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Industrial Electronics –II
DETCE/S6

Stepper Motor
Group C
Unit 7.1 - 7.2

STEPPER MOTOR

7.1 Types and principle of operation of stepper motor
7.2 Stepper Motor Control: Stepper drive - Dual Voltage Drive – Chopper Drive

After completion of this topic learners should be able to

- **Understand basic concept of Stepper Motor**
- **Describe the operation of different types of stepper motor**
- **Select proper drive circuit for a particular operation**

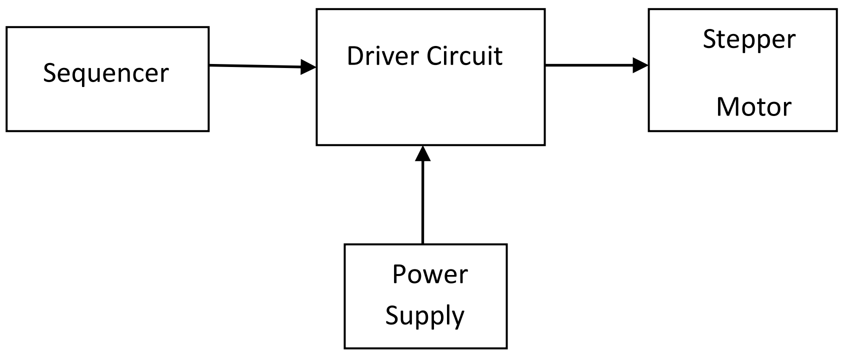
INTRODUCTION

Stepper motor is a special type of electric motor that moves in precisely defined increments of rotor position (Steps). The size of the increment is measured in degrees and can vary depending on the application. Due to precise control, stepper motors are commonly used in medical, satellites, robotic and control applications.

There are several features common to all stepper motors that make them ideally suited for these types of applications. They are as under

- High accuracy: Operate under open loop
- Reliability: Stepper motors are brushless.
- Load independent: Stepper motors rotate at a set speed under different load, provided the rated torque is maintained.
- Holding torque: For each and every step, the motor holds its position without brakes.

Stepper motor requires sequencers and driver to operate. Sequencer generates sequence for switching which determines the direction of rotation and mode of operation. Driver is required to change the flux direction in the phase windings. The block diagram of stepper motor system is shown below



Block diagram of stepper motor system

TYPES OF STEPPER MOTORS

It can be classified into several types according to machine structure and principle of operation as explained by Kenjo (1984). Basically there are three types of Stepper motors

1. Variable Reluctance Motor (VRM)
2. Permanent Magnet Stepper Motor (PMSM)
3. Hybrid Stepper Motor (HSM)

1. **Variable Reluctance Motor**

It consists of a soft iron multi-toothed rotor and a wound stator. When the stator windings are energized with DC current, the poles become magnetized. Rotation occurs when the rotor teeth are attracted to the energized stator poles. Both the stator and rotor materials must have high permeability and be capable of allowing high magnetic flux to pass through even if a low magneto motive force is applied. When the rotor teeth are directly lined up with the stator poles, the rotor is in a position of minimum reluctance to the magnetic flux i.e. the rotor aligns itself with the axis of stator as the stator winding is energized. The rotor is now stable in this position and cannot move until phase is de-energized.

A rotor 'step' takes place when one stator phase is deenergized and the next phase in sequence is energized, thus creating a new position of minimum reluctance for the rotor as explained by Kenjo (1984). Cross-section of variable reluctance motor is shown below

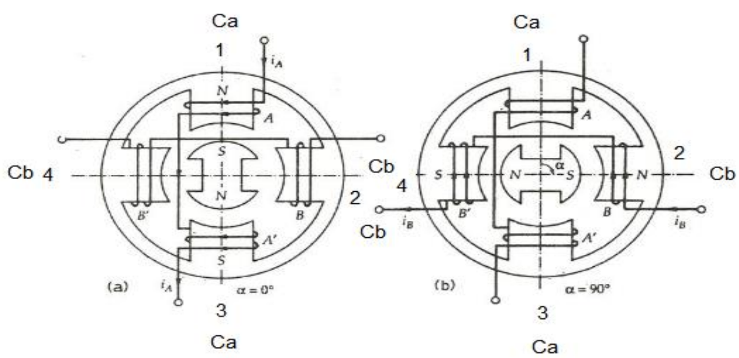
Cross-section of variable reluctance motor

2. **Permanent Magnet Stepper Motor**

A stepper motor using a permanent magnet in the rotor is called a PMSM. The rotor no longer has teeth as with the VRM. Instead the rotor is magnetized with alternating north and south poles situated in a straight line parallel to the rotor shaft, these magnetized rotor poles provide an increased magnetic flux intensity and, because of this the PM motor exhibits improved torque characteristics when compared with the VRM type. An elementary PM motor employs a cylindrical permanent magnet as the rotor and possesses four poles in its stator.

Two overlapping windings are wound as one winding on poles 1 and 3 and these two windings are separated from each other at terminals to keep them as independent windings. The same is true for poles 2 and 4. The terminals marked Ca or Cb denotes connected to the positive terminal of the power supply as explained by Kenjo (1984).

When the windings are excited in the sequence A - A' –B - B' the rotor will be driven in a clockwise direction. The step length is 90° in this machine. If the number of stator teeth and magnetic poles on the rotor are both doubled, a two-phase motor with a step length of 45° will be realized.



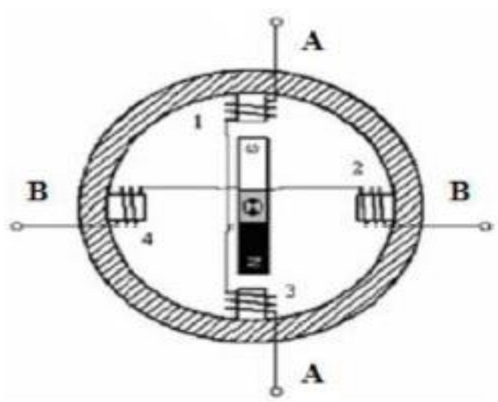
Cross Section of permanent Stepper Motor

For this particular sequence rotational angle is given below -

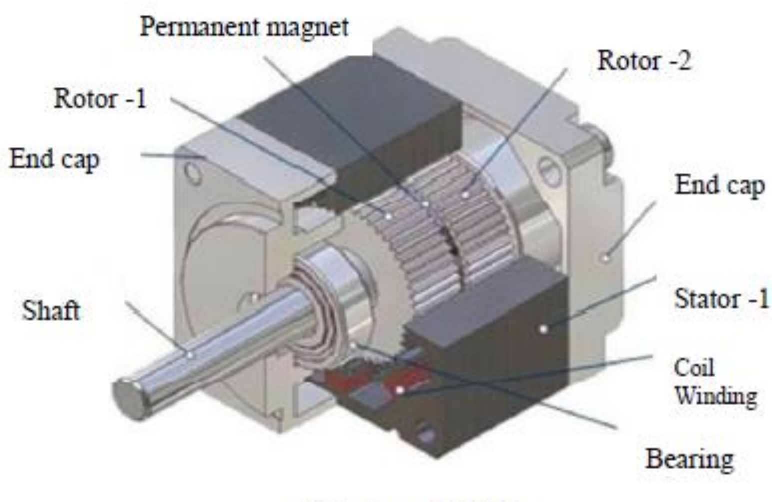
A	**A'**	**B**	**B'**	**Rotational Angle of Rotor**
+ve	-Ve	Off	Off	α = 0°
Off	Off	+ve	-Ve	α = 90°
-Ve	+Ve	Off	Off	α =180°
Off	Off	-Ve	+ve	α = 360°

3. Hybrid Stepper Motor

The term 'Hybrid' is derived from the fact that motor is operated with the combined principles of the permanent magnet and variable reluctance motors in order to achieve small step length and high torque in spite of motor size. Standard HSM have 50 rotor teeth and rotate at 1.8 degree per step. Cross section and cut view of two phase HSM are given below. The windings are placed on the stator poles and a PM is mounted on the rotor. The important feature of the HSM is its rotor structure. A cylindrical or disk-shaped magnet lies in the rotor core. Stator and rotor end-caps are toothed. The coil in pole 1 and pole 3 is connected in series consisting of phase A and poles 2 and 4 are for phase B. If stator phase A is excited pole 1 acquires north polarity while pole 2acquires south south pole while pole 3 aligns north pole.



Cross Section of HSM



Cut view of HSM

When the excitation is shifted from phase A to phase B, in which case the stator pole 2 becomes north pole and stator pole 4 becomes south pole, it would cause the rotor to turn 90° in the clockwise direction. Again phase A is excited with pole 1 as south pole and pole 3 as north pole causing the rotor to move 90° in the clockwise direction.

If excitation is removed from phase A and phase B is excited, then pole 2 produces south pole and pole 4 produces north pole resulting in rotor movement of 900 in the clockwise direction. A complete cycle of excitation for the HSM consists of four states and produces four steps of rotor movement. The excitation state is the same before and after these four steps and hence the alignment of stator/rotor teeth occurs under the same stator poles as explained by Kenjo (1984). The step length for a HSM and angle through which the rotor moves for each step pulse is known as step angle and is calculated by

Step length = 90°/Nr

Step angle is calculated using the formula as $\theta = \frac{360°}{m*Nr}$ or, $\theta = \frac{360°(Ns-Nr)}{Ns*Nr}$

Where,

Θ - Step angle in degrees
Ns - Number of stator teeth
Nr - Number of rotor teeth
m - Number of phases

Mechanical angle represents the step angle of the step. In the full step mode of a 1.8° motor, the mechanical angle is 1.8°. In the 10 micro step mode of a 1.8° motor, the mechanical angle is 0.18°. An electrical angle is defined as 360° divided by the number of mechanical phases and the number of micro step. In the full step mode of a 1.8° motor, the electrical angle is 90°. In the 10 micro step excitation of a 1.8° motor, the electrical angle is 9°.

Standard step angle of HSM

Step angle	**Steps per revolution**
0.9	400
1.8	200
3.6	100
7.2	50
1.5	24

Advantages and disadvantages of HSM are discussed by Acarnely (2002) and in a nutshell, they are as here below

A. **Advantages**

1. Step angle error is very small and non-cumulative.
2. Rapid response to starting, stopping and reversing.
3. Brushless design for reliability and simplicity.
4. High torque per package size.
5. Holding torque at standstill.
6. Can be stalled repeatedly and indefinitely without damage.
7. No extra feedback components required (encoders).

B. DISADVANTAGES

1. Resonance
2. Vibration
3. Torque ripple

COMPARISON OF STEPPER MOTOR TYPES

The choice of the type of the stepper motor depends on the application. Selection of stepper motor depends on torque requirements, step angle and control technique.

Comparison based on motor advantages and disadvantages

Motor type	Advantages	Disadvantages
Variable Reluctance Motor	1. Robust –No magnet 2. Smooth movement due to no cogging torque. 3. High stepping rate and speed slewing capability.	1. Vibrations 2. Complex circuit for control 3. No smaller step angle 4. No detent torque.
Permanent Magnet Stepper Motor	1. Detent torque 2. Higher holding torque 3. Better damping	1. Bigger step angle 2. Fixed rated torque. 3. Limited power output and size
Hybrid Stepper Motor	1. Detent torque 2. No cumulative position error 3. Smaller step angle 4. Operate in open loop	1. Resonance 2. Vibration

The increased number of phases requires complicated control circuits, which provide better dynamics and considerable increase in the number of steps.

Driver Circuit of Stepper motor:

Stepper motor performance is strongly dependent on the driver circuit. Torque curves may be extended to greater speeds if the stator poles can be reversed more quickly, the limiting factor being a combination of the winding inductance. To overcome the inductance and switch the windings quickly, one must increase the drive voltage. This leads further to the necessity of limiting the current that these high voltages may otherwise induce.

An additional limitation, often comparable to the effects of inductance, is the back-EMF of the motor. As the motor's rotor turns, a sinusoidal voltage is generated proportional to the speed (step rate). This AC voltage is subtracted from the voltage waveform available to induce a change in the current.

L/R driver circuits

L/R driver circuits are also referred to as constant voltage drives because a constant positive or negative voltage is applied to each winding to set the step positions. However, it is current winding, not voltage that applies torque to the stepper motor shaft. The current (I) in each winding is related to the motor time constant which is the function of winding inductance (L) and the winding resistance (R). The resistance R determines the maximum current according to Ohm's law $I=V/R$. The inductance L determines the maximum rate of change of the current in the winding according to the formula for an inductor $dI/dt = V/L$. The resulting current for a voltage pulse is a quickly increasing current as a function of inductance. This reaches the V/R value and holds for the remainder of the pulse. Thus when controlled by an constant voltage drive, the maximum speed of a stepper motor is limited by its inductance since at some speed, the voltage will be changing faster than the current I can keep up. In simple terms the rate of change of current is L / R (e.g. a 10 mH inductance with 2 ohms resistance will take 5 ms to reach approx 2/3 of maximum torque or around 24 ms to reach 99% of max torque). To obtain high torque at high speeds requires a large drive voltage with a low resistance and low inductance.

With an L/R drive it is possible to control a low voltage resistive motor with a higher voltage drive simply by adding an external resistor in series with each winding. This will waste power in the resistors, and generate heat. It is therefore considered a low performing option, albeit simple and cheap.

Modern voltage-mode drivers overcome some of these limitations by approximating a sinusoidal voltage waveform to the motor phases. The amplitude of the voltage waveform is set up to increase with step rate. If properly tuned, this compensates the effects of inductance and back-EMF, allowing decent performance relative to current-mode drivers, but at the expense of design effort (tuning procedures) that are simpler for current-mode drivers.

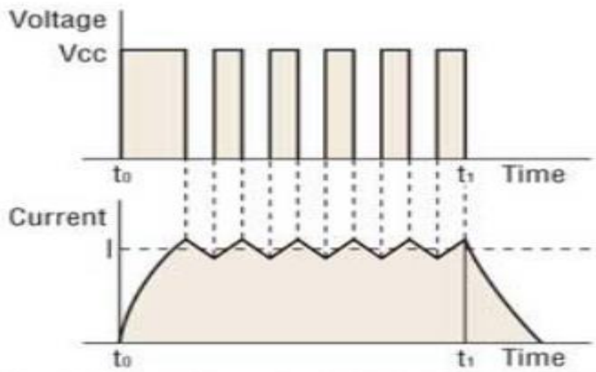
Chopper drive circuits

Chopper drive circuits are referred to as <u>controlled current drives</u> because they generate a controlled current in each winding rather than applying a constant voltage. Because of the torque and speed limitations of L/R stepper drives, an increasing number of stepper motor applications now use chopper drives. These drives are also referred to as “constant current” drives because they supply constant current to the motor windings by “chopping” the output voltage (i.e. turning the output voltage on-and-off very rapidly).

With each motor step, a very high voltage (typically eight times the motor’s nominal voltage) is supplied to the motor windings. This high voltage gives a very short current rise time, according to the relationship for an inductor (dI/dt = V/L), and it causes higher current to be produced, according to Ohm’s law (I = V/R).

Voltage chopping also modulates the width of the output pulses (pulse width modulation) and is typically done at a frequency of 20 kHz or higher, above the audible range. The impedance in the windings varies with the motor speed, so it plays a role in determining the voltage on-time.

At slow motor speeds and low impedance, the chopper drive provides a short on-time for the voltage, producing a small pulse width. Alternatively, at high speeds and high winding impedance the chopper drive provides a long on-time for the voltage, producing a large pulse width and allowing time for the current to rise sufficiently to produce the rated torque.



Relationship in between voltage and current in a chopper drive

A current-sensing resistor placed in series with each winding regulates the current and ensures the shortest time possible for current to build up and decline. As the current increases, voltage develops across the resistor. This voltage is monitored by a comparator and at a predetermined reference voltage, the output voltage from the drive is turned off (chopped) until the next pulse occurs. This allows current to build and decline as the voltage is switched on and off.

By controlling the duty cycle of the drive through chopping, the *average* voltage and current are kept equal to the motor's nominal voltage and current ratings. The result is precise torque control, and more importantly, higher torque production at high motor speeds.