Course Code - EEE-401
Course Title – Energy Conversion and Special Machine
Lecture- Stepper Motor

Stepper Motor

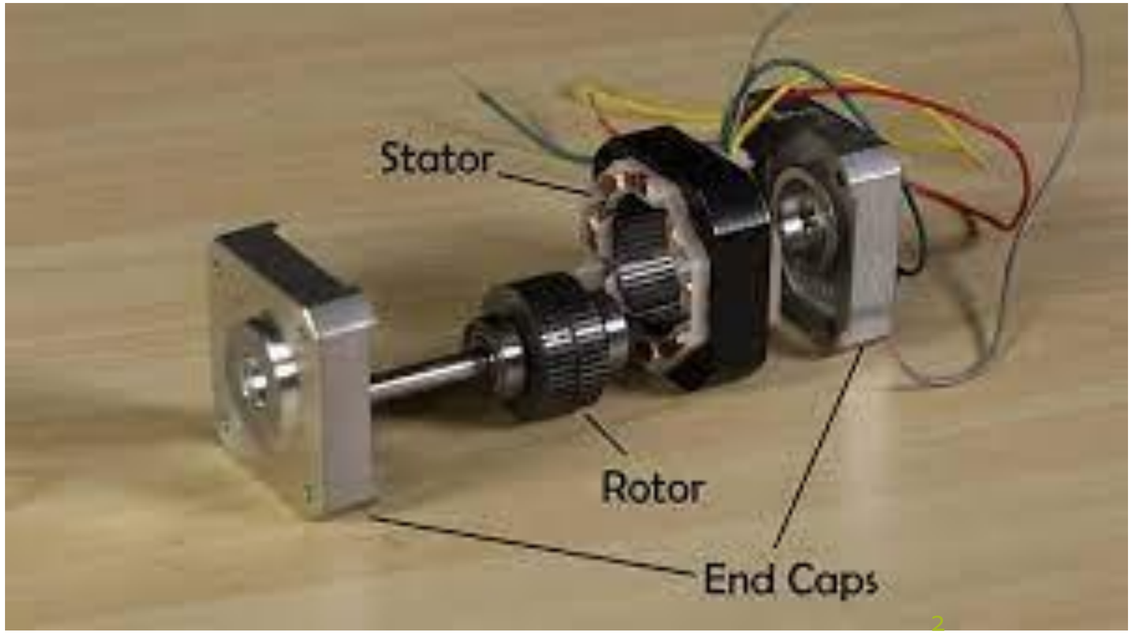
Stepper Motor

- 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.

- Their popularity is due to the fact that they can be controlled directly by computers, microprocessors and programmable controllers.

- Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.

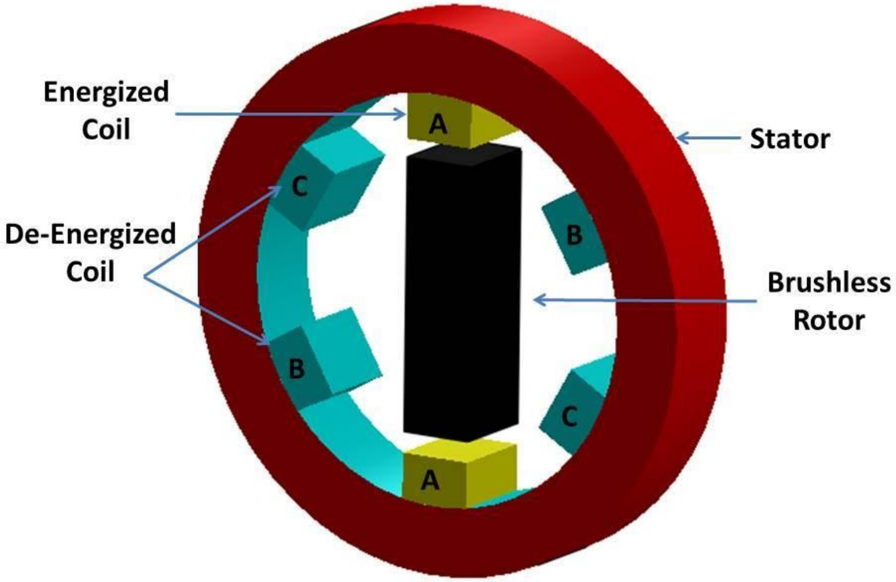
- It's output shaft rotates in a series of discrete angular intervals or steps, one step being taken each time a command pulse is received. When a definite number of pulses are supplied, the shaft turns through a definite known angle.



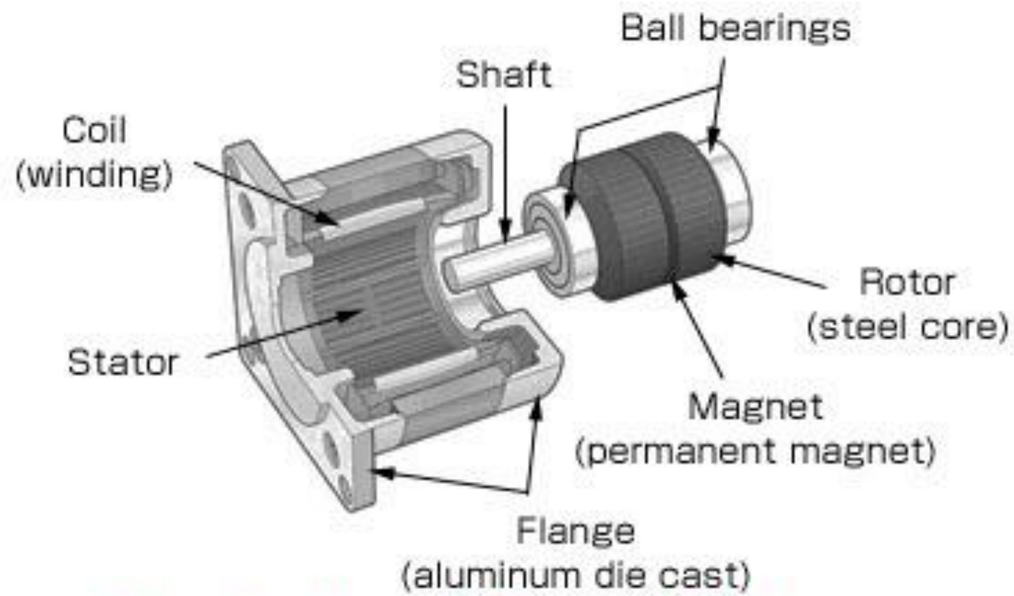
Constructions of Stepper Motor

Construction

- Like all electric motors, it has stator and rotor.
- The rotor is the movable part which has no windings, brushes and a commutator. Usually the rotors are either variable reluctance or permanent magnet kind.
- The stator is often constructed with multipole and multiphase windings, usually of three or four phase windings wound for a required number of poles decided by desired angular displacement per input pulse.



Stepper Motor

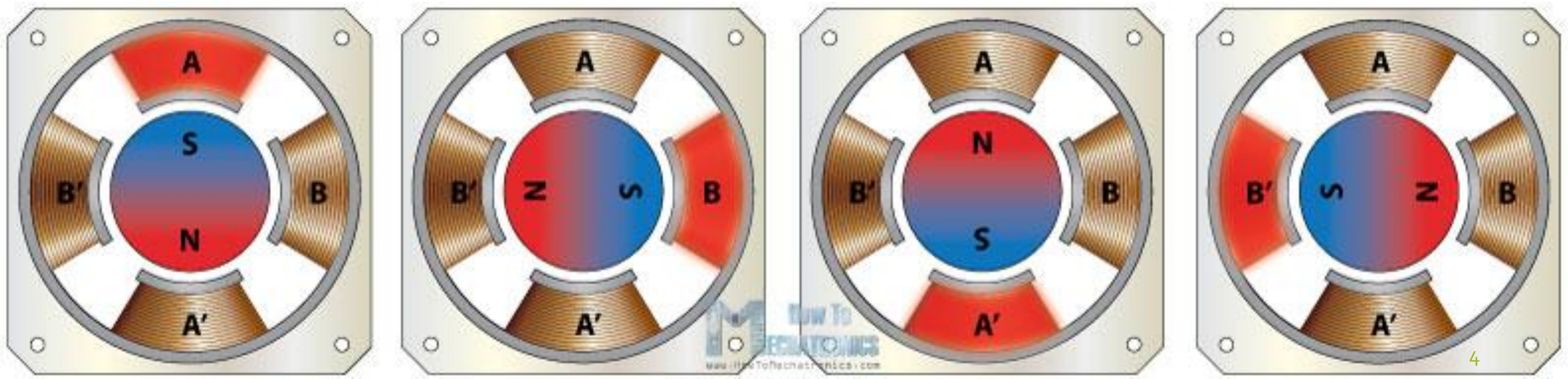


Construction of Stepper Motor

Working Principle of Stepper Motor

Working Principle

- By energizing one or more of the stator phases, a magnetic field is generated by the current flowing in the coil and the rotor aligns with this field.
- By supplying different phases in sequence, the rotor can be rotated by a specific amount to reach the desired final position.
- Figure shows a representation of the working principle. At the beginning, coil A is energized and the rotor is aligned with the magnetic field it produces.
- When coil B is energized, the rotor rotates clockwise by 90° to align with the new magnetic field.
- The same happens when coil A’ and B’ are energized. In the pictures, the colors of the stator teeth indicate the direction of the magnetic field generated by the stator winding.



Types of Stepper Motor

Types of Stepper Motor

There is a large variety of stepper motors which can be divided into the following three basic categories

1. Variable Reluctance Stepper Motor

    I. Single-stack Variable Reluctance Stepper Motor
    II. Multi-stack Variable Reluctance Stepper Motor

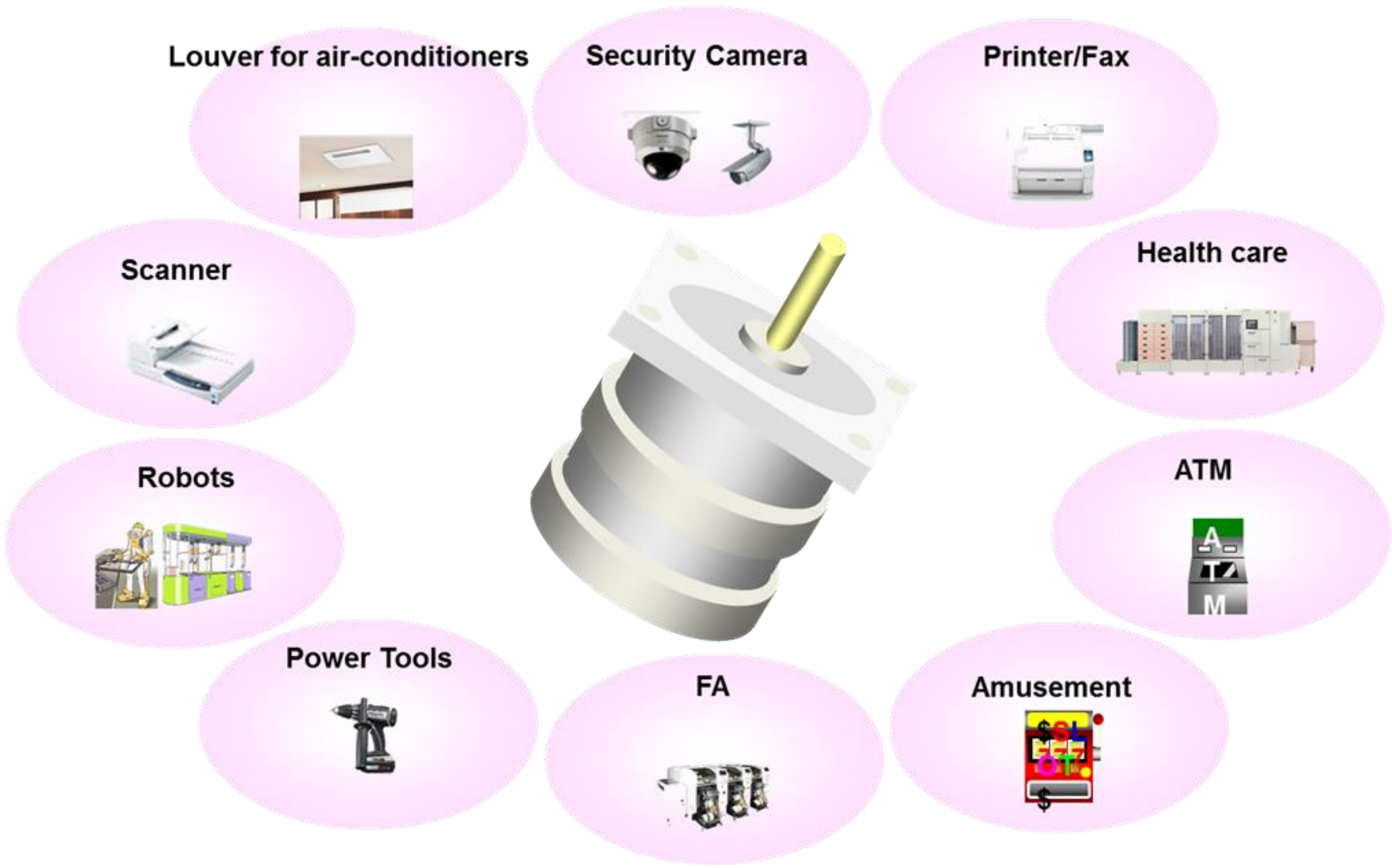
2. Permanent Magnet Stepper Motor

3. Hybrid Stepper Motor

Stepper Motor

Application of Stepper Motor

- Such motors are used for operation control in computer peripherals, textile industry, IC fabrications and robotics etc.
- Also applicable in typewriters, line printers, tape drives, floppy disk drives, numerically-controlled machine tools, process control systems and X -Y plotters.
- 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 and even the production of science fiction movies.



Advantages and Disadvantages of Stepper Motor

Advantages

- At standstill position, the motor has full torque. No matter if there is no moment or changing position.
- It has a good response to starting, stopping and reversing position.
- As there is no contact brushes in the stepper motor, It is reliable and the life expectancy depends on the bearings of the motor.
- The motor rotation angle is directly proportional to the input signals.
- The motor speed is directly proportional to the input pulses frequency, this way a wide range of rotational speed can be achieved.
- When load is coupled to the shaft, it is still possible to realize the synchronous rotation with low speed.
- The exact positioning and repeatability of movement is good as it has a 3-5% accuracy of a step where the error is non cumulative from one step to another.
- Stepper motors are safer and low cost (as compared to servo motors), having high torque at low speeds, high reliability with simple construction which operates at any environment.

Disadvantages

- Stepper motors having low Efficiency.
- It has low Accuracy.
- Its torque declines very quickly with speed.
- As stepper motor operates in open loop control, there is no feedback to indicate potential missed steps.
- It has low torque to inertia ratio means it can't accelerate the load very quickly.
- They are noisy.

Step Angle of Stepper Motor

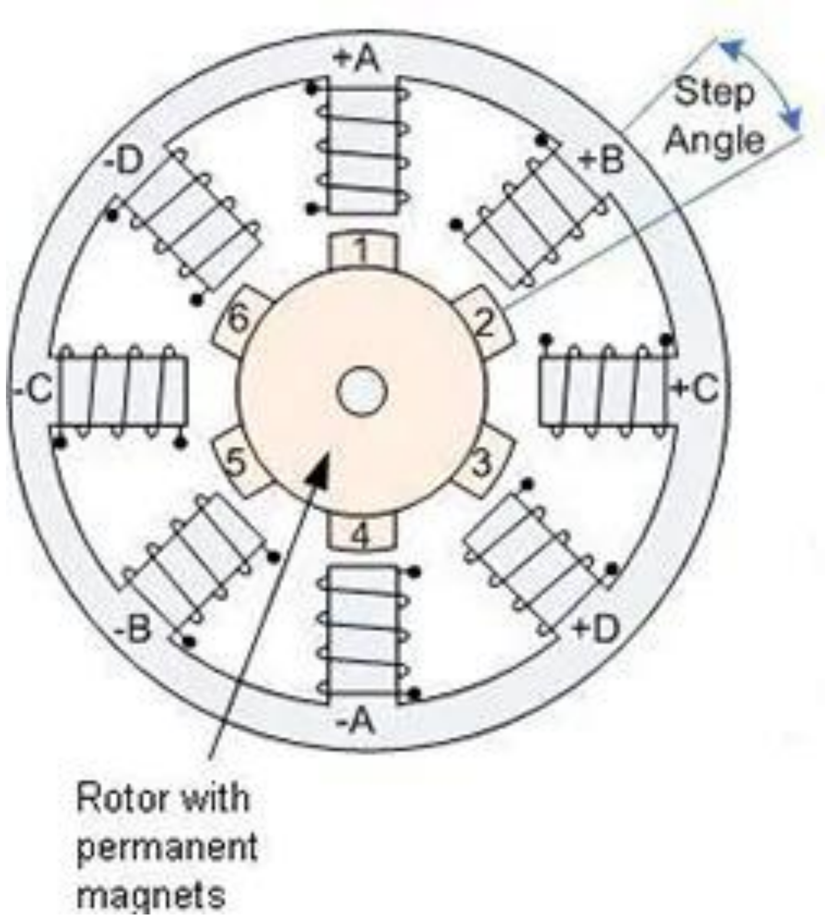
Step Angle

- 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.
- The step angles can be as small as 0.72º or as large as 90º. But the most common step sizes are 1.8º, 2.5º, 7.5º and 15º.
- The value of step angle can be expressed either in terms of the rotor and stator poles (teeth) Nr and Ns respectively or in terms of the number of stator phases (m) and the number of rotor teeth.

- **Step Angle,β** = $\frac{Ns-Nr}{Ns.Nr}$ *** 360º**

- **Or β =** $\frac{\mathbf{360^o}}{m.Nr}$

Here
Ns = No. of stator teeth
Nr = No. of rotor teeth
m = No. of stator phase



Step Angle of Stepper Motor

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. When stepper motor operate at high speeds is called ‘slewing’

Shaft speed of a stepper motor

- 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

$$n = (\beta * f) / 360 \text{ rps} = \text{pulse frequency resolution}$$

- **If the stepping rate is increased too quickly, the motor loses synchronism and stops.**
- **Same thing happens if when the motor is slewing, command pulses are suddenly stopped instead of being progressively slowed.**

Mathematical problems of Stepper motor

Problem-01

A hybrid VR stepping motor has 8 main poles which have been castellated to have 5 teeth each. If rotor has 50 teeth, calculate the stepping angle.

Ns=

Nr=

$$\beta = \frac{Ns - Nr}{Ns.Nr} * 360^{\circ}$$

Problem-02

A stepper motor has a step angle of 2.5º. Determine (a) resolution (b) number of steps required for the shaft to make 25 revolutions and (c) shaft speed, if the stepping frequency is 3600 pps.

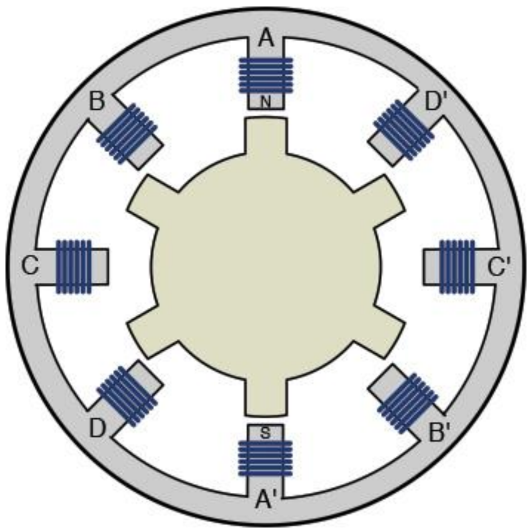
Resolution = 360º / β

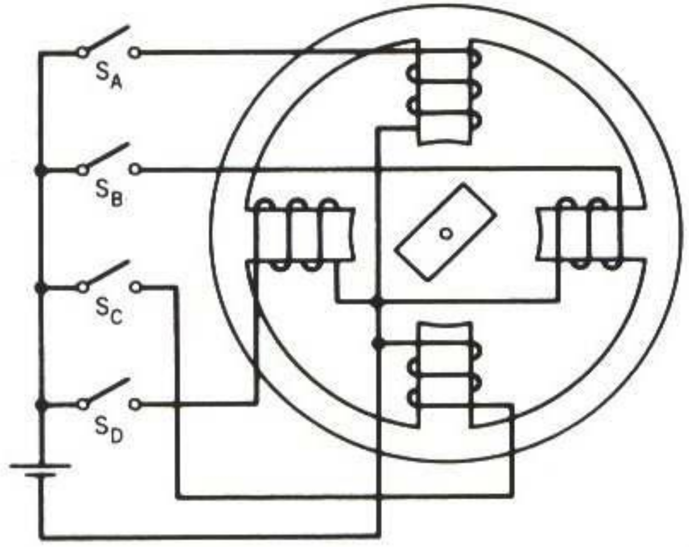
n = (β * f) / 360 rps

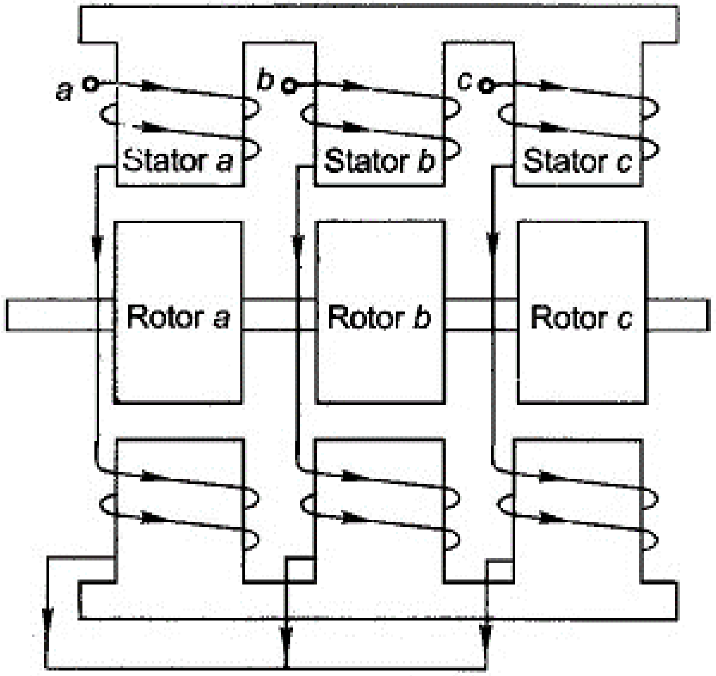
Variable Reluctance Stepper Motor

Variable Reluctance Stepper Motor

- It has wound stator poles but the rotor poles are made of a ferromagnetic material.
- It can be of the single stack type or multi-stack type which gives smaller step angles.
- Direction of motor rotation is independent of the polarity of the stator current.
- It is called variable reluctance motor because the reluctance of the magnetic circuit formed by the rotor and stator teeth varies with the angular position of the rotor.







Construction of Variable Reluctance Stepper Motor

Construction VR Stepper Motor

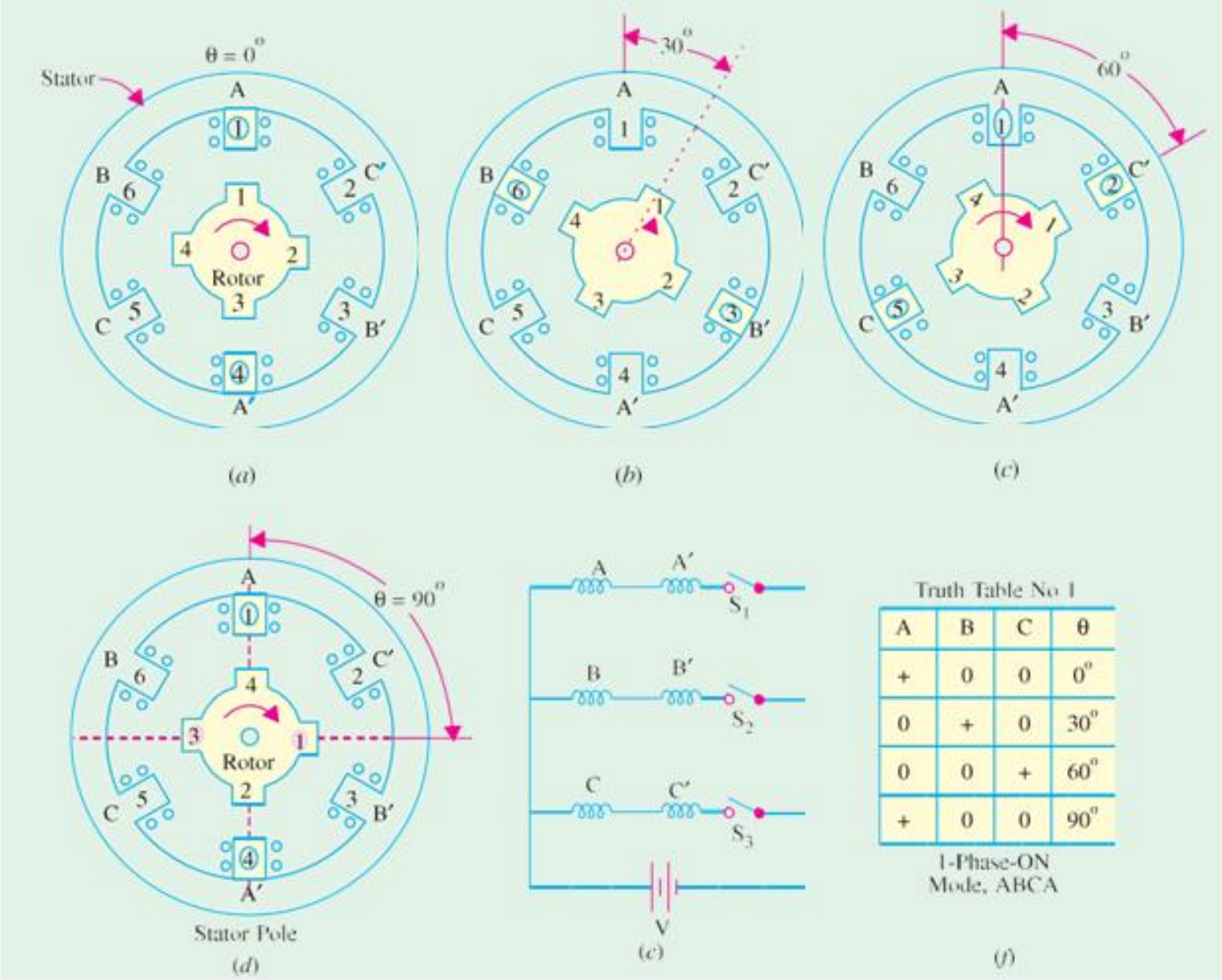
- A variable-reluctance motor is constructed from ferromagnetic material with salient poles as shown in figure.

- 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.

- As seen, there are three independent stator phases A , B and C and each one can be energized by a direct current pulse from the drive circuit.

- The step angle of this three-phase, four rotor teeth motor is β = 360/ 4 * 3 = 30º.



A	B	C	θ
+	0	0	0°
0	+	0	30°
0	0	+	60°
+	0	0	90°

Working of Variable Reluctance Stepper Motor

Working

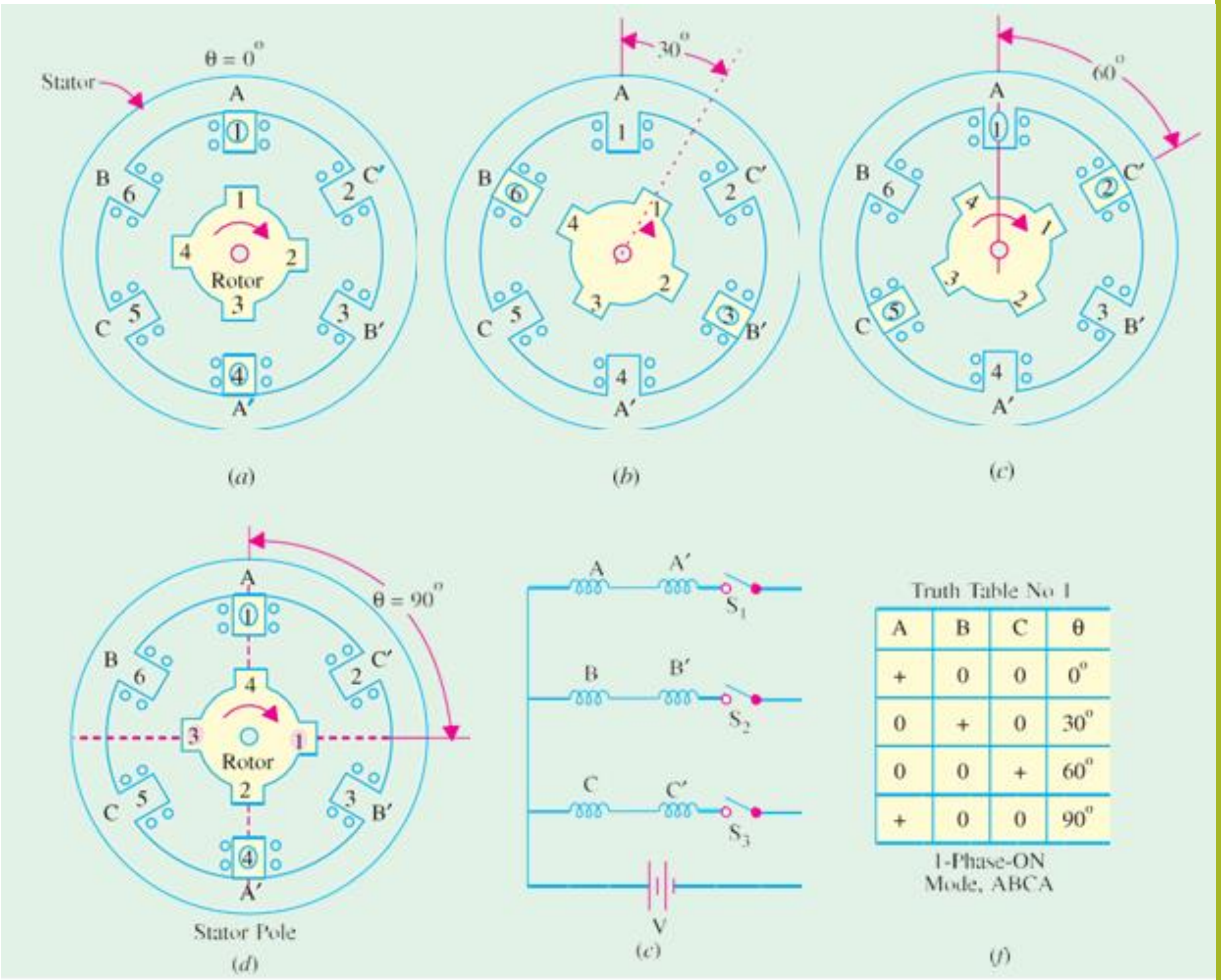
The motor has following modes of operation

1) 1-phase-ON or Full-step Operation

i. When switch S1 has been closed then phase A is energized. 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.(fig-a)

ii. Closing S2 and opening S1 energizes phase B causing rotor teeth 2 and 4 to align with stator teeth 3 and 6 respectively. The rotor rotates through full-step of 30º in the clockwise (CW) direction.(fig-b)

iii. Similarly, when S3 is closed after opening S2, phase C is energized which causes rotor teeth 1 and 3 to line up with stator teeth 2 and 5 respectively. The rotor rotates through an additional angle of 30º in the clockwise (CW) direction.(fig-c)



Working of Variable Reluctance Stepper Motor

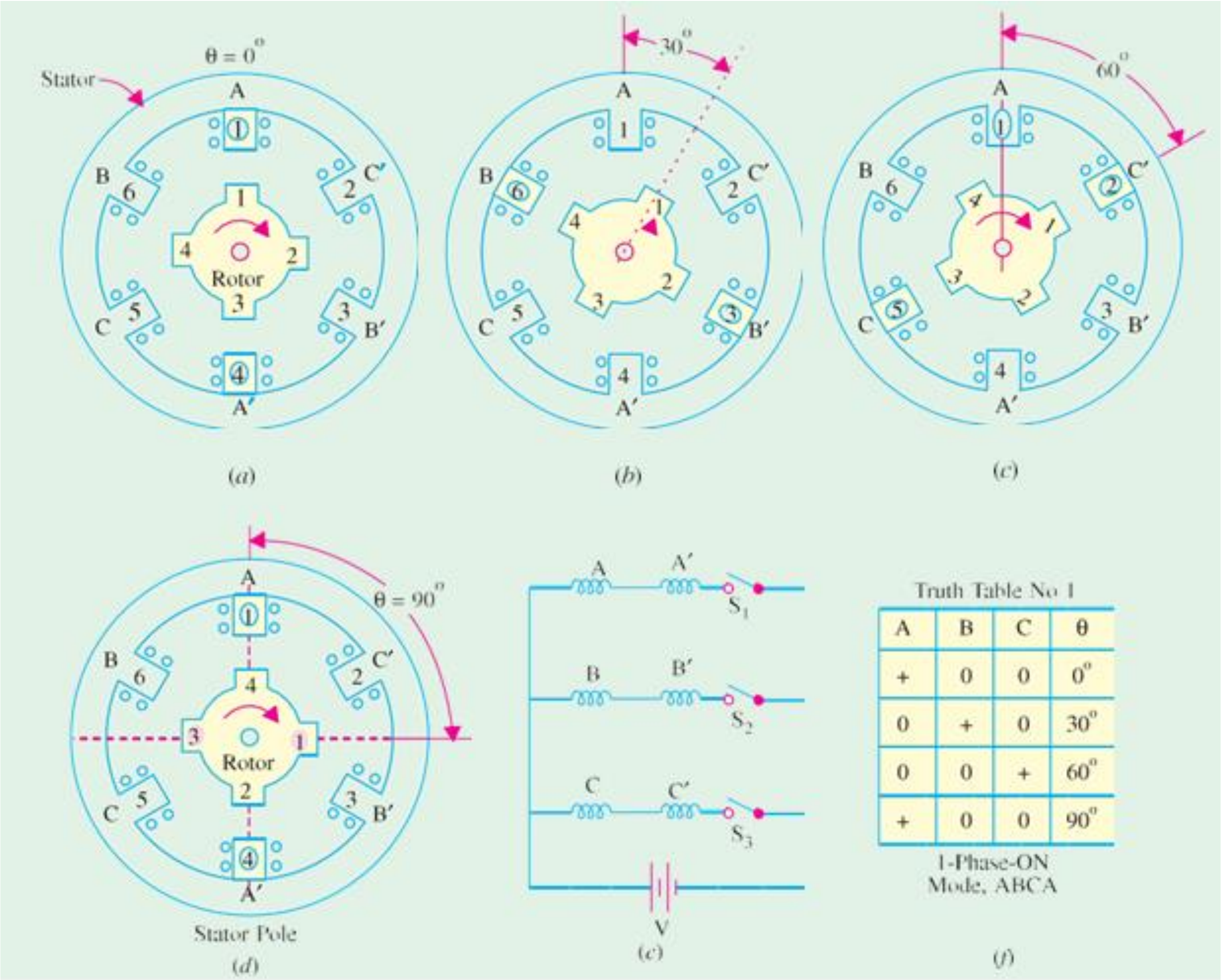
1) 1-phase-ON or Full-step Operation

iv. Next if S3 is opened and S1 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. By now the total angle turned is 90º.(fig-d)

v. As each switch is closed and the preceding one opened, the rotor each time rotates through an angle of 30º.

vi. Thus energizing stator phases in sequence ABCA etc., the rotor will rotate clockwise in 30º steps.

vii. 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.



A	B	C	θ
+	0	0	0°
0	+	0	30°
0	0	+	60°
+	0	0	90°

Working of Variable Reluctance Stepper Motor

2) 2-phase-ON Mode

i. In this mode of operation, two stator phases are excited simultaneously.

ii. 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.

iii. If the stator phases are switched in the sequence A B, BC, C A, AB 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.

iv. The phase switching truth table for this mode is shown here.

v. 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

Working of Variable Reluctance Stepper Motor

3) Half-step Operation

i. Half-step operation or ‘half-stepping’ can be obtained by exciting the three phases in the sequence A, AB, B, BC, C etc. 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 here.

ii. Energizing only phase A causes the rotor position shown in fig-a .

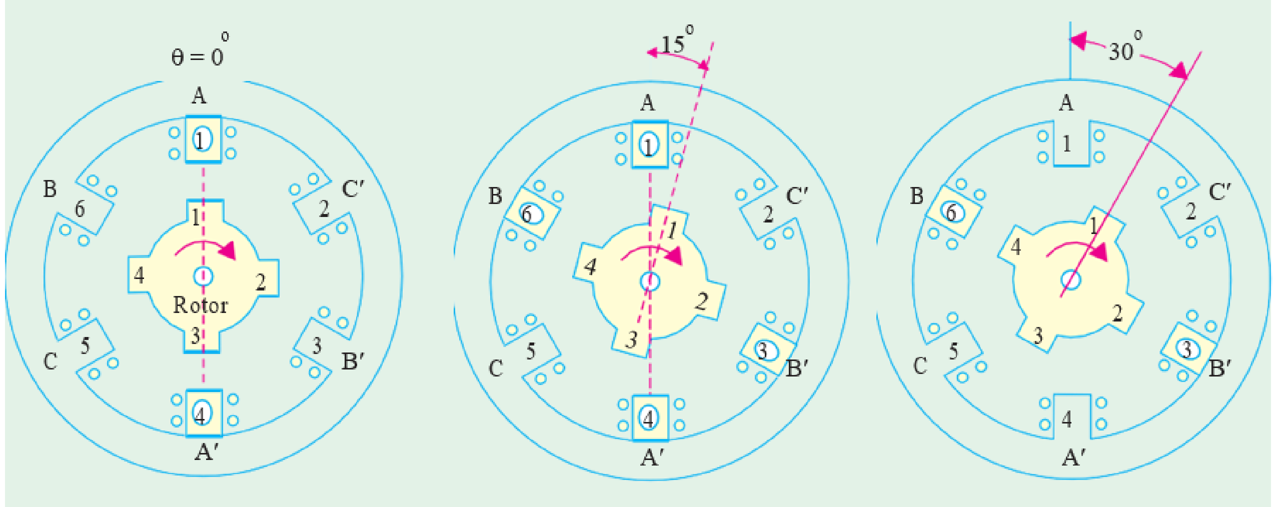
iii. Energizing phases A and B simultaneously moves the rotor to the position shown in fig-b where rotor has moved through half a step only.

iv. Energizing only phase B moves the rotor through another half-step as shown in fig-c.

v. With each pulse, the rotor moves 30 / 2 = 15º in the CCW direction.

vi. It will be seen that in half-stepping mode, the step angle is halved thereby doubling the resolution.

vii. Moreover, continuous half-stepping produces a smoother shaft rotation.



A Only (a) | A & B Half-Step Operation (b) | B Only (c)

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

Working of Variable Reluctance Stepper Motor

4) Micro-stepping

i. It is also known as mini-stepping.

ii. 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).

iii. The current in phase A is held constant while that in phase B is increased in very small increments until maximum current is reached.

iv. The current in phase A is then reduced to zero using the same very small increments.

v. In this way, the resultant step becomes very small and is called a micro-step.

vi. For example, a VR stepper motor with a resolution of 200 steps / rev ($\beta = 1.8^{o}$) can with micro-stepping have a resolution of 20,000 steps / rev ($\beta = 0.018^{o}$).

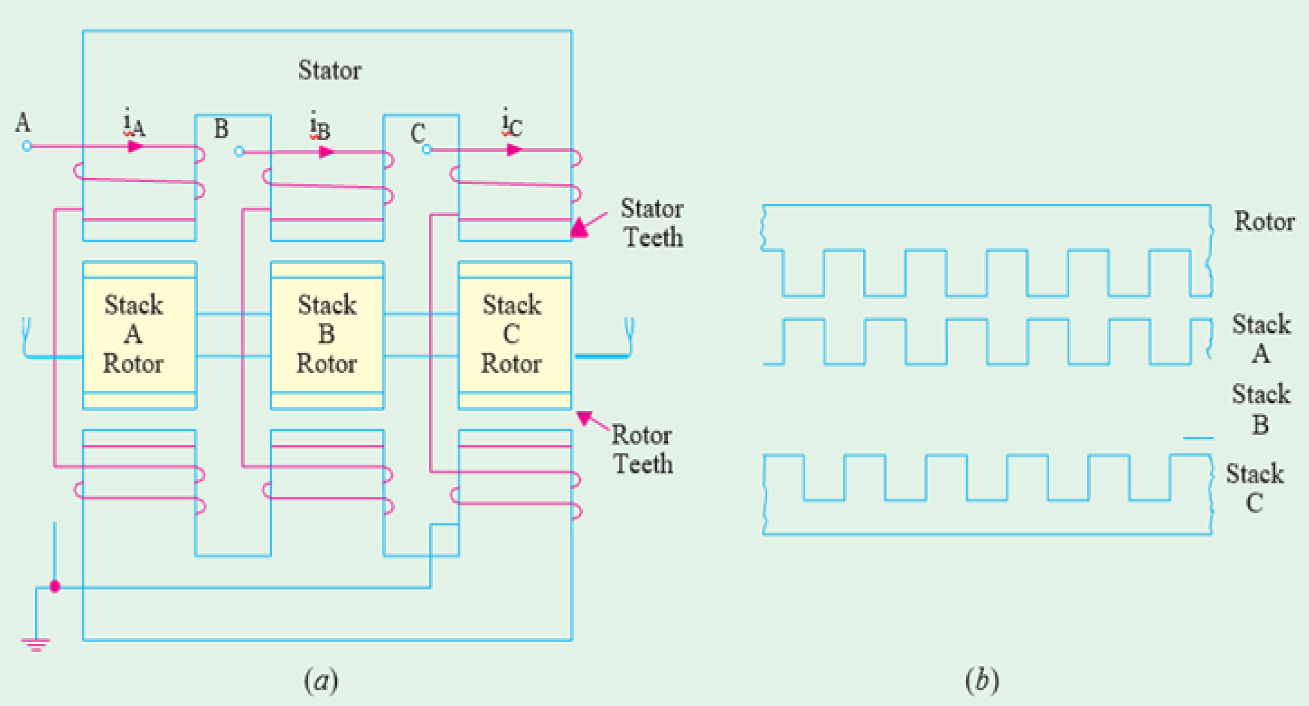
vii. Stepper motors employing micro-stepping technique are used in printing and phototypesetting where very fine resolution is called for.

viii. Micro-stepping provides smooth low-speed operation and high resolution.

Multi-stack Variable Reluctance Stepper Motor

Multi-stack VR Stepper Motor

- 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 Fig- (b) for phase excitation.
- Three-stack motors are most common although motors with up to seven stacks and phases are available.
- They have step angles in the range of 2º to 15º. For example, in a six-stack VR motor having 20 rotor teeth, the step angle β = 360º / 6 * 20 = 3º.



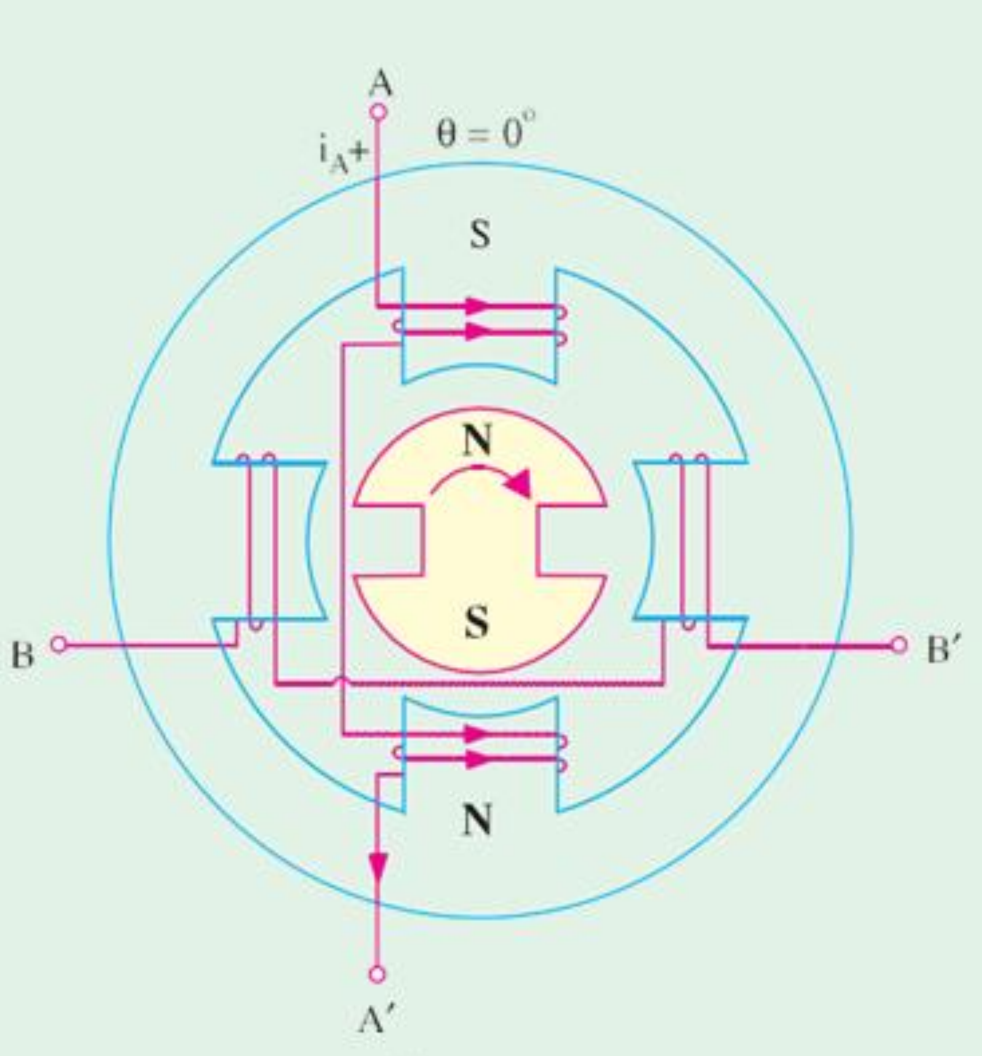
Construction of Permanent Magnet Stepping Motor

Construction of Permanent Magnet Stepping Motor

- Its stator construction is similar to that of the single-stack VR motor but the rotor is made of a permanent-magnet material like magnetically ‘hard’ ferrite shown in the Fig- (a),
- The stator has projecting poles but the rotor is cylindrical and has radially magnetized permanent magnets.
- The operating principle of such a motor can be understood with the help of Fig- (a) where the rotor has two poles and the stator has four poles.
- Since two stator poles are energized by one winding, the motor has two windings or phases marked A and B.
- The step angle of this motor

$$\beta = 360^{o} / m*Nr$$
$$= 360^{o} / 2 * 2$$
$$= 90^{o}$$

or $\beta = \frac{4-2}{4*2} * 360^{o} = 90^{o}$.

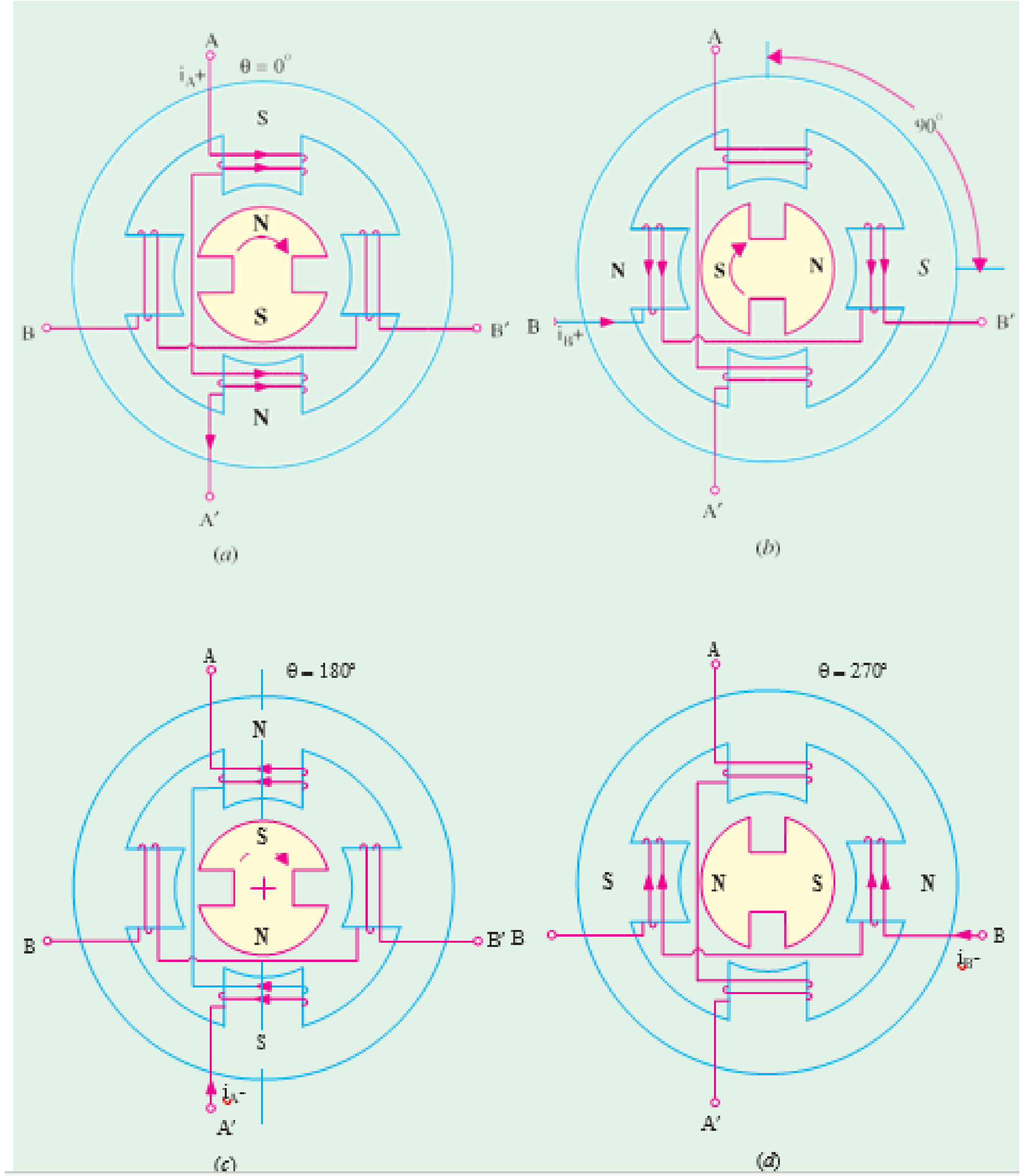


(a)

Working of Permanent Magnet Stepping Motor

Working of Permanent Magnet Stepping Motor

- 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-).
- When phase A is excited then the current in A phase is positive I_A+ as shown in Fig-(a). Here, θ = 0º.
- 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 CW 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.



Working of Permanent Magnet Stepping Motor

Working of Permanent Magnet Stepping Motor

- Truth tables for three possible current sequences for producing clockwise rotation are given in Fig.
- 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 energized 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). Micro-stepping can also be employed which will give further reduced step sizes thereby increasing the resolution.

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

Mathematical problems of Stepper motor

Problem-03

A single-stack, 3-phase VR motor has a step angle of 15º. Find the number of its rotor and stator poles.

Solution

Now,

$\beta = 360^\circ / m*N_r$

$15^\circ = 360^\circ / 3 * N_r;$

$N_r = 8.$

For finding the value of Ns, we will use the relation

$$\beta = (N_s - N_r) * 360^\circ / N_s . N_r$$

(i) When $N_s > N_r$.

Here, $\beta = (N_s - N_r) * 360^\circ / N_s . N_r$

or $15^\circ = (N_s - 8) * 360^\circ / 8 N_s ;$

$N_s = 12$

(ii) When $N_s < N_r$.

Here, $15^\circ = (8 - N_s) * 360^\circ / 8 N_s;$

$N_s = 6.$

Problem-04

A four-stack VR stepper motor has a step angle of 1.8º. Find the number of its rotor and stator teeth.

Permanent Magnet Stepping Motor

Advantages and Disadvantages of Permanent Magnet Stepping Motor

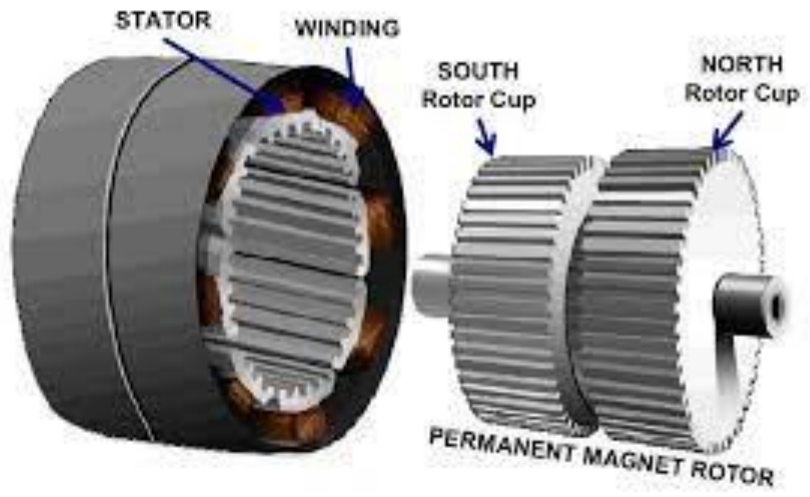
Advantages

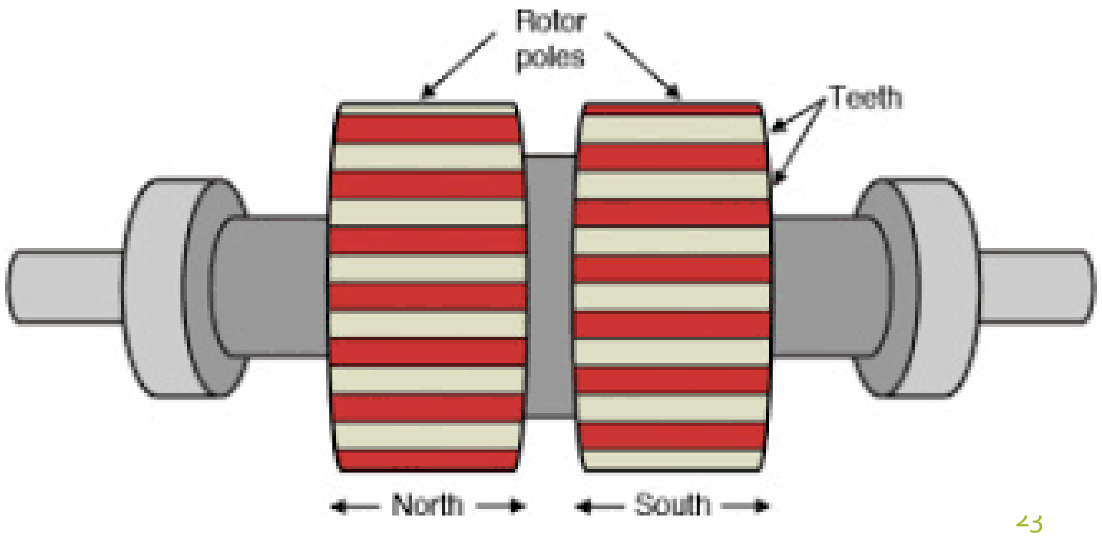
- Since the permanent magnets of the motor do not require external exciting current, it has a low power requirement but possesses a high detent torque as compared to a VR stepper motor.
- This motor has higher inertia and hence slower acceleration.
- However, it produces more torque per ampere stator current than a VR motor.

Disadvantages

- 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.
- However, recently disc rotors have been manufactured which are magnetized axially to give a small step size and low inertia.

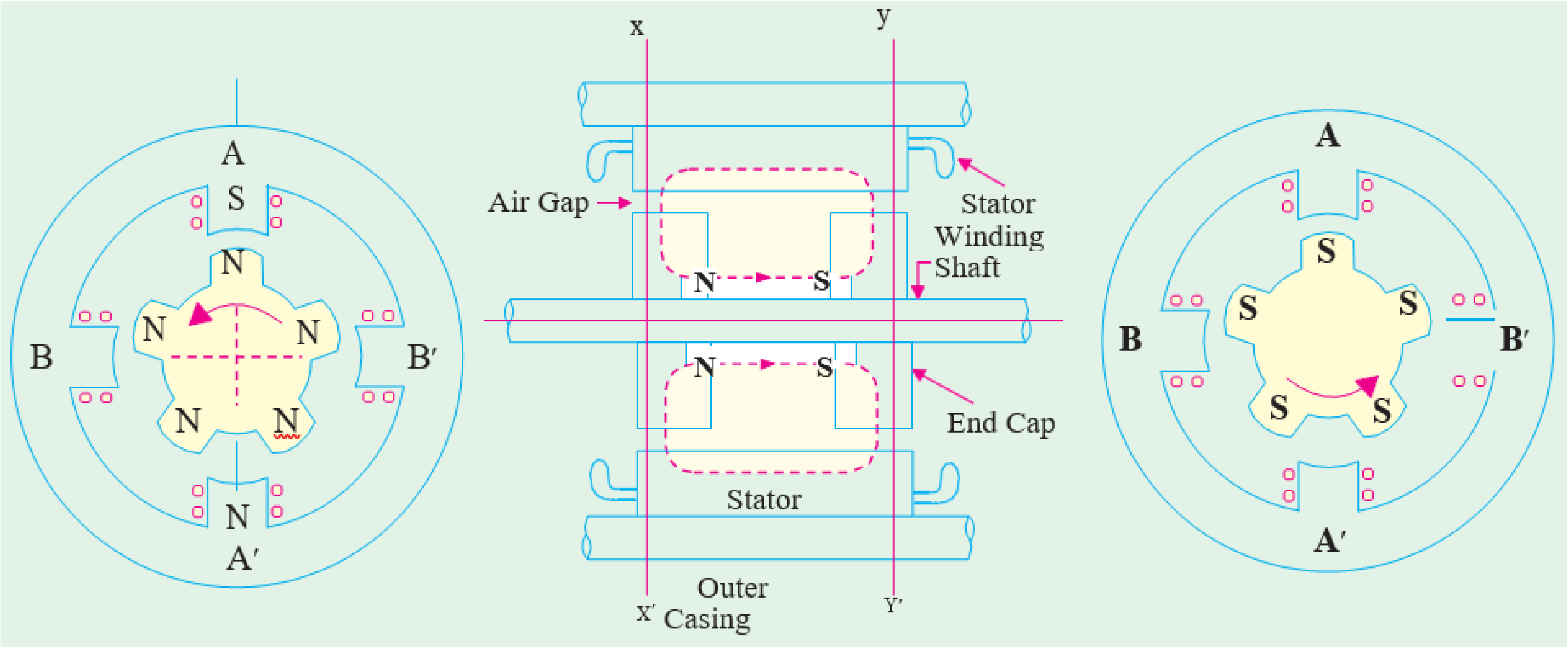
Hybrid stepper Motor





Hybrid Stepper Motor

Hybrid Stepper Motor Construction



(a) (b) (c)

- 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.
- 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 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 $\beta = (5 - 4) * 360^{o} / 5 * 4 = 18^{o}$.

Hybrid Stepper Motor

Hybrid Stepper Motor Working

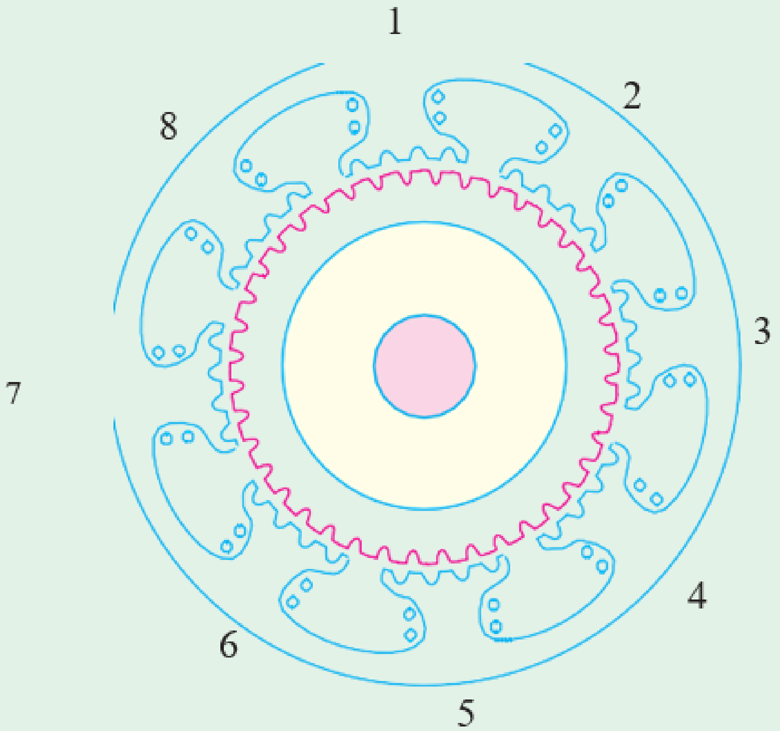
- In Fig.-a, phase A is shown excited such that the top stator pole is a S-pole so that it attracts the top N-pole of the rotor and brings it in line with the A –A' axis.
- To turn the rotor. Phase A is deenergized and phase B is excited positively. The rotor will turn in the CCW direction by a full 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.

Truth Table

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

1-Phase ON
Full-Step Mode

(*a*)



(*b*)

- Practical hybrid stepping motors are built with more rotor poles in order to give higher angular resolution.
- Hence, the stator poles are often slotted to increase the number of stator teeth. As shown in Fig. (b), each of the eight stator poles has been allotted into five smaller poles making Ns = 8 * 5 = 40º.

- If rotor has 50 teeth, then step angle = (50 - 40) * 360º / 50 * 40 = 1.8º.
- Step angle can also be decreased by having more than two stacks on the rotor.