UNIT V SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES

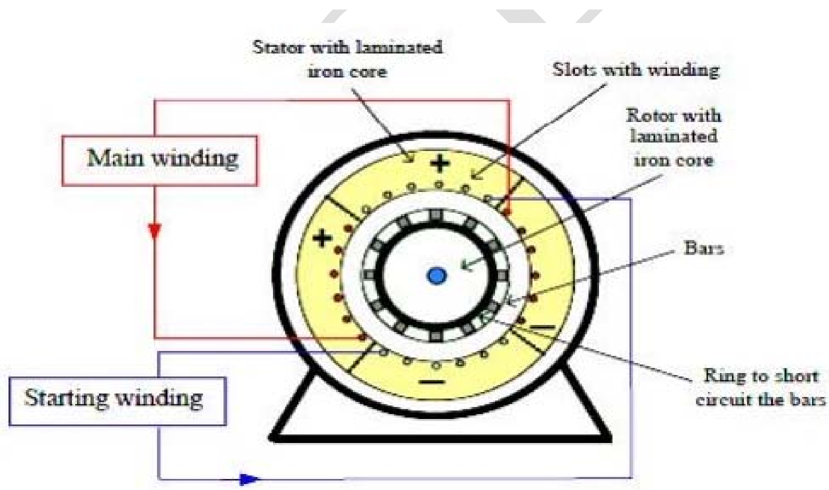
Constructional details of single phase induction motor – Double field revolving theory and operation – Equivalent circuit – No load and blocked rotor test – Performance analysis – Starting methods of single-phase induction motors – Capacitor-start capacitor run Induction motor- Shaded pole induction motor - Linear induction motor – Repulsion motor - Hysteresis motor - AC series motor- Servo motors- Stepper motors - introduction to magnetic levitation systems.

CONSTRUCTIONAL DETAILS OF SINGLE PHASE INDUCTION MOTOR

Constructionally, single phase induction motor is similar to polyphase induction motor except that (i) its stator is provided with a single phase winding and (ii) a centrifugal switch in order to cut out a winding used for starting purposes. It has distributed stator winding and a squirrel cage rotor.

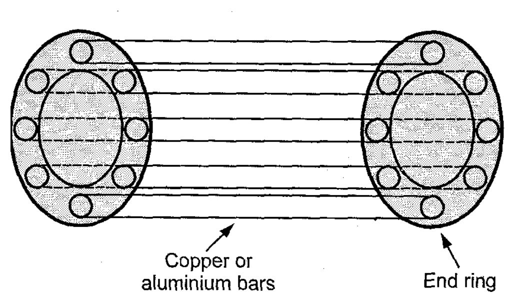
The constructional details of single phase induction motor are shown in figure.

1. Stator of Single Phase Induction Motor

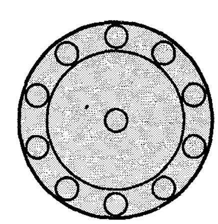


- The single-phase motor stator has a laminated iron core with two windings arranged perpendicularly
- One is the main and other is the auxiliary winding or starting winding.
- The stator has laminated construction, made up of stampings. The stampings are slotted on its periphery to carry the winding called stator winding or main winding.
- This is excited by a single phase a.c. supply. The laminated construction keeps iron losses to minimum, lie stampings are made up of material like silicon steel which minimizes the hysteresis loss.
- The stator winding is wound for certain definite number of poles means when excited by single phase a.c. supply, stator produces the magnetic field which creates the effect of certain definite number of poles.
- The number of poles for which stator winding is wound, decides the synchronous speed of the motor. The synchronous speed is denoted as N_s and it has a fixed relation with supply frequency f and number of poles P. The relation is given by, $N_s = 120f/P$.

2. Rotor of Single Phase Induction Motor



(a) Cage type structure of rotor

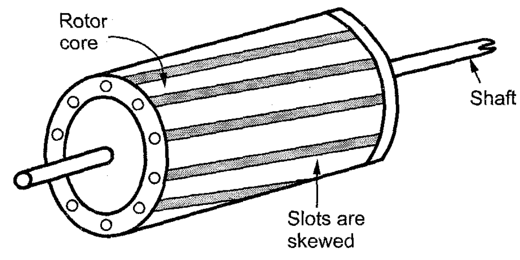


(b) Symbolic representation

- The rotor of single phase induction motor is shown in figure.
- The construction of the rotor of the single phase induction motor is similar to the squirrel cage three phase inductions motor.
- The rotor is cylindrical in shape and has slots all over its periphery.
- The slots are not made parallel to each other but are bit skewed as the

skewing prevents magnetic locking of stator and rotor teeth and makes the working of induction motor more smooth and quieter.

- The squirrel cage rotor consists of aluminium, brass or copper bars. These aluminium or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor.
- The rotor conductors are permanently shorted by the copper or aluminium rings called the end rings.
- In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor".



Skewing in rotor construction

- As the bars are permanently shorted by end rings, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars are permanently shorted.
- The absence of slip ring and brushes make the construction of single phase induction motor very simple and robust.

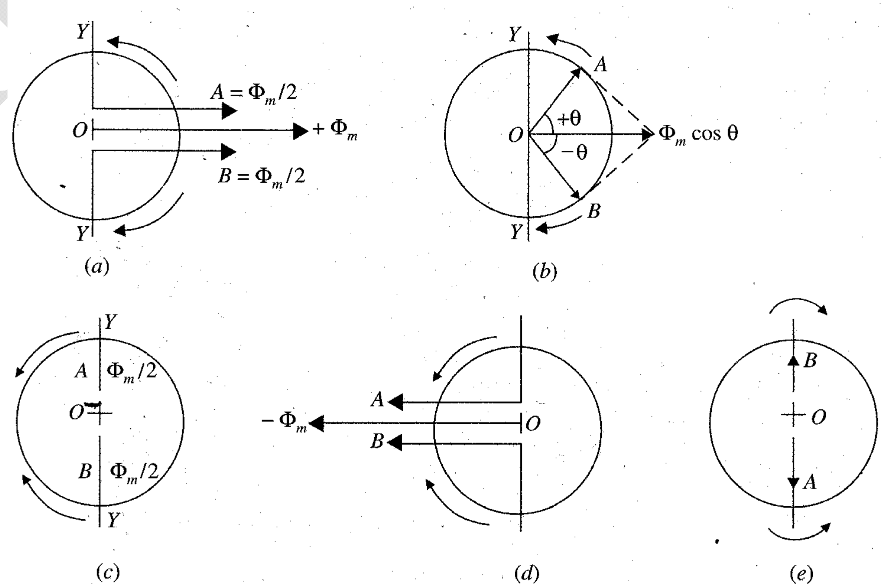
DOUBLE FIELD REVOLVING THEORY

When fed from a single-phase supply, its stator winding produces a flux (or field) which is only alternating i.e. one which alternates along one space axis only. It is a synchronously revolving (or rotating) flux, as in the case of a two- or a three-phase stator winding, fed from a 2-or 3-phase supply. Now, alternating or pulsating flux acting on a stationary squirrel-cage rotor cannot produce rotation (only a revolving flux can). That is why a single-phase motor is not self starting.

However, if the rotor of such a machine is given an initial start by hand (or small motor) or otherwise, in either direction, then immediately a torque arises and the motor accelerates to its final speed (unless the applied torque is too high).

This peculiar behaviour of the motor can be explained in two ways (i) by two -field or double- field revolving theory and (ii) by cross-field theory.

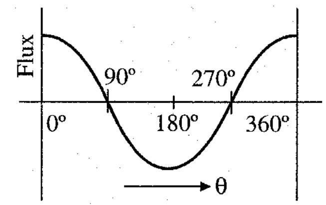
According to double field revolving theory, an alternating uniaxial quantity can be represented by two oppositely rotating vectors of half magnitude. Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously (N_s = 120f/p) in opposite direction.



As shown in fig. (a), let the alternating flux have a maximum value of Φ_m. its component fluxes A and B will each be equal to $\Phi_m/2$ revolving in anticlockwise and clockwise direction respectively.

After some time, when A and B would have rotated through angle +θ and –θ as in fig (b), the resultant flux would be

$= 2 \times \frac{\Phi_m}{2} \cos \frac{2\theta}{2} = \Phi_m \cos \theta$



After a quarter cycle of rotation, fluxes A and B will be oppositely directed as shown in fig (c) so that the resultant flux would be zero.

After half a cycle, fluxes A and B will have a resultant of $- 2 \times \frac{\Phi_m}{2} = - \Phi_m$.

After three quarters of a cycle, again the resultant is zero as shown in fig. (e) and so on.

If we plot the resultant flux against θ between $\theta = 0^0$ and 360^0, an alternating flux is obtained. That is why alternating flux is considered to have two fluxes, each half the value and revolving synchronously in opposite directions.

SINGLE PHASE INDUCTION MOTOR IS NOT SELF STARTING

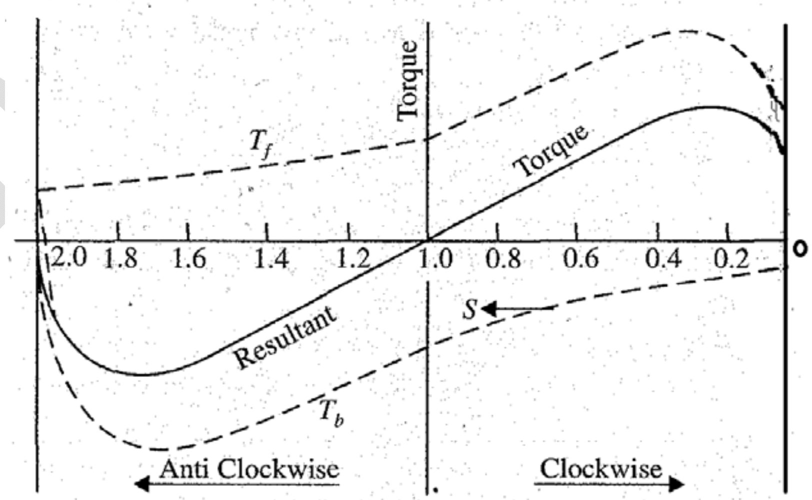
- If the slip of rotor is s with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2-s).
  If N is the r.p.m. of the rotor, then its slip w.r.t forward rotating flux is

  $$s = \frac{Ns - N}{Ns} = 1 - \frac{N}{N_s} \text{ or } \frac{N}{N_s} = 1 - s$$

  Backward rotating flux rotates opposite to the rotor, the rotor slip w.r.t this flux is

  $$s_b = \frac{Ns - (-N)}{Ns} = 1 + \frac{N}{N_s} = 1 + (1 - s) = (2 - s)$$

  Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an emf and this produces its own torque. The two torques, called forward and backward rotating torques are oppositely directed, so that the resultant torque is equal to their difference as shown in figure.

  Power developed by a rotor is $P_g = \frac{1-s}{s} I_2^2 R_2$

  If N is the rotor r.p.s., then torque is given by

  $T_g = \frac{1}{2\pi N} \cdot \frac{1-s}{s} \cdot I_2^2 R_2$

  $N = N_s (1 - s)$

  $T_g = \frac{1}{2\pi N_s} \cdot \frac{I_2^2 R_2}{s} = k. \frac{I_2^2 R_2}{s}$

  Forward torque $T_f = k. \frac{I_2^2 R_2}{s}$

  Backward torque $T_b = - k. \frac{I_2^2 R_2}{(2-s)}$

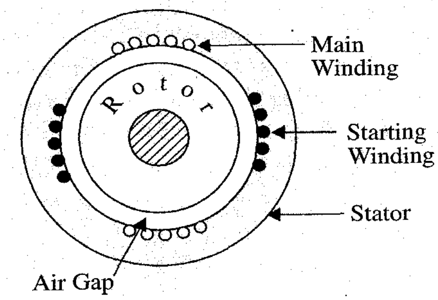
  $T_f = \frac{I_2^2 R_2}{s}$ syn. Watt and $T_b = - \frac{I_2^2 R_2}{(2-s)}$ syn. Watt

  Total torque $T = T_f + T_b$

  The figure shows both the torques and resultant torque for slips between zero and +2.

  At standstill condition, s = 1 and (2-s) = 1.hence T_f and T_b are numerically equal but being oppositely directed, produce no resultant torque. That is why there is no starting torque in a single phase induction motor.

MAKING SINGLE PHASE INDUCTION MOTOR SELF-STARTING



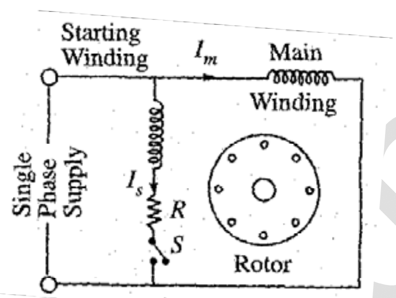
- A single phase induction motor is not self starting. To overcome this drawback and make the motor self starting, it is temporarily converted into a two phase motor during starting period.
- For this purpose, the stator of a single phase motor is provided with an extra winding, known as starting or auxiliary winding, in addition to the main or running winding.
- The two windings are spaced 90^0 electrically apart and are connected in parallel across the single phase supply.
- It is so arranged that the phase difference between the currents in the two stator windings is very large (ideal value is 90^0).
- Hence the motor behaves as a two phase motor. These two currents produce a revolving flux and hence make the motor self starting.

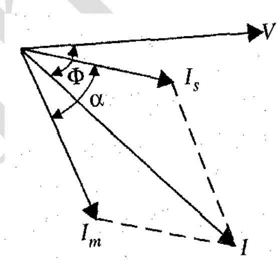
Depending on the methods by which the necessary phase difference between the two currents can be created, the single phase induction motors are classified as,

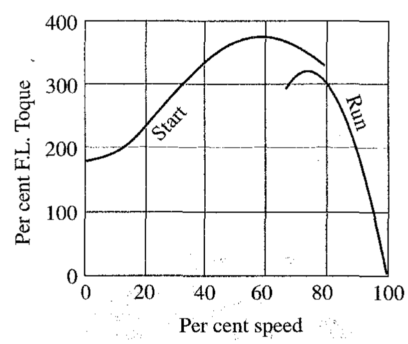
1. Split phase motor
2. Capacitor start induction run motors
3. Capacitor start and run motors
4. Shaded pole single phase motors\

1. Split Phase Motors (Resistance Start split phase induction motors)

- In split phase machine, the main winding has low resistance but high reactance whereas the starting winding has a high resistance but low reactance.
- Hence the current I_s drawn by the starting winding lags behind the applied voltage V by a small angle whereas current I_m drawn by the main winding lags behind V by a very large angle.







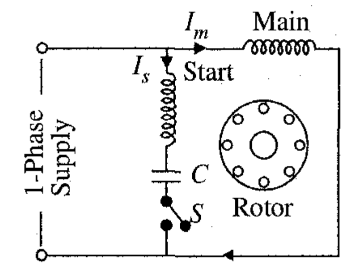
- Phase angle between I_s and I_m is made as large as possible because the starting torque of a split phase motor is proportional to sin α.
- A centrifugal switch S is connected in series with the starting winding and located inside he motor.
- Its function is to automatically disconnect the starting winding from the supply when the motor has reached 70 to 80 percent of its full load speed.
- The starting torque is 150 to 200 percent of the full load torque.
- Starting current is 6 to 8 times the full load current.

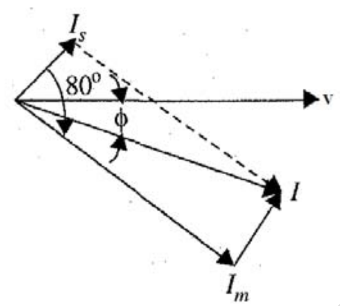
Applications

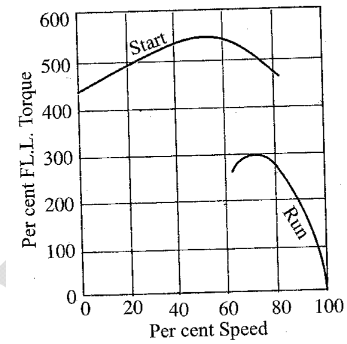
- Fans, blowers, centrifugal pumps and separators, washing machines, small machine tools, duplicating machines, domestic refrigerators, and oil burners etc.
- Available sizes range from 1/20 to 1/3 h.p. (40 to 250 W) with speeds ranging from 3450 to 865 rpm.

2. Capacitor Start Induction Run Motors

- In this motor, the phase difference between I_s and I_m is produced by connecting a capacitor in series with the starting winding.
- The capacitor is electrolytic type and is mounted outside the motor as a separate unit.







- When the motor reaches about 75 percent of the full speed, the centrifugal switch S opens and cuts out both the starting winding and capacitor from the supply, thus leaving only the running winding across the lines.
- As shown in figure, current I_m drawn by the main winding lags the supply voltage V by a large angle whereas I_s leads V by a certain angle.
- The two currents are out of phase with each other by about 80^0 as compared to nearly 30^0 for a split phase motor.
- Torque developed is proportional to sin α (angle between I_s and I_m), therefore starting torque is as high as 350 to 450 percent.

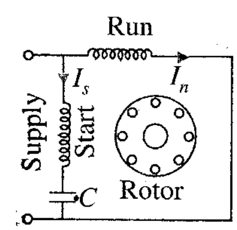
3. Capacitor Start and Run motor

- This motor is similar to the capacitor start motor except that the starting winding and capacitor are connected in the circuit at all times.
- The advantages of leaving the capacitor permanently in the circuit are
    - Improvement of overload capacity of the motor
    - A higher power factor
    - Higher efficiency
    - Quieter running of the motor

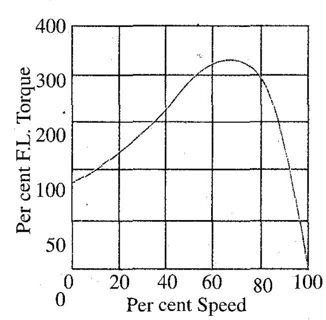
Types

(a) Single value Capacitor Run motor – start and run with one value of capacitance in the circuit
(b) Two Value Capacitor Run motor – start with high value of capacitance but run with low value of capacitance.

(a) Single value Capacitor Run motor



- It has one running winding and one starting winding in series with a capacitor.
- Since capacitor remains in the circuit permanently, this motor is referred to as permanent split capacitor run motor.
- Since the same capacitor is used for starting and running, neither optimum starting not optimum running performance can be obtained.
- Capacitors of 2 to 20 μF are used.
- The low value capacitor result in small starting torque which is about 50 to 100 % of the rated torque.
- This type of motor can be easily reversed by an external switch provided its running and starting windings are identical.

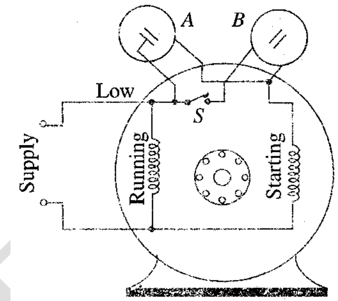


Applications

Fans, blowers, voltage regulators etc.

(b) Two Value Capacitor Run motor

- This motor starts with a high capacitor in series with the starting winding so that the starting torque is high.
- For running, a lower capacitor is substituted by the centrifugal switch.
- Both the running and stating windings remain in the circuit.



- The two values of capacitance can be obtained by using two capacitors in parallel at start and then switching out one for low value run.
- At start, when the centrifugal switch is closed, the two capacitors are put in parallel, so that their combined capacitance is sum of their individual capacitances.
- After the motor has reached 75% of full load speed, the switch opens and only capacitor A remains in the starting winding circuit.
- Thus both optimum starting and running performance is achieved.

Advantages

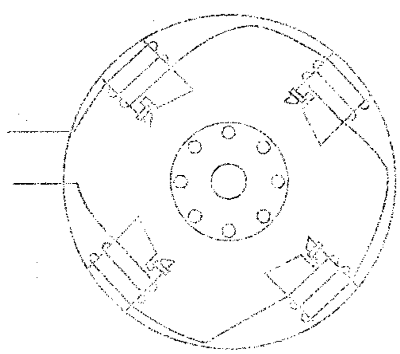
(i) Ability to start heavy loads
(ii) Extremely quiet operation
(iii) Higher efficiency and power factor
(iv) Ability to develop 25 percent overload capacity

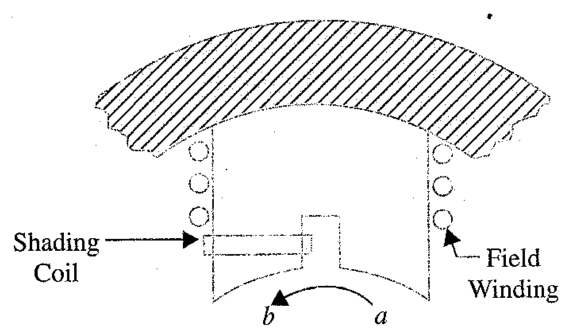
Applications

Compressors, fire strokers etc.

4. Shaded pole Single Phase Motor

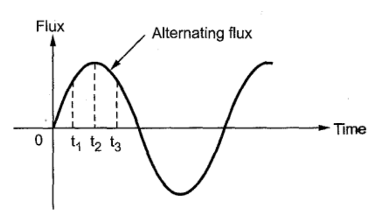
- In such motors, the phase splitting is produced by induction.
- These motors have salient poles on the stator and a squirrel cage type rotor.





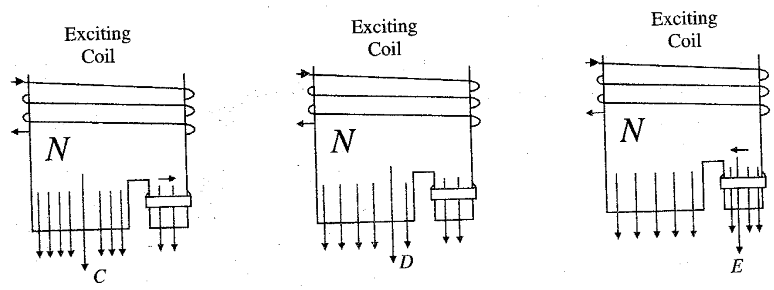
- The figure shows a four pole motor with the field poles connected in series for alternate polarity.
- The laminated pole has a slot cut across the laminations approximately one third distance from one edge.
- Around the small part of the pole is placed a short circuited Cu coil known as shading coil. This part of the pole is known as shaded part and the other as unshaded part.
- When an alternating current is passed through the exciting (or field) winding surrounding the pole, the axis of the pole shifts from the unshaded part a to the shade part b.
- This shifting of magnetic axis is equivalent to the actual physical movement of the pole. Hence the motor starts rotating in the direction of the shift i.e. from unshaded part to the shaded part.

The production of rotating magnetic field is explained as follows:

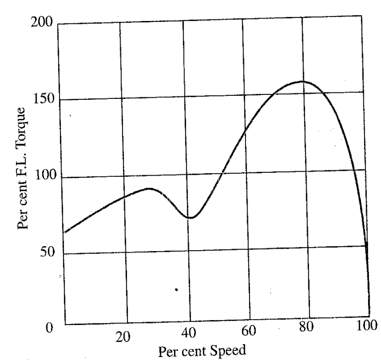


- The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in the Fig.

- Consider the three instants say t1, t2 and t3 during first half cycle of the flux as shown, in the Fig.
- At instant $t = t_1$, rate of rise of current and hence the flux is very high. Due to the transformer action, large e.m.f. gets induced in the copper shading band.
- This circulates current through shading band as it is short circuited, producing its own flux.
- According to Lenz's law, the direction of this current is so as to oppose the cause i.e. rise in current. Hence shading ring flux is opposing to the main flux.
- Hence there is crowding of flux in unshaded part while weakening of flux in shaded part. Overall magnetic axis shifts in unshaded part as shown in the Fig.



- At instant $t = t_2$, rate of rise of current and hence the rate of change of flux is almost zero as flux almost reaches to its maximum value. Hence there is very little induced e.m.f. in the shading ring.
- Hence the shading ring flux is also negligible, hardly affecting the distribution of the main flux. Hence the main flux distribution is uniform and magnetic axis lies at the centre of the pole face as shown in the Fig.
- At instant $t = t_3$, the current and the flux is decreasing. The rate of decrease is high which again induces a very large e.m.f. in the shading ring.
- This circulates current through the ring which produces its own flux. Now direction of the flux produced by the shaded ring current is so as to oppose the cause which is decrease in flux. So it oppose the decrease in flux means its direction is same as that of main flux, strengthening it.
- So there is crowding of flux in the shaded part as compared to unshaded part. Due to this the magnetic axis shifts to the middle of the shaded part of the pole.
- This sequence keeps on repeating for negative half cycle too. Consequently this produces an effect of rotating magnetic field, the direction of which is from unshaded part of the pole to the shaded part of the pole.
- Due to this, motor produces the starting torque and starts rotating. The starting torque is low which is about 40 to 50 % of the full load torque for this type of motor. The torque speed characteristic is shown in the fig.



- Shaded pole motors are built in very small sizes varying from 1/250 h.p. (3W) to 1/6 h.p. (125 W).

<u>Advantages</u>

  - Simple in construction
  - Extremely rugged
  - Reliable
  - Cheap

<u>Disadvantages</u>

  - Low starting torque
  - Very little overload capacity
  - Low efficiency
  - Direction of rotation cannot be changed, because it is fixed by the position of copper rings.

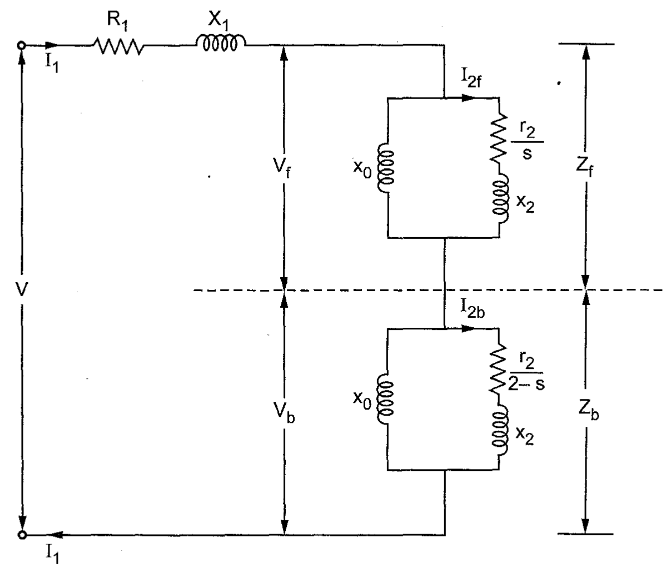
<u>Applications</u>

  - Used for small fans, toys, hair dryers, ventilators, electric clocks etc.

EQUIVALENT CIRCUIT

Imagine that the single phase induction motor is made up of one stator winding and two imaginary rotor windings. One rotor is rotating in forward direction i.e. in the direction of rotating magnetic field with slip s while other is rotating in backward direction i.e. in direction of oppositely directed rotating magnetic field with slip 2 - s.

Without Core Loss



Let the stator impedance be Z Ω

$Z = R_1 + jX_1$

Where R_1 = Stator resistance, X_1 = Stator reactance,

X_2 = Rotor reactance referred to stator

R_2 = Rotor resistance referred to stator

Hence the impedance of each rotor is $r_2 + j\,x_2$

Where $x_2 = \frac{X_2}{2}$; $r_2 = \frac{R_2}{2}$;

The resistance of forward field rotor is $\frac{r_2}{2}$ while the resistance of backward field rotor is $\frac{r_2}{(2-s)}$.

As the core loss is neglected, R_0 does not exist in the equivalent circuit. The x_0 is half of the actual magnetising reactance of the motor. Therefore, $x_0 = \frac{X_0}{2}$;

So the equivalent circuit referred to stator is shown in the Fig.

The impedance of the forward field rotor is Z_f is parallel combination of $(j\,x_0)$ and $(r_2/s) + j\,x_2$.

$$\therefore \quad Z_f = \frac{jx_0\left[\left(\frac{r_2}{s}\right)+j\,x_2\right]}{\frac{r_2}{s}+j\,(x_0+x_2)}$$

While the impedance of the backward field rotor is Z_b is parallel combination of $(j\,x_0)$ and $(r_2/(2-s)) + j\,x_2$.

$$\therefore \quad Z_b = \frac{jx_0\left[\left(\frac{r_2}{2-s}\right)+j\,x_2\right]}{\frac{r_2}{2-s}+j\,(x_0+x_2)}$$

Under standstill condition, s = 1 and 2 - s = 1. Hence $Z_f = Z_b$ and $V_f = V_b$. But in the running condition, V_f becomes almost 90 to 95 % of the applied voltage.

Equivalent impedance, $Z_{eq} = Z_1 + Z_f + Z_b$

Let I_{2f} = Current through forward rotor referred to stator

and I_{2b} = Current through backward rotor referred to stator

$$\therefore \qquad I_{2f} = \frac{V_f}{\left(\frac{r_2}{s} + j x_2\right)} \quad \text{where } V_f = I_1 \times Z_f$$

$$\text{and} \qquad I_{2b} = \frac{V_b}{\left(\frac{r_2}{2-s} + j x_2\right)} \quad \text{where } V_b = I_1 \times Z_b$$

Power input to forward field rotor, $P_f = (I_{2f}^2).\frac{r_2}{2}$ watts

Power input to backward field rotor, $P_b = (I_{2b}^2).\frac{r_2}{2-s}$ watts.

Mechanical power developed, Pm = (1 - s) [Net power input] = (1 - s) ($P_f - P_b$) watts

Output power, $P_{out} = P_m$ - Mechanical loss - Core loss

Forward Torque, $T_f = \frac{P_f}{\frac{2\pi N}{60}}$ N-m

Backward Torque, $T_b = \frac{P_b}{\frac{2\pi N}{60}}$ N-m

Net torque, $T = T_f - T_b$

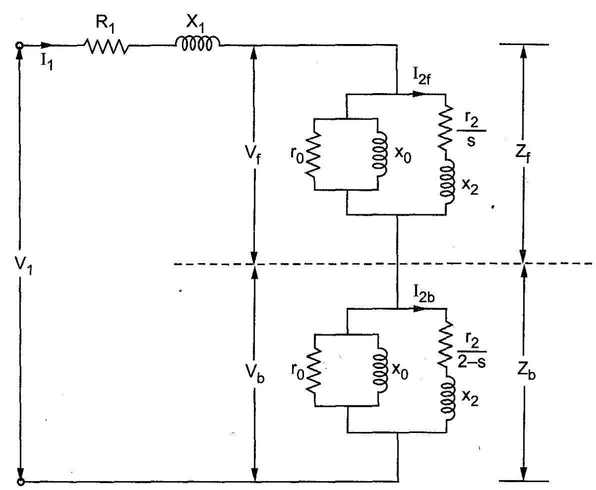
Shaft Torque, $T_{sh} = \frac{P_{out}}{\frac{2\pi N}{60}}$ N-m

$\% \eta = \frac{\text{Net output}}{\text{Net input}} \times 100$

With Core Loss

If core loss is to be considered then it is necessary to connect a resistance r_0 in parallel with x_0, in an exciting branch of each rotor.

r_0 is half the value of actual core loss resistance. Thus the equivalent circuit with core loss is as shown in the fig.



Let,

Z_{0f} = Equivalent impedance of exciting branch in forward rotor = $r_0 \parallel (jx_0)$

Z_{ob} = Equivalent impedance of exciting branch in backward rotor = $r_0 \parallel (jx_0)$

Therefore, the impedance of the forward field rotor is Z_f is

$$Z_f = Z_{of} \parallel (r_2/s + jx_2)$$

While the impedance of the backward field rotor is Z_b is

$$Z_b = Z_{ob} \parallel (r_2/(2\text{-}s) + jx_2)$$

All other expressions remain same as in case of equivalent circuit without core loss.

TESTS ON SINGLE PHASE INDUCTION MOTOR

1. No load test or open circuit test
2. Blocked rotor test or short circuit test

No Load Test

The test is conducted by rotating the motor without load. The input current, voltage and power are measured by connecting the ammeter, voltmeter and wattmeter in the circuit. These readings are denoted as V_0, I_0 and W_0.

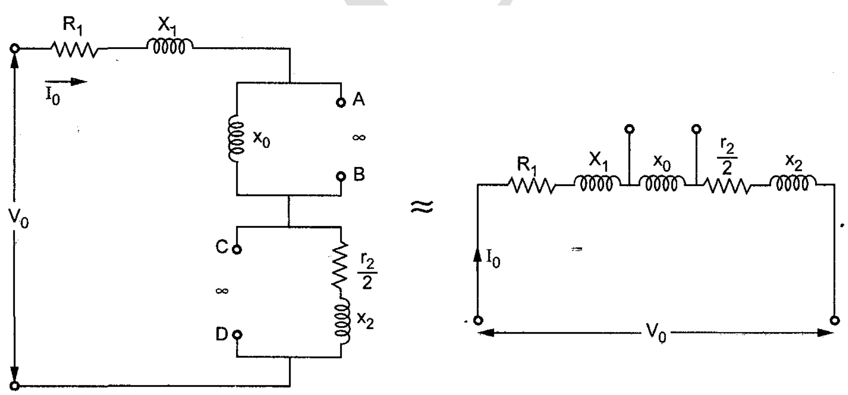
$W_0 = V_0 I_0 \cos\Phi_0$

Therefore, No load power factor, $\cos\Phi_0 = \frac{W_0}{V_0 I_0}$

The motor speed on no load is almost equal to its synchronous speed hence for practical purposes, the slip can be assumed zero. Hence $\frac{r_2}{2}$ becomes ∞ and acts as open circuit in the equivalent circuit. Hence for forward rotor circuit, the branch $r_2/s + j\,x_2$ gets eliminated.

While for a backward rotor circuit, the term $r_2 / (2\text{-}s)$ tends to $r_2/2$. Thus x_0 is much higher than the impedance $\frac{r_2}{2} + j\,x2$. Hence it can be assumed that no current can flow through x_m and that branch can be eliminated.

So circuit reduces to as shown in the Fig.



The voltage across x_0 is V_{AB}

$V_{AB} = V_0 - I_0\,[(R_1 + \frac{r_2}{2}) + j(x_1 + x_2)]$

Also $V_{AB} = I_0 x_0$

Therefore $x_0 = \frac{V_{AB}}{I_0}$

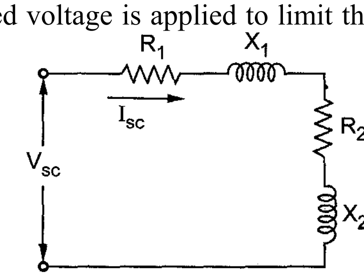
But $x_0 = \frac{X_0}{2}$

Therefore, magnetizing reactance, $X_0 = 2\,x_0 = \frac{2V_{AB}}{I_0}$

No load power W_0 = rotational losses.

Blocked Rotor Test

In blocked rotor test, the rotor is held fixed so that it will not rotate. A reduced voltage is applied to limit the short circuit current. This voltage is adjusted with the help of autotransformer so that the rated current flows through main winding. The input voltage, current and power is measured by connecting voltmeter, ammeter and wattmeter respectively. These readings are denoted as V_{sc}, I_{sc} and W_{sc}.



As rotor is blocked, the slip s = 1. Hence the magnetising reactance x_0 is much higher than the rotor impedance and hence it can be neglected as connected in parallel with the rotor. Thus the equivalent circuit for blocked rotor test is as shown in the Fig.

$W_{sc} = V_{sc} I_{sc} \cos\Phi_{sc}$

Short circuit power factor, $\cos\Phi_{sc} = \frac{W_{sc}}{V_{sc} I_{sc}}$

$Z_{eq} = \frac{V_{sc}}{I_{sc}}$; $R_{eq} = \frac{W_{sc}}{I_{sc}^2}$; but $R_{eq} = R_1 + R_2$; therefore Rotor resistance referred to stator, $R_2 = R_{eq} - R_1$;

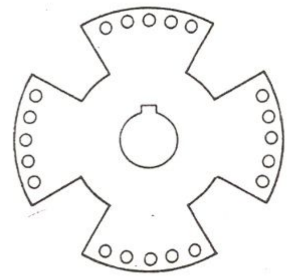
$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$;

Assume, $X_1 = X_2$; therefore rotor reactance referred to stator, $X_2 = \frac{X_{eq}}{2}$

The stator resistance R_1 is measured by voltmeter-ammeter method, by disconnecting the auxiliary winding and capacitors present if any. Due, to skin effect, the a.c. resistance is 1.2 to 1.5 times more than the d.c resistance.

Thus with these two tests, all the parameters of single phase induction motor can be obtained.

RELUCTANCE MOTOR

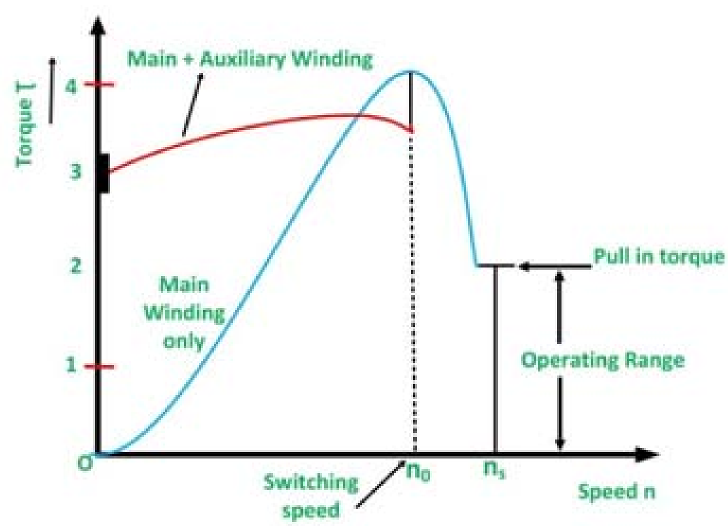


- A single phase synchronous **Reluctance Motor** is basically the same as the single cage type induction motor.
- The stator of the motor has the main and auxiliary winding. The stator of the single phase reluctance and induction motor are same.
- The rotor of a reluctance motor is a squirrel cage with some rotor teeth removed in the certain places to provide the desired number of salient rotor poles.

The figure shows the 4 pole reluctance type synchronous motor.

- In the figure the teeth have been removed in four locations to produce a 4 pole structure. The two end rings are short circuited.
- When the stator is connected to a single phase supply, the motor starts as a single phase induction motor.
- A centrifugal switch disconnects the auxiliary winding as soon as the speed of the motor reaches about 75% of the synchronous speed.
- The motor continues to speed up as a single phase motor with the main winding in operation.
- A reluctance motor torque is produced due to the tendency of the rotor to align itself in the minimum reluctance position, when the speed of the motor is close to the synchronous speed. Thus, the rotor pulls in synchronism.
- The load inertia should be within the limits, for proper effectiveness.
- At synchronism, the induction torque disappears, but the rotor remains in synchronism due to synchronous reluctance torque.

The **Torque Speed Characteristic** of a single phase Reluctance Motor is shown below.



- The starting torque depends upon the rotor position.
- The value of the starting torque varies between 300 to 400 % of its full load torque.
- As motor attains speed nearly of synchronous speed the auxiliary winding is disconnected and the rotor continues to rotate at the synchronous speed.
- The motor operates at a constant speed up to a little over than 200% of its full load torque.
- If the loading of the motor is increased above the value of the pull out torque, the motor loose synchronism but continues to run as a single phase induction motor up to over 500% of its rated torque.
- At the starting the motor is subjected to Cogging. This can be reduced by skewing the rotor bars and by having the rotor slots not exact multiples of the

number of poles.
- The rotor of a Reluctance Motor is unexcited, therefore, the power factor is low as compared to the induction motor.
- As the motor has no DC field excitation so the output of a reluctance motor is reduced.
- Hence, the size of the motor is large as compared to synchronous motor.

Advantages
1) No d.c. supply is necessary for rotor
2) Constant speed characteristics
3) Robust construction
4) Less maintenance.

Limitations
1) Less efficiency
2) Poor power factor
3) Need of very low inertia rotor
4) Less capacity to drive the loads.

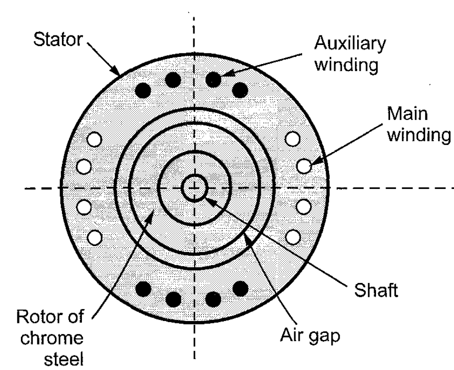
Applications
This motor is used in signalling devices, control apparatus, automatic regulators, recording instruments, clocks and all kinds of timing devices, teleprinters, gramophones etc.

HYSTERESIS MOTOR

- A **Hysteresis Motor** is a synchronous motor with a uniform air gap and without DC excitation. It operates both in single and three phase supply.
- The Torque in a Hysteresis Motor is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.
- The working of the motor depends on the working of the continuously revolving magnetic flux. For the split phase operation, the stator winding of the motor has two single phase supply. This stator winding remains continuously connected to the single phase supply both at the starting as well as the running of the motor.
- The rotor of the motor is made up of smooth chrome steel cylinder and it has no winding. It has high retentivity and because of this, it is very difficult to change the magnetic polarities once they are caused by the revolving flux of the rotor. The rotor of the hysteresis motor moves synchronously because the pole of the motor magnetically locks with the stator which has opposite polarities.

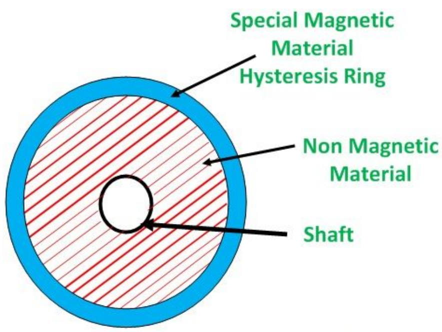
Construction of Stator of Hysteresis Motor

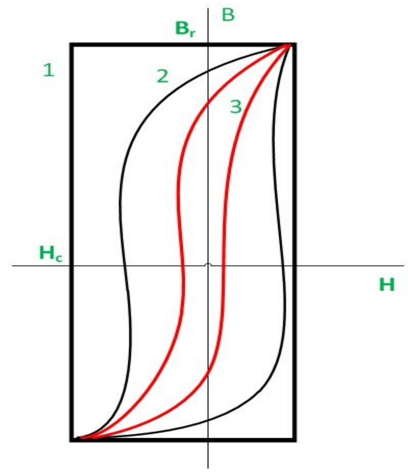
- The stator of the hysteresis motor produces a rotating magnetic field and is almost similar to the stator of the induction motor. Thus, the stator of the motor is connected either to single supply or to the three phase supply.
- The stator winding of the single-phase hysteresis motor is made of permanent split capacitor type or shaded pole type. The capacitor is used with an auxiliary winding in order to produce a uniform field.



Construction of Rotor of Hysteresis Motor

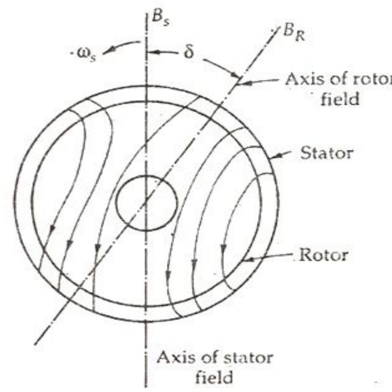
- The rotor of the hysteresis motor consists of the core of aluminium or some other non-magnetic material which carries a layer of special magnetic material. The figure shows the rotor of the hysteresis motor.
- The outer layer has a number of thin rings forming a laminated rotor. The rotor of the motor is a smooth cylinder, and it does not carry any windings. The ring is made of hard chrome or cobalt steel having a large hysteresis loop as shown in the figure below.





Operation of a Hysteresis Motor

- When supply is given applied to the stator, a rotating magnetic field is produced. This magnetic field magnetises the rotor ring and induces pole within it.
- Due to the hysteresis loss in the rotor, the induced rotor flux lags behind the rotating stator flux.
- The angle δ between the stator magnetic field B_S and the rotor magnetic field B_R is responsible for the production of the torque. The angle δ depends on the shape of the hysteresis loop and not on the frequency.
- Thus, the value of Coercive force and residual flux density of the magnetic material should be large.
- The ideal material would have a rectangular hysteresis loop as shown by loop 1 in the hysteresis loop figure. The stator magnetic field produces Eddy currents in the rotor. As a result, they produce their own magnetic field.



The eddy current loss is given by the equation, $P_e = K_e f_2^2 B^2$

Where, k_e is Eddy current constant, f_2 is the eddy current frequency, B is the flux density

The relation between rotor frequency f_2 and supply frequency f_1 is $f_2 = sf_1$
where s is the slip.

Therefore, $P_e = K_e s^2 f_1^2 B^2$

The torque due to eddy current is $T_e = \frac{P_e}{s\omega_s}$ or $T_e = K's$ ……….(1)

Where $K' = \frac{K_e f_1^2 B^2}{\omega_s}$

The hysteresis loss is $P_h = K_h f_2 B^{1.6}$ or $K_h s f_1 B^{1.6}$ ……………..(2)

The Torque due to hysteresis is $T_h = \frac{P_h}{s\omega_s} = k''$ …………….(3)

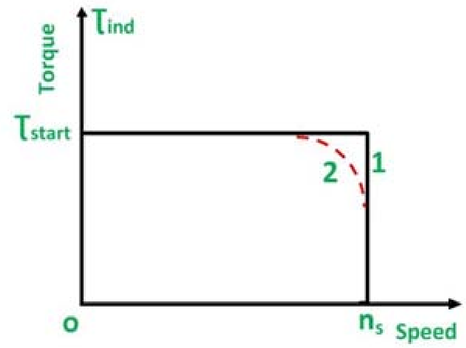
Where $k'' = \frac{K_h f_1 B^{1.6}}{\omega_s}$

- From the equation (1) it is clear that the torque is proportional to the slip. Therefore, as the speed of the rotor increases the value of T_e decreases.
- As the speed of the motor reaches synchronous speed, the slip becomes zero and torque also becomes zero.
- As the electromagnet torque is developed by the motor is because of the hysteresis loss and remains constant at all rotor speed until the breakdown torque.

- At the synchronous speed, the eddy current torque is zero and only torque due to hysteresis loss is present.

Torque Speed characteristic of Hysteresis Motor

The speed torque curve of the motor is shown below.



- Curve 1 is the ideal curve, and the curve 2 is the practical hysteresis motor curve.
- The torque-speed characteristic of the hysteresis motor is different from an induction motor.
- Since, at the synchronous speed, the torque developed by an induction motor becomes zero, whereas in the hysteresis motor the torque is constant at all the speed even at the synchronous speed.
- Thus, from the curve, it is seen that the locked rotor, starting and pull out torque is equal.
- The noise level of the hysteresis motor is very low as compared to the induction motor because it operates at a constant speed and its rotor is smooth.
- This type of motor is smoothest running, quietest single phase motor and is used for quality sound reproduction equipment like record players, tape recorders, etc. It is also employed in electric clocks and other timing devices.

Advantages:

The advantages of hysteresis motor are:

1. As rotor has no teeth, no winding, there are no mechanical vibrations.
2. Due to absence of vibrations, the operation is quiet and noiseless.
3. Suitability to accelerate inertia loads.
4. Possibility of multispeed operation by employing gear train.

Disadvantages

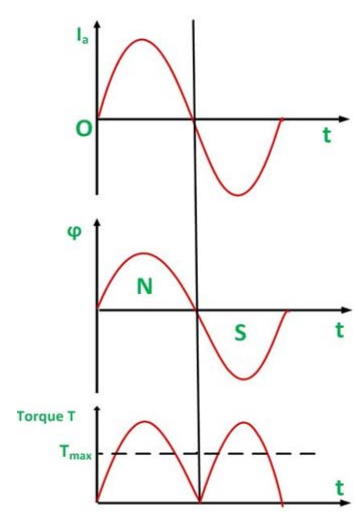
The disadvantages of hysteresis motor are:

1. The output is about one-quarter that of an induction motor of the same dimension.
2. Low efficiency
3. Low power factor
4. Low torque
5. Available in very small sizes

Applications

Due to noiseless operation it is used in sound recording instruments, sound producing equipments, high quality record players, electric clocks, tele printers, timing devices etc.

UNIVERSAL MOTOR

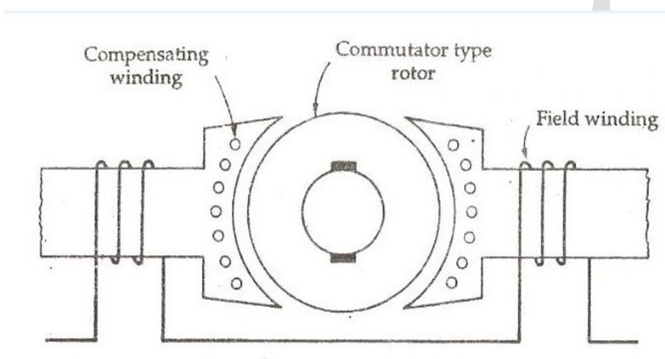


- The motors which can be used with a single phase AC source as well as a DC source of supply and voltages are called as **Universal Motor**. It is also known as **Single Phase Series Motor**.
- A universal motor is a commutation type motor. If the polarity of the line terminals of a DC Series Motor is reversed, the motor will continue to run in the same direction.
- The direction is determined by both field polarity and the direction of current through the armature as torque is proportional to the flux and the armature current.
- Let the DC series motor be connected across a single phase AC supply. Since the same current flows through the field winding and the armature winding, the AC reversal from positive to negative or vice versa will affect the field flux polarity and the current direction through the armature.
- The direction of the developed torque will remain positive, and direction of the rotation will be as it was before.

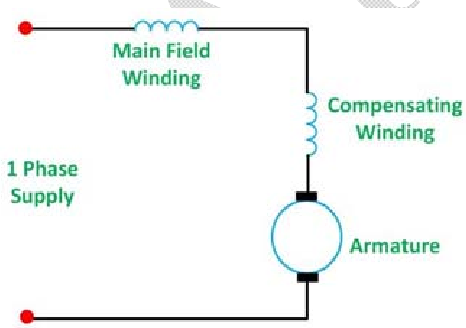
- The nature of the torque will be pulsating, and the frequency will be twice that of line frequency as shown in the waveform. Thus, a Universal motor can work on both AC and DC.
- However, a series motor which is mainly designed for DC operation if works on single phase AC supply suffers from the following drawbacks.
  - ✓ The efficiency becomes low because of hysteresis and eddy current losses.
  - ✓ The power factor is low due to the large reactance of the field and the armature windings.
  - ✓ The sparking at the brushes is in excess.

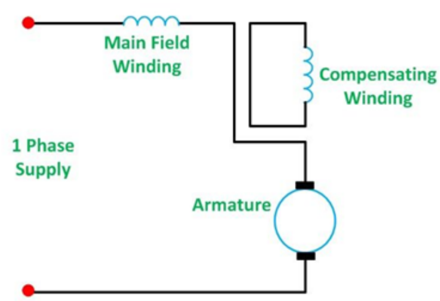
In order to overcome the above following drawbacks, certain modifications are made in a DC series motor so that it can work even on the AC current. They are as follows:-

  - ✓ The field core is made up of the material having a low hysteresis loss. It is laminated to reduce the eddy current loss.
  - ✓ The area of the field poles is increased to reduce the flux density. As a result, the iron loss and the reactive voltage drop are reduced.
  - ✓ To get the required torque the number of conductors in the armature is increased.
- A compensating winding is used for reducing the effect of the armature reaction and improving the commutation process. The winding is placed in the stator slots as shown in the figure below.

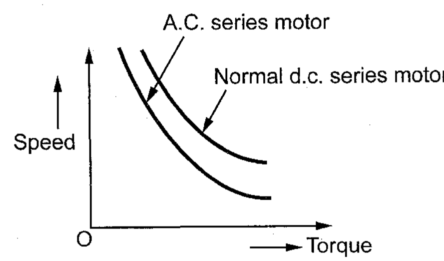


- The winding is put in the stator slot. The axis of compensating winding is 90 degrees with the main field axis. The compensating winding is connected in series with both the armature and the field; hence, it is called conductively compensated.
- If the compensating winding is short circuited, the motor is said to be inductively compensated. The connection diagram is shown below.





- The construction of the universal motor is same as that of the series motor.
- In order to minimize the problem of commutation, high resistance brushes with increased brush area are used.
- To reduce Eddy current losses the stator core and yoke are laminated.
- The Universal motor is simple and less costly. It is used usually for rating not greater than 750 W.



- The characteristic of Universal motor is similar to that of the DC series motor.
- When operating from an AC supply, the series motor develops less torque.
- By interchanging connections of the fields with respect to the armature, the direction of rotation can be altered.
- Speed control of the universal motors is obtained by solid state devices.
- This motor is most suitable for applications requiring high speeds.
- Since the speed of these motors is not limited by the supply frequency and is as high as 20000 rpm.

Applications of Universal Motor

The Universal motor is used for the purposes where speed control and high values of the speed are necessary. The various applications of the Universal Motor are as follows:-

- Portable drill machine.
- Used in hair dryers, grinders and table fans.
- used in blowers, polishers and kitchen appliances.

REPULSION MOTOR

Repulsion Type Motors

These can be divided into the following four distinct categories:

1. Repulsion Motor. It consists of ***(a)*** one stator winding ***(b)*** one rotor which is wound like a d.c. armature ***(c)*** commutator and ***(d)*** a set of brushes, which are short-circuited and remain in contact with the commutator at all times. It operates continuously on the 'repulsion' principle. No short-circuiting mechanism is required for this type.

2. Compensated Repulsion Motor. It is identical with repulsion motor in all respects, except that

(a) It carries an additional stator winding, called compensating winding

(b) There is another set of two brushes which are placed midway between the usual short- circuited brush set. The compensating winding and this added set are connected in series.

3. Repulsion-start Induction-run Motor. This motor starts as a repulsion motor, but normally runs as an induction motor, with constant speed characteristics. It consists of ***(a)*** one stator winding ***(b)*** one rotor which is similar to the wire-wound d.c. armature ***(c)*** a commutator and ***(d)*** a centrifugal mechanism which short-circuits the commutator bars all the way round (with the help of a short-circuiting necklace) when the motor has reached nearly 75 per cent of full speed.

4. Repulsion Induction Motor. It works on the combined principle of repulsion and induction. It consists of ***(a)*** stator winding ***(b)*** two rotor windings: one squirrel cage and the other usual d.c. winding connected to the commutator and ***(c)*** a short-circuited set of two brushes.

Repulsion Motor

Constructionally, it consists of the following:

1. Stator winding of the distributed non-salient pole type housed in the slots of a smooth-cored stator (just as in the case of split-phase motors). The stator is generally wound for four, six or eight poles.

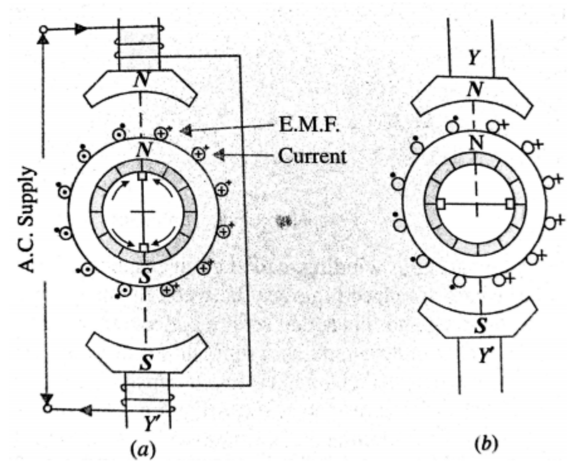
2. A rotor (slotted core type) carrying a distributed winding (either lap or wave) which is connected to the commutator. The rotor is identical in construction to the d.c. armature.

3. A commutator, which may be one of the two types : an axial commutator with bars parallel to the shaft or a radial or vertical commutator having radial bars on which brushes press horizontally.

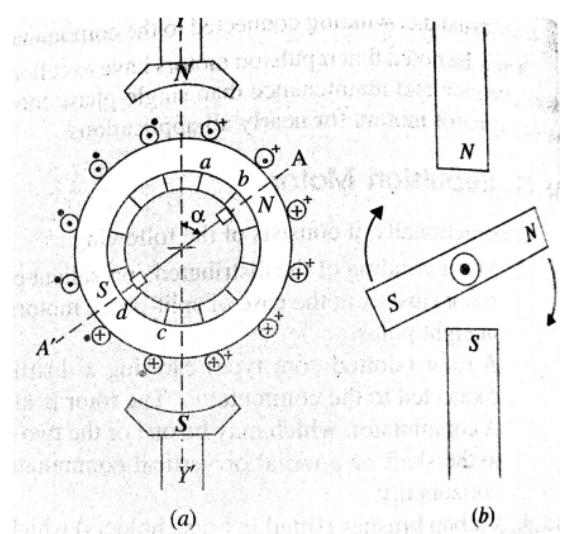
4. Carbon brushes (fitted in brush holders) which ride against the commutator and are used for conducting current through the armature (*i.e.* rotor) winding.

Repulsion Principle

Consider Fig. which shows a 2-pole salient pole motor with the magnetic axis vertical.



- Suppose that the direction of flow of the alternating current in the exciting or field (stator) winding is such that it creates an *N*-pole at the top and an *S*-pole at the bottom.
- The alternating flux produced by the stator winding will induce e.m.f. in the armature conductors by transformer action.
- The direction of the induced e.m.f. can be found by using Lenz's law and is as shown in Fig. (*a*).
- However, the direction of the ***induced*** currents in the armature conductors will depend on the ***positions of the short-circuited brushes***.
- If brush axis is colinear with magnetic axis of the main poles, the directions of the induced currents (shown by dots and arrows) will be as indicated in Fig. (*a*).
- As a result, the armature will become an electromagnet with a *N*-pole on its top, directly under the main *N*-pole and with a *S*-pole at the bottom, directly over the main *S*-pole.
- Because of this face-to- face positioning of the main and induced magnetic poles, no torque will be developed. The two forces of repulsion on top and bottom act along *Y Y*' in direct opposition to each other.
- If brushes are shifted through 90^0 to the position shown in Fig. (*b*) So that the brush axis is at right angles to the magnetic axis of the main poles, the directions of the induced voltages at any time in the respective armature conductors are exactly the same as they were for the brush position of Fig. (*a*).
- However, with brush positions of Fig. (*b*), the voltages induced in the armature conductors in each path between the brush terminals will neutralize each other, hence there will be no net voltage across brushes to produce armature current. If there is no armature current, obviously, no torque will be developed.
- If the brushes are set in position shown in Fig. so that the brush axis is neither in line with nor 90º from the magnetic axis *Y Y*' of the main poles, a net voltage will be induced between the brush terminals which will produce armature current.
- The armature will again act as an electromagnet and develop its own *N*-and *S*-poles which, in this case, will not directly face the respective main poles.



- As shown in Fig., the armature poles lie along *AA*' making an angle of α with *Y Y*'.
- Hence, *rotor N*-pole will be repelled by the main *N*-pole and the rotor *S*-pole will, similarly, be repelled by the ***main*** *S*-pole.
- Consequently, the rotor will rotate in clockwise direction. Since the forces are those of ***repulsion***, it is appropriate to call the motor as repulsion motor.
- If the brushes are shifted counter-clockwise from *YY'*, rotation will also be counter-clockwise.
- Direction of rotation of the motor is determined by the position of brushes with respect to the main magnetic axis.
- The value of starting torque developed will depend on the ***amount*** of brush-shift whereas direction of rotation will depend on the ***direction*** of shift.
- Maximum starting torque is developed at some position where brush axis makes, an angle lying between 0º and 45º with the

magnetic axis of main poles.
- Motor speed can also be controlled by means of brush shift. Variation of starting torque of a repulsion motor with brush-shift is shown in Fig.

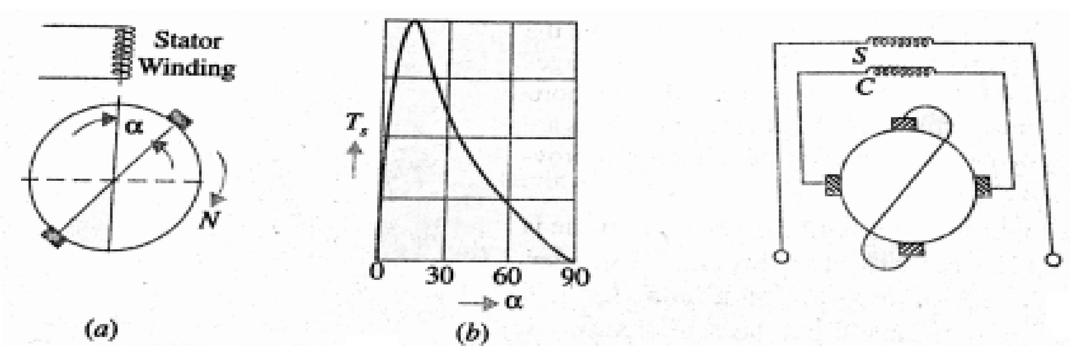
A straight repulsion type motor has high starting torque (about 350 per cent) and moderate starting current (about 3 to 4 times full-load value).

Principal shortcomings of such a motor are:

1. speed varies with changing load, becoming dangerously high at no load.
2. low power factor, except at high speeds.
3. tendency to spark at brushes.

Compensated repulsion motor

- In this type of motor an additional stator winding called compensation winding is provided. This is the modified form of the basic repulsion motor.
- The compensation winding serves for two purposes: ·
  - To Improve the Power factor ·
  - For better speed regulation
- This type of motor is used whenever there is a need for motor to run at constant speed and at higher power factor so an additional stator winding called compensating winding is used.
- The additional winding which is connected in series with the armature, is smaller than stator winding and wounded to the inner slots of main pole.
- It also consists of additional set of brushes which are placed mid way between the short circuited brushes.
- Such a type of modification reduces the quadrature drop and improves the power factor. And speed regulation also improves due to this compensation.
- Quadrature drop occurs in salient pole types due to non-uniform air gap length. Due to quadrature drop crossmagnetizing effect occurs which opposes the mmf waves.
- By providing such a type of compensation, this effect can be reduced which increases power factor. Further the leakage between armature and field is reduced



Repulsion start induction run motors

- As the name suggests this motor starts as a repulsion motor and runs as an Induction motor.
- This type of motor starts as a normal Repulsion motor and after achieving three-fourths of its full speed, it runs as an Induction motor.
- For this purpose a centrifugal force-operated device is used. This centrifugal device short circuits the commutator segments and this aids in running the motor as a squirrel cage motor.
- As soon as the commutator is short circuited, the brushes present do not carry any current.
- So the brushes can be removed to avoid the wear and tear.
- The advantage in running the motor as a squirrel cage one is that, it provides high starting torque, 350 percent without excessive current. Also constant speed is ensured for wide range of torque.
- There are two different designs in repulsion start motors:

BRUSH LIFTING TYPE- In this type the brush is lifted as soon as the commutator is short circuited to avoid unnecessary wear and tear and losses due to friction. So in this type the brush is present only when the motor is started as a repulsion one.

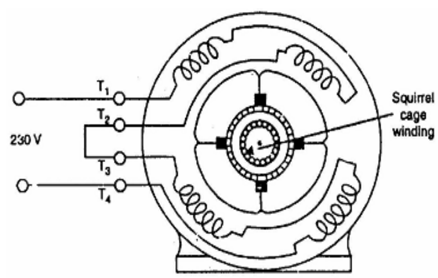
BRUSH RIDING TYPE- In this type of motors the brushes ride along with the commutator at all times. So the brushes are present even after the commutator is short circuited.

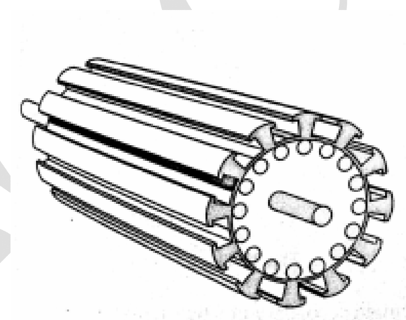
<u>Applications</u>

Compressors, Hoists, Pumps, Machine tools, Floor-polishing

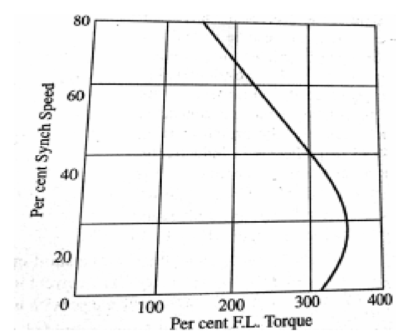
<u>Repulsion induction motor</u>

- This type of motor is a combination of repulsion motor and induction motor. It is also referred as ***squirrel cage repulsion motor***.
- This motor possesses the characteristic of both induction motor and repulsion motor. It combines the desirable starting characteristics of repulsion motor and constant speed characteristics of an induction motor.
- Here the stator winding is same as every other repulsion motor but there are two separate rotor windings
    - A squirrel cage winding ·
    - A Commutator winding
- The commutator winding lies on the outer slots while the squirrel cage winding is located in the inner slots. Both the windings operate during the entire period of operation of motors. The brushes are in contact with the commutator all the time.





- The biggest advantage in such type of motors is that they don't need a separate centrifugal short-circuit system as in Repulsion-start Induction-run motors.
- As soon as the motor is started, the squirrel cage winding is practically inactive for a small period of time due to high reluctance.
- Only the commutator winding supplies most of the torque.
- But during normal running condition, the squirrel cage winding supplies most of the torque and commutator winding supplies relatively lower torque when compared to Squirrel cage winding.
- So the squirrel cage winding takes up most of the load as the rotor accelerates
- The starting torque is very high, 300 percent with better speed regulation.



<u>Applications</u>

Petrol pumps, Compressors, Refrigerators, Mixing machines, Lifts and Hoists

LINEAR INDUCTION MOTOR

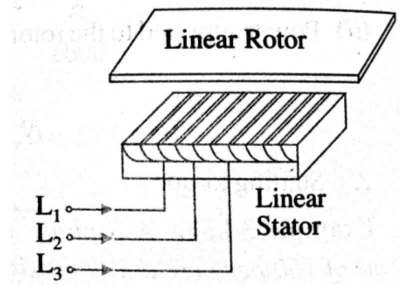
- If the stator is laid out flat and a flat squirrel cage winding is brought near to it, we get a linear induction motor.
- In practice, instead of a flat squirrel cage winding, an aluminium or copper or iron plate is used as a 'rotor'.
- The flat stator produces a flux that moves in a straight line from its one end to the other at a linear synchronous speed given by

$$v_s = 2.w.f$$

where v_s = linear synchronous speed (m/s)

w = width of one pole pitch (m)

f = supply frequency (Hz)



- The speed does not depend on the number of poles, but only on the pole pitch and stator supply frequency.
- As the flux moves linearly, it drags the rotor plate along with it in the same direction.
- In practical applications, the 'rotor' is stationary, while the stator moves.
- For example, in high speed trains, which utilize magnetic levitation, the rotor is composed of thick aluminium plate that is fixed to the ground and extends over the full length of the track.
- The linear stator is bolted to the undercarriage of the train.

Properties of a Linear Induction Motor

1. Synchronous speed, $v_s = 2.w.f$
2. Slip, $s = (v_s - v) / v_s$ where v is the actual speed
3. Thrust or Force, $F = P_2 / v_s$ where P_2 is the active power supplied to the rotor.
4. Active power flow (i) $P_{cr} = sP_2$ (ii) $P_m = (1\text{-}s) P_2$

SERVOMOTORS

This is nothing but a simple electrical motor, controlled with the help of servomechanism. If the motor as controlled device, associated with servomechanism is DC motor, then it is commonly known as DC servo motor. If the controlled motor is operated by AC, it is called AC servo motor.

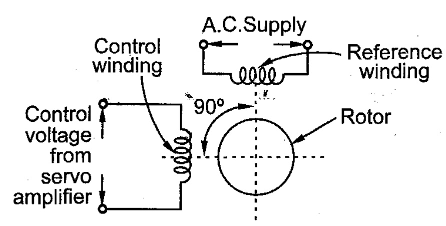
Requirements of Good Servomotor

i) Linear relationship between electrical control signal and the rotor speed over a wide range.
ii) Inertia of rotor should be as low as possible. A servomotor must stop running without any time delay, if control signal to it is removed.
iii) Its response should be as fast as possible.
iv) It should be easily reversible.
v) It should have linear torque - speed characteristics.
vi) Its operation should be stable without any oscillations or overshoots.

Servo motor is a special type of motor which is automatically operated up to certain limit for a given command with help of error-sensing feedback to correct the performance.

A.C. Servomotor

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



Stator of A.C. servomotor

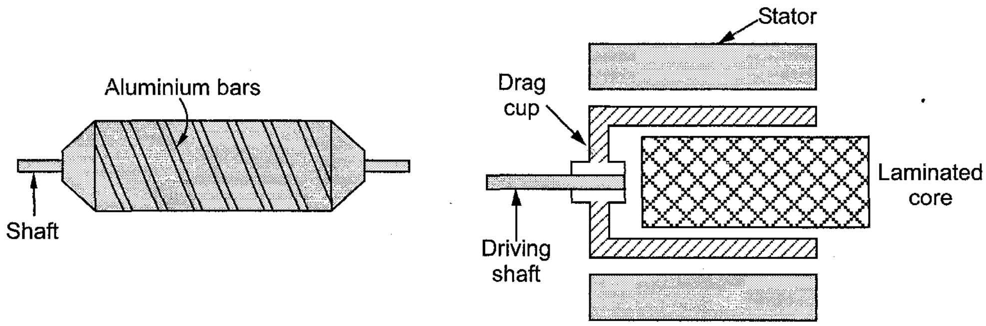
Construction

- It is mainly divided into two parts namely stator and rotor.
- The stator carries two windings, uniformly distributed and displaced by 90°, in space.
- One winding is called main winding or fixed winding or reference winding. This is excited by a constant voltage a.c. supply.
- The other winding is called control winding. It is excited by variable control voltage, which is obtained from a servo amplifier. This voltage is 90° out of phase with respect to the voltage applied to the reference winding. This is necessary to obtain rotating magnetic field.

Rotor

- The rotor is generally of two types. The one is usual squirrel cage rotor. This has small diameter and large length. Aluminium conductors are used to keep weight small. Its resistance is very high to keep torque speed characteristics as linear as possible. Air gap is kept very small which reduces magnetising current. This cage type of rotor is shown with skewed bars in the Fig. (a).

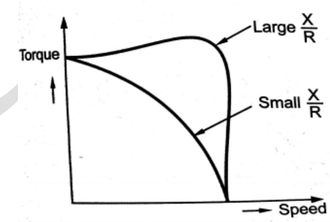
- The other type of rotor is drag cup type. There are two air gaps in such construction. Such a construction reduces inertia considerably and hence such type of rotor is used in very low power applications. The aluminium is used for the cup construction. The construction is shown in the Fig. (b).



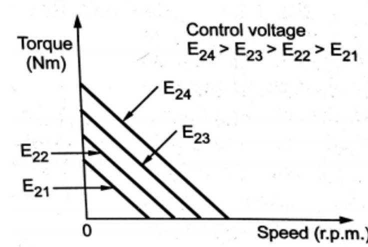
(a) Squirrel cage rotor **(b) Drag cup type rotor**

Torque-Speed Characteristics

- The torque-speed characteristics of a two phase induction motor, mainly depends on the ratio of reactance to resistance. For small X to R ratio i.e. high resistance low reactance motor, the characteristics is much more linear while it is nonlinear for large X to R ratio as shown in the Fig.



- In practice, design of the motor is so as to get almost linear torque-speed characteristics. The Fig. shows the torque-speed characteristics for various control voltages.
- The torque varies almost linearly with speed. All the characteristics are equally spaced for equal increments of control voltage. It is generally operated with low speeds.



Features of A.C. Servomotor

i) Light in weight ii) Robust construction iii) Reliable and stable operation iv) Smooth and noise free operation v) Large torque to weight ratio vi) Large R to X ratio i.e. small X to R ratio vii) No brushes or slip rings hence maintenance free viii) Simple driving circuits.

Applications

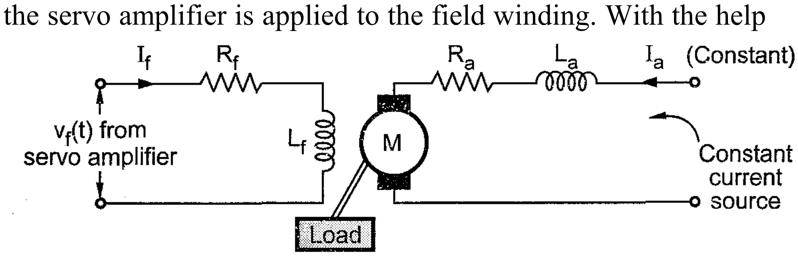
Due to the above features it is widely used in instrument servomechanisms, remote positioning devices, process control systems, self balancing recorders, computers, tracking and guidaice systems, robotics, machine tools etc.

D.C. Servomotor

- Basically d.c. servomotor is more or less same as normal d.c.motor. There are some minor differences between the two.
- All d.c. servomotors are essentially separately excited type. This ensures linear torque-speed characteristics.
- The control of d.c. servomotor can be from field side or from armature side.
- Depending upon this, these are classified as field controlled d.c. servomotor and armature controlled d.c. servomotor.

Field Controlled D.C. Servomotor

- In this motor, the controlled signal obtained from the servo amplifier is applied to the field winding. With the help of constant current source, the armature current is maintained constant. The arrangement is shown in the Fig.



- This type of motor has large L_f /R_f ratio where L_f is reactance and R_f is resistance of field winding.
- Due to this the time constant of the motor is

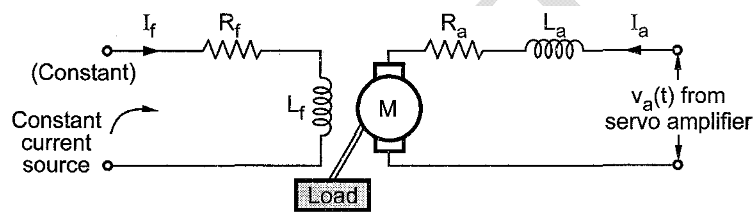
high. This means it cannot give rapid response to the quick changing control signals hence this is uncommon in practice.

Features of Field Controlled D.C. Servomotor

i) Preferred for small rated motors.
ii) It has large time constant.
iii) It is open loop system. This means any change in output has no effect on the input.
iv) Control circuit is simple to design.

Armature Controlled D.C. Servomotor

- In this type of motor, the input voltage 'V_a' is applied to the armature with a resistance of R_a and inductance L_a.
- The field winding is supplied with constant current I_f.
- Thus armature input voltage controls the motor shaft output. The arrangement is shown in figure.
- The constant field can be supplied with the help of permanent magnets. In such case no field coils are necessary.

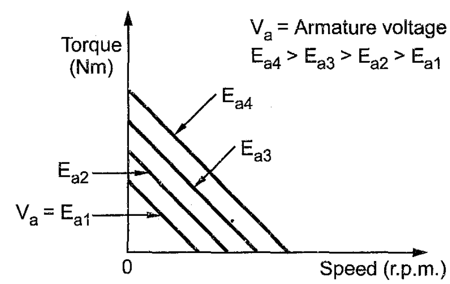


Features of Armature controlled DC Servomotor

(i) Suitable for large rated motors.
(ii) It has small time constant hence its response is fast to the control signal.
(iii) It is a closed loop system.
(iv) The back e.m.f. provides internal damping which makes motor operation more stable.
(v) The efficiency and overall performance is better than field controlled motor.

Characteristics of D.C. Servomotors

The characteristics of d.c. servomotors are mainly similar to the torque-speed characteristics of a.c. servomotor. The characteristics are shown in the Fig.



Applications of D.C. Servomotor

These are widely used in air craft control systems, electromechanical actuators, process controllers, robotics, machine tools etc.

STEPPER MOTORS

- These motors are also called stepping motors or step motors. The name stepper is used because this motor rotates through a fixed angular step in response to each input current pulse received by its controller.
- Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.
- The unique feature of a stepper motor is that its output shaft rotates in a series of discrete angular intervals or steps, one step being taken each time a command pulse is received.
- When a definite number of pulses are supplied, the shaft turns through a definite known angle. This fact makes the motor well-suited for open-loop position control because no feedback need be taken from the output shaft.
- Such motors develop torques ranging from 1 μN-m (in a tiny wrist watch motor of 3 mm diameter) upto 40 N-m in a motor of 15 cm diameter suitable for machine tool applications.
- Their power output ranges from about 1 W to a maximum of 2500 W. The only moving part in a stepping motor is its rotor which has no windings, commutator or brushes.
- This feature makes the motor quite robust and reliable.

Step Angle

- The angle through which the motor shaft rotates for each command pulse is called the step angle β.
- Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained.

Step angle $\beta = \frac{N_s - N_r}{N_s N_r} \times 360^0$ where N_s = No. of stator poles (teeth), N_r = No. of rotor poles (teeth)

Or $\beta = \frac{360^0}{m\, N_r} = \frac{360^0}{\text{No.of stator phases x No.of rotor teeth}}$

Resolution

Resolution is given by the number of steps needed to complete one revolution of the rotor shaft. Higher the resolution, greater the accuracy of positioning of objects by the motor

∴ Resolution = No. of steps / revolution = $360^o / \beta$

Slewing

When the pulse rate is high, the shaft rotation seems continuous. Operation at high speeds is called 'slewing'. When in the slewing range, the motor generally emits an audible whine having a fundamental frequency equal to the stepping rate. If *f* is the stepping frequency (or pulse rate) in pulses per second (pps) and β is the step angle, then motor shaft speed is given by

$$n = \beta \times f / 360 \text{ rps} = \text{pulse frequency resolution}$$

Applications:

- Such motors are used for operation control in computer peripherals, textile industry, IC fabrications and robotics etc.
- Applications requiring incremental motion are typewriters, line printers, tape drives, floppy disk drives, numerically-controlled machine tools, process control systems and *X* -*Y* plotters.
- Stepper motors also perform countless tasks outside the computer industry. It includes commercial, military and medical applications where these motors perform such functions as mixing, cutting, striking, metering, blending and purging.
- They also take part in the manufacture of packed food stuffs, commercial end-products

Types of Stepper Motors

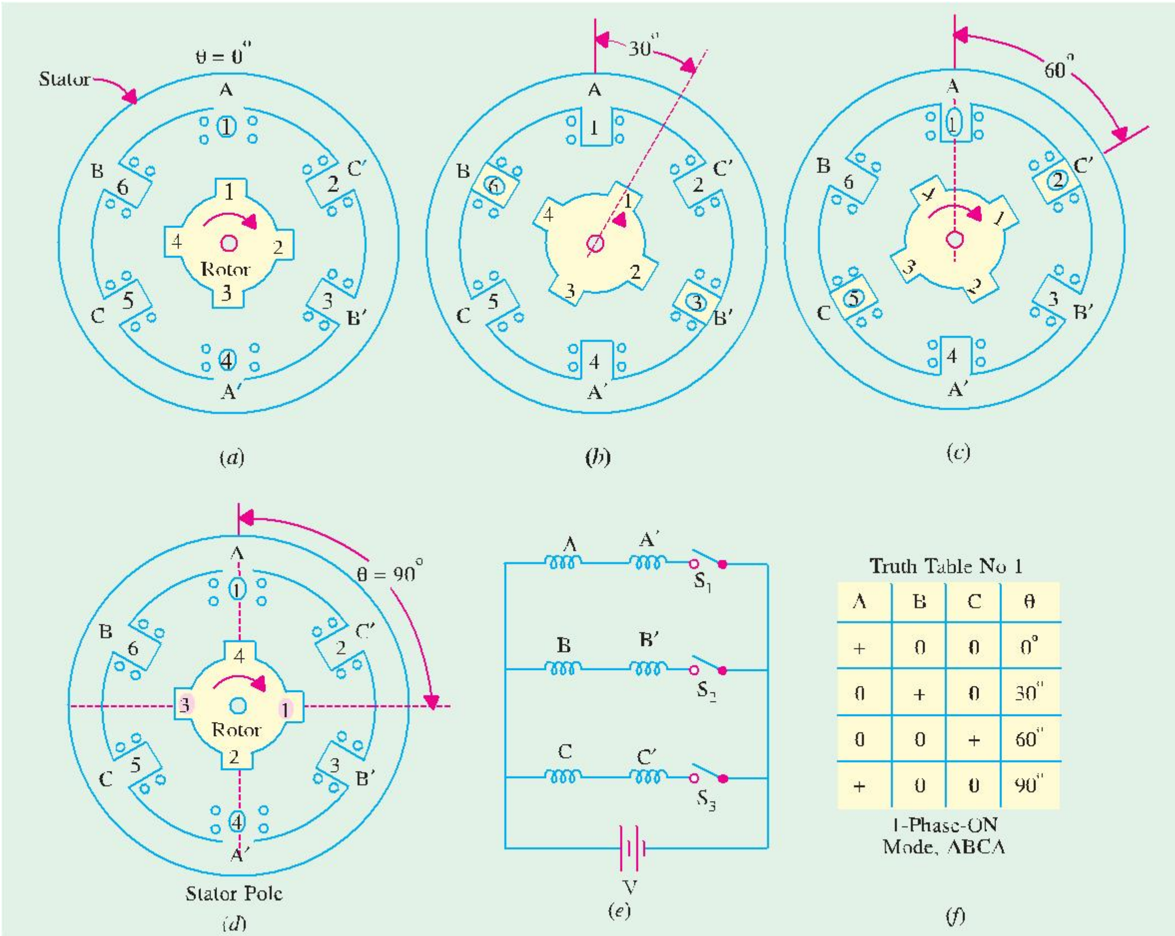
(i) Variable Reluctance Stepper Motor
(ii) Permanent Magnet Stepper Motor
(iii) Hybrid Stepper Motor

Variable Reluctance Stepper Motors

Construction:

- A variable-reluctance motor is constructed from ferromagnetic material with salient poles as shown in Fig.
- The stator is made from a stack of steel laminations and has six equally-spaced projecting poles (or teeth) each wound with an exciting coil.
- The rotor which may be solid or laminated has four projecting teeth of the same width as the stator teeth.
- There are three independent stator circuits or phases *A*, *B* and *C* and each one can be energised by a direct current pulse from the drive circuit.
- A simple circuit arrangement for supplying current to the stator coils in proper sequence is shown in Fig. (*e*).
- The six stator coils are connected in 2-coil groups to form three separate circuits called phases. Each phase has its own independent switch.
- Diametrically opposite pairs of stator coils are connected in series such that when one tooth becomes a *N*-pole, the other one becomes a *S*-pole.
- When there is no current in the stator coils, the rotor is completely free to rotate.
- Energising one or more stator coils causes the rotor to step forward (or backward) to a position that forms a path of least reluctance with the magnetized stator teeth.
- The step angle of this three-phase, four rotor teeth motor is $\beta = 360/ 4 \times 3 = 30^o$.

Working. The motor has following modes of operation:



(*a*) 1-phase-ON or Full-step Operation

- Fig. (*a*) shows the position of the rotor when switch S_1 has been closed for energising phase *A* .
- A magnetic field with its axis along the stator poles of phase *A* is created. The rotor is therefore, attracted into a position of minimum reluctance with diametrically opposite rotor teeth 1 and 3 lining up with stator teeth 1 and 4 respectively.
- Closing S_2 and opening S_1 energizes phase *B* causing rotor teeth 2 and 4 to align with stator teeth 3 and 6 respectively as shown in Fig. (*b*). The rotor rotates through full-step of 30º in the clockwise (CW) direction.
- Similarly, when S_3 is closed after opening S_2, phase *C* is energized which causes rotor teeth 1 and 3 to line up with stator teeth 2 and 5 respectively as shown in Fig. (*c*). The rotor rotates through an additional angle of 30º in the clockwise (CW) direction.
- Next if S_3 is opened and S_1 is closed again, the rotor teeth 2 and 4 will align with stator teeth 4 and 1 respectively thereby making the rotor turn through a further angle of 30º as shown in Fig. (*d*).
- By now the total angle turned is 90º. As each switch is closed and the preceding one opened, the rotor each time rotates through an angle of 30º.
- By repetitively closing the switches in the sequence 1-2-3-1 and thus energizing stator phases in sequence *A B C A* etc., the rotor will rotate clockwise in 30º steps.
- If the switch sequence is made 3-2-1-3 which makes phase sequence *CBAC* (or *ACB*), the rotor will rotate anticlockwise. This mode of operation is known as 1-phase-ON mode or full-step operation and is the simplest and widely-used way of making the motor step.
- The stator phase switching truth table is shown in Fig. (*f*). It may be noted that the direction of the stator magnetizing current is not significant because a stator pole of either magnetic polarity will always attract the rotor pole by inducing opposite polarity.

(*b*) 2-phase-ON Mode

- In this mode of operation, two stator phases are excited simultaneously.
- When phases *A* and *B* are energized together, the rotor experiences torques from both phases and comes to rest at a point mid-way between the two adjacent full-step positions.
- If the stator phases are switched in the sequence *A B*, *BC*, *C A*, *A B* etc., the motor will take full steps of 30º each (as in the 1-phase-*ON* mode) but its equilibrium positions will be interleaved between the full-step positions. The phase switching truth table for this mode is shown in Fig. (*a*).
- The 2-phase-ON mode provides greater holding torque and a much better damped single-stack response than the 1-phase-ON mode of operation.

Truth Table No. 2

A	B	C	θ
+	+	0	15°
0	+	+	45°
+	0	+	75°
+	+	0	105°

2 Phase-ON Mode
AB, BC, CA, AB

Truth Table No. 3

	A	B	C	θ	
A	+	0	0	0°	
	+	+	0	15°	AB
B	0	+	0	30°	
	0	+	+	45°	BC
C	0	0	+	65°	
	+	0	+	75°	CA
A	+	0	0	90°	

Half-Stepping Alternate
1-Phase-On &
2-Phase-on Mode
A, AB, B, BC, C, CA, A

(*c*) Half-step Operation

Half-step operation or 'half-stepping' can be obtained by exciting the three phases in the sequence *A*, *AB*, *B*, *BC*, *C* etc. *i.e*. alternately in the 1-phase-ON and 2-phase-ON modes. It is sometime known as 'wave' excitation and it causes the rotor to advance in steps of 15º *i.e*. half the full-step angle. The truth table for the phase pulsing sequence in half-stepping is shown in Fig. (*b*).

(*d*) Microstepping

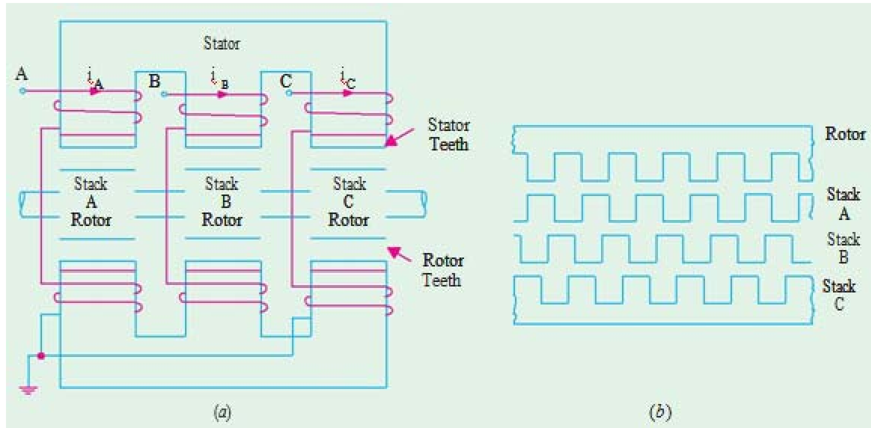
- It is also known as mini-stepping. It utilizes two phases simultaneously as in 2-phase-*ON* mode but with the two currents deliberately made unequal (unlike in half-stepping where the two phase currents have to be kept equal).
- The current in phase *A* is held constant while that in phase *B* is increased in very small increments until maximum current is reached. The current in phase *A* is then reduced to zero using the same very small increments.
- In this way, the resultant step becomes very small and is called a microstep.
- For example, a *VR* stepper motor with a resolution of 200 steps / rev (β = 1.8º) can with microstepping have a resolution of 20,000 steps / rev (β = 0.018º).
- Stepper motors employing microstepping technique are used in printing and phototypesetting where very fine resolution is called for.
- Microstepping provides smooth low-speed operation and high resolution.

Torque. If I_a is the d.c. current pulse passing through phase *A*, the torque produced by it is given by $T = (1/2)\, I_a^2\, dL / d\theta$. *VR* stepper motors have a high (torque / inertia) ratio giving high rates of acceleration and fast response.

A possible disadvantage is the absence of detent torque which is necessary to retain the rotor at the step position in the event of a power failure.

Multi-stack VR Stepper Motor

- Multi-stack motors provide smaller step angles.
- The multi-stack motor is divided along its axial length into a number of magnetically-isolated sections or stacks which can be excited by a separate winding or phase.
- Both stator and rotor have the same number of poles.
- The stators have a common frame while rotors have a common shaft as shown in Fig. (*a*) which represents a three-stack *VR* motor.
- The teeth of all the rotors are perfectly aligned with respect to themselves but the stator teeth of various stacks have a progressive angular displacement as shown in the developed diagram of Fig. (*b*) for phase excitation.

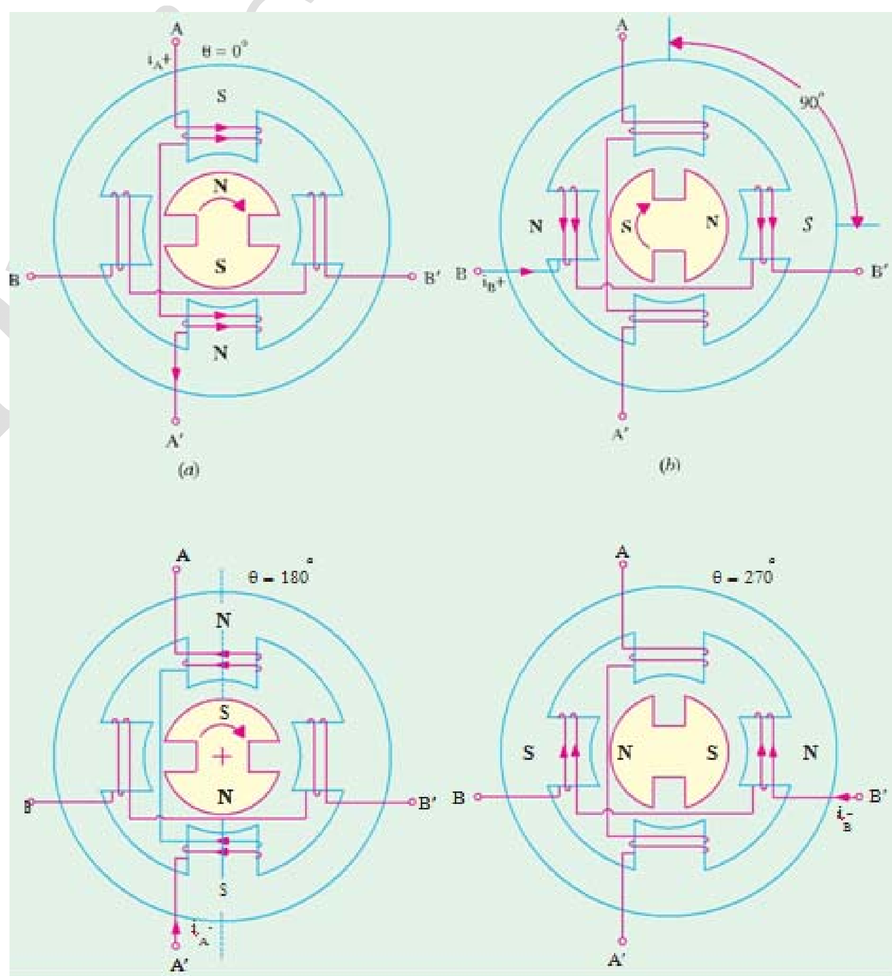


- Three-stack motors are most common although motors with upto seven stacks and phases are available.
- They have step angles in the range of 2º to 15º. For example, in a six-stack *V R* motor having 20 rotor teeth, the step angle β = 360º / 6 x 20 = 3º.

Permanent Magnet Stepper Motor

Construction

- Its construction is similar to that of the single stack VR motor except the rotor is made of a permanent magnet material like magnetically hard ferrite.
- The stator has projecting poles but the rotor is cylindrical and has radially magnetized permanent magnets.
- The operating principle is explained with fig. (a) where the rotor has two poles and stator has four poles.
- Since stator poles are energized by one winding, the motor has two windings or phases marked A and B.
- The step angle $\beta = 360^0 / mN_r = 360^0 / 2 \times 2 = 90^0$ or $\beta = (4 - 2) / 360^0 / 2 \times 4 = 90^0$.



Working.

- When a particular stator phase is energized, the rotor magnetic poles move into alignment with the excited stator poles. The stator windings *A* and *B* can be excited with either polarity current (A^+ refers to positive current i_{A+} in the phase A and A^- to negative current i_{A-}).
- The fig. (a) shows the condition when phase A is excited with positive current i_{A+}. Here $\theta = 0^0$.

- If excitation is now switched to phase B as in Fig. (b), the rotor rotates by a full step of 90º in the clockwise direction.
- Next, when phase A is excited with negative current $i_A^{\,-}$, the rotor turns through another 90º in $C\,W$ direction as shown in Fig. (c).
- Similarly, excitation of phase B with i_B- further turns the rotor through another 90º in the same direction as shown in Fig. (d).
- After this, excitation of phase A with i_A+ makes the rotor turn through one complete revolution of 360º.

Truth Table No. 1

A	B	θ
+	0	0°
0	+	90°
–	0	180°
0	–	270°
+	0	0°

1-Phase-ON Mode

Truth Table No. 2

A	B	θ
+	+	45°
–	+	135°
–	–	225°
+	–	315°
+	+	45°

1-Phase-ON Mode

Truth Table No. 3

A	B	θ
+	0	0°
+	+	45°
0	+	90°
–	+	135°
–	0	180°
–	–	225°
0	–	270°
+	–	315°
+	0	0°

Alternate 1-Phase-On & 2-Phase-On Modes

- Table No.1 applies when only one phase is energized at a time in 1-phase-*ON* mode giving step size of 90º.
- Table No.2 represents 2-phase-*ON* mode when two phases are energised simultaneously. The resulting steps are of the same size but the effective rotor pole positions are midway between the two adjacent full-step positions.
- Table No.3 represents half-stepping when 1-phase-*ON* and 2-phase-*ON* modes are used alternately. In this case, the step size becomes half of the normal step or one-fourth of the pole-pitch (*i.e.* 90º / 2 = 45º or 180º / 4 = 45º). Microstepping can also be employed which will give further reduced step sizes thereby increasing the resolution.

Advantages and Disadvantages.

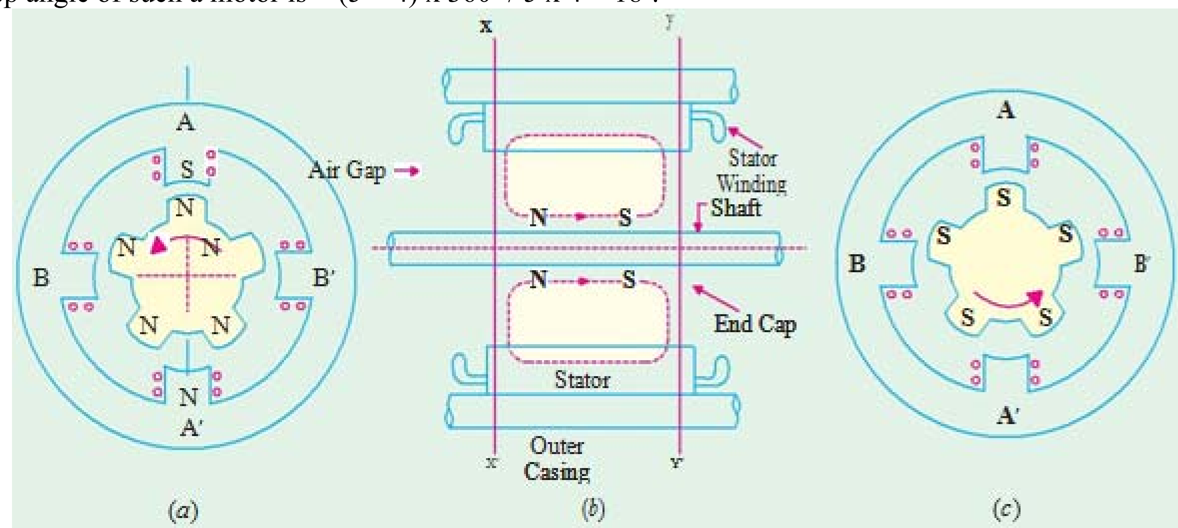
- Since the permanent magnets of the motor do not require external exciting current, it has a low power requirement but possesses a high detent torque as compared to a *VR* stepper motor.
- This motor has higher inertia and hence slower acceleration.
- However, it produces more torque per ampere stator current than a *VR* motor.
- Since it is difficult to manufacture a small permanent-magnet rotor with large number of poles, the step size in such motors is relatively large ranging from 30º to 90º.

Hybrid Stepper Motor

Construction.

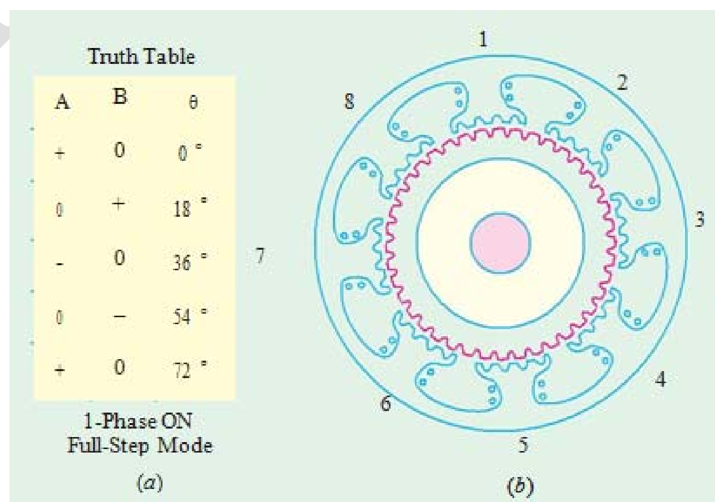
- It combines the features of the variable reluctance and permanent-magnet stepper motors.
- The rotor consists of a permanent-magnet that is magnetized axially to create a pair of poles marked N and S in Fig. (b).
- Two end-caps are fitted at both ends of this axial magnet. These end-caps consist of equal number of teeth which are magnetized by the respective polarities of the axial magnet.

- The rotor teeth of one end-cap are offset by a half tooth pitch so that a tooth at one end-cap coincides with a slot at the other. The cross-sectional views perpendicular to the shaft along X -*X '* and *Y* -*Y '* axes are shown in Fig. (*a*) and (*c*) respectively.
- As seen, the stator consists of four stator poles which are excited by two stator windings in pairs. The rotor has five *N*-poles at one end and five *S*-poles at the other end of the axial magnet.
- The step angle of such a motor is = (5 − 4) x 360º / 5 x 4 = 18º.



Working.

- In Fig. (*a*), phase *A* is shown excited such that the top stator pole is a *S*-pole so that it attracts the top *N*-pole of the rotor and brings it in line with the *A* -*A '* axis.
- To turn the rotor, phase *A* is denergized and phase *B* is excited positively. The rotor will turn in the CCW direction by a full step of 18º.
- Next, phase *A* and *B* are energized negatively one after the other to produce further rotations of 18º each in the same direction. The truth table is shown in Fig. (*a*).
- For producing clockwise rotation, the phase sequence should be A^+; B^-; A^-; B^+; A^+ etc.
- In order to give high resolution, hybrid stepping motors are built with more rotor poles.
- Hence, the stator poles are often slotted or castleated to increase the number of stator teeth.
- As shown in Fig. (*b*), each of the eight stator poles has been alloted or castleated into five smaller poles making N_s = 8 x 5 = 40º.
- If rotor has 50 teeth, then step angle = (50 − 40) x 360º / 50 x 40 = 1.8º.
- Step angle can also be decreased (and hence resolution increased) by having more than two stacks on the rotor.



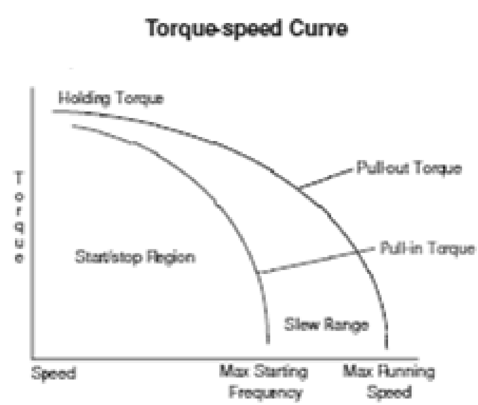
A	B	θ
+	0	0 °
0	+	18 °
-	0	36 °
0	−	54 °
+	0	72 °

- This motor achieves small step sizes easily and with a simpler magnet structure whereas a purely *PM* motor requires a multiple permanent-magnet.
- As compared to *VR* motor, hybrid motor requires less excitation to achieve a given torque.
- However, like a *PM* motor, this motor also develops good detent torque provided by the permanent-magnet flux. This torque holds the rotor stationary while the power is switched off.
- This fact is quite helpful because the motor can be left overnight without fear of its being accidentally moved to a new position.

Summary of Stepper Motors

- A stepper motor can be looked upon as a digital electromagnetic device where each pulse input results in a discrete output *i.e*. a definite angle of shaft rotation. It is ideally-suited for open-loop operation because by keeping a count of the number of input pulses, it is possible to know the exact position of the rotor shaft.
- In a *VR* motor, excitation of the stator phases gives rise to a torque in a direction which minimizes the magnetic circuit reluctance. The reluctance torque depends on the square of the phase current and its direction is independent of the polarity of the phase current. A *VR* motor can be a single-stack or multi-stack motor. The step angle $\beta = 360^o / m N_r$ where N_r is the number of rotor teeth and m is the number of phases in the single-stack motor or the number of stacks in the multi-stack motor.
- A permanent-magnet stepper motor has a permanently-magnetized cylindrical rotor. The direction of the torque produced depends on the polarity of the stator current.
- A hybrid motor combines the features of *VR* and *PM* stepper motors. The direction of its torque also depends on the polarity of the stator current. Its step angle $\beta = 360^o / m N_r$.
- In the 1-phase *ON* mode of excitation, the rotor moves by one full-step for each change of excitation. In the 2-phase-*ON* mode, the rotor moves in full steps although it comes to rest at a point midway between the two adjacent full step positions.
- Half-stepping can be achieved by alternating between the 1-phase-*ON* and 2-phase-*ON* modes. Step angle is reduced by half.
- Microstepping is obtained by deliberately making two phase currents unequal in the 2-phase-*ON* mode.

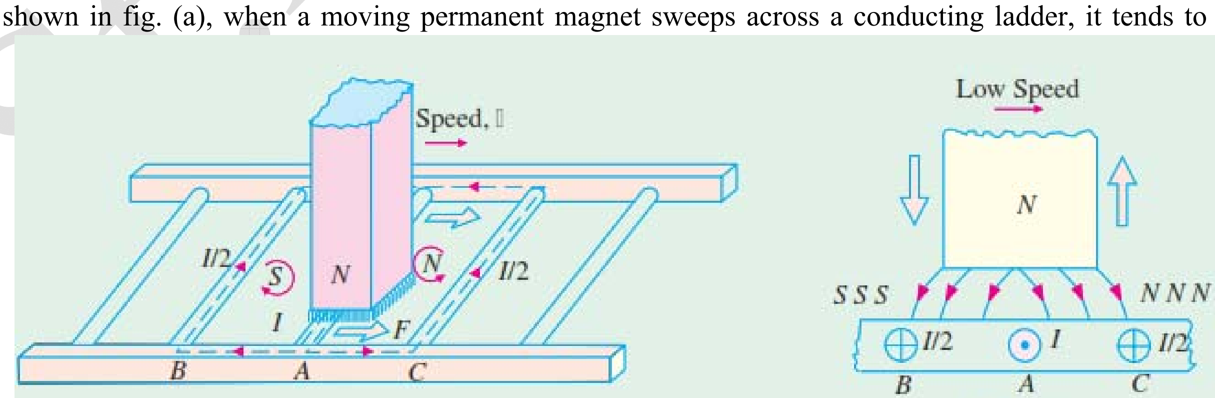
Important Definitions



Holding Torque - amount of torque that the motor produces when it has rated current flowing through the windings but the motor is at rest.
Detent Torque - amount of torque that the motor produces when it is not energized. No current is flowing through the windings.
Pull-in Torque Curve - Shows the maximum value of torque at given speeds that the motor can start, stop or reverse in synchronism with the input pulses. The motor cannot start at a speed that is beyond this curve. It also cannot instantly reverse or stop with any accuracy at a point beyond this curve.
Stop / Start Region - area on and underneath the pull-in curve. For any load value in this region, the motor can start, stop, or reverse "instantly" (no ramping required) at the corresponding speed value.
Pull-out Torque Curve - Shows the maximum value of torque at given speeds that the motor can generate while running in synchronism. If the motor is run outside of this curve, it will stall.
Slew Range - the area between the pull-in and the pull-out curves, where to maintain synchronism, the motor speed must be ramped (adjusted gradually).

INTRODUCTION TO MAGNETIC LEVITATION SYSTEMS

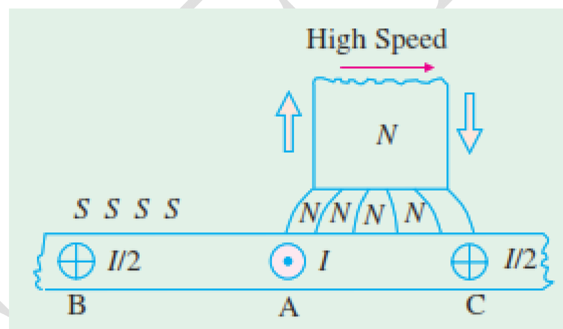
- As shown in fig. (a), when a moving permanent magnet sweeps across a conducting ladder, it tends to drag the



(*a*) (*b*) Gateway

ladder along with, because it applies a horizontal tractive force F = BI*l* .

- This horizontal force will be accompanied by a vertical force, which tends to push the magnet away from the ladder in the upward direction.
- A portion of the conducting ladder of fig. (a) has been shown in fig. (b). the voltage induced in conductor A is maximum because flux is greatest at the centre of the N pole.
- If the magnet speed is very low, the induced current reaches its maximum value in A at virtually the same time (because delay due conductor inductance is negligible).
- As this current flows via conductors B and C, it produces induced SSS and NNN poles.
- Consequently, the front half of the magnet is pushed upwards while the rear half is pulled downwards.
- Since the distribution of SSS and NNN pole is symmetrical with respect to the centre of the magnet, the vertical forces of attraction and repulsion, being equal and opposite, cancel each other out, leaving behind only horizontal tractive force.
- Consider the case, when the magnet sweeps over the conductor A with a very high speed.



- Due to conductor inductance, current A reaches its maximum value a fraction of a second (Δt) after voltage reaches its maximum value.
- Hence, by the time I in conductor A reaches its maximum valu, the centre of the magnet is already ahead by a distance = *v*.Δt where *v* is the magnet velocity.
- The induced poles SSS and NNN are produced as before, by the currents returning via conductors B and C respectively.
- But, by now, the N pole of the permanent magnet lies over the induced NNN pole, which pushes it upwards with a strong vertical force. This forms the basis of magnetic levitation which literally means ‘floating in air’.
- Magnetic levitation is being used in ultra high speed trains (upto 300 km/h) which float in the air about 100mm to 300mm above the metallic track.
- They do not have any wheels and do not require the traditional steel rail.
- A powerful electromagnet fixed underneath the train moves across the conducting rail, thereby inducing current in the rail. This gives raise to vertical force called force of levitation, which keeps the train pushed up in the air above the track.
- Linear motors are used to propel the train.