

STEPPER MOTOR



What is a Stepper Motor?

Stepper motors consist of a rotor with permanent magnets and a stationary stator that carries the windings.

It is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation.

The shaft of the motor rotates through a fixed angle for each discrete pulse.

This rotation can be linear or angular.

It gets one step movement for a single pulse input.

-]] When a train of pulses is applied, it gets turned through a certain angle.
-]] The angle through which the stepper motor shaft turns for each pulse is referred as the step angle, which is generally expressed in degrees

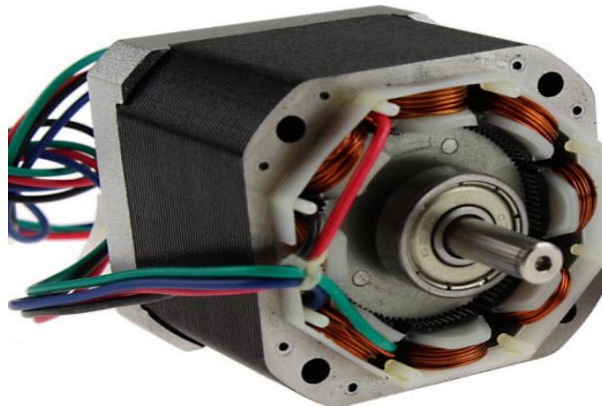


Stepper Motor

-]] The number of input pulses given to the motor decides the step angle and hence the position of motor shaft is controlled by controlling the number of pulses.
-]] This unique feature makes the stepper motor to be well suitable for open-loop control system wherein the precise position of the shaft is maintained with exact number of pulses without using a feedback sensor.

Stepper Motor

-]] **If the step angle is smaller, the greater will be the number of steps per revolutions and higher will be the accuracy of the position obtained.**
-]] The step angles can be as large as 90 degrees and as small as 0.72 degrees, however, the commonly used step angles are 1.8 degrees, 2.5 degrees, 7.5 degrees and 15 degrees.



Stepper Motor

-]] The direction of the shaft rotation depends on the sequence of pulses applied to the stator.
-]] **The speed of the shaft or the average motor speed is directly proportional to the frequency (the rate of input pulses) of input pulses being applied at excitation windings.**
-]] Therefore, if the frequency is low, the stepper motor rotates in steps and for high frequency, it continuously rotates like a DC motor due to inertia.

Stepper Motor Advantages

1. The rotation angle of the motor is proportional to the input pulse.
2. Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next.
3. Excellent response to starting/stopping/reversing.
4. Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependant on the life of the bearing.

- 
5. The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
 6. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
 7. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Disadvantages



1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds.

Applications

-]] **Industrial Machines** – Stepper motors are used in automotive gauges and machine tooling automated production equipments.
-]] **Security** – new surveillance products for the security industry.
-]] **Medical** – Stepper motors are used inside medical scanners, samplers, and also found inside digital dental photography, fluid pumps, respirators and blood analysis machinery.
-]] **Consumer Electronics** – Stepper motors in cameras for automatic digital camera focus and zoom functions

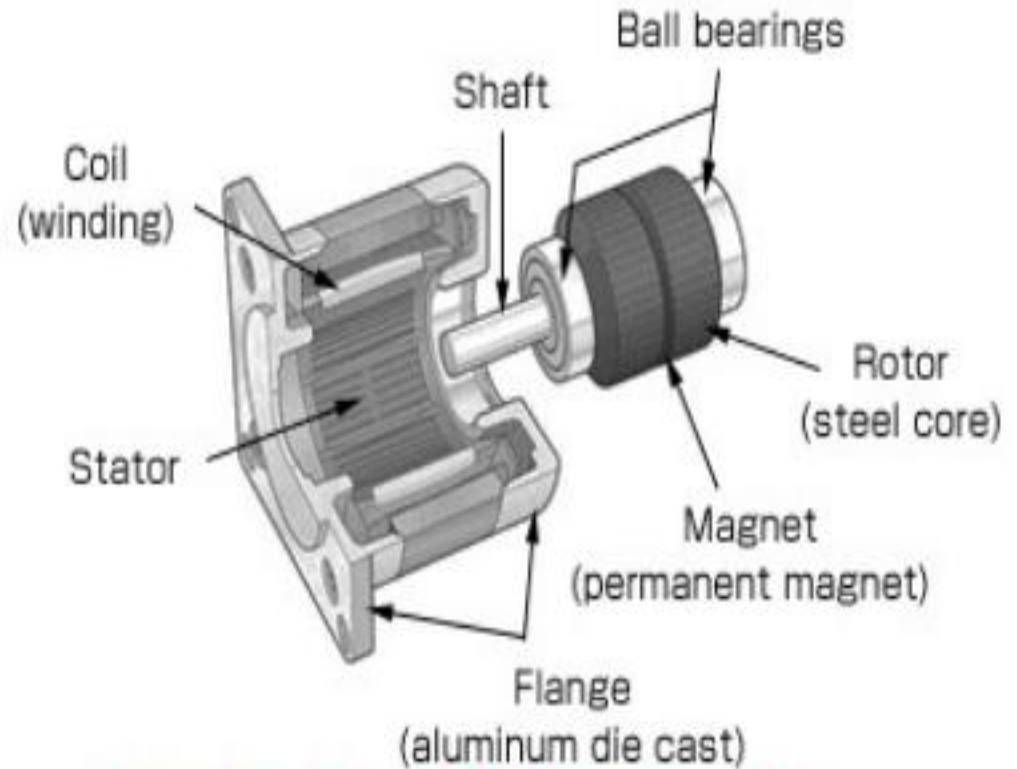
Construction

-]] 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.

Construction

Unlike other motors it operates on a **programmed discrete control pulses** that are applied to the stator windings via an electronic drive.

The rotation occurs due to the magnetic interaction between poles of sequentially energized stator



Construction of Stepper Motor

Step Angle

]] **The angle through which the motor shaft rotates for each command pulse is called step angle.**

(i) In terms of stator poles (N_s) and rotor poles (N_r) , the step an

$$” = \frac{N_s - N_r}{N_s \cdot N_r} \cdot 360^\circ$$

(i i) In terms of stator phase (m) and rotor poles(N_r), the step angle is given by:

$$” = \frac{360^\circ}{mN_r}$$

Stepper Motor Types

There are three basic stepper motor types.
They are :

-]] Variable-reluctance
-]] Permanent-magnet
-]] Hybrid

Permanent Magnet (PM)

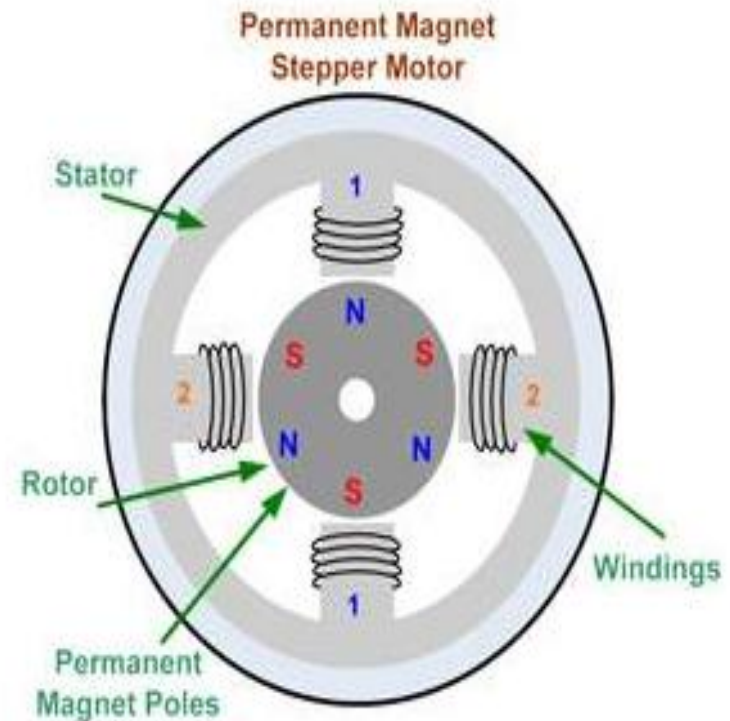
-]] Permanent Magnet (PM) motors use permanent magnet rotors and are commanded by electrical pulses.
-]] **They are widely used in printers, copies, and scanners, among other applications.**
-]] They are also used to operate valves in household water and gas systems as well as drive actuators in automotive applications.
-]] One of the main benefits of the PM stepper motor is that, in addition to being electronically commutated like a brushless DC motor or any other type of stepper motor, the PM stepper motor requires no “teeth”. **This makes the permanent magnet stepper an extremely popular choice for many motor applications.**

Permanent Magnet (PM) Construction

A permanent magnet stepping motor consists of a stator with windings and a rotor with permanent magnet poles.

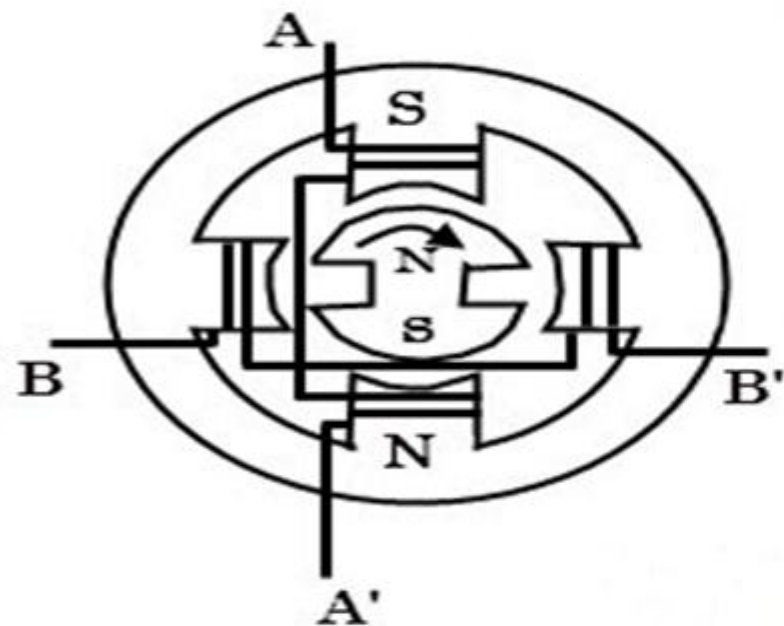
Alternate rotor poles have rectilinear forms parallel to the motor axis.

Stepping motors with magnetized rotors provide greater flux and torque than motors with variable reluctance.

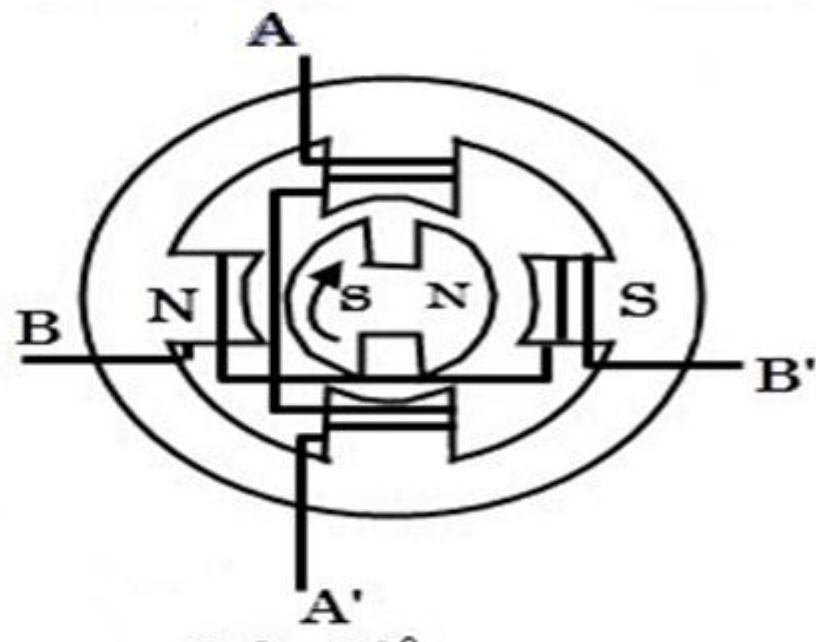


Permanent Magnet (PM) Construction

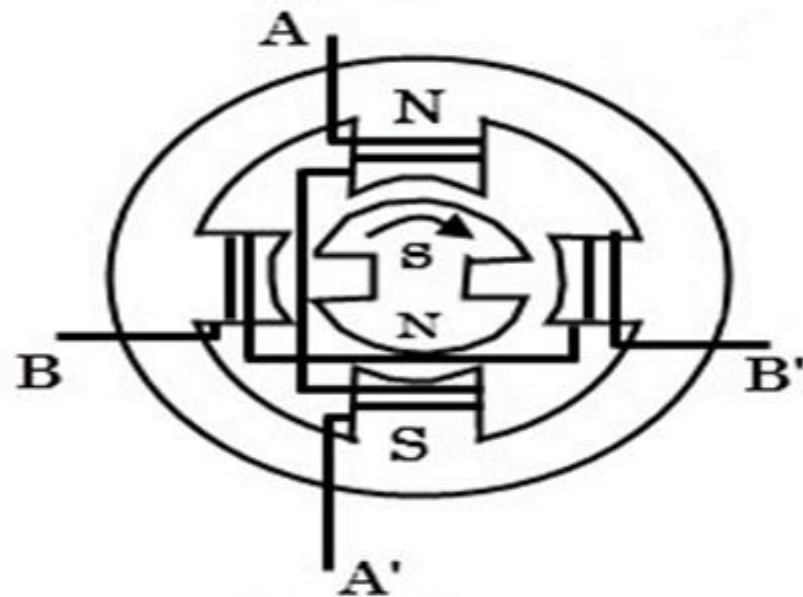
-]] Rotation of a permanent magnet stepping motor is produced by energizing individual windings in a positive or negative direction.
-]] When a winding is energized, **a north and south pole** are created, depending on the polarity of the current flowing.
-]] These generated poles attract the permanent poles of the rotor.
-]] **The rotor moves one step to align the offset permanent poles to the corresponding energized windings.**
-]] At this position, the next adjacent windings can be energized to continue rotation to another step, or the current winding can remain energized to hold the motor at its current position.
-]] When the phases are turned on sequentially the rotor is continuously rotated.



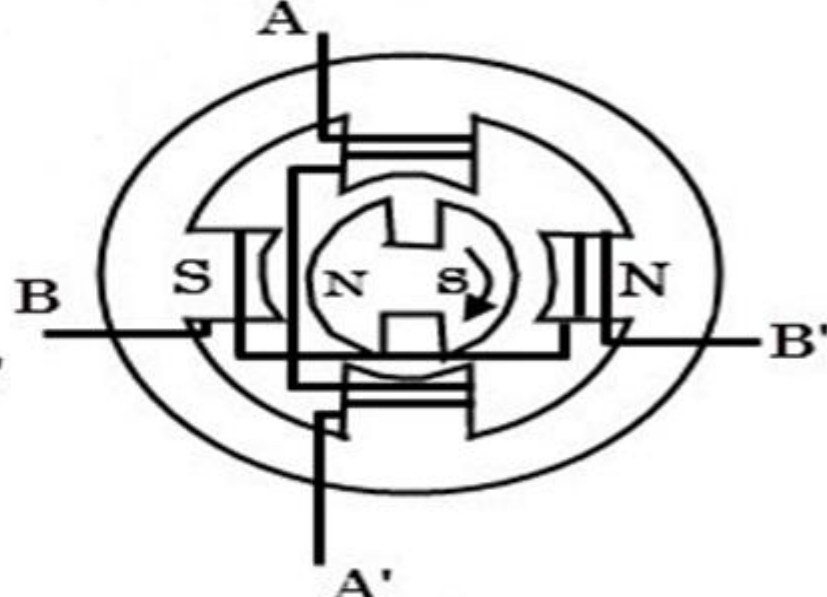
1. $\theta = 0^\circ$



2. $\theta = 90^\circ$



3. $\theta = 180^\circ$



4. $\theta = 270^\circ$

Working of PM Stepper Motor

-]] When the **phase A is energized** with a positive with respect to the A', **the windings establish North and South poles**.
-]] Due to the force of attraction, the rotor poles align with stator poles such that the magnetic pole axis of rotor adjusts with that of stator as shown in figure.
-]] When the excitation is switched to **B phase** and switching off phase A, the rotor further adjusts to magnetic axis of phase B, and thus **rotates through 90 degrees in clockwise direction**.
-]] Next, if the **phase A is energized** with a negative current with respect to A', the formation of stator poles causes the rotor to move through **another**

Working of PM Stepper Motor

-]] In the same way, if the phase B is excited with negative current by closing phase A switch, the rotor rotates through another 90 degrees in the same direction.
-]] Next, if the phase A is excited with positive current, the rotor comes to the original position thus making a 360 degrees complete revolution.
-]] This implies that, whenever the stator is excited, the rotor tends to rotate through 90 degrees in clockwise direction.

Working of PM Stepper Motor

-]] The step angle of this 2-phase 2-pole permanent magnet rotor motor is expressed as, $360 / (2 \times 2) = 90$ degrees.
-]] The step size can be reduced by energizing two phases simultaneously or a sequence of 1-phase ON and 2-phase ON modes with a proper polarity.

	A	B	ANGLE IN DEGREES
A+	+	0	0
B+	0	+	90
A-	-	0	180
B-	0	-	270
A+	+	0	0

Stepper Motor

- As the name suggests, the angular position of the rotor depends on the reluctance of the magnetic circuit formed between the stator poles (teeth) and rotor teeth.

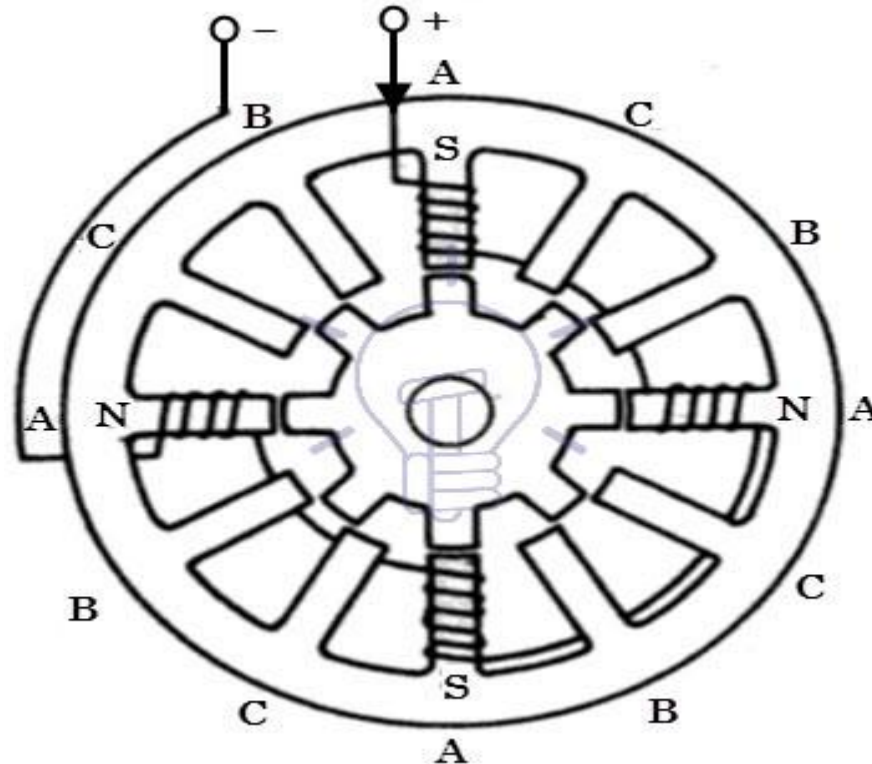


Construction of Variable Reluctance Stepper Motor:

-]] It consists of a wound stator and a soft iron multi-tooth rotor.
-]] The stator has a stack of silicon steel laminations on which stator windings are wound.
-]] Usually, it is wound for three phases which are distributed between the pole pairs.
-]] The number of poles on stator thus formed is equal to an even multiple of the number of phases for which windings are wound on stator.

Stator

-]] In the figure below, the stator has 12 equally spaced projecting poles where each pole is wound with an exciting coil. These three phases are energized from of a DC source with the help of solid state switches.



Rotor

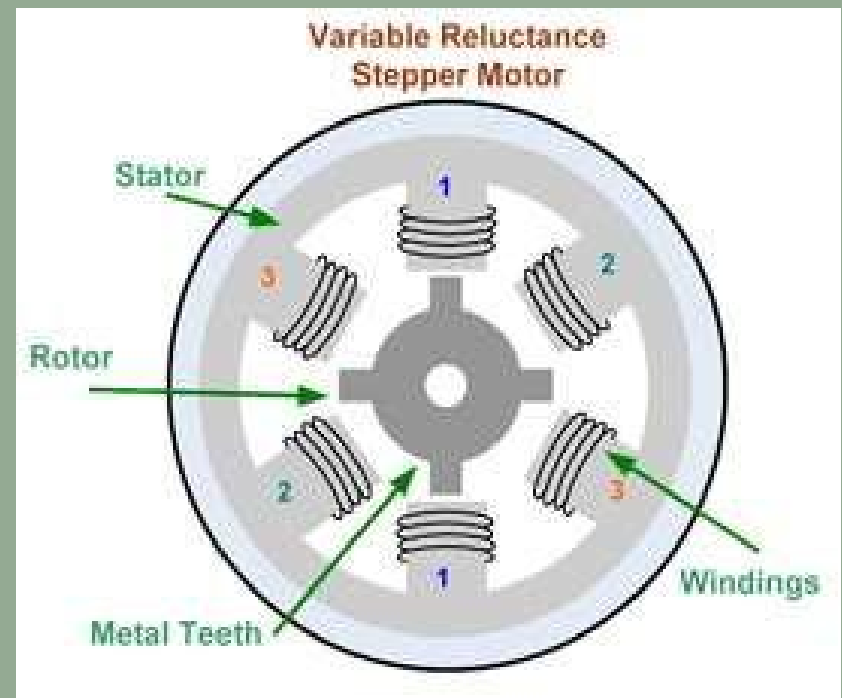
-]] The rotor carries no windings and is of salient pole type made entirely of slotted steel laminations
-]] The rotor pole's projected teeth have the same width as that of stator teeth.
-]] The number of poles on stator differs to that of rotor poles, which provides **the ability to self start and bidirectional rotation of the motor**

Variable reluctance stepper

plain iron rotor

Minimum reluctance
occurs with minimum
gap.

Rotor points
attracted towards
stator poles



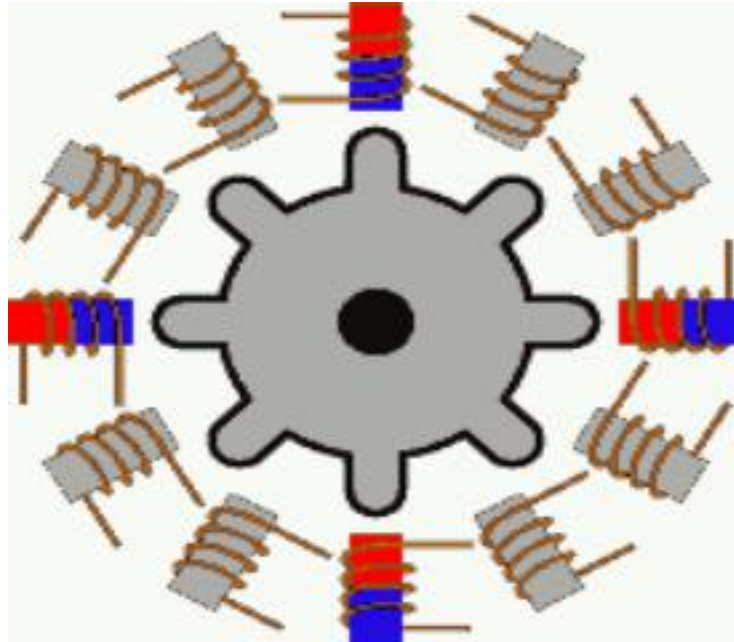
Working Variable

Reluctance Stepper Motor

-]] The *stepper motor works on the principle* that the rotor aligns in a particular position with the teeth of the excitation pole in a magnetic circuit wherein **minimum reluctance path exist**.
-]] **Whenever power is applied to the motor and by exciting a particular winding, it produces its magnetic field and develops its own magnetic poles.**
-]] Due to the residual magnetism in the rotor magnet poles, it will cause the rotor to move in such a position so as to achieve minimum reluctance position and hence one set of poles of rotor aligns with the energized set of poles of the stator.
-]] At this position, the axis of the stator magnetic

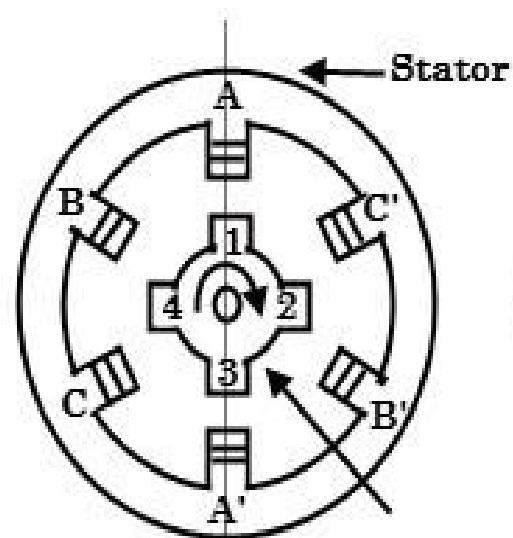
Working Variable Reluctance Stepper Motor

- When the rotor aligns with stator poles, it has enough magnetic force to hold the shaft from moving to the next position, either in clockwise or counter clockwise direction

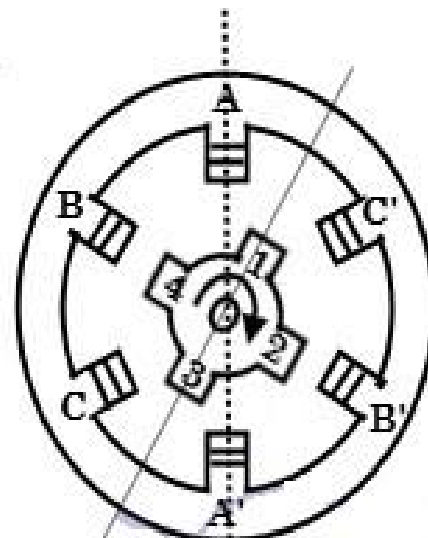


Working Variable Reluctance Stepper Motor

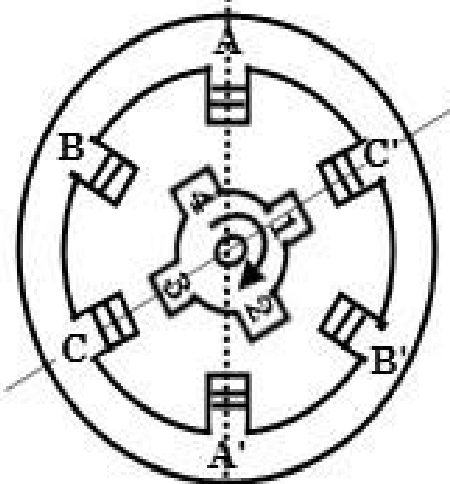
-]] Consider the schematic diagram of a 3-phase, 6 stator poles and 4 rotor.
-]] When the phase A-A' is supplied with a DC supply by closing the switch -1, the winding become a magnet which results one tooth become North and other South.
-]] So the stator magnetic axis lies along these poles.
-]] Due to the force of attraction, stator coil North Pole attracts nearest rotor tooth of opposite polarity, i.e., South and South Pole attract nearest rotor tooth of opposite polarity, i.e., North.
-]] The rotor then adjusts to its minimum reluctance position where the rotor magnetic axis exactly matches with stator



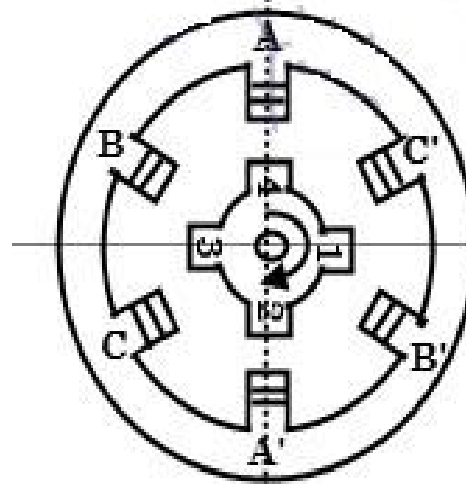
$$1. \theta = 0^\circ$$



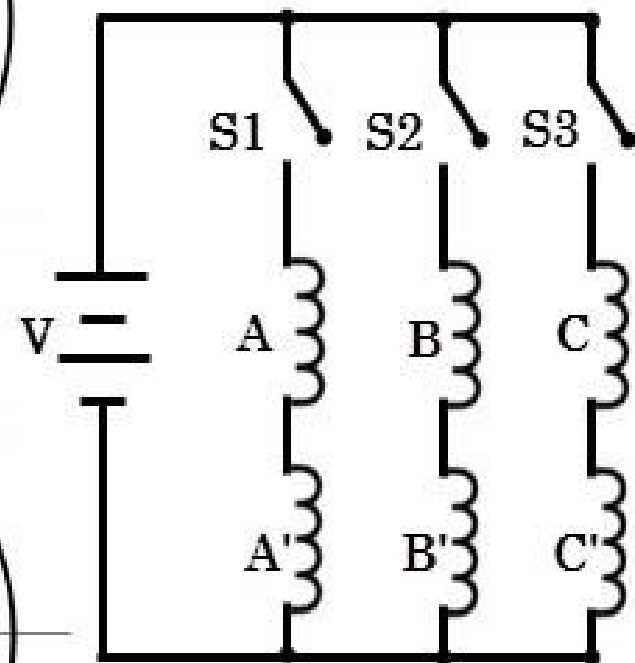
$$2. \theta = 30^\circ$$



$$3. \theta = 60^\circ$$



$$4. \theta = 90^\circ$$



Working Variable

Reluctance Stepper Motor

-]] When the phase B-B' is energized by closing switch -2 keeping phase A-A' remain de-energized by opening switch-1, winding B-B' will produce the magnetic flux and hence the stator magnetic axis shifts along the poles thus formed by it.
-]] Hence the rotor shifts to the least reluctance with magnetized stator teeth and rotates through an angle of 30 degrees in the clockwise direction.

Working Variable Reluctance Stepper Motor

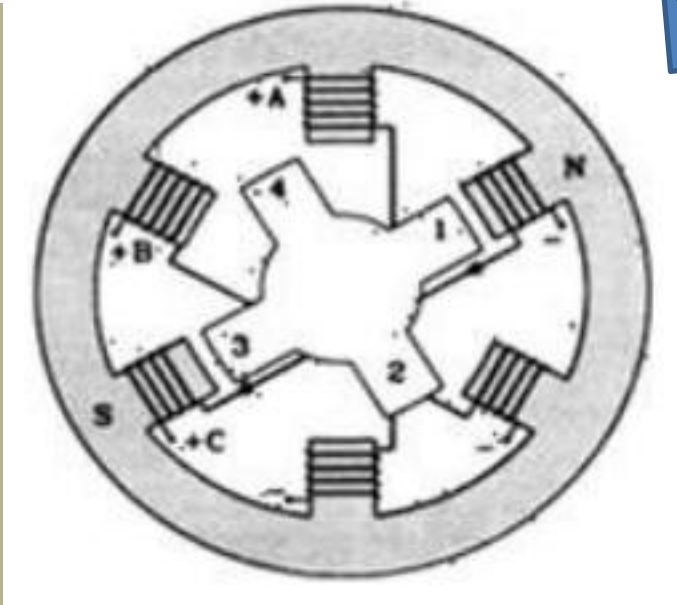
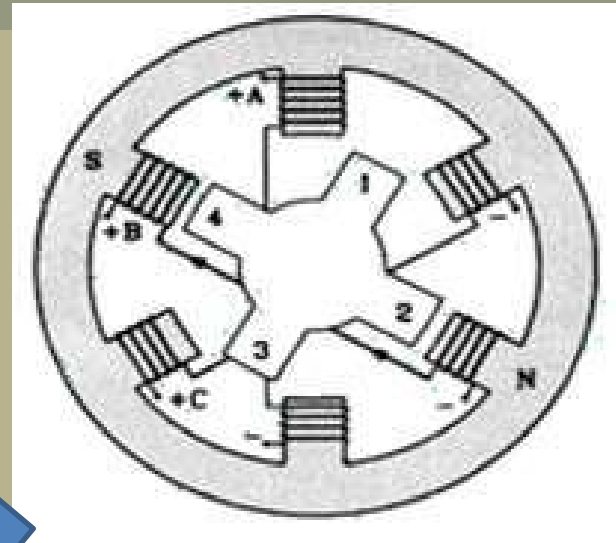
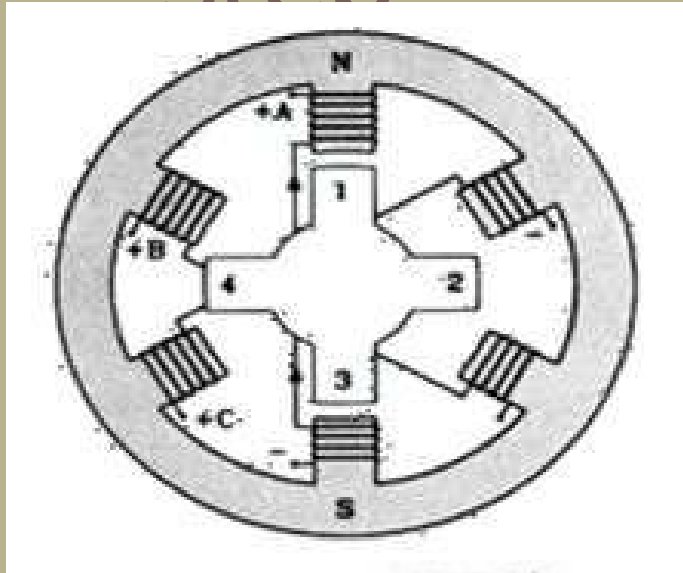
-]] When the switch-3 is energized after opening switch-2, the phase C-C' is energized, the rotor teeth align with new position by moving through an additional angle of 30 degrees.
-]] By this way, the rotor moves clockwise or counterclockwise direction by successively exciting stator windings in a particular sequence.
-]] **The step angle of this 3-phase 4-pole rotor teeth stepper motor is expressed as, $360 / (4 \times 3) = 30$ degrees (as step angle = $360 / N_r \times q$).**

Working Variable

Reluctance Stepper Motor

-]] The step angle can be further reduced by increasing the number of poles on the stator and rotor, in such case motors are often wound with additional phase windings.
-]] This can also be achieved by a adopting different construction of stepper motors such as multistack arrangement and reduction gear mechanism.

One phase on mode full step

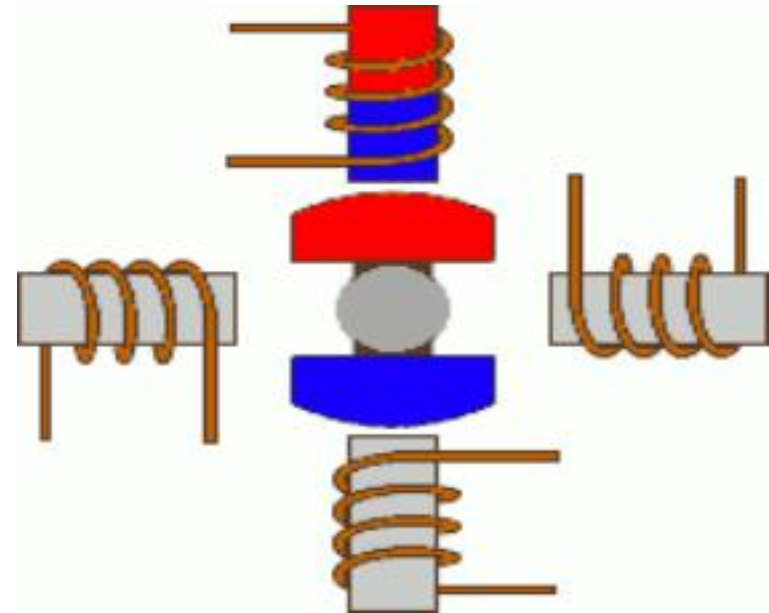


	A	B	C	θ
A	+	0	0	0°
B	0	+	0	30°
C	0	0	+	60°
A	+	0	0	90°

Driving modes

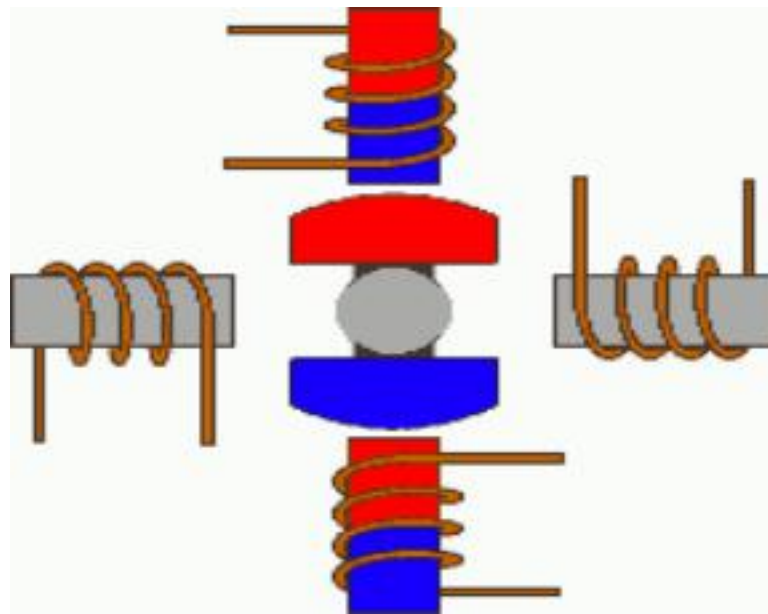
Wave drive or Single-Coil Excitation :

-]] The first way is the one described previously. This is called **Single-Coil Excitation**, and means that only one coil is energized each time.
-]] This method is rarely used, generally when power saving is necessary.
-]] It provides less than half of the nominal torque of the motor, therefore the motor load cannot be high.



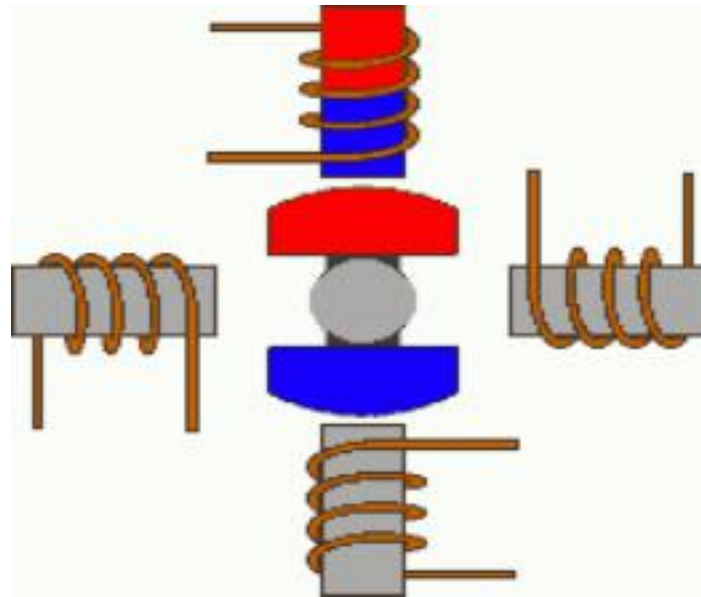
Full step drive

The second and most often used method, is the **Full step drive**. According to this method, the coils are energized in pairs. According to the connection of the coils (series or parallel) the motor will require double the voltage or double the current to operate that needs when driving with Single-Coil Excitation. Yet, it produces 100% the nominal torque of the motor.



Half stepping

This is a very interesting way to achieve double the accuracy of a positioning system, without changing anything from the hardware. According to this method, all coil pairs can be energized simultaneously, causing the rotor to rotate half the way as a normal step. This method can be single-coil or two-coil excitation as well.



Single-Coil excitation

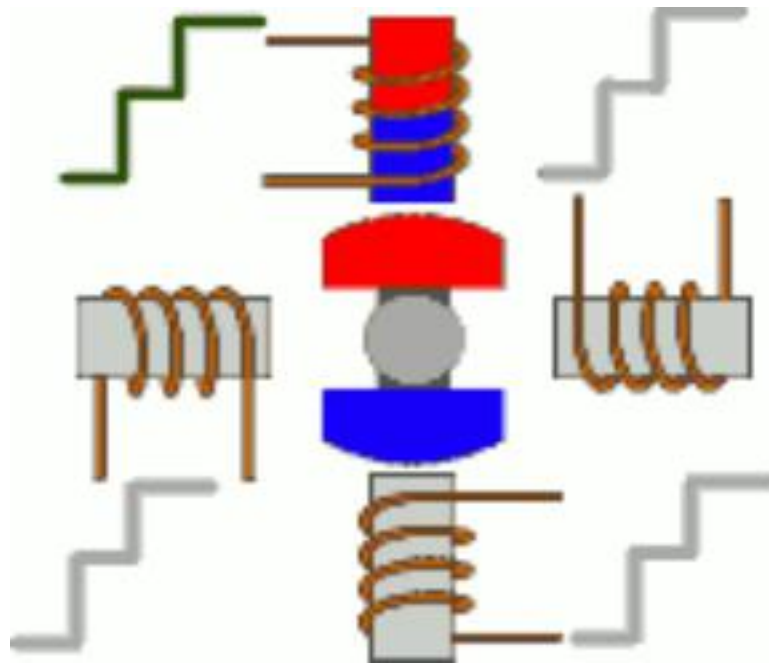
phase on mode, half step operation

	A	B	C	ANGLE
A	+	0	0	0
AB	+	+	0	15
B	0	+	0	30
BC	0	+	+	45
C	0	0	+	60
CA	+	0	+	75
A	+	0	0	90

Microstepping

-]] Microstepping is the most common method to control stepper motors nowadays.
-]] The idea of microstepping, is to power the coils of the motor NOT with pulses, but with a waveform similar to a sine waveform.
-]] This way, the positioning from one step to the other is smoother, making the stepper motor suitable to be used for high accuracy applications such as CNC positioning systems.
-]] Also, the stress of the parts connected on the motor, as well as the stress on the motor itself is significantly decreased.

- With microstepping, a stepper motor can rotate almost continuous, like simple DC motors.



Hybrid Stepper Motor

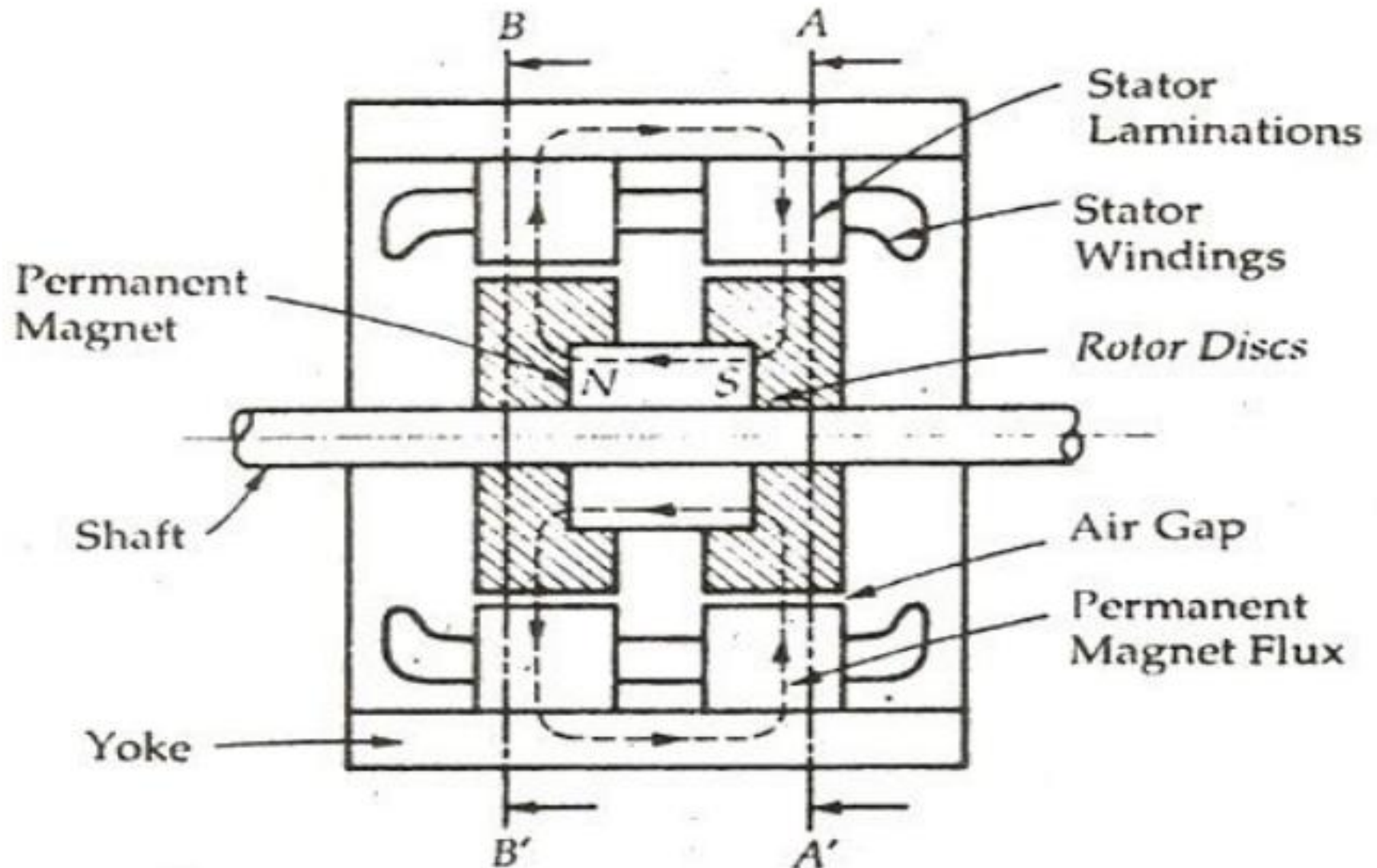
- It is the *most popular type of stepper motor* as it provides better performance than permanent magnet rotor in terms of step resolution, holding torque and speed.
- However, these motors are more expensive than PM stepper motors.
- It combines the best features of both variable reluctance and permanent magnet stepper motors.
- These motors are used in applications that require very small step angles such as 1.5, 1.8 and 2.5 degrees.**

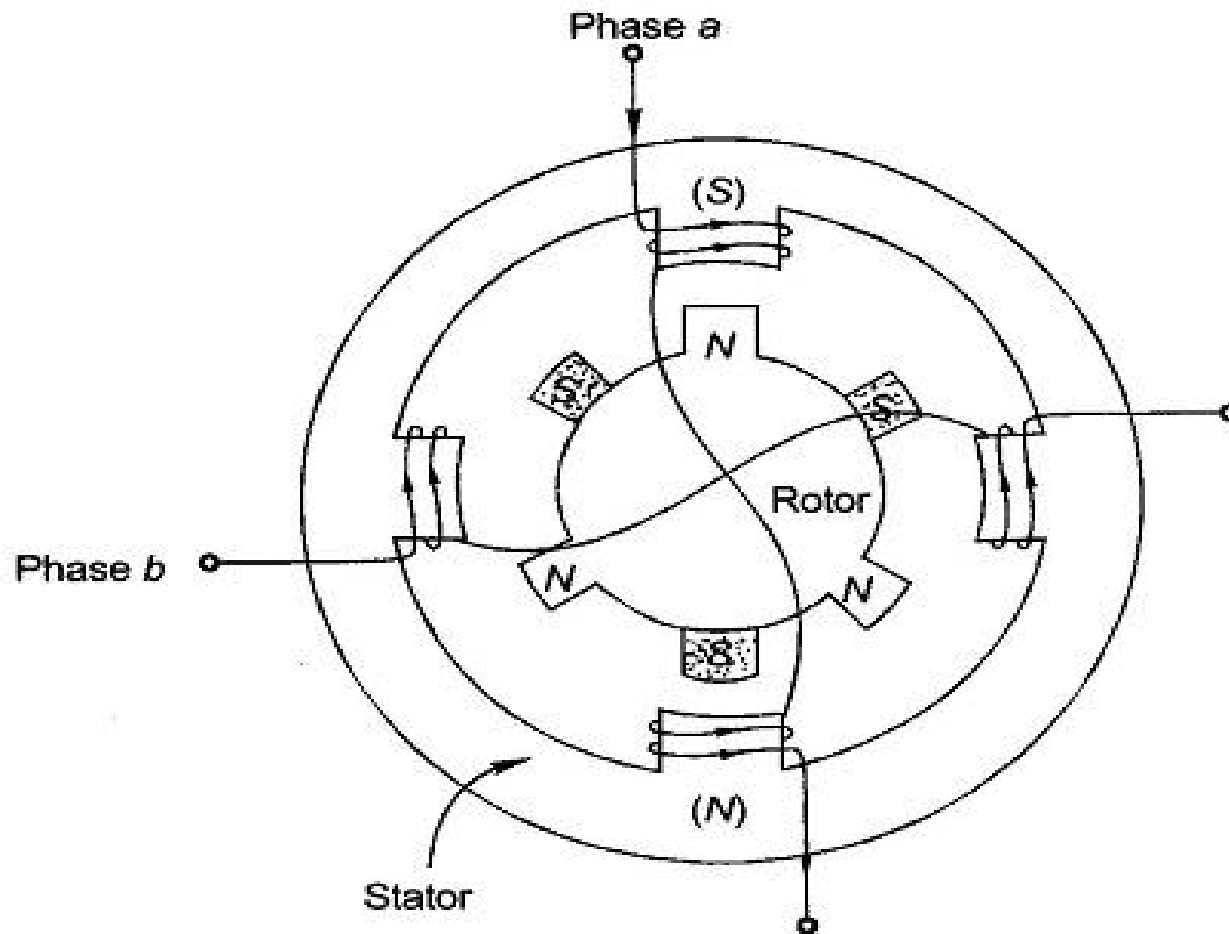


Construction of Hybrid Stepper Motor:

-]] The stator of this motor is same as its permanent magnet or reluctance type counterpart.
-]] The stator coils are wound on alternate poles.
-]] In this, the coils of different phases are wound on each pole, usually two coils at a pole.
-]] The rotor consists of a permanent magnet which is magnetized in axial direction to create a pair of magnetic poles (N and S poles).
-]] Each pole is covered with uniformly spaced teeth.
-]] The teeth are made up of soft steel.

Construction





Working of Hybrid Stepper Motor:

-]] This motor works similar to that of permanent magnet stepper motor.
-]] The figure above shows 2-phase, 4-pole, 6-tooth rotor hybrid stepper motor.
-]] When the phase A-A' is excited with a DC supply, keeping B-B' unexcited, the rotor aligns such that the south pole of the rotor faces north pole of the stator while north pole of rotor faces south pole of the stator.

Working of Hybrid Stepper Motor:

- Now, if the phase B-B' is excited, keeping A-A' switched off in such a way that upper pole becomes north and lower becomes south, then the rotor will align to a new position by moving through counterclockwise direction.
- If the phase B-B' is oppositely excited such that the upper pole becomes south and lower becomes north, then the rotor will turn clockwise direction.

Working of Hybrid Stepper Motor:

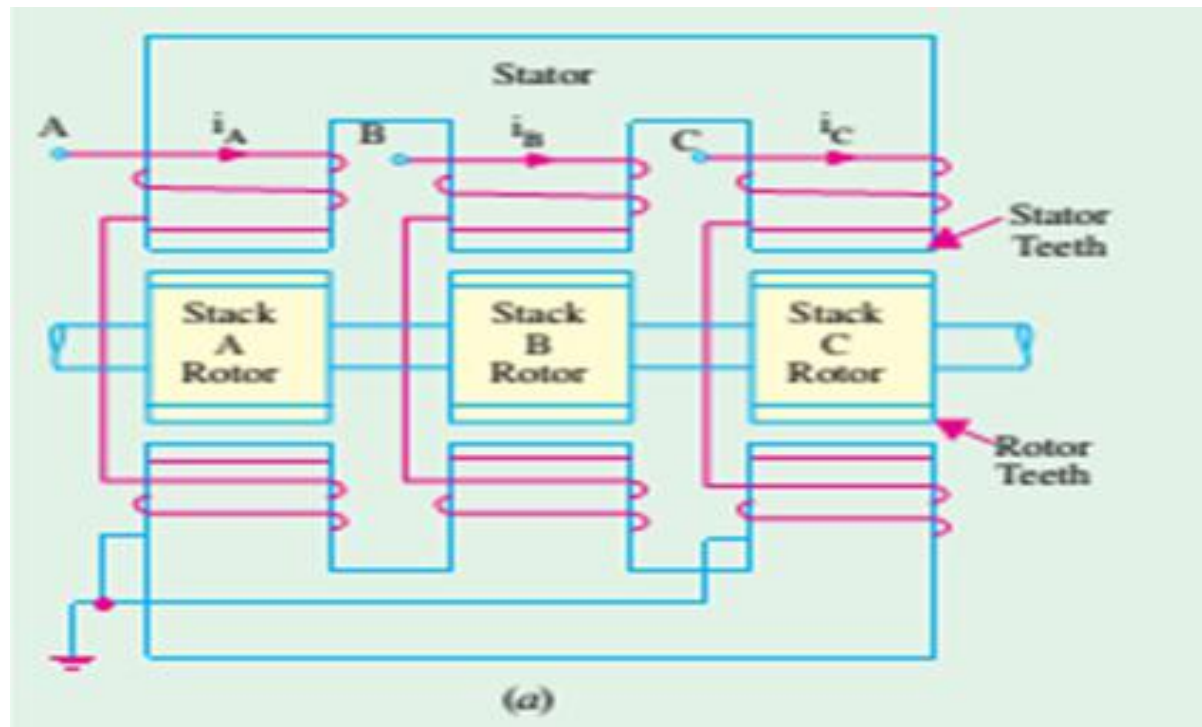
-]] By a proper sequence of pulses to the stator, the motor will turn in desired direction.
-]] For every excitation, rotor will get locked into new position, and even if excitation is removed motor still maintains its locked condition due to the permanent magnet excitation.
-]] **The step angle of this 2-phase, 4-pole, 6-tooth rotor motor is given as $360 / (2 \times 6) = 30$ degrees.**
-]] In practice, hybrid motors are constructed with more number of rotor poles in order to get high angular resolution.

Hybrid stepper motor

-]] If the stator excitation were to be removed, the rotor will continue to **remain locked into the same position** as it is prevented to move in either direction by torque because of the permanent magnet excitation.
-]] Compared to PM motor **finers steps for better resolution** are easily obtained in hybrid motor by increasing the number of stack teeth and also by adding additional stack pairs on the rotor.
-]] Also compared to variable-reluctance motor a hybrid motor requires **less stator excitation current** because of the PM excited rotor.

MULTISTACK VARIABLE RELUCTANCE STEPPER MOTOR

- These are used to obtain smaller step sizes, typically in the range of 2° to 15° .
- Although three stacks are common and a multistack motor may employ as many as seven stacks.
- This type is also known as the cascade type



-]] A multistack (or m-stack) variable reluctance stepper motor can be considered to be made up of 'm' identical single stack variable reluctance motors with their rotors mounted on a single shaft.
-]] The stators and rotors have the same number of poles (or teeth) and therefore same pole (tooth) pitch.

- 】 **For a $m0$ stack motor, the stator poles (or teeth) in all m stacks are aligned, but the rotor poles (teeth) are displaced by $1/m$ of the pole pitch angle from one another.**
- 】 All the stator pole windings in a given stack are exited simultaneously and, therefore the stator winding of each stack forms one phase.
- 】 Thus the motor has the same number of phases as number of stacks.

-]] In each stack, stator and rotors have 12 poles (teeth). For a 12 pole rotor, pole pitch is 30° and therefore, the rotor poles (teeth) are displaced from each other by 1/3rd of the pole pitch or 10° .
-]] The stator teeth in each stack are aligned.

$$T_p = \frac{360^\circ}{N_r} \dots \dots \dots (1)$$

Therefore,

$$\text{Step angle} = \frac{360^\circ}{m N_r} \dots \dots \dots (2)$$

- 
-]] When the phase winding A is excited the rotor teeth of stack A are aligned with the stator teeth.
 -]] When phase A is de-energized, and phase B is excited, rotor teeth of the stack B are aligned with the stator teeth.
 -]] The rotor movement is about 10 degrees in the anticlockwise direction.
 -]] The motor moves one step which is equal to $\frac{1}{3}$ of the pole pitch due to change of excitation from stack A to stack B.

-]] Similarly, now phase B is de-energized, and phase C is excited.
-]] The rotor moves another step of $1/3$ of the pole pitch in the anticlockwise direction.
-]] Again, another change in the excitation of the rotor takes place, and the stator and rotor teeth align it with stack A.
-]] However, during this whole process (A – B – C – A) the rotor has moved one rotor tooth pitch.

Other type of Stepper Motor

Single Phase Stepper Motor:

-]] These are motors which are designed to be operated from single phase supply.
-]] They are widely use in watches and clocks, timers and counters.
-]] Present single phase stepping motors use one or more (two) permanent magnets, because permanent magnets are quite necessary to raise the ratio of torque to input power in a miniature motor.

CONSTRUCTION

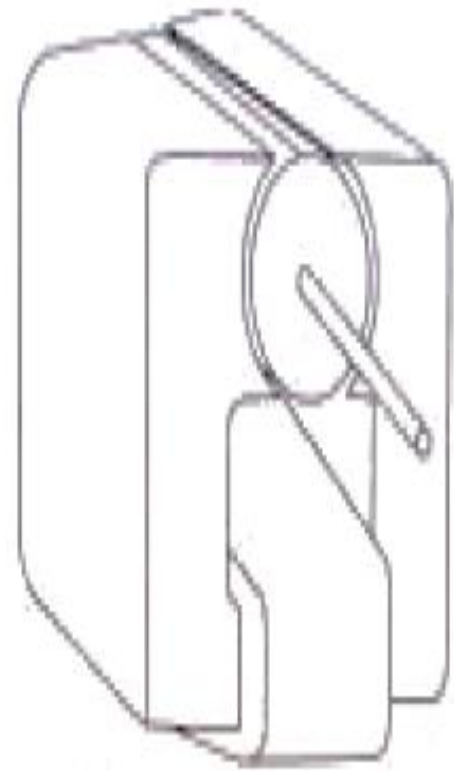
- It is a permanent magnet type stepper motor with two poles.

- Rotor is a circular type of permanent magnet as shown in fig.

- stator is made of silicon steel stampings with two salient poles.

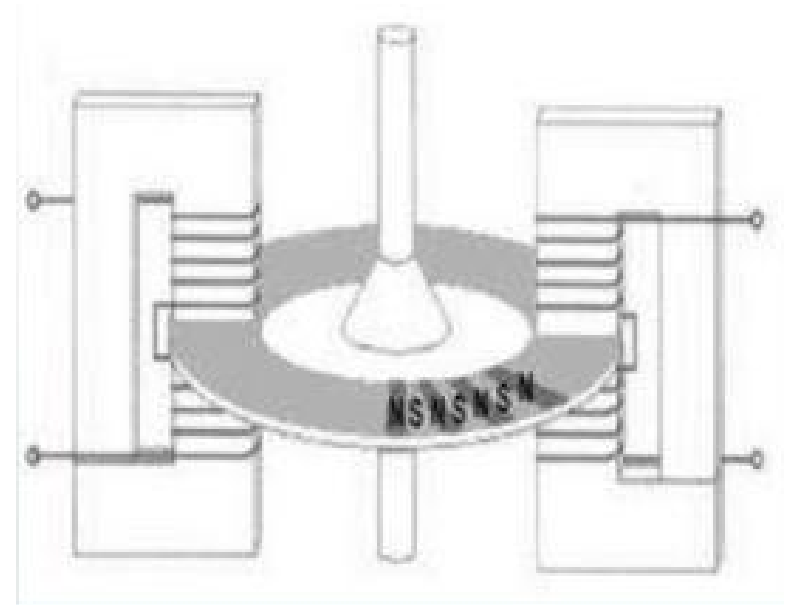
- Stator carries a coil which is connected to a pulsed supply.

- The air gap is specially designed so that specific reluctance at different radial axes are different



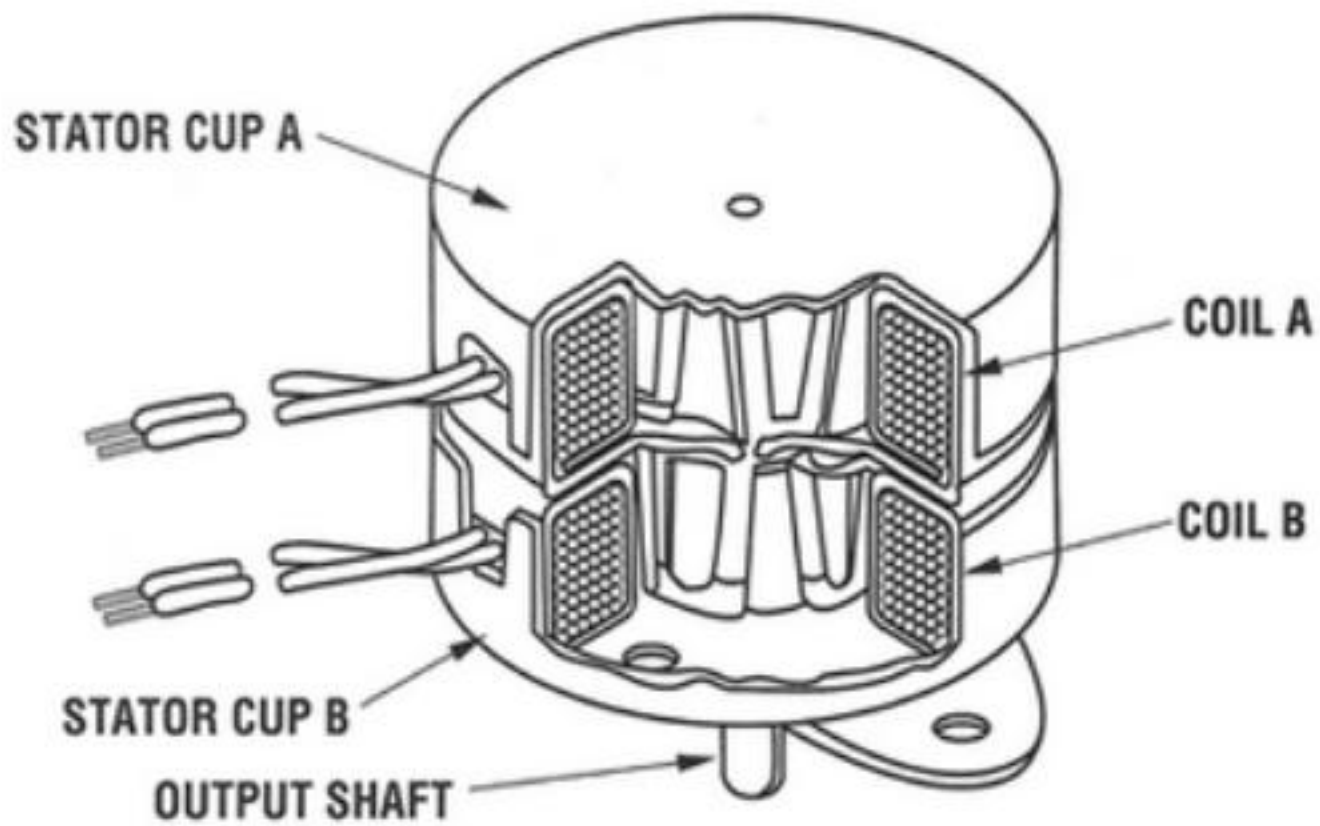
Disc Magnet Type Stepper Motor

-]] This motor has advantages like high torque to weight, torque to size, power to size and power to weight ratios.
-]] It is ideal for microstepping operation.
-]] Its stator is made up of CRGO material and has windings on tip of the poles.
-]] The rotor is thin disc of rare earth cobalt..



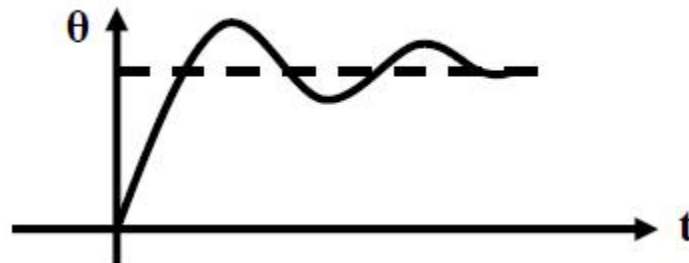
Claw Tooth Type Stepper Motor

-]] This is another type of stepping motor.
-]] This is also known as can-stack Stepping motor, as the stator of this motor consists of a sort of metal can.
-]] The top and bottom claws for sandwiching the coil are arranged to fit into each other.
-]] When the coil is energized, the inductor is magnetized to the N-pole, then to the S-pole, then to the N-pole, and then to the S-pole.



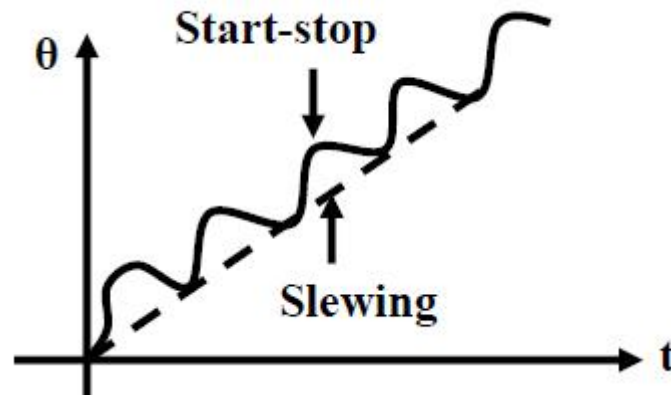
Dynamic Response

-]] Ideally the rotor of a step motor should rotate by step angle once it receives a pulse and the rotation should occur instantaneously. But due to the inertia of the rotor, the rotor cannot settle down at its final position instantaneously and it undergoes through some oscillations as shown in Fig.



Dynamic Response of a Step motor

- Before settling down after some time.
- The overshoot increases if the inertia of the rotor is large. This will cause large settling time.
- In order to decrease the overshoot, additional damping arrangement is sometimes provided.



Start-stop and slewing mode of operation

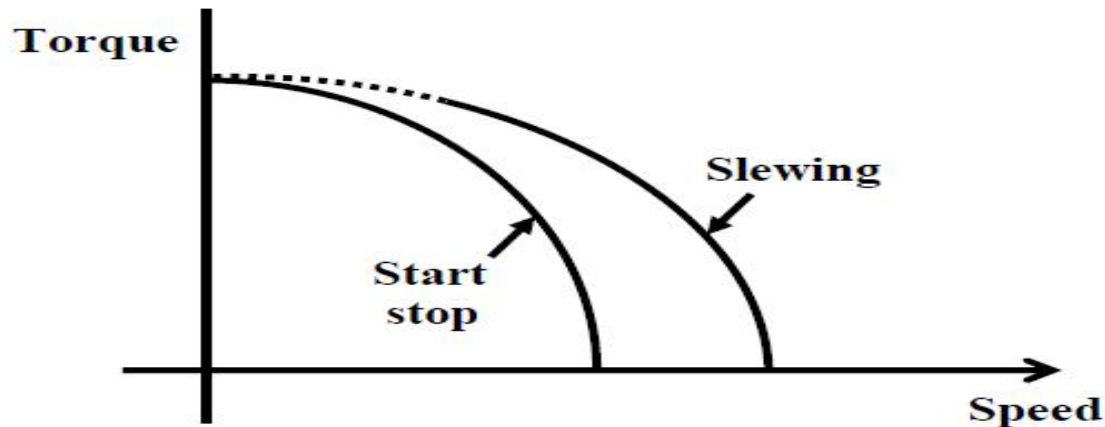
Continuous Operation

- It has been mentioned earlier that though the step motors are normally used for discrete step operations, they can be used for continuous rotation also.
- A train of control pulses will rotate the motor continuously.
- Continuous operation can be achieved in two ways: *start-stop and slewing mode of operation*.
- In the first case, one pulse is applied, the rotor rotates through one step, settles at its stable location and then another pulse is sent*

-]] On the other hand, the pulses received are at much faster rate in slewing mode and the control circuit generates a pulse before the rotor comes to a steady state.
-]] As a result, the rotor runs at uniform speed without stopping after each step.
-]] The inertia effect is absent because of the continuous rotation and the motor can take more load when it is slewing.

The torque vs. speed characteristics

From this figure it is clear that at a particular speed the torque generated in slewing mode is more in slewing mode.



- But there is a problem if we want to start a motor with load under slewing operation.
- When a motor starts with load, it cannot suddenly start rotating at high speed.
- It has to be accelerated gradually by increasing the number of steps/sec.

This process of starting and acceleration is known as

CHARACTERISTICS OF STEPPER MOTOR

Stepper motor characteristics are divided into two groups

- 】 Static characteristics
- 】 Dynamic characteristics

Terminologies

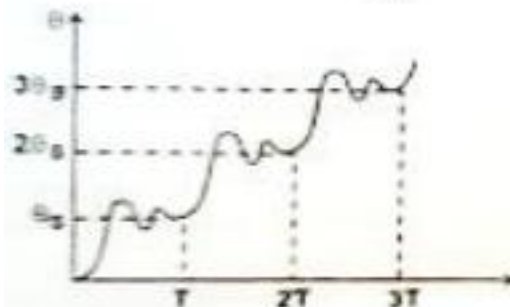
-]] **Holding Torque (TH)** :It is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the static equilibrium position
-]] **Detent torque (TD)**: It is the maximum load torque which the un-energized stepper motor can withstand slipping. Detent torque is due to magnetism, and is therefore available only in permanent magnet and hybrid stepper motor. It is about 5-10 % of holding torque.

Slewing mode:

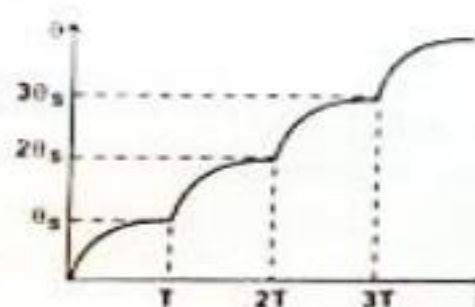
-]] In start -stop mode the stepper motor always operate in synchronism and the motor can be started and stopped without using synchronism.
-]] In slewing mode the motor will be in synchronism, but it cannot be started or stopped without losing synchronism.
-]] To operate the motor in slewing mode first the motor is to be started in start stop mode and then to slewing mode. Similarly to stop the motor operating in slewing mode, first the motor is to be brought to the start stop mode and then

Start Stop mode

-]] In this second pulse is given to the stepper motor only after the rotor attained a steady or rest position due to first pulse.
-]] The region of start-stop mode of operation depends on the operation depends on the torque developed and the stepping rate or stepping frequency of stepper motor.



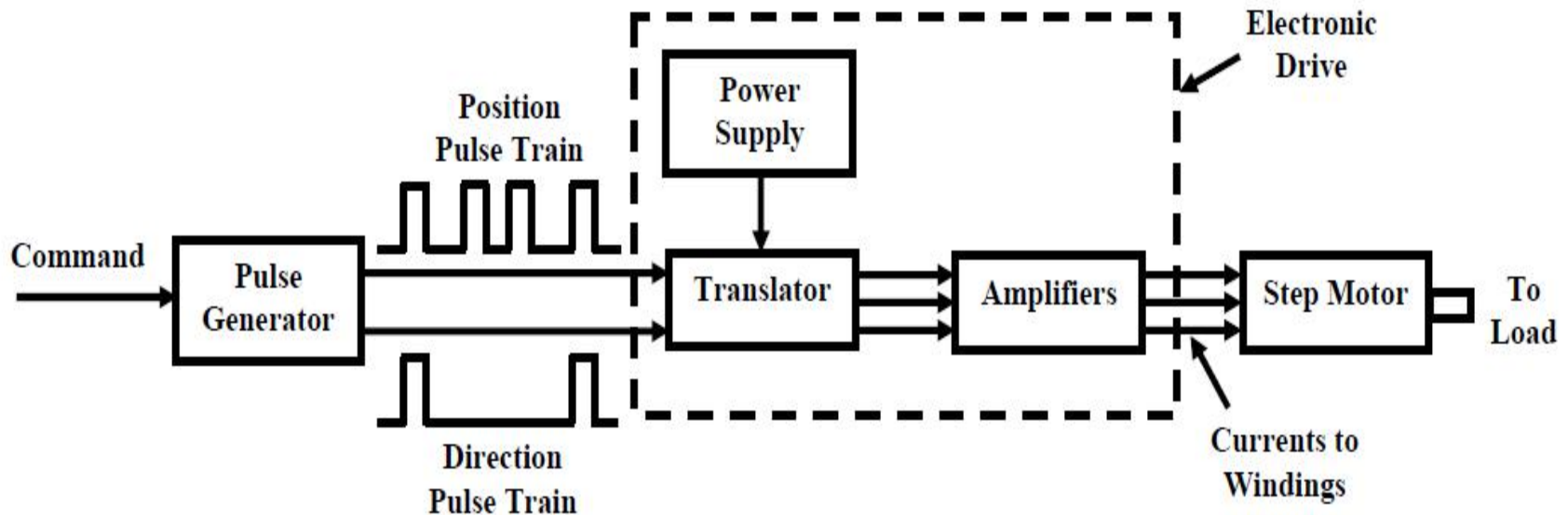
(a) Start-Stop Mode



(b) Slewing Mode

Control of Step Motors

- Control of step motors can be achieved in two ways: open loop and closed loop.
- The open loop control is simpler and more widely used, such a scheme is shown schematically in Fig.



-]] The command to the pulse generator sets the number of steps for rotation and direction of rotation.
-]] The pulse generator correspondingly generates a train of pulse.
-]] The Translator is a simple logical device and distributes the position pulse train to the different phases.
-]] The amplifier block amplifies this signal and drives current in the corresponding winding.
-]] The direction of rotation can also be reversed by sending a direction pulse train to the translator.
-]] After receiving a directional pulse the step motor

-]] The major disadvantage of the open loop scheme is that in case of a missed pulse, there is no way to detect it and correct the switching sequence.
-]] A missed pulse may be due to malfunctioning of the driver circuit or the pulse generator.
-]] This may give rise to erratic behaviour of the rotor.

Closed Loop Control

-]] The closed loop arrangement has the advantage over open loop control, as it does not allow any pulse to be missed and a pulse is sent to the driving circuit after making sure that the motor has rotated in the proper direction by the earlier pulse sent.
-]] In order to implement this, we need a feedback mechanism that will detect the rotation in every step and send the information back to the controller.
-]] The incremental encoder here is a digital

Feedback control of a step motor

