy. The slotted rotor laminations in this construction are wound for as many number of poles as possible so that operating speed of the motor is very low. Such a construction is used in very low-power applications. A drag cup type rotor construction is shown in Fig.



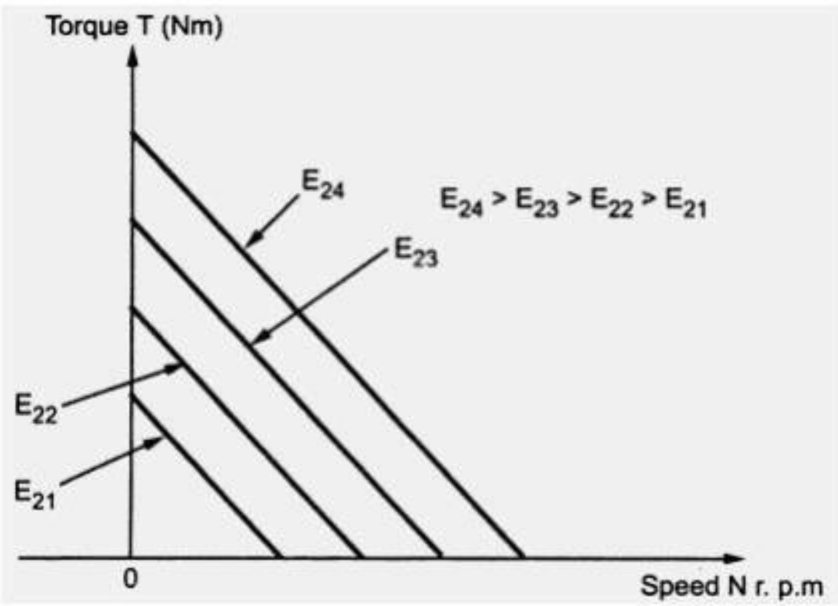
Drag cup-type rotor construction

Operating Principle :

The operating principle of two-phase a.c. a servomotor is the same as that of a normal three-phase induction motor. The control voltage applied to the control winding and the voltage applied to the reference winding is 90^0 out of phase. Hence the flux produced by current through control winding is also 90^0 out of phase with respect to the flux produced by the current through the reference winding. The resultant flux in the air gap is hence rotating flux sweeps over the rotor, the e.m.f. gets induced in the rotor. This e.m.f. circulates the current through the rotor. The rotor current produces its own flux called as rotor flux. This flux interacts with the rotating magnetic field, producing a torque on the rotor and the rotor starts rotating.

In the two-phase a.c. servomotors, the polarity of the control voltage determines the direction of rotation. A change in the sign of the control voltage reverses the direction of rotation of the motor. Since the reference voltage is constant, the torque and the angular speed are the functions of the control voltage.

Torque-Speed Characteristics:



Torque-speed characteristics of a.c servomotor

Applications of A.C. Servomotor:
1. Instrument servos 2. Process controllers 3. Robotics 4. Self-balancing recorders 5. Machine tools

14. Linear Induction Motor:

The linear induction motor works on the same principle as that of a normal induction motor with the difference that instead of rotational movement, the rotor moves linearly. If the stator and rotor of the induction motor are made flat then it forms the linear induction motor. The flux produced by the flat stator moves linearly with the synchronous speed from one end to the other. The synchronous speed is given by,

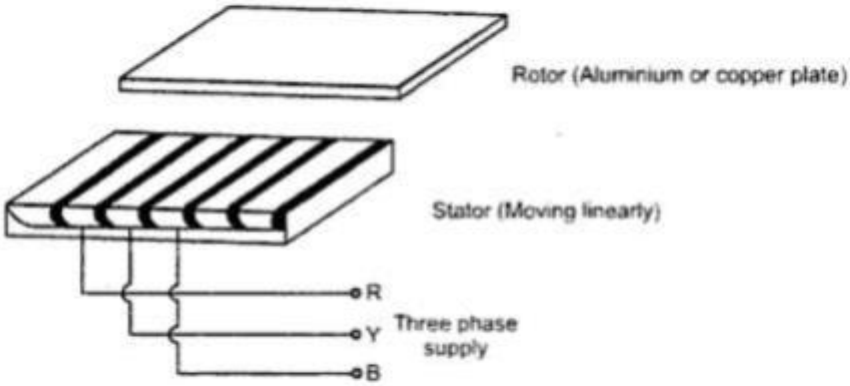
$v_s = 2wf$

where v_s = Linear Synchronous Speed (m/s)

w = Width of one pole pitch (m)

f = Frequency of supply (Hz)

It can be seen that the synchronous speed is independent of the number of poles but depends only on one width of pole pitch and supply frequency. The schematic of the linear induction motor is shown in the Fig.



The flux moves linearly and forces the rotor to move in straight line in the same directions. In many of the practical applications the rotor plate is a stationary member whereas stator moves. The analysis of linear machines is nearly same as that of rotating machines. All the angular dimensions and displacements are displaced by linear ones and torque is replaced by the force. The expressions for machine parameters are derived analogously and the results are similar in form. Some of the typical results are as given below,

Slip, $s = \frac{v_s - v}{v_s}$ where v is the actual speed.

Force, $F = \frac{P_2}{v_s}$ where P_2 is active power supplied.

Rotor Cu loss, $P_{cu} = sP_2$

Mechanical power, $P_m = (1 - s)\, P_2$

Linear induction motors are widely used in transportation fields i.e. in electric trains. The stator is mounted on the moving vehicle and a conducting stationary rotor forms the rails. The induced currents in the rail not only force the stator to move but also provide magnetic levitation in which the train floats in the air above the track. This mechanism proves better for high-speed transportation without the difficulties associated with wheel-rail interactions present in conventional rail transport. Thus the trains may have a speed of about 300 km/hr. A powerful electromagnet fixed underneath the train moves across the rails that are conducting. The induces the currents in the rail which provides levitation so that the train is pushed up above the track in the air. The operation of such a system is automatic and the system is reliable and safe. Linear motors also find application in the machine tool industry and in robotics where linear motion is required for positioning and for operation of the manipulators. In addition to this, reciprocating compressors can also be driven by linear machines.

15. Stepper Motor:

The Stepper motor is known for its important property to convert a train of input pulses i.e. square wave pulses into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle. So the stepper motor is an electromechanical device that actuates a train of step movements of the shaft in response to the train of input pulses. The step movement may be angular or linear.

Types of Stepper Motors

The stepper motors can be divided into three categories :

1. Variable Reluctance Stepper Motors
2. Permanent Magnet Stepper Motors
3. Hybrid Stepper Motors

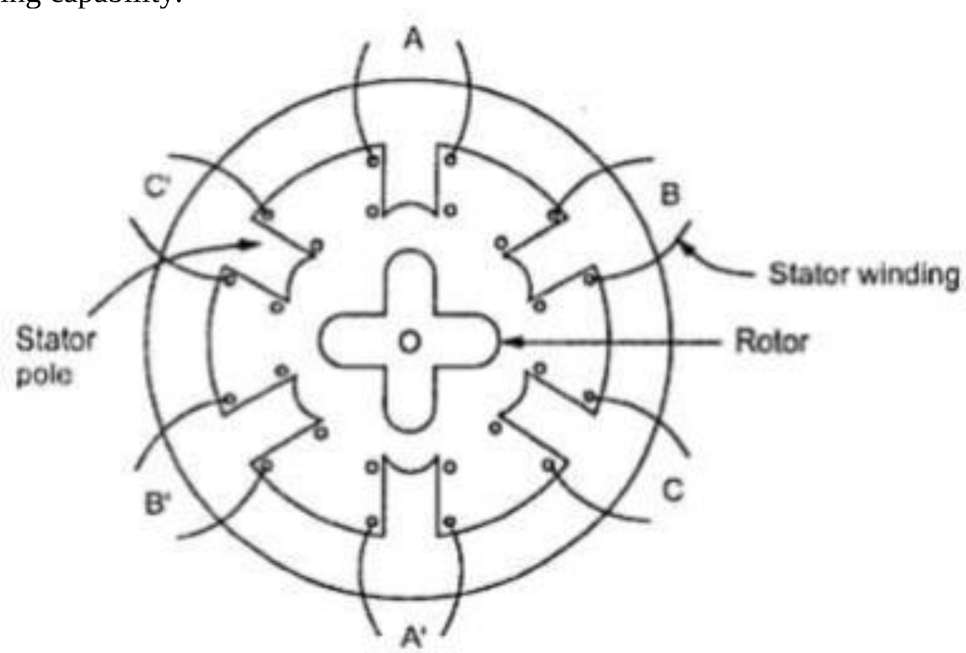
1. Variable Reluctance Stepper Motors:

It is the most basic type of stepper motor. This helps to explain the principle of operation of the stepper motors.

The motors have a stator which is usually wound for three phases. The stator has six salient poles with concentrated exciting windings around each one of them. The stator construction is laminated and assembled in a single stack. The number of poles on the stator and rotor are different. This gives the motor ability,

1.Bidirectional rotation and

2. Self-starting capability.



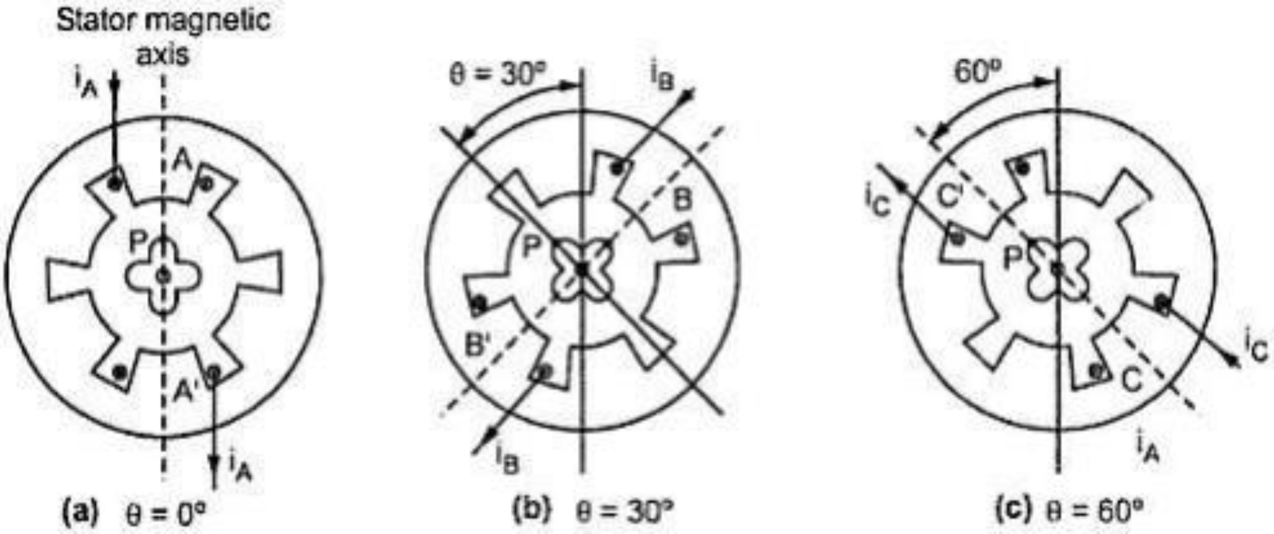
Schematic arrangement of variable reluctance motor

The coils wound around diametrically opposite poles are connected in series and the three phases are energized from a d.c. source with the help of switches.

Operation:

The operation is based on various reluctance positions of rotor with respect to stator. When any one phase of the stator is excited, it produces its magnetic field whose axis lies along the poles, the phase around which is excited. Then rotor moves in such a direction so as to achieve minimum reluctance position. Such a position means a position where axis of magnetic field of stator matches with the axis passing through any two poles of the rotor. Let us see the operation when phases A, B and C are energized in sequence one after the other, with the help of switches SW1, SW2 and SW3.

1. When the phase AA' is excited with the switch SW1 closed, then stator magnetic axis exists along the poles formed due to AA' i.e. vertical. Then rotor adjusts itself in a minimum reluctance position i.e. matching its own axis passing through the two poles exactly with the stator magnetic axis. This position is shown in the Fig. (a).



Steps in variable reluctance motor

2. When phase BB' is excited with the switch SW2 closed and phase AA' de-energized with the switch SW1 open, the stator magnetic axis shifts along the poles formed due to BB;, shown dotted in Fig. (b). Then rotor tries to align in the minimum reluctance position and turns through 30^0in an anticlockwise direction. So axis passing through two diagonally opposite poles of the rotor matches with the stator magnetic axis. This is the new minimum reluctance position. The point P shown on the rotor has rotated through 30^0in an anticlockwise direction as shown in the Fig. 3(b).

3. When the phase CC' is excited with the switch SW3 closed and the phases AA' and BB' are de-energized, then the stator magnetic axis shifts along the poles formed due to CC', shown dotted in Fig. (c). Then to achieve minimum reluctance position, the rotor gets subjected to further anticlockwise torque. So it turns through a further 30^0 in an anticlockwise direction. Hence point P is now at 60^0 from its starting position, in an anticlockwise direction as shown in Fig (c). By successively exciting the three phases in the specific sequence, the motor takes twelve steps to complete on revolution.

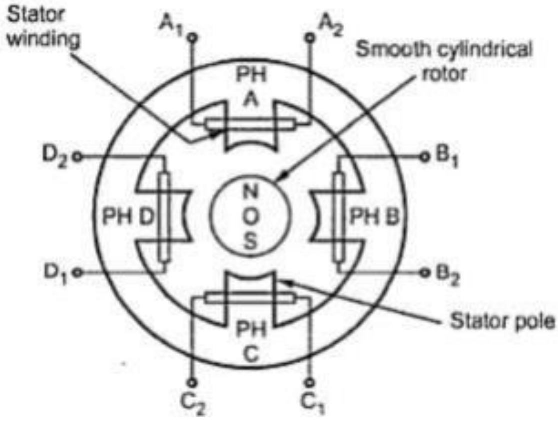
Advantages of Variable Reluctance Motor:

The variable reluctance stepper motor has the following advantages.

1. High torque to inertia ratio
2. High rates of acceleration.
3. Fast dynamic response
4. Simple and low-cost machine
5. Efficient cooling arrangement as all the windings are the n the stator and there is no winding on the rotor.

2. Permanent Magnet Stepper Motor:

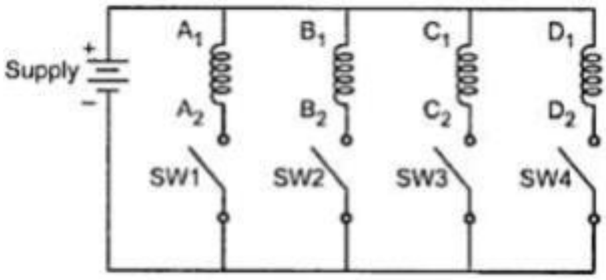
The stator of this type is multi-polar. As shown in the Fig. the stator has four poles. Around the poles, the exciting coils are wound. The number of slots per pole per phase is usually chosen as one in such multi-polar machines.



Four-phase permanent magnet stepper motor

The rotor may be salient or smooth cylindrical. But generally, it is a smooth cylindrical type as shown in the Fig It is made out of ferrite material which is permanently magnetized. Due to this, the motor is called a permanent magnet stepper motor.

The voltage pulses to the stator winding can be obtained by using a driving circuit. The basic driving circuit for the phase permanent magnet stepper motor is shown in Fig.



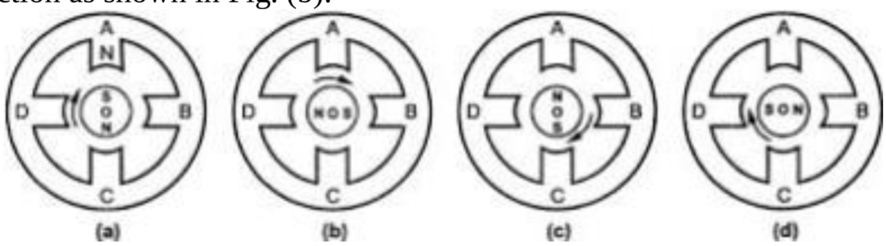
Basic drive circuit for permanent magnet four-phase stepper motor

Operation:

As soon as the voltage pulses are applied to various phases with the help of the driving circuit, a rotor starts rotating through a step fir each input voltage pulse.

1. At first, switch SW1 is closed exciting phase A. Due to its excitation, we have N pole in phase A as shown in Fig. (a). Due to the electromechanical torque developed, the rotor rotates such that the magnetic axis of the permanent magnet rotor adjusts with the magnetic axis of the stator, as shown in Fig. (a).

2. Next phase B is excited with switch SW2, disconnecting phase A. Due to this, the rotor further adjusts its own magnetic axis with the N pole of phase B. Hence it rotates through 90^0 further in a clockwise direction as shown in Fig. (b).



Steps in four-phase permanent magnet stepper motor

Similarly, when phase C and phase D are sequentially excited, the rotor tends to rotate through 90^0in a clockwise direction, every time the phase is excited. When such a sequence is repeated, it results in a step motion of a permanent magnet stepper motor.

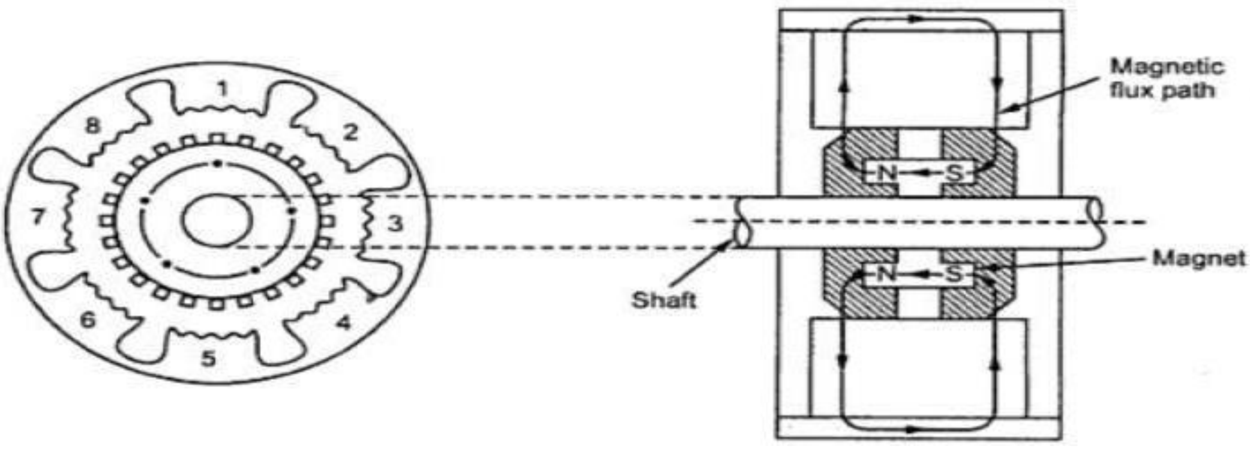
The stepper motors with permanent magnet rotors with a large number of poles can not be manufactured in small sizes. Hence small steps are not possible. This is the biggest disadvantage of a permanent magnet stepper motor. This is overcome by the use of variable reluctance type stepper.

Comparison Between Variable Reluctance and Permanent Magnet Stepper Motor

	Variable reluctance stepper motor	Permanent magnet stepper motor
1.	The rotor is not magnetised.	The rotor is magnetised.
2.	High torque to inertia ratio.	Low torque to inertia ratio.
3.	High rates of acceleration.	Acceleration is slow.
4.	The dynamic response is fast.	Very slow dynamic response.
5.	Maximum stepping rate can be as high as 1200 pulses per second.	Maximum stepping rate can be around 300 pulses per second.
6.	It can be manufactured for large number of poles.	It can not be manufactured for large number of poles due to difficulties in construction.
7.	Very small step angle is possible.	The step angles are high in the range of 30° to 90°
8.	It does not have a detent torque.	Its main advantage is the presence of a detent torque.
9.	The rotor has salient pole construction.	The rotor has mostly smooth cylindrical type of construction.

3. Hybrid Stepper Motor:

The hybrid stepper motor uses the principles of the permanent magnet and variable reluctance stepper motors. In the hybrid motors, the rotor flux is produced by the permanent magnet and is directed by the rotor teeth to the appropriate parts of the airgap. The permanent magnet is placed in the middle of the rotor. It is magnetized in the axial direction. Each pole of the magnet is surrounded with soft-toothed laminations.



Hybrid Stepper motor

The main flux path is from the north pole of the magnet, into the end stack, across the airgap through the stator pole, axially along the stator, through the stator pole, across the air and back the magnet south pole via the other end stack.

There are usually 8 poles on the stator. Each pole has between 2 to 6 teeth. There is two-phase winding. The coils on poles 1, 3, 5, and 7 are connected in series to form phase A while the coils on poles 2, 4, 6, and 8 are connected in series to form phase B. The windings A and B are energized alternately.

When phase A carries a positive current, stator poles 1 and 5 become south and 3 and 7 become north. The rotor teeth with north and south polarity align with the teeth of stator poles 1 and 5 and 3 and 7 respectively. When phase A is de-energized and phase B is excited, the rotor will move by one-quarter of a tooth pitch.

The torque in a hybrid motor is produced by the interaction of the rotor and the stator-produced fluxes. The rotor field remains constant as it is produced by the permanent magnet. The motor torque Tm is proportional to the phase current.

Applications of Stepper Motors:

Due to the digital circuit compatibility of the stepper motors, they are widely used in computer peripherals such as serial printers, linear stepper motors to printers, tape drivers, floppy disc drivers, memory access mechanisms etc. The stepper motors are also used in serial printers in typewriters or word processor systems, numerical control of machine tools, robotic control systems, number of process control systems, actuators, spacecraft, watches etc. X-Y recorders and plotters is another field in which stepper motors are preferred.