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Stepper Motor

A stepper motor is a special electrical machine which rotates in discrete angular steps in response to a programmed sequence of input electrical pulses. It is also known as a step motor or stepping motor. The stepper motor works on the principle that a magnetic interaction takes place between the rotor and the stator, which makes the rotor move. The stator has windings. The rotor is of salient structure without any windings, and it may or may not have permanent magnets. The robustness and reliability of a stepper motor makes it very popular. At present, for automation systems requiring control of position or speed or both, at low cost, the first choice is stepper motor. As the input–output relation is direct and rigid, it is possible to have an open-loop system without any feedback sensors. We can find the applications of stepper motor in diverse areas ranging from a small wrist watch to artificial satellites. Stepper motors with power range 1 W to 2.5 kW and torque range 1 μN-m to 40 N-m are available. In this chapter, we will discuss various types of stepper motors, their construction, working, characteristics and applications. Stepper motors can be classified into variable reluctance type, permanent magnet type and hybrid type stepper motors.

1.1 Variable Reluctance (VR) Stepper Motor

VR stepper motor works on the principle that a magnetic material placed in a magnetic field experiences a force to align it in a path of minimum reluctance. It has a stator with salient poles that have concentric windings which form different phases. The stator phases are excited by current pulses to establish a magnetic field. The rotor also has salient structure with projecting teeth and has no windings or permanent magnet. There are two types of VR stepper motors: single-stack stepper motors and multiple-stack stepper motors.

1.1.1 Single-stack VR Stepper Motors

Construction

The stator of a single-stack VR stepper motor is made up of silicon steel stampings. It has projecting poles, usually even number of poles used. The poles carry concentric windings. In stator with even number of poles, the windings on opposite poles are connected in series such that the currents in them establish a magnetic flux that aid each other. Windings connected in this way form different phases of the motor. For stator with odd number of poles, the numbers of phases and poles are equal. Rotor is usually made of laminated silicon steel. Solid silicon steel is also used for rotor core. The material used for stator and rotor should be of high permeability. The rotor has projecting teeth on its outer periphery. It has no windings or permanent magnets. The numbers of rotor teeth and stator poles should not be equal. This is to make the motor self-starting and also to have bidirectional rotation of the rotor. The constructional detail of a four-phase, eight-pole single-stack VR stepper motor is shown in Fig. 1.1. It has six rotor teeth. The switching circuit for exciting the stator phases is shown in Fig. 1.2.

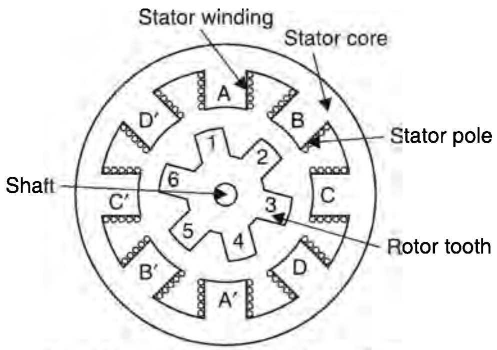

Fig. 1.1 Four-phase, eight-pole single-stack VR stepper motor

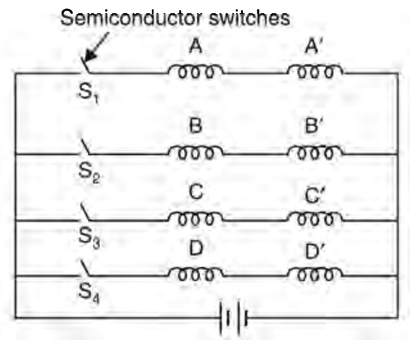

Fig. 1.2 Switching circuit

Working

Rotor teeth can assume any position until the stator winding is energised. Let the initial position of the rotor be as shown in Fig. 1.1 with all switches S_1 to S_4 in OFF position. Now turn ON switch S_1, so that phase A is energised. This will make stator poles A and A′ as north and south magnetic poles. The stator poles attract rotor teeth and the rotor moves to occupy a position of minimum reluctance. Thus, rotor teeth 1 and 4 take the rest positions as shown in Fig. 1.3.

Next, switch S_2 is turned ON and S_1 is turned OFF. This operation deenergises phase A and excites phase B. Stator poles B and B′ get magnetised. The rotor will move in such a direction to occupy the minimum reluctance path by travelling minimum angular distance. This is achieved by the movement of the rotor in counterclockwise (CCW) direction by 15°. The rotor takes its rest position (equilibrium position) as shown in Fig. 1.4. The angle through which the rotor moves for a switching operation is called step angle and is given by,

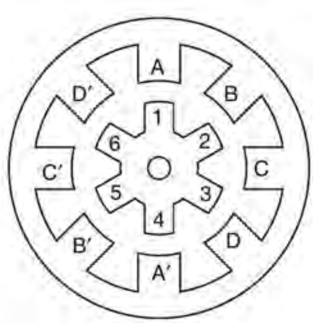

Fig. 1.3 Rotor position when phase A is excited

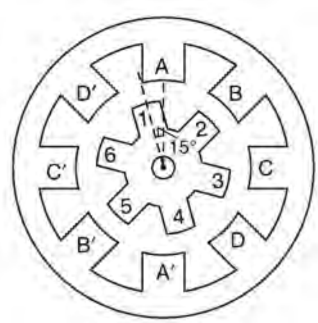

Fig. 1.4 Rotor position when phase B is energised

$$\theta_s = \frac{360}{m N_r}$$

where m is the number of stator phases, N_r the number of rotor teeth.

In the present case, $m = 4, N_r = 6$

$$\therefore \qquad \theta_s = \frac{360}{4 \times 6} = 15°$$

With S_2 OFF and S_3 ON, the rotor moves again by 15° in the CCW direction and comes to rest in the position shown in Fig. 1.5. By switching S_4 ON and S_3 OFF, the rotor rotates by 15° in CCW direction and takes the root position shown in Fig. 1.6. By continuing this switching operation in the sequence S_1, S_2, S_3, S_4, S_1, …, rotor moves in CCW direction with step angle of 15°.

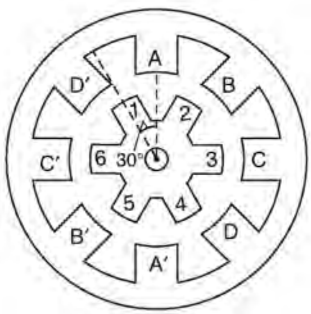

Fig. 1.5 Position of rotor after switching phase C

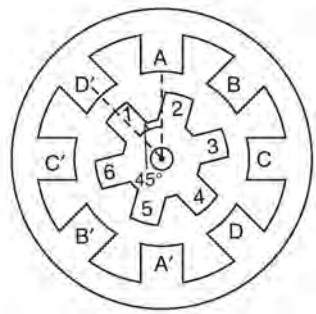

Fig. 1.6 Rotor position after switching phase D

The final position corresponds to the last switch in ON position. Finally, closed switch should remain in ON position to hold the rotor in that position and to prevent further movement due to external disturbances. The rotor remains in this position untill and external torque greater than holding torque is applied on the motor. Certain oscillation around the resting position corresponding to the excitation can be observed in the motor. This is due to the inertia of the rotating part. This oscillation will die out due to the bearing friction. The inertia may also increase stepping time. The inertia should be as small as possible for getting fast response. Usually, viscous damping is provided for suppressing oscillations. By increasing the stator current, the stepping time can be reduced. But there is limitation for current due to thermal constraints. Increase in current results in increased copper loss and hence increased temperature.

The operation of the stepper motor can be represented by the truth table given in Table 1.1. For reversing the direction of rotation, switching is done in the sequence S_1, S_4, S_3, S_2, S_1,…

Table 1.1 Truth table

S_1	S_2	S_3	S_4	θ
1	0	0	0	0
0	1	0	0	15°
0	0	1	0	30°
0	0	0	1	45°
1	0	0	0	60°

1 – ON; 0 – OFF

Modes of excitation

Stepper motor can be operated in different modes depending on the excitation of stator phases. When phases are energised one at a time, the mode of operation is known as single-phase, one-phase or full-step ON mode. In this mode, stepper motor gives maximum step angle. Two-phase ON mode, half-step mode and micro-step mode are the other modes of operation.

Two-phase ON mode: To explain this mode, consider the stepper motor shown in Fig. 1.1. With switch S_1 ON, the rotor assumes the position shown in Fig. 1.3. With S_1 in ON position, S_2 is also switched ON. With this condition, the rotor tries to move in CCW and occupies the position shown in Fig. 1.4. But as stator poles A and A^1 are also magnetised, there is a repulsive force on rotor teeth to move in CW direction. The rotor moves by 7.5° in CCW direction and takes the rest position shown in Fig. 1.7, where magnetic forces produced by phases A and B are equal.

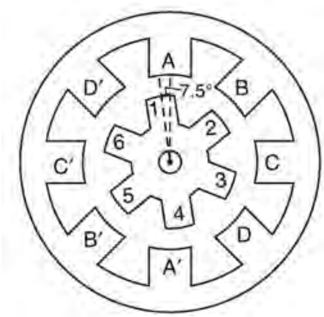

Fig. 1.7 Rotor position with S_1 and S_2 ON

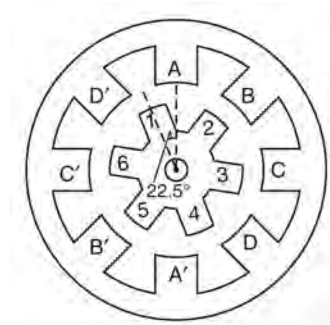

Fig. 1.8 Rotor position with S_2 and S_3 ON

Next, open S_1 and keep S_3 closed. The poles corresponding to B and C phases are magnetised. The attractive forces due to the magnetic poles make the rotor move in CCW direction by 15° and finally take the equilibrium position shown in Fig. 1.8. Opening switch S_2 and closing switch S_4 results in the rotation of the rotor again by 15° in CCW direction. The rotor assumes the position shown in Fig. 1.9. The truth table for this mode of operation is shown in Table 1.2.

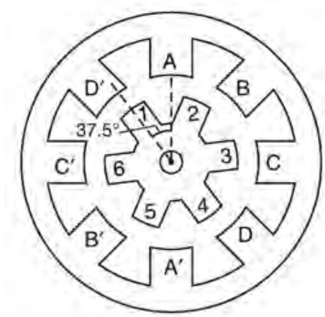

Fig. 1.9 Rotor position with S_3 and S_4 ON

Table 1.2 Truth table for two-phase ON mode

S_1	S_2	S_3	S_4	θ
1	0	0	0	0°
1	1	0	0	7.5°
0	1	1	0	22.5°
0	0	1	1	37.5°
1	0	0	1	52.5°
1	1	0	0	67.5°

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In two-phase ON mode, the step angle is 15° (full-step angle). The stable positions corresponding to switching operation lie in between the stable positions corresponding to single-phase ON operation.

2–1–2–1 phase or half-step mode of operation: In this mode of operation, we can get a step angle whose value is half of the full-step angle. This mode combines one-phase and two-phase ON modes. For explaining this mode, consider the motor shown in Fig. 1.3. With S_1 in ON position, rotor attains the position indicated in Fig. 1.3. With S_1 in ON position, S_2 is also switched ON. This causes the rotor to move in CCW direction and stay in the position shown in Fig. 1.7. Then, S_1 is switched OFF with S_2 in the same position. This action makes the rotor to rotate in CCW direction and finally take the position shown in Fig. 1.4. Next, with S_2 in ON position, S_3 is closed. This makes the rotor to attain the position shown in Fig. 1.8. With S_3 in closed position, S_2 is opened. This results the position shown in Fig. 1.5. By following the sequence of operations S_1, S_1–S_2, S_2, S_2–S_3, S_3, S_3–S_4, S_4, S_4–S_1, S_1, …, the rotor moves in steps of 7.5° in CCW direction. The truth table for half-step mode of operation is given in Table 1.3.

Table 1.3 Truth table for half-step mode

S_1	S_2	S_3	S_4	θ
1	0	0	0	0°
1	1	0	0	7.5°
0	1	0	0	15°
0	1	1	0	22.5°
0	0	1	0	30°
0	0	1	1	37.5°
0	0	0	1	45°
1	0	0	0	60°

The excitation sequences for various modes of operation are summarised in Table 1.4.

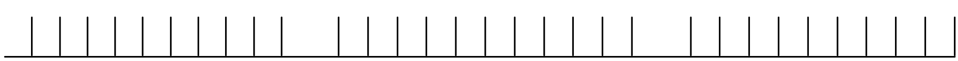
Table 1.4 Excitation sequence

	1-phase ON										
Clockstate	*R*	1	2	3	4	5	6	7	8	9	10
Phase A	1	1	0	0	0	1	0	0	0	0	1
Phase B	0	0	1	0	0	0	1	0	0	0	0
Phase C	0	0	0	1	0	0	0	1	0	0	0
Phase D	0	0	0	0	1	0	0	0	1	0	0

	2-phase ON										
Clockstate	*R*	1	2	3	4	5	6	7	8	9	10
Phase A	1	1	0	0	1	1	0	0	0	0	0
Phase B	0	1	1	0	0	1	1	0	0	0	0
Phase C	0	0	1	1	0	0	0	1	1	0	0
Phase D	1			1	1	0	0	0	0	1	1

	1–2–1–2 phase ON										
Clockstate	*R*	1	2	3	4	5	6	7	8	9	10
Phase A	1	1	0	0	0	0	0	1	1	1	0
Phase B	0	1	1	1	0	0	0	0	0	1	1
Phase C	0	0	0	1	1	1	0	0	0	0	0
Phase D	0	0	0	0	0	1	1	1	0	0	0

Pulses

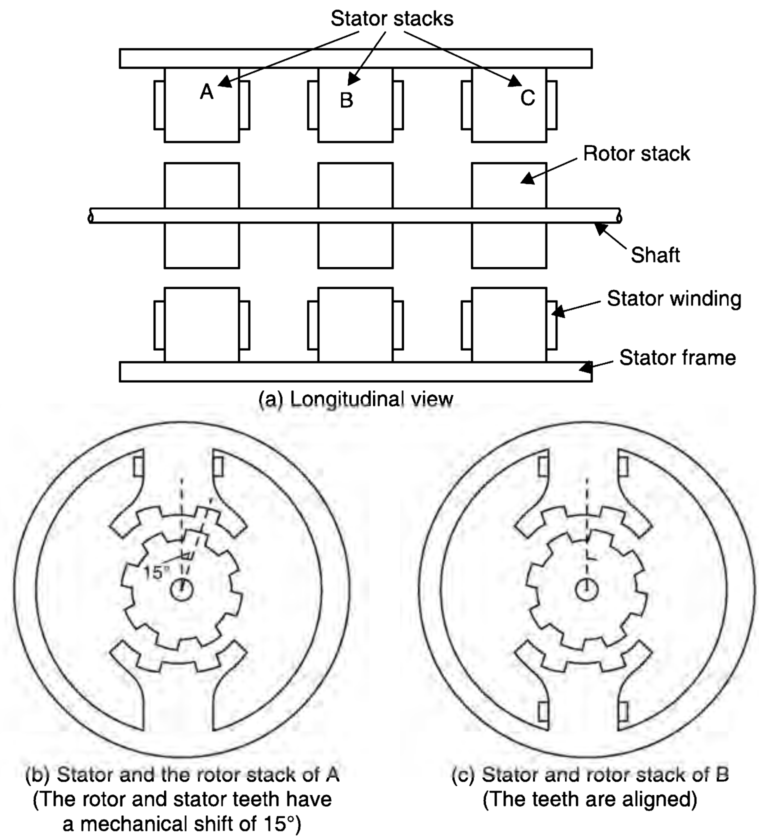


The two-phase ON mode has an advantage over one-phase ON mode as the oscillations in the rotor position are less in the former than in the latter. In two-phase mode, the two conducting phases form closed loop for the current generated by the emf induced in the oscillations of the rotor. The torque produced by this current is in opposition to the achiral torque developed. The oscillations dies out quickly by dissipating the heat produced by the current due to the oscillations.

This type of closed circuit is absent in single-phase ON mode. In half-step mode, this type of closed circuit is formed when a pair of phases are conducting. So for half-step mode, oscillations are damped out quickly.

1.1.2 Multi-stack Variable Reluctance Stepper Motor

Multi-stack VR stepper motor has higher torque to volume ratio and more efficiency compared to the single-stack VR stepper motor. In this type, each phase has separate stator and rotor sections called stacks. The stator stack consists of salient poles wires windings. All the coils in the stator stack are connected in series and all the poles facing the rotor become north or south when excited. The magnetic circuit of each stack is independent from that of others. Usually, stator poles have subteeth. The rotor stacks are unwound and have projecting teeth. The pitch of rotor and stator teeth is equal. The rotor stacks are mounted on the shaft in such a way that their teeth are mechanically displaced by $1/m$ tooth pitch, where m is the number of phases. The stator stacks are in alignment with respect to their teeth. The constructional details of a three-phase, two-pole multi-stack variable reluctance stepper motor with eight rotor teeth are shown in Fig. 1.10. The stator pole has three subteeth each. The three stator stacks carry winding that corresponds to three phases. The rotor teeth of stack A is displaced by 15° from stack B and 30° from stack C. The rotor teeth of phases B and C also have 15° mechanical offset.



(a) Longitudinal view

(b) Stator and the rotor stack of A (The rotor and stator teeth have a mechanical shift of 15°)

(c) Stator and rotor stack of B (The teeth are aligned)

Fig. 1.10 *Contd...*

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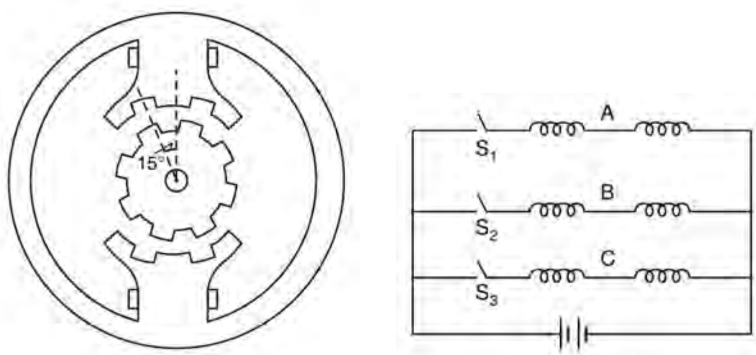


(d) Stator and rotor stacks of C (e) Switching circuit

Fig. 1.10 Constructional details of a multi-stack VR stepper motor working

Let the initial positions of rotor stacks be as shown in Fig. 1.10. This position can be achieved by exciting phase B (by closing switch S_2) with all other phases in unenergised conditions. Next, phase C is excited by closing switch S_3, while switch S_2 is opened. This operation magnetises the poles of C, and the rotor stack C moves in CCW direction by 15°. Next, phase A is excited by closing switch S_1 and opening switch S_3.

This switching makes the rotor move in the same direction again by 15°. Now, close S_2 and open S_1. The rotor rotates by 15° in CCW direction. The movement of the rotor is illustrated in Fig. 1.11. For reversing the direction of rotation, the switching is done in the sequence S_1, S_3, S_2, S_1,… .

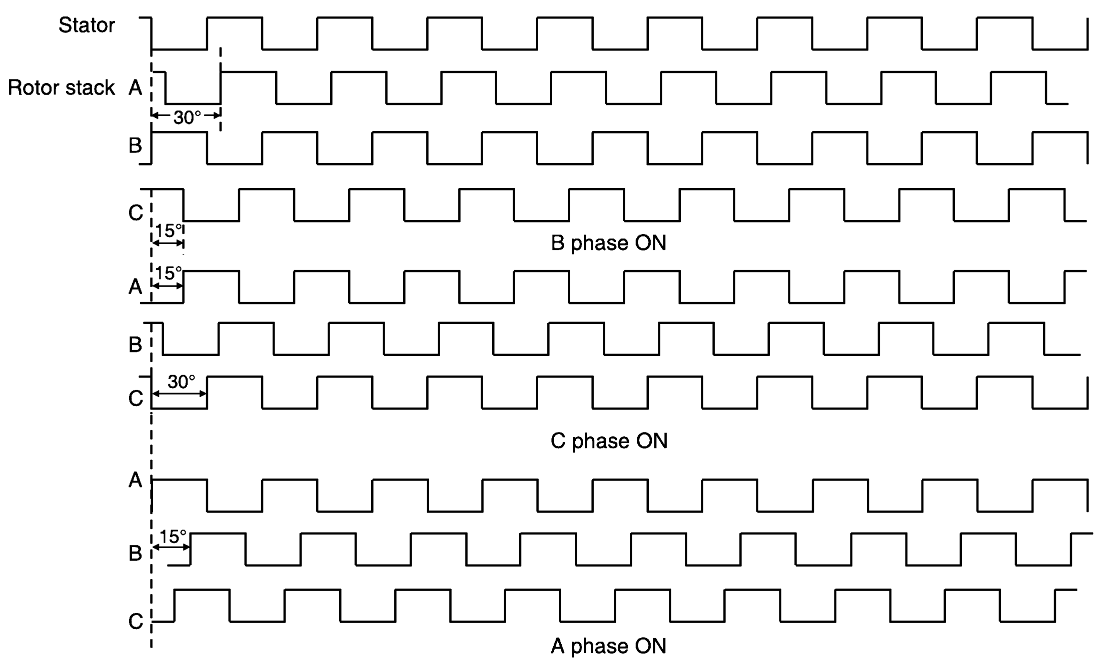


Fig. 1.11 Relative positions of rotor and stator teeth after switching

The logic sequence for one-phase ON mode is given in Table 1.5 and the timing diagram is given in Fig. 1.12.

Table 1.5 Logic sequence

Step	A	B	C
1	1	0	0
2	0	1	0
3	0	0	1
4	1	0	0

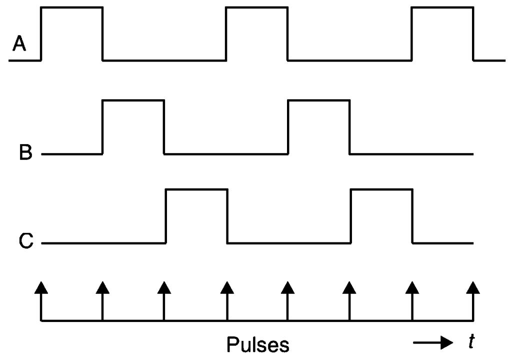
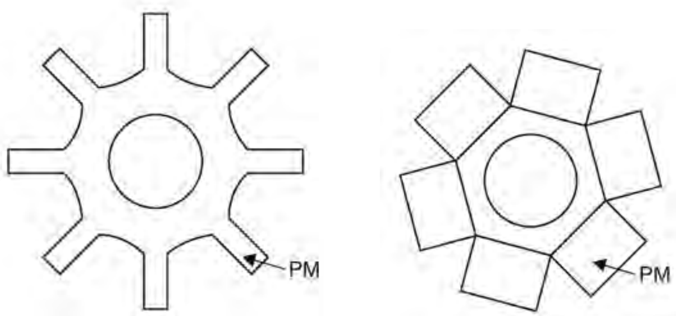


Fig. 1.12 Timing diagram

1.2 Permanent Magnet Stepper Motor

Permanent magnet (PM) stepper motor is another version of stepper motor. Its construction is similar to that of a VR stepper motor. The stator consists of salient poles wound with concentric coils. The coils are grouped and connected in series to form different phases. The rotor carries no winding but has permanent magnets. The rotor can be made in the form a PM spider cast integral or an assembled structure of PMs as shown in Fig. 1.13.



(a) Cast integral (b) Assembled

Fig. 1.13 Structure of rotor for PM stepper motor

As the motor has permanent magnets, it has detent torque. The rotor will remain in the position corresponding to the last phase energised even if the motor is unexcited. This position is maintained until the external torque exceeds a limiting value. PM stepper motors have higher torque to volume ratio compared to that of VR stepper motors. Due to higher inertia, PM stepper motors cannot be accelerated as can be done with VR motors. Due to the difficulty in manufacturing small PMs, the number of poles in the rotor is limited and the step size is relatively large in the range 30° to 90°. Axially magnetised PMs of disc type are now available. This type of PMs can offer smaller step size and the inertia can be considerably reduced.

Working

To study the principle of operation of PM stepper motor, a two-phase motor is considered. It has four stator poles and two rotor poles. The stator has windings on its poles. The motor structure is shown in Fig. 1.14. Two stator coils each are connected to form the two phases of the motor. The excitation circuit is also shown in Fig. 1.14.

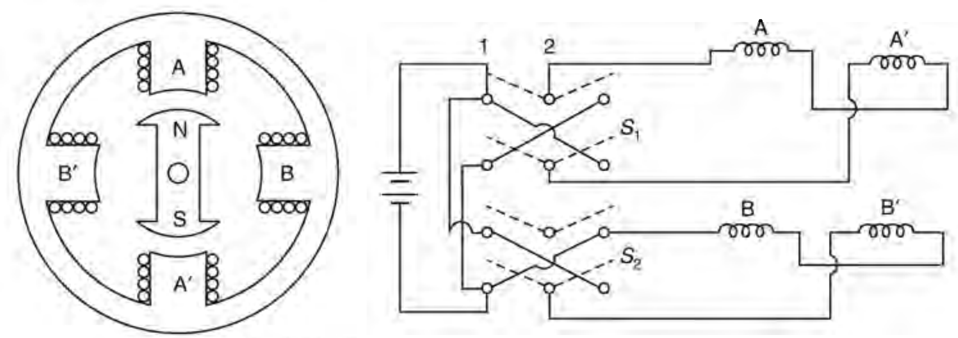


Fig. 1.14 Four-pole, two-phase PM stepper motor

When a phase is energised, it sets up a magnetic flux and rotor will position to lock its N pole and S pole to stator S pole and N pole, respectively. Single-phase ON mode, two-phase ON mode and alternate one-phase and two-phase ON modes are possible with PM stepper motors. These modes of operation are described below.

Single-phase ON mode: Initially, phase A is energised by closing switch S_1 to position 1. The rotor and stator magnetic fields make the rotor move and occupy the position shown in Fig. 1.14. Here, the N pole of the rotor and S pole formed by stator phase A get interlocked and further movement of the rotor is arrested. Next, S_2 is moved to position 1 and S_1 is opened. The rotor moves by 90° in clockwise direction and takes the position shown in Fig. 1.15. Now, S_1 is closed in position 2 and S_2 is opened. Rotor moves again by 90° in the same direction and rests in the position indicated in Fig. 1.16. This sequence of switch operations is repeated so that for each operation the rotor moves in clockwise direction with step angle 90°. Truth table is given in Table 1.6.

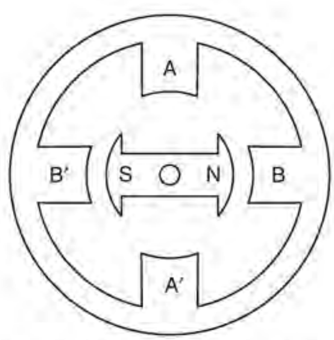


Fig. 1.15 Position of rotor when B is energised

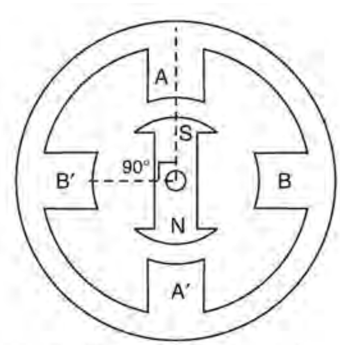


Fig. 1.16 Position of rotor when A is energised

Table 1.6 Truth table for clockwise rotation

S_1	S_2	θ
+	O	0°
O	+	90°
–	O	180°
O	–	270°
+	O	360°

+ = Position 1, – = Position 2, O = Open

Two-phase ON mode: Let the initial position of the rotor be as shown in Fig. 1.16. Here, switch S_1 is in position 1. With S_1 in this position, S_2 is switched to position 1 so that both the phases are excited. The rotor moves by 45° in clockwise direction and rests in the position shown in Fig. 1.17. With S_2 in same position, S_1 is moved to position 2. The rotor advances by 90° in the same direction and rests in the position shown in Fig. 1.18. Keeping S_1 in position 2 and switching S_2 to position 2 results in movement of rotor by 90° in the same direction and assumes the position shown in Fig. 1.19. Here also, the step angle is 90° but the equilibrium position is in one-phase mode. Truth table is given in Table 1.7.

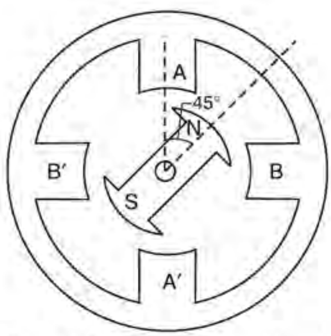


Fig. 1.17 S_1 and S_2 in position 1

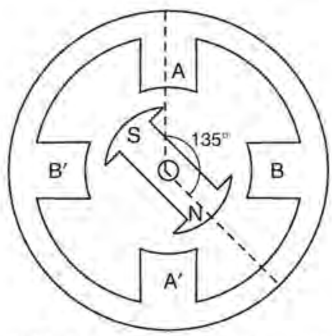


Fig. 1.18 S_1 in position 2, S_2 in position 1

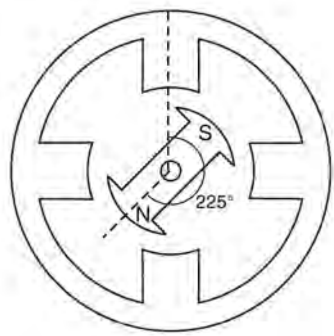


Fig. 1.19 S_1 and S_2 in position 2

Table 1.7 Truth table for clockwise rotation

S_1	S_2	θ
+	+	45°
–	+	135°
–	–	225°
+	–	315°
+	+	45°

Alternate one-phase and two-phase mode or half-step mode: Initially, S_1 is switched ON in position 1. The stator and rotor poles attract but the rotor remains in equilibrium position shown in Fig. 1.16. With S_1 in this position, S_2 is closed in position 1. The rotor moves by 45° and occupies the position shown in Fig. 1.17. Next, S_1 is opened. The rotor moves by 45° and stays in the position shown in Fig. 1.20. Keeping S_2 in the same position, close S_1 to position 2. The rotor moves in the same direction and rests in the position as shown in Fig. 1.21. Here also, the step angle is 45°. By operating the switches in this sequence, the rotor moves in clockwise direction in steps of 45° (half of the step in one-phase mode). Switching and corresponding displacements are given in Table 1.8.

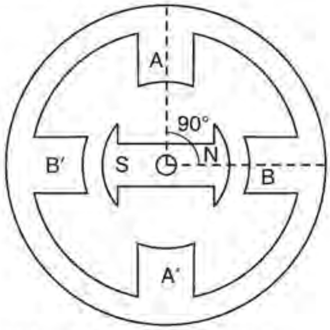


Fig. 1.20 S_2 in position 1 and S_1 opened.

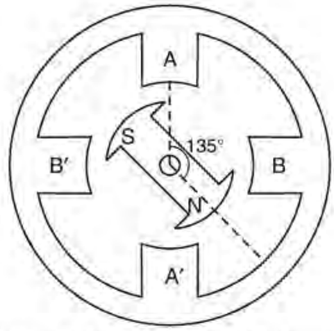


Fig. 1.21 S_2 in position 1 and S_1 in position 2.

Table 1.8 Truth table for clockwise rotation

S_1	S_2	θ
+	O	0°
+	+	45°
O	+	90°
–	+	135°
–	O	180°
–	–	225°
O	–	270°
+	–	315°
+	O	360°

1.3 Hybrid Stepper Motor (HSM)

Hybrid stepper motor is the most widely used motor among the various types of stepper motors. It has the advantages of both PM and VR stepper motors and its operation is based on the combined principles of both PM and VR stepper motors. HSM is the best choice for applications where small-step angles and high starting torque are essential.

Construction

The constructional details of a 5-phase, 10-pole HSM with 50 rotor teeth are shown in Fig. 1.22. The stator has 10 poles with subteeth. It is made up of soft iron stampings. The poles are provided with windings. Windings on diametrically opposite pole pair are connected in series to form a phase. The phases are energised with DC source through semiconductor switching devices. At the centre of the rotor, an axially magnetised cylindrical permanent magnet is mounted on the shaft. This PM produces unipolar magnetic field. The stator magnetic field produced by external excitation is heteropolar. Two end caps made of laminated silicon sheet steel cover the poles of the PM. The end caps have 50 teeth on their outer periphery. Two rotor stacks are mounted on the shaft in such a way that their teeth are displaced mechanically by 1/2 tooth pitch in space between each other.

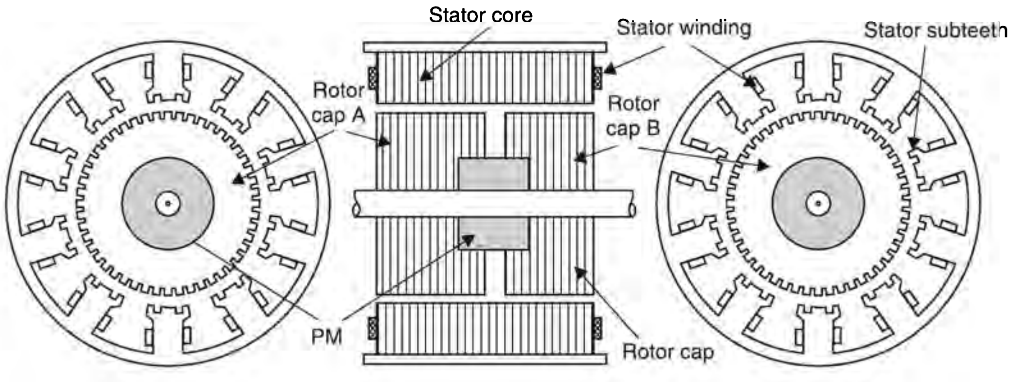


Fig. 1.22 Constructional details of five-phase HSM

Working

Consider a four-pole, two-phase HSM with 15 rotor teeth on each rotor section, as shown in Fig. 1.23.

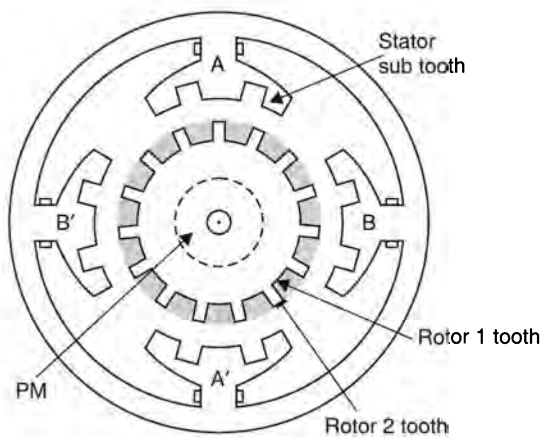


Fig. 1.23 Two-phase, four-pole HSM

Coils wound on poles A and A′ are connected in series to form phase A and on pole B and B′ to form phase B. The tooth pitch is 360/15 = 24° and the step angle is 360/(2 × 2 × 15) = 6°. PM is assumed to be mounted on the shaft in such a way that teeth of rotor 1 are magnetised south and those of rotor 2 are magnetised north. The switching circuit for exciting the phases is shown in Fig. 1.24.

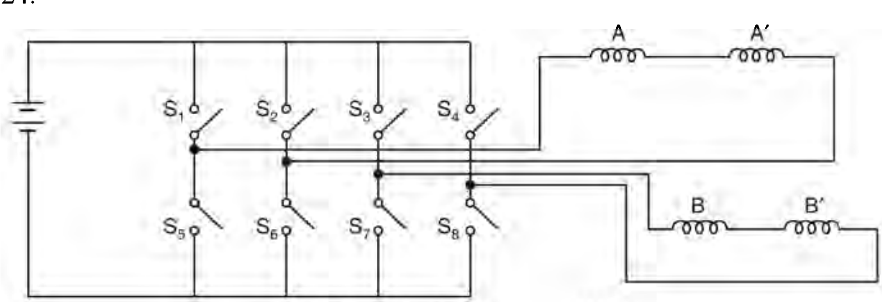


Fig. 1.24 Switching circuit for HSM

With S_1 and S_6 in the ON position, phase A is excited. This will make pole A magnetised north and A′ south. This will cause the attraction of some teeth of rotor 1 towards pole A and few teeth of rotor 2 towards pole A′. The rotor moves by 6° in clockwise direction and occupies the position shown in Fig. 1.25a. Next S_1 and S_6 are switched OFF and S_3 and S_8 are switched ON. This action magnetises pole B and B′ north and south, respectively. Rotor teeth again move by 6° and stay in position shown in Fig. 1.25c. Then, S_3 and S_8 are switched OFF and S_2 and S_5 are switched ON. Pole A′ becomes south and A becomes north. This switching operation makes the rotor move in the clockwise direction by 6° and remain in the position indicated in Fig. 1.25d. Switching ON switches S_4 and S_7, at the same time turning OFF switches S_2 and S_5, makes the rotor rotate, again by 6°, and occupy the position shown in Fig. 1.25e. Repeating this sequence of operation, we can get the rotation of rotor with steps of 6° in the clockwise direction.

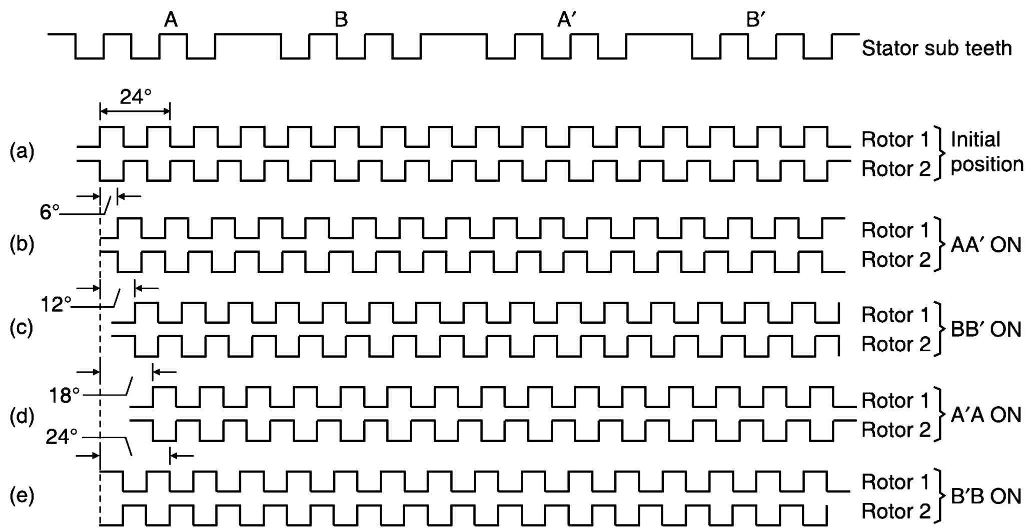


Fig. 1.25 Developed diagram showing the rotor positions corresponding to switching

The excitation sequences for one-phase ON, two-phase ON and half-step modes are given in Table 1.9.

Table 1.9 Excitation sequence

(a) One-phase mode

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	0	0	0	0	1	0	0
0	0	1	0	0	0	0	1
0	1	0	0	1	0	0	0
0	0	0	1	0	0	1	0
1	0	0	1	0	1	1	0

Continue ...

(b) Two-phase mode

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	0	1	0	0	1	0	1
0	1	1	0	1	0	0	1
0	1	0	1	1	0	1	0
1	0	0	1	0	1	1	0
1	0	1	0	0	1	0	1
0	1	1	0	1	0	0	1
0	1	0	1	1	0	1	0
1	0	0	1	0	1	1	0
1	0	1	0	0	1	0	1

(c) Half-step mode

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	0	1	0	0	1	0	1
0	0	1	0	0	0	0	1
0	1	1	0	1	0	0	1
0	1	0	0	1	0	0	0
0	1	0	1	1	0	1	0
0	0	0	1	0	0	1	0
1	0	0	1	0	1	1	0
1	0	0	0	0	1	0	0

1 = ON, 0 – OFF

In addition to single phase ON, two-phase ON and half-step modes of operation, there is another mode of excitation for hybrid stepper motor. This mode is called microstepping mode. In this mode, the phase current is adjusted by electronic circuit and phases are excited with stepped sine wave as shown in Fig. 1.26.

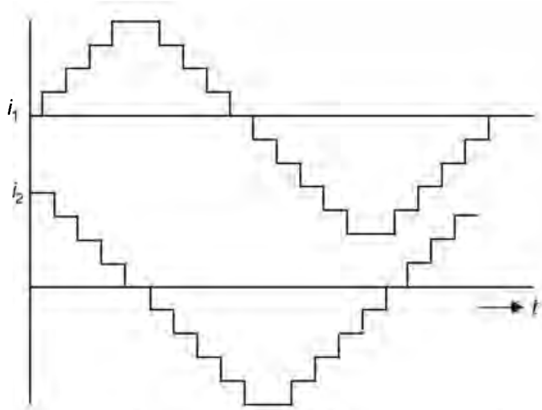


Fig. 1.26 Phase current for a two-phase hybrid stepper motor for microstepping

Another method is to adjust the magnitude of phase current applied to phases. This method is useful for two-phase ON mode. For getting a step angle of 'θ' the current in the first phase is kept at $I \sin \theta$ and in the second phase adjusted to $I \cos \theta$ by keeping the first phase current constant. Yet, another method for microstepping operation is to arrange the stator poles in spaces with unequal angular distances. This method is applicable on disc rotor stepper motor.

1.4 Other Types of Stepper Motors

In addition to the stepper motors we have discussed so far, there are several other types. A few of them are described in this section.

1.4.1 Single-phase Stepper Motor

Tiny stepper motors which are found in wrist watches, timers, counters, etc. are of single-phase type. They are operated from a single-phase source. As their size is very small, usually one or two permanent magnets are used to get high torque to input power ratio. In this motor, the variation in reluctance of the air gap is achieved by removing some portion of stator pole as shown in Fig. 1.27.

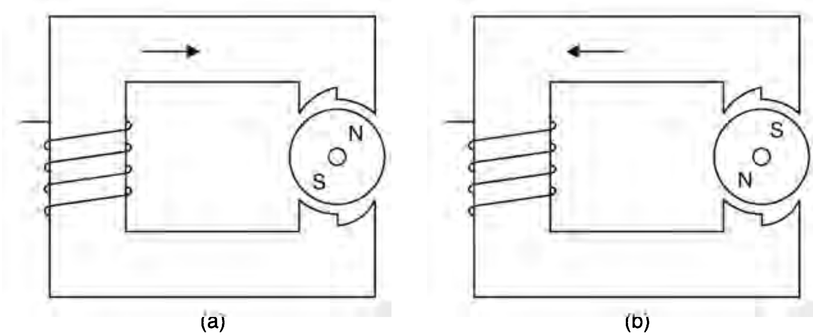


Fig. 1.27 Single-phase stepper motor

Assume that the rest position of the rotor is as shown in Fig. 1.27a. To make the rotor move voltage is applied to the coil in such a direction that the flux has a direction as shown in Fig. 1.27a. After rotating through 180°, the rotor takes the position shown in Fig. 1.27b. To get movement of the rotor from this position in the same direction, the voltage should be reversed to establish flux in the direction shown in Fig. 1.27b. By adjusting the frequency of the AC supplied to the coil, we can have any number of steps per second.

1.4.2 Disc Magnet (DM) Stepper Motor

This type of motor has the advantages like high torque to weight, torque to size, power to size and power to weight ratios. It is characterised by very low mutual flux and mutual inductance. It is ideal for microstepping operation. Its stator is made up of cold rolled grain-oriented laminations and has windings on the tips of the poles. The rotor is a thin disc of rare earth cobalt. A large number of alternate N and S poles are provided on the rotor by selective magnetisation process. Constructional diagram of a typical DM stepper motor is shown in Fig. 1.28.

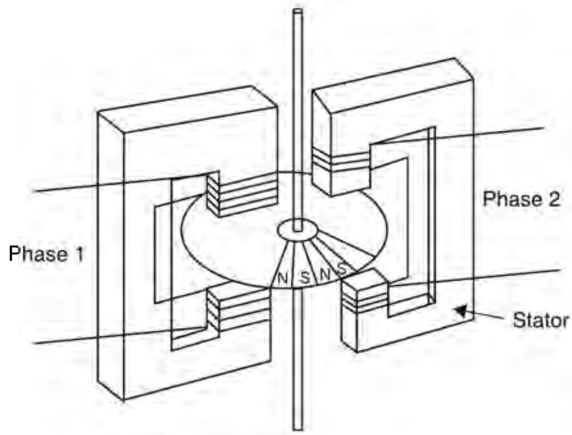


Fig. 1.28 DM stepper motor

1.4.3 Claw-Tooth or Can-Stack Permanent Magnet Stepper Motor

The manufacturing cost of a claw-tooth motor is comparatively low. It cannot be designed for very small step angles. The stator teeth are punched out of a circular metal sheet. The sheet is then made into a bell-shaped structure. The teeth are given the form of claw teeth by drawing the teeth inside. By joining two such bell-shaped casing, a stack of stator is made. The teeth are intermeshed and the stator coils in the form torroids are placed. The stator produces heteropolar magnetic field when current flows through the coils. The rotor is made of ceramic magnet and is of cylindrical shape. The field produced by the rotor magnets is also heteropolar. The axially aligned magnetic poles are common for both stator stacks. The stator teeth are misaligned by (1/4)th tooth pitch.

1.5 Windings in Stepper Motors

Multi-stack VR and PM stepper motors have solenoidal or ring coils for their stators. Single-stack VR and hybrid stepper motors concentrated coils are used for stator winding. There are two types of windings: monofilar and bifilar windings. In monofilar winding, poles carry only one winding. In bifilar winding, two coils are provided on each pole and they are connected in series with a common point. They are magnetically coupled on excitation of one of the coils. Bipolar and unipolar windings are the two types of windings used in stepper motors.

1.5.1 Bipolar Winding

For explaining this type of winding, consider a two-phase, four-pole stepper motor with two rotor poles as shown in Fig. 1.29. The pairs of coils A and A′ and B and B′ form the two phases of the motor. For the operation of the motor, the currents in the phases should alternate in polarity. The switching circuit is also shown in Fig. 1.29. With this switching circuit, the motor can be operated in one-phase ON, two-phase ON and half-step modes.

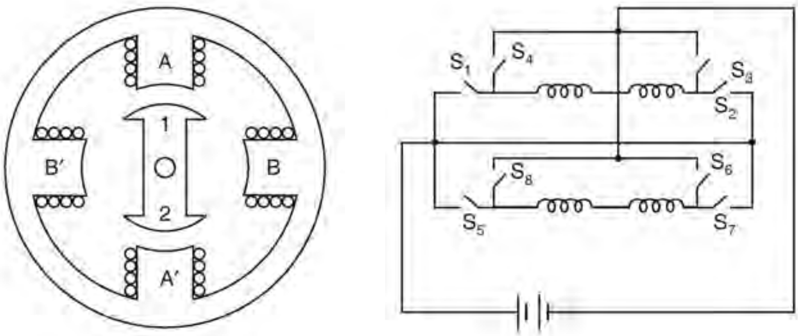


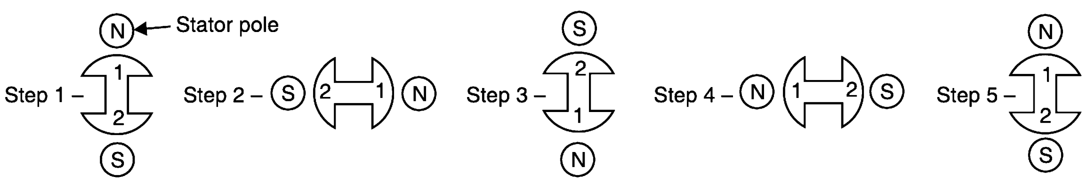
Fig. 1.29 Stepper motor and excitation circuit

In one-phase ON mode, the phases are excited one at a time. The switching sequence is given in Table 1.10. The rotor position along with the stator poles is shown in the right side of the table. The direction of rotation is clockwise.

Table 1.10 Single-phase ON mode

Step ↓	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	1	1	0	0	0	0	0	0
2	0	0	0	0	1	1	0	0
3	0	0	1	1	0	0	0	0
4	0	0	0	0	0	0	1	1
5	1	1	0	0	0	0	0	0

1 = ON; 0 = OFF

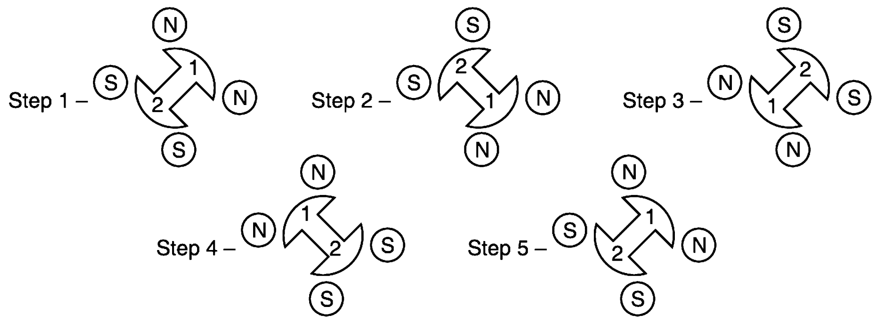


Rotor position after each step

In two-phase ON mode, both phases are excited simultaneously. The switching sequence for clockwise rotation is given in Table 1.11.

Table 1.11 Switching sequence for two-phase ON mode

Step ↓	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	1	1	0	0	1	1	0	0
2	0	0	1	1	1	1	0	0
3	0	0	1	1	0	0	1	1
4	1	1	0	0	0	0	1	1
5	1	1	0	0	1	1	0	0

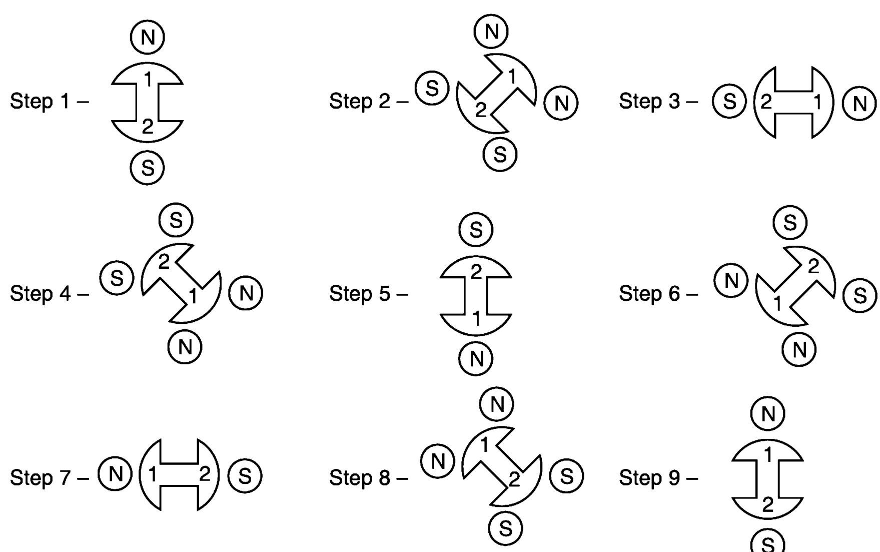


Rotor position after each step

The sequence of switching and the relative rotor positions for half-step mode are given in Table 1.12. The step angles for one-phase ON and two-phase ON are 90°. For half-step mode, the angle is 45°.

Table 1.12 Switching sequence for half-step mode

Step ↓	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	1	1	0	0	0	0	0	0
2	1	1	0	0	1	1	0	0
3	0	0	0	0	1	1	0	0
4	0	0	1	1	1	1	0	0
5	0	0	1	1	0	0	0	0
6	0	0	1	1	0	0	1	1
7	0	0	0	0	0	0	1	1
8	1	1	0	0	0	0	1	1
9	1	1	0	0	0	0	0	0



Rotor position after each step

1.5.2 Unipolar Winding

By using unipolar winding, the number of switching devices can be reduced. In this type, each pole carries two coils. A two-phase motor using unipolar winding is shown in Fig. 1.30.

The switching circuit is shown in Fig. 1.31.

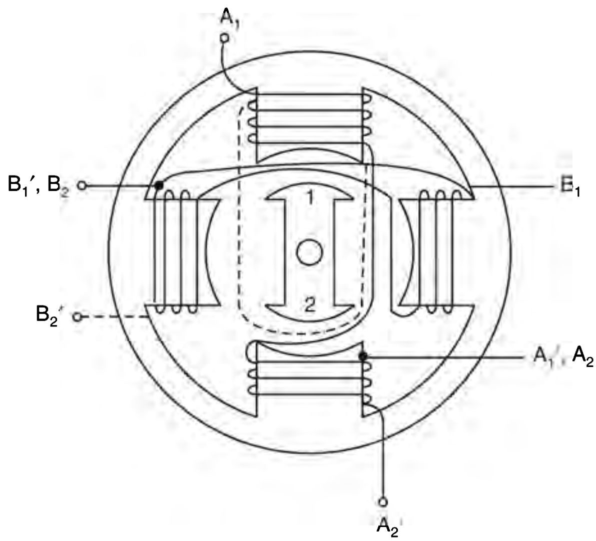


Fig. 1.30 Unipolar winding

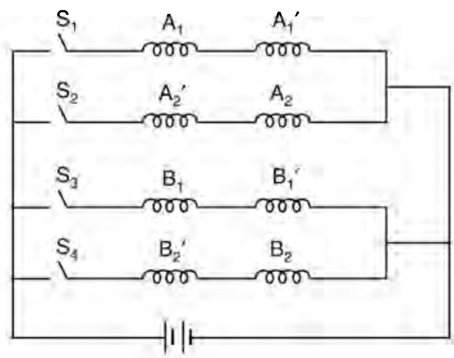
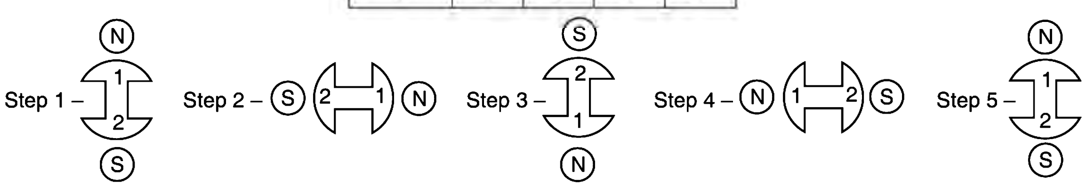


Fig. 1.31 Switching circuit

The switching sequence and the relative positions of the rotor after each switching operation are given in Table 1.13.

Table 1.13 Switching sequence for one-phase ON mode (monopolar winding)

Step ↓	S_1	S_2	S_3	S_4
1	1	0	0	0
2	0	0	1	0
3	0	1	0	0
4	0	0	0	1
5	1	0	0	0



Rotor position after each step

1.6 Torque Equation

Consider a variable reluctance stepper motor. Let

$v(t)$ = applied voltage per phase

$i(t)$ = current per phase
T_{ph} = torque produced by one phase
$\theta(t)$ = angular displacement
T = total torque produced by the motor
R = resistance per phase
$L(\theta)$ = inductance per phase
J = moment of inertia of load plus rotor
B = viscous friction coefficient of load plus rotor
N_r = number of rotor teeth
n = number of phases

The voltage equation of stator phase is as follows:

$$v(t) = R\, i(t) + \frac{d}{dt}[\, i(t)L(\theta)]$$

$$= R\, i(t) + L(\theta)\frac{di}{dt} + i\frac{d}{dt}\, L(\theta)$$

i.e.
$$v(t) = R\, i(t) + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{d\theta}\cdot\frac{d\theta}{dt} \tag{1.1}$$

where $L(\theta)\ \frac{di}{dt}$ denotes the transformer emf and $\frac{idL(\theta)}{dt}\cdot\frac{d\theta}{dt}$ represents back emf

Energy in the air gap is given by

$$E = \frac{1}{2}L(\theta)i^2(t) \tag{1.2}$$

Torque developed by the rotor can be given by

$$T_{ph} = \frac{\partial}{\partial\theta}[Ei(t),\ \theta(t)]$$

i.e.
$$T_{ph} = \frac{1}{2}i^2(t)\frac{dL(\theta)}{d\theta} \tag{1.3}$$

Also,
$$T_{ph} = J\frac{d^2\theta(t)}{dt^2} + B\frac{d\theta(t)}{dt} \tag{1.4}$$

The motor inductance is a function of displacement and can be written as:

$$L(\theta) = L_1 + L_2\cos(N_r\theta(t)) \tag{1.5}$$

where L_1 and L_2 are constants.

∴
$$T_{ph} = -\frac{1}{2}\ L_2\, N_r\, i^2(t)\ \sin[N_r\theta(t)]$$

i.e.
$$T_{ph} = K\, i^2(t)\ \sin\,[N_r\theta(t)] \tag{1.6}$$

where $K = -\frac{1}{2}\ L_2\, N_r$, a constant.

∴ $$T_{\text{ph}} = K\, j^2(t)\, \sin\,[N_r \theta(t)]$$

The torque developed by n phases may be given by

$$T_{\text{ph}_1} = K\, i_1^{\,2}(t)\, \sin[N_r\ \theta(t)]$$
$$T_{\text{ph}_2} = K\, i_2^{\,2}(t)\, \sin[2N_r\ \theta(t) - (360/n)]$$
$$T_{\text{ph}_3} = K\, i_3^{\,2}(t)\, \sin[3N_r\ \theta(t) - 2 \times (360/n)]$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$T_{\text{ph}_n} = K\, i_n^{\,2}(t)\, \sin[N_r\ \theta(t) - n - 1 \times (360/n)] \tag{1.7}$$

So, the total torque developed is given by

$$T = T_{\text{ph}_1} + T_{\text{ph}_2} + \cdots + T_{\text{ph}_n} \tag{1.8}$$

The torque equation can also be derived as follows:
Let emf induced/phase = $e(t)$

$$e(t) = \frac{d}{dt} L(\theta)\, i(t)$$
$$= L(\theta)\frac{di(t)}{dt} + i(t)\frac{dL(\theta)}{dt}$$
$$= L(\theta)\frac{di(t)}{dt} + i(t)\frac{dL(\theta)}{dt}\cdot\frac{d\theta}{dt}$$
$$= L(\theta)\frac{di(t)}{dt} + i(t)\frac{dL(\theta)}{dt}\cdot\omega \qquad (\omega = \text{angular velocity})$$

∴ $$e(t) = L(\theta)\frac{di(t)}{dt} + \omega i(t)\frac{dL(\theta)}{dt} \tag{1.9}$$

Power developed,

$$P_m = e(t)\, i(t)$$

i.e. $$P_m = i(t)\, L(\theta)\frac{di(t)}{dt} + \omega i(t)^2\, \frac{dL(\theta)}{dt} \tag{1.10}$$

Energy stored in the magnetic field,

$$W_e = \frac{1}{2} L(\theta)\, i(t)^2 \tag{1.11}$$

Power due to energy stored,

$$P_e = \frac{dW_e}{dt}$$
$$= \frac{1}{2}\left[\frac{dL(\theta)}{dt} i(t)^2\right]$$
$$= \frac{1}{2}\left[L(\theta)\cdot 2\cdot i(t)\frac{di(t)}{dt} + i(t)^2\,\frac{dL(\theta)}{dt}\right]$$

i.e. $$P_e = i(t)\, L(\theta)\frac{di(t)}{dt} + \frac{1}{2}\, i(t)^2\, \frac{dL(\theta)}{d\theta}\omega \tag{1.12}$$

∴ Power available,

$$P = P_m - P_e$$

i.e.

$$P = \frac{1}{2} i(t^2) \frac{dL(\theta)}{d\theta} \omega \qquad (1.13)$$

∴ Torque,

$$T = \frac{P}{\omega}$$

i.e.

$$T = \frac{1}{2} i(t^2) \frac{dL(\theta)}{d\theta} \qquad (1.14)$$

1.7 Characteristics of Stepper Motor

Here in this section, we discuss some of technical terms associated with the performance and characteristics of stepper motor.

Step angle

Step angle is the angular displacement of the rotor for a single pulse of excitation applied to the stator winding. It is given by

$$\theta_s = \frac{360°}{n N_r}$$

where n = number of phases

N_r = number of rotor teeth

The above equation is applicable to VR stepper motor. For hybrid stepper motor, it is given by

$$\theta_s = \frac{360°}{2n N_r}$$

Resolution

Resolution is defined as the number of steps per revolution. It is given by

$$z = \frac{360°}{\theta_s}$$

Stepping rate

The number of steps completed per second is called stepping rate or stepping frequency.

Hold position

Hold position corresponds to the resting position of the rotor of an excited motor.

Detent position

This position corresponds to the position of the rotor of an unexcited motor.

Stepping error

Due to the tolerances in manufacturing and the properties of magnetic materials and other materials used for the construction of a stepper motor, the actual step angle may differ from the theoretical angle. The percentage stepping error is given by

$$\% \text{ stepping error} = \frac{\text{Actual step angle} - \text{Theoretical step angle}}{\text{Theoretical step angle}} \times 100$$

Positional error

The maximum range of cumulative percentage errors taken over a complete revolution of the rotor is known as positional error.

Holding torque

It is the maximum torque that can be applied to an excited motor without slipping the rotor from the equilibrium position.

Detent torque

It is the maximum torque that can be applied to an unexcited motor without slipping the rotor from the equilibrium position. This torque is present only in PM and hybrid motors.

Start-stop mode

This is a mode of operation of a stepper motor in which the second pulse is applied to the motor only after the rotor has attained the steady or rest position due to the first pulse.

Slewing mode

In this mode of operation, the second pulse is applied before the motor has attained the steady position due to the first pulse. In this mode, the motor cannot be stopped immediately by stopping the applied pulses. Also, the motor cannot be started in this mode.

Pull-in torque

Pull-in torque corresponds to the maximum torque developed by a stepper motor for a given stepping rate in the start–stop mode of operation without loosing synchronism.

Pull-in range

It is the maximum stepping rate at which the stepper motor can operate in start–stop mode developing a specified torque without loosing synchronism.

Pull-out torque

It is maximum torque developed by a stepper motor for a given stepping rate in the slewing mode without loosing synchronism.

Pull-out range

It corresponds to the maximum stepping rate at which the stepper motor can operate in slewing mode developing a given torque without loosing synchronism.

Pull-in rate

It is the maximum stepping rate at which the stepper motor will start or stop without loosing synchronism against a given load torque.

Pull-out rate

Pull-out rate corresponds to the maximum stepping rate at which the stepper motor will slew, without loosing synchronism, against a given load torque.

Synchronism

Synchronism means one-to-one correspondence between the number of pulses applied to the stator and the number of steps through which the rotor has actually moved.

Mid-frequency resonance

At certain input pulse frequencies, the motor torque drops to a low value. This phenomenon is called mid-frequency resonance.

Slew range

Slew range is the range of switching rates between pull-in and pull-out with which the motor runs in synchronism, but cannot start up or reverse.

Response range

The range of stepping rates in which the stepper motor can start or stop without missing steps is called response range.

Start–Stop stepping rate

When a stepper motor is running in start–stop mode, the permissible stepping rate has an upper limit. If the pulse rate is very high, the rotor cannot follow the pulses. This will result in missing of steps. The rotor must be settled down before moving to the next position. So the pulse rate should be limited to achieve synchronism. The inertia of the load also influences the maximum stepping rate. The permissible maximum stepping rate with inertia is less than that without inertia.

Ramping

When motor starts from rest with load, it cannot follow the pulses. Also, a motor running in slewing mode cannot be stopped suddenly by drawing the pulses. For bringing loaded motor to desired speed, it must be accelerated, and for stopping it, it must be decelerated in synchronism. The process of accelerating or decelerating a loaded stepper motor is called ramping. The ramping should be completed in very small time. The ramp signal is generated by the drive circuit of the stepper motor.

1.7.1 Static Characteristics of Stepper Motor

Torque versus step angle and torque versus current are called static characteristics of stepper motor. First the stepper motor is excited and brought to an equilibrium position. Then, external torque is applied. This makes the rotor move from the rest position. The angular displacement is measured. Vary the load torque and find the corresponding displacement. The variation of displacement is plotted against the torque. This curve is called torque–angle characteristics. A typical torque–angle characteristic is shown in Fig. 1.32.

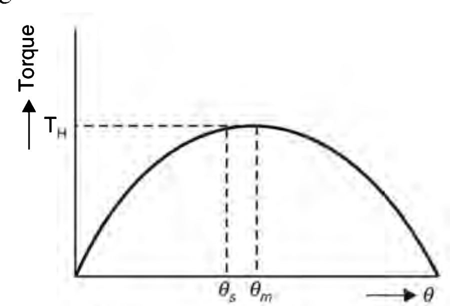


Fig. 1.32 Torque–angle characteristics

The torque–current characteristics for a typical VR and hybrid stepper motors are shown in Fig. 1.33.

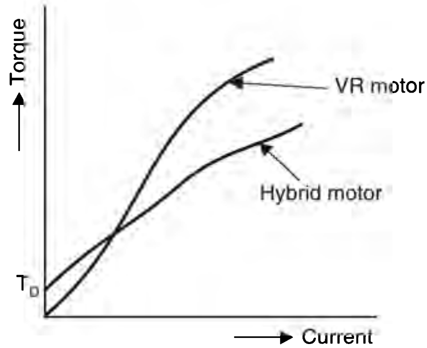


Fig. 1.33 Torque–current characteristics

1.7.2 Dynamic Characteristics of Stepper Motor

The dynamic characteristics of a stepper motor represent the characteristics when it is running or about to run. Pull-in and pull-out torque characteristics are called dynamic characteristics. Pull-in characteristics is also known as starting characteristics. This curve refers to the range of frictional torque against which a motor can start without loosing any steps.

The pull-out or slewing characteristic is the plot of the relation between the friction load torque and the maximum pulse rate at which the motor can be synchronised. The dynamic characteristics of a typical motor are shown in Fig. 1.34.

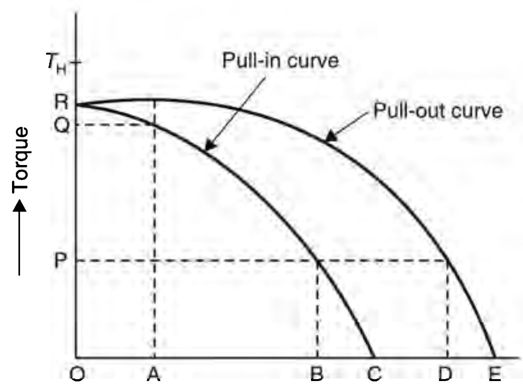


Fig. 1.34 Dynamic characteristics

In Fig. 1.34,

Pull-in torque is OQ at stepping rate A.
Pull-out torque is OR at stepping rate A.
Pull-in rate is B for torque OP.
Pull-out rate is C for torque OP.
Response range is OB.

Slewing range is BD.

Maximum slewing frequency is E.

The angular position versus time for start–stop and slewing modes are shown in Fig. 1.35.

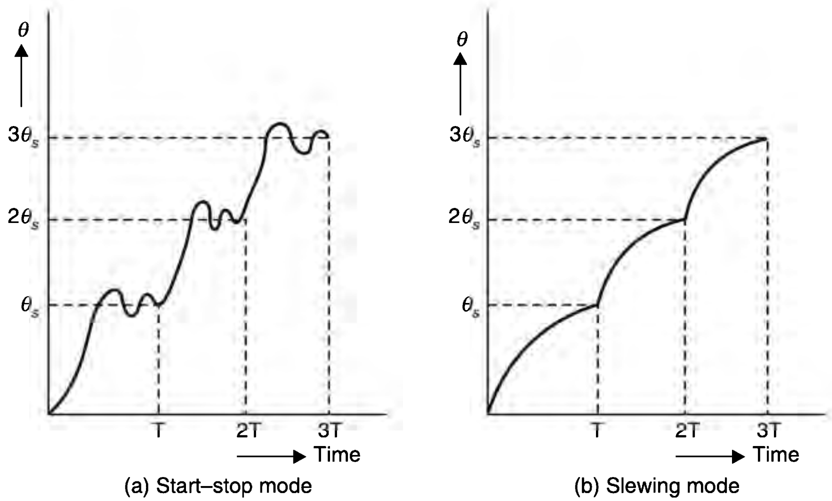


Fig. 1.35 θ–time curves

Worked Examples

1. A stepper motor has a step angle of 1.8°. Find (a) resolution, (b) number of steps required for 50 revolutions and (c) shaft speed if the stepping frequency is 5000 pulse/sec.

Solution

Given:

Step angle, $\theta_s = 1.8°$

(a) Resolution,

$$z = \frac{360}{\theta_s} = \frac{360}{1.8} = 200 \text{ steps/rev}$$

(b) Number of steps for 50 revolutions = $z \times 50 = 200 \times 50 = 10000$

(c) Stepping frequency, $f = 5000$

Revolutions per sec.,

$$n = \frac{\theta_s \times f}{360} = \frac{1.8 \times 5000}{360} = 25$$

∴ Shaft speed = 25 × 60 = 1500 rpm

2. A three-phase three-stack variable reluctance stepper motor has 10 rotor teeth. Find its step angle.

Solution

Given:

Number of phases = 3

Number of rotor teeth = 10

$$\text{Step angle} = \frac{360}{\text{Number of phases} \times \text{Number of rotor tooth}} = \frac{360}{3 \times 10} = 12°$$

3. A stepper motor has 10 stator poles with 4 subteeth. The rotor has 50 teeth. Find its step angle and resolution.

Solution

Given:

Number of poles = 10

Number of teeth on stator = 10 × 4

i.e. $N_s = 40$

Number of rotor teeth $N_r = 50$

Step angle,

$$\theta_s = \frac{N_s \sim N_r}{N_s N_r} \times 360$$

$$= \frac{40 \sim 50}{40 \times 50} \times 360$$

$$= 1.8°$$

Resolution, $z = \frac{360}{\theta_s} = \frac{360}{1.8}$

= 200 steps/revolution

4. A 10-pole, 5-phase hybrid stepper motor has two rotors of 50 teeth each. Find the step angle for one-phase mode.

Solution

Given:

Number of stator poles = 10

Number of phases = 5

Number of rotor teeth = 50

In single-phase mode, when one phase is excited, teeth of one rotor are attracted and those of the others are repelled. Total rotor teeth is twice the teeth/rotor.

$$\therefore \quad \text{Step angle} = \frac{360}{2 \times \text{No. of phases} \times \text{No. of rotor teeth}}$$

$$= \frac{360}{2 \times 5 \times 50}$$

$$= 0.72°$$

5. A stepper motor has a resolution of 300 steps/revolution in single phase ON mode. If it is operated in half-step mode, find the resolution and the number of steps required to turn the rotor through 60°.

Solution

Resolution in one-phase ON mode = 300 steps/rev

Resolution in half-step mode = 300 × 2

= 600 steps/rev

Number of steps for 60° rotation = $\frac{60}{\theta_s}$

where θ_s = step angle = $\frac{360}{600} = 0.6$

$\therefore$ Number of steps for 60° rotation = $\frac{60}{0.6}$ = 100 steps

6. A stepper motor is operating at a pulse rate of 5000 pulse/sec. It travels 100° in 0.02 sec. Find its resolution.

Solution

Pulse frequency,

$$f = 5000$$

Number of steps in 0.02 sec = 5000 × 0.02 = 100

Step angle, $\theta_s = \frac{100°}{100} = 1°$

Resolution, $z = \frac{360}{\theta_s}$

= 360 steps/revolution

7. A stepper motor is wound for two-phases and has four-poles. It has 10 rotor poles. Find its resolution.

Solution

Number of phases, $n = 2$

Number rotor poles, $N_r = 10$

Step angle, $\theta_s = \frac{360}{n \times N_r} = 18°$

Resolution, $z = \frac{360}{\theta_s}$ = 20 steps/resolution

8. A permanent magnet stepper motor is driven by a series of pulses of duration 20 ms. It has four-stator poles and six-rotor poles. How long will it take for the motor to make a complete rotation?

Solution

Given:

Number of stator poles, $N_s = 4$

Number of rotor poles, $N_r = 6$

Duration of a pulse = 20 ms

Step angle, $\theta_s = \frac{N_s \sim N_r}{N_s N_r} \times 360$

$$= \frac{2}{4 \times 6} \times 360$$

$$= 30°$$

Number of steps required for one revolution = $\frac{360}{30}$ = 12

Time for one revolution = 12 × 20 = 240 ms

9. A five-phase stepper motor has 40 rotor teeth. It drives a lead screw having a pitch of 10 threads per cm. The lead screw, in turn, produces a linear motion of a cutting tool. The input pulse is applied 10 times. Find the distance covered by the cutting tool.

Solution

Given:

Number of phases, $n = 5$

Number of rotor poles, $N_r = 40$

Number of threads/cm = 10

Linear displacement/revolution $= \frac{1}{10}$ cm

Linear displacement/degree rotation $= \frac{1}{360 \times 10}$ cm

Step angle, $\theta_s = \frac{360}{n \times N_r}$

$= 1.8°$

Angular displacement for 10 pulse = 1.8 × 10 = 18°

Distance moved by the cutting tool $= \frac{18}{360 \times 10}$

$= \frac{1}{200}$

= 0.005 cm

10. Find the resolution of a stepper motor that is to be operated at an input pulse frequency of 6000 pulse/sec and travel a distance of 180° in 0.025 sec.

Solution

Given:

Input frequency, $f = 6000$

Step angle, $\theta_s = \frac{180}{\text{Number of steps in 0.025 sec}}$

$= \frac{180}{6000 \times 0.025}$

$= 1.2°$

Resolution $= \frac{360}{\theta_s}$

= 300 steps/revolution

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11. A stepper motor has a resolution of 500 steps/revolution in single phase ON mode. Find its resolution in half-step mode. Find the number of steps required for the rotor to move a distance of 72°.

Solution

Given:

Resolution for one-phase ON mode = 500

Resolution for half-step mode = 2 × 500 = 1000

Step angle in half-step mode,

$$\theta_s = \frac{360}{1000} = 0.36°$$

$$\text{Number of steps for travelling } 72° = \frac{72}{0.36} = 200 \text{ steps}$$

12. A stepper motor has a resolution of 200 steps/rev. Find the pulse rate required to run the motor at 2400 rpm.

Solution

Given: Resolution, $z = 200$

$$\text{Step angle, } \theta_s = \frac{360}{z} = \frac{360}{200} = 1.8°$$

$$\text{Required revolution/sec} = \frac{2400}{60} = 40$$

Required angular distance/sec = 40 × 360

$$\text{Pulse frequency required} = \frac{40 \times 360}{\theta_s}$$

$$= 8000 \text{ pulse/sec}$$

13. For a three-phase variable reluctance motor, give the logic sequences for (i) one-phase ON mode (ii) two-phase ON mode and (iii) half-step mode.

Solution

The logic sequences for the required modes of operation are given as:

1-ph ON			2-ph ON			Half-step		
R	Y	B	R	Y	B	R	Y	B
1	0	0	1	1	0	1	0	0
0	1	0	0	1	1	1	1	0
0	0	1	1	0	1	0	1	0
						0	1	1
						0	0	1
						1	0	1