INTRODUCTION

It is an electrodynamics and electromagnetic equipment.

These motors are also referred to as step motors or stepping motors.

On account of its unusual construction, operation and characteristics it is difficult to define a stepper motor. Definition given in British Standard specification (BSS) is

A stepper motor is brushless dc motor whose rotor rotates in discrete angular displacements when its stator windings are energized in a programmed manner. Rotation occurs because of magnetic interaction between rotor poles and poles of the sequentially energized winding. The rotor has no electrical windings, but has salient and magnetic/or magnetized poles.

The stepper motor is a digital actuator whose input is in the form of digital signals and whose output is in the form of discrete angular rotation. The angular rotation is dependent on the number of input pulses the motor is suitable for controlling the position by controlling the number of input pulses. Thus they are identically suited for open position and speed control.

Applications:

- Printers
- Graph plotters
- Tape driver
- Disk Drives
- Machine Tools
- X-Y Recorders
- Robotics space Vehicle
- IC Fabrication and Electric Watches

CLASSIFICATION OF STEPPER MOTORS

As construction is concerned stepper motors may be divided into two major groups.

1. Without Permanent Magnet (PM)
   (a) Single Stack
   (b) Multi Stack
2. With Permanent Magnet
   (a) Claw Pole Motor
   (b) Hybrid Motors
SINGLE STACK VARIABLE RELUCTANCE STEPPER MOTOR

Construction:

The VR stepper motor characterized by the fact there is no permanent magnet either on the rotor or the stator. The construction of a 3-phase VR stepper motor with 6 poles on the stator and 4-pole on the rotor as shown.

![Fig 2.1 Single Stack Variable Reluctance Stepper Motor](image)

The stator is made up of silicon steel stampings with inward projected even or odd number of poles or teeth. Each and every stator poles carries a field coil an exciting coil. In case of even number of poles the exciting coils of opposite poles are connected in series. The two coils are connected such that their MMF gets added. the combination of two coils is known as phase winding.

The rotor is also made up of silicon steel stampings with outward projected poles and it does not have any electrical windings. The number of rotor poles should be different from that of stators in order to have self-starting capability and bi direction. The width of rotor teeth should be same as stator teeth. Solid silicon steel rotors are extensively employed. Both the stator and rotor materials must have lowering a high magnetic flux to pass through them even if a low magneto motive force is applied.

Electrical Connection

Electrical connection of VR stepper as shown fig. Coil A and A’ are connected in series to form a phase winding. This phase winding is connected to a DC source with the help of semiconductor switch S1. Similarly B and B’ and C and C’ are connected to the same source through semiconductor switches S2 and S3 respectively. The motor has 3 –phases a, b and c.

- a phase consist of A and A’ Coils
- b phase consist of B and B’ Coils
- c phase consist of C and C’ Coils
Principle of Operation

It works on the principle of variable reluctance. The principle of operation of VR stepper motor explained by referring fig.

(a). Mode 1: One phase ON or full step operation

In this mode of operation of stepper motor only one phase is energized at any time. If current is applied to the coils of phase \( a' \) (or) phase \( a' \) is excited, the reluctance torque causes the rotor to run until aligns with the axis of phase \( a \). The axis of rotor poles 1 and 3 are in alignment with the axis of stator poles \( A' \) and \( A'' \). Then angle \( \theta = 0^\circ \) the magnetic reluctance is minimized and this state provides a rest or equilibrium position to the rotor and rotor cannot move until phase \( a' \) is energized.

Next phase \( b \) is energized by turning on the semiconductor switch \( S2 \) and phase \( a' \) is de-energized by turning off \( S1 \). Then the rotor poles 1 and 3 and 2 and 4 experience torques in opposite direction. When the rotor and stator teeth are out of alignment in the excited phase the magnetic reluctance is large. The torque experienced by 1 and 3 are in clockwise direction and that of 2 and 4 is in counter clockwise direction. The latter is more than the former. As a result the rotor makes an angular displacement of 30° in counterclockwise direction so that \( B \) and \( B' \) and 2 and 4 in alignment. The phases are excited in sequence a, b and c the rotor turns with a step of 30° in counter clockwise direction. The direction of rotation can be reversed by reversing the switching sequence in which are energized and is independent of the direction of currents through the phase winding.
Fig 2.3 step motions as switching sequence process in a three phase VR motor

The truth table for mode I operation in counter and clockwise directions are given in the table

Table 2.1: Counter Clockwise Rotation (CCW)  Table 2: Clockwise Rotation (CW)

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(b) Mode II: Two Phase on Mode

In this mode two stator phases are excited simultaneously. When phases a and b are energized together, the rotor experiences torque from both phases and comes to rest in a point mid-way between the two adjacent full step position. If the phases b and c are excited, the rotor occupies a position such that angle between AA’ axis of stator and 1-3 axis of rotor is equal to 45°. To reverse the direction of rotation switching sequence is changed a and b, a and c etc. The main advantage of this type of operation is that torque developed by the stepper motor is more than that due to single phase ON mode of operation.

The truth table for mode II operation in counter clockwise and clockwise directions is given in a table

Table 2.3: Counter Clockwise Rotation (CCW)  
Table 2.4: Clockwise Rotation (CW)

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(C) Mode III: Half step Mode

In this type of mode of operation on phase is ON for some duration and two phases are ON during some other duration. The step angle can be reduced from 30° to 15° by exciting phase sequence a, a+b, b, b+c, c etc. The technique of shifting excitation from one phase to another from a to b with an intermediate step of a+b is known as half step and is used to realize smaller steps continuous half stepping produces smoother shaft rotation.
The truth table for mode III operation in counter and clockwise directions are given in the table.

Table 2.5: Counter Clockwise Rotation (CCW)       Table 2.6: Clockwise Rotation (CW)

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**MICRO STEPPING CONTROL OF STEPPING MOTOR**

Stepping motor is a digital actuator which moves in steps of 0° in response to input pulses. Such incremental motion results in the following limitations of the stepper motor.

**Limited resolution**

As 0° is the smallest angle through which the stepper motor can move, this has an effect on position accuracy of incremental servo system employing stepper motors because the stepper motor cannot position the load to an accuracy finer than 0°.

**Mid frequency Resonance**

A phenomenon in which the motor torque suddenly drops to a low value at certain pulse frequencies as in fig.

![Fig 2.4 Mid frequency Resonance](image)
A new principal known as micro stepping control has been developed with a view of overcoming the above limitation. It enables the stepping motor to move through a tiny micro step of size $\Delta \theta s \ll \theta s$ full step angle is response to input pulses.

### 2.4.1 Principle of micro stepping

Assume a two phase stepper motor operating in one phase ON sequence. Assume also that only B2 winding is on and carrying current $IB2 = IR$, the rated phase current. All the other winding are OFF. In this state the stator magnetic field is along the positive real axis as show in fig (a). Naturally the rotor will also as be in $\theta = 0^\circ$ position.

When the next input pulse comes, B2 is switched OFF while A1 is switched ON. In this condition $IA1 = IR$ while all the phase current are zero. As a result the stator magnetic field rotates through $90^\circ$ in counter clockwise direction as show in fig (a).

The rotor follows suit by rotating through $90^\circ$ in the process of aligning itself with stator magnetic field. Thus with a conventional controller the stator magnetic field rotates through $90^\circ$ when a new input pulse is received causing the rotor to rotate full step.

However in micro stepping we want the stator magnetic field to rotate through a small angle $\theta s \ll 90^\circ$ in respect to input pulse. This is achieved by modulating the current through B2 and A1 winding as show in fig (b) such that

$$\begin{align*}
IA1 &= IR \sin \theta \\
IB1 &= IR \cos \theta
\end{align*}$$

Then the resulting stator magnetic field will be at an angle $\theta ^\circ$ with respect to the positive real axis. Consequently the rotor will rotate through an angle $\theta s \ll 90^\circ$.

This method of modulating current through stator winding so as to obtain rotation of stator magnetic field through a small angle $\theta ^\circ$.

![Fig 2.5 Principle of micro stepping](image-url)
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 a multistack motor may employ as many as seven stacks. This type is also known as the cascade type. A cutaway view of a three stack motor is shown in fig. 2.6.

![Fig. 2.6: Construction of multi-stack VR motor.](image1)

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 m0stack 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.

![Fig. 2.7: Cross-section of a 3-stack, VR stepper motor parallel to the shaft.](image2)

Figure 2.7 shows the cross section of a three stack (3-phase) motor parallel to the shaft. 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. When the phase winding A is excited rotor teeth of stack A are aligned with the stator teeth as shown in fig. 2.8.
When phase A is de-energized and phase B is excited the rotor teeth of stack B are aligned with stator teeth. The new alignment is made by the rotor movement of 10° in the anticlockwise direction. Thus the motor moves one step (equal to ½ pole pitch) due to change of excitation from stack A to stack B.

Next phase B is de-energized and phase C is excited. The rotor moves by another step 1/3rd of pole pitch in the anticlockwise direction. Another change of excitation from stack C to stack A will once more align the stator and rotor teeth in stack A. however during this process (A → B → C → A) the rotor has moved one rotor tooth pitch.

![Fig. 2.8: Position of stator & rotor teeth of 3 stack VR motor](image)

Let Nr be the number of rotor teeth and \( m \) the number of stacks or phases, then:

Tooth pitch \( T_p = \frac{360}{N_r} \) \... (2.1)

Step Angle \( \alpha = \frac{360°}{mN_r} \) \... (2.2)

**Hybrid stepper motor**

**Principle of operation**

Most widely used hybrid motor is the two phase type as shown in fig2.11. This model has four poles and operates on one phase on excitation.
The coil in pole 1 and that in pole 3 are connected in series consisting of phase A, and pole 2 and 4 are for phase B. Fig 2.12 shows the process of rotor journey as the winding currents are switched in one phase ON excitation.

The poles of phase A are excited the teeth of pole 1 attract some of the rotors north poles, while the teeth of pole 3 align with rotor’s south poles. Current is then switched to phase B. The rotor will travel a quarter tooth pitch so that tooth alignment takes place in 2 and 4.

Next current is switched back to phase A but in opposite polarity to before, the rotor will make another quarter tooth journey. The tooth alignment occurs in opposite magnetic polarity to state 1. When current is switched to phase B in opposite polarity (4) Occurs as a result of quarter tooth pitch journey.

The structures of two phase motor considered in fig.2.11 will not produce force in a symmetrical manner with respect to the axis. The motor having 8 poles in the stator shown in fig2.13 considered as the structure in which torque is generated at a symmetrical position on the surface.

2.7 CLAW TOOTH PM 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. Teeth are punched out of a circular metal sheet and the circle is then drawn into a bell shape. The teeth are then drawn inside to form claw teeth. A Stack of the stator is formed by joining two bell shaped casings so that the teeth of both of them are intermeshed and the toroid coil is contained within them.
This type of motor shown in fig 2.14 is usually of two stacks. Since the rotor has magnetic poles that are axially aligned and is common for both stator stacks, the stator tooth pitches are misaligned by a quarter pitches between the two stacks.

![Fig. 2.12 Cutaway diagram of a claw-tooth PM motor](image)

The sequence of excitation is shown in fig. when phase A is excited, the rotor moves by the tension of magnetic lines (state 1). State 2 is the equilibrium position with phase A excited. Next if current is switched to phase B, the rotor will be driven further in the same direction, because the stator teeth in stack B are misaligned by a quarter tooth pitch to the left.

![Fig. 2.13 Current waveform supplied to a claw-tooth PM motor](image)

with respect to the teeth in stack A. State 3 shows the result due to this excitation. To advance the rotor further to the left and place in the next state (4), phase B is de-energized and phase A is excited. Next, current will be switched to phase B.

The claw tooth motor has low manufacturing cost through it cannot realize a very small step angle.

**SINGLE PHASE STEPPING 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.

The two requirements of single phase stepping motor are
To detent the motor at a particular position when the coil is not excited.

To rotate the motor at desired direction by switching the magnetic polarity of only one coil.

2.8.1 CONSTRUCTION

It is a permanent magnet type stepper motor with two poles. Rotor is a circular type of permanent magnet as shown in figure 2.27. 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. Minimum values occur at one tip of the poles. Under normal conditions the rotor occupies any one of the decent position shown in fig 2.28(a) or as in (b) to minimum reluctance position. Two positions shown in figures 2.28(a) & (b) are the detent positions of the rotor of the stepper motor.

![Fig. 2.14 A single-phase stepping motor](image1)

![Fig. 2.15 Detent positions and coil polarity to rotate motor.](image2)

2.8.2. PRINCIPLE OF OPERATION

When the coil is given an electric positive pulse, pole A in position 1 as shown in figure. 2.28(a) it experiences a torque in clockwise direction and finally attains a steady state as in fig 2.28(b). Then pulse given to the coil is zero. After a lapse of a second, from the start of the pulse, a negative pulse is given to the coil which makes the pole A as south and pole B as north. Rotor experiences another torque in figure 2.28(a). By repeating the cycle the rotor rotates continuously in step. It is not possible to develop torque in counter clockwise direction by altering pulses.

THEORY OF TORQUE PREDICTION

According to Faradays laws of electromagnetic induction
Flux linkages \( \lambda = N \phi \)  
\[ \lambda = Li \]  

Flux linkages can be varied by 

Varying flux \( \phi \) 

Varying the current \( i \) of an electromagnet (i.e) equivalent of varying the mmf 

Varying the reluctance \( L = \frac{N^2}{s} \) 

By varying reluctance 

\( \text{mmf} = N \phi \)  
\[ \text{Reluctance} = \frac{1}{A \mu} \]  
\[ \text{Flux} = \frac{Ni}{s} \]  

Flux linkages \( \lambda = \frac{N Ni}{s} = \frac{N^2}{s} \)  

Inductance \( L = \frac{\text{flux linkages}}{\text{Ampere}} \)  
\[ L = \frac{N^2 i}{s} \]  
\[ L = \frac{N^2}{s} \] 

If the reluctance of magnetic circuit can be varied, inductance \( L \) and the flux linkages \( \lambda \) can also be varied. 

Consider a magnetic circuit as shown in fig. 2.29. 

![Fig. 2.16 Magnetic circuit](image) 

The stator consists magnetic core with two pole arrangement. Stator core carries a coil. Rotor is also made up of ferrous material. The motor core is similar to a salient pole machine. Let the angle between the axis of stator pole and rotor pole be \( \theta \). Let the angular displacement be illustrated using fig. 2.29 (a, b and c).
Case 1: $\theta = 0$

As shown in fig. 2.29 (a) the air gap between the stator and rotor is very very small. Thereby the reluctance of the magnetic path is least. Due to minimum reluctance, the inductance of the circuit is minimum. Let it be $L_{\text{max}}$

Case 2: $\theta = 45^0$

As shown in fig. 2.29(b) in this only a portion of rotor poles cover the stator poles. Therefore reluctance of the magnetic path is more than that of case 1.due to which the inductance becomes less $L_{\text{max}}$.

Case 3: $\theta = 90^0$

As shown in fig. 2.29(c) the air gap between the stator poles has maximum value. Thereby reluctance has a value yielding minimum inductance. Let it be $L_{\text{min}}$.

Variation in inductance with respect to the angle between the stator and rotor poles is shown in fig. 2.30.

![Fig. 2.17 Variation in inductance w.r to $\theta$.](image)

**Derivation for reluctance torque**

As per faradays law of electromagnetic induction an emf induced in an electric circuit when there exists a change in flux linkages.

$$\text{emf induced } e = - \frac{\partial \lambda}{\partial t}$$

Where $\lambda = N\Phi$ or $\lambda = Li$  

$\ldots\ldots\ldots (2.12)$

Therefore $e = - \frac{d}{dt}[Li]$  

$\ldots\ldots\ldots (2.13)$

$$= - L \frac{dI}{dt} - i \frac{dL}{dt}$$

$\ldots\ldots\ldots (2.14(a))$

$$= - L \frac{dI}{dt} - i \frac{dL}{d\theta} \frac{d\theta}{dt}$$

$\ldots\ldots\ldots (2.14(b))$

$$= - L \frac{dI}{dt} + \omega i \frac{dL}{d\theta}$$

$\ldots\ldots\ldots (2.14(c))$

Magnitude of $e = L \frac{di}{dt} + \omega i \frac{dL}{d\theta}$  

$\ldots\ldots\ldots (2.15)$
If the direction of current $I$ is opposite to that of $e$, then the electric power is transferred from the source to the inductor. On the other hand, if the direction of current $I$ is same as that of $e$, then the source gets the electrical power from the inductor.

On the basis of magnetic circuit/field theory it is known that the stored energy in a magnetic field.

$$W_e = \frac{1}{2} L i^2 \quad \ldots \ldots \quad (2.16)$$

The rate of change of energy transfer due to variation in stored energy or power due to variation in stored energy.

$$\frac{dW_e}{dt} = \frac{1}{2} L \frac{di}{dt} + \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.17)$$

Mechanical power developed/consumed = power received from the electrical source – power due to change in stored energy in the inductor

Power received from the electrical source = $ei$

$$ei = i \frac{di}{dt} + \omega i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.18)$$

Power due to change in stored energy

$$= L \frac{di}{dt} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.19)$$

Mechanical power developed

$$= i \frac{di}{dt} + \omega i^2 \frac{\partial L}{\partial \theta} + L \frac{di}{dt} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.20)$$

Mechanical power developed

$$P_m = \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.21)$$

$$P_m = \frac{2 \pi N T}{\omega} \quad \ldots \ldots \quad (2.22)$$

$$P_m = \omega T \quad \ldots \ldots \quad (2.23)$$

Where $\omega = \frac{2 \pi N}{\omega_0}$

Therefore reluctance torque $T = \frac{P_m}{\omega}$ \ldots \ldots \quad (2.24)

Reluctance torque $T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \quad \ldots \ldots \quad (2.25)$

Note:

* Torque corresponds to monitoring when $\frac{\partial L}{\partial \theta}$ is +ve.
* Torque corresponds to generating when $\frac{\partial L}{\partial \theta}$ is -ve.

* Torque is proportional to $i^2$ : Therefore it does not depend upon the direction of the current.

**TERMINOLOGIES USED IN STEPPER MOTOR**

1. Step motor
2. Resolution
3. Stepping rate
4. Hold position
5. Detent position
6. Stepping error
7. Position Error

1. **Step angle ($\Theta_s$ or $\beta$)**

   It is the angular displacement of rotor of a stepper motor for every pulse of excitation given to the stator winding of the motor. It is determined by the number of teeth on the rotor and stator, as well as the number of steps in the energisation sequence. It is given by

   $$\Theta_s = \beta = \frac{360}{mN_r}$$

   Where

   - $m =$ Number of phases (m and q)
   - $N_r =$ number of teeth on rotor.

   Also, $\Theta_s = ((N_s - N_r)/(N_s N_r)) \times 360$

2. **Resolution**

   It is the number of steps per revolution. It is denoted as S or Z. It is given by

   $$Z = \frac{360}{\Theta_s}$$

   For variable reluctance motor $Z = (q N_r)$ or $(m N_r)$

   For PM motor and hybrid motor $Z = 2q N_r$

   Also, $Z = (N_s N_r)/(N_s - N_r)$

   Where $N_s =$ number of teeth/poles on stator.
3. **Stepping Rate**

The number of steps per second is known as stepping rate or stepping frequency.

4. **Hold Position**

It corresponds to the rest position when the stepper motor is excited or energized (this corresponds to align position of VR motor).

5. **Detent Position**

It corresponds to rest position of the motor when it is not excited.

6. **Stepping Error**

Actual step angle is slightly different from the theoretical step angle. This is mainly due to tolerances in the manufacture of stepper motor and the properties of the magnetic and other materials used.

The error in the step angle is expressed as a percentage of the theoretical step angle.

\[
\%\text{error} = \left(\frac{\text{step angle} - \text{theoretical step angle}}{\text{theoretical step angle}}\right) \times 100
\]

Percentage error is restricted to ±5%. In some cases it is restricted to ±2%. The cumulative error between the actual angular displacement and theoretical angular displacement is expressed as a percentage of theoretical angular displacement. It is usually considered for one complete cycle.

7. **Positional Error**

The maximum range of cumulative percentage of error taken over a complete rotation of stepper motor is referred to as positional accuracy as shown in fig below.

![Fig. 2.18 Positional Accuracy](image)

**CHARACTERISTICS OF STEPPER MOTOR**

Stepper motor characteristics are divided into two groups:

- Static characteristics
- Dynamic characteristics
Static characteristics

It is divided into two characteristics.

(i) Torque Angle curve

(ii) Torque current curve

(i) Torque-Angle curve

Torque angle curve of a step motor is shown in fig. 2.32. It is seen that the Torque increases almost sinusoidally with angle $\Theta$ from equilibrium.

Fig. 2.19 Torque Angle

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.

Torque current curve

A typical torque curve for a stepper motor is shown in fig. 2.34. It is seen the curve is initially linear but later on its slope progressively decreases as the magnetic circuit of the motor saturates.
Torque constant (Kt)

Torque constant of the stepper is defined as the initial slope of the torque-current (T-I) curve of the stepper motor. It is also known as torque sensitivity. Its units N-mA, kg-cm/A or OZ-in/A

Dynamic characteristics

A stepper motor is said to be operated in synchronism when there exist strictly one to one correspondence between number of pulses applied and the number of steps through which the motor has actually moved. There are two modes of operation.

Start-Stop mode

Also called as pull in curve or single stepping mode.

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 stop.

Start Stop mode

Start stop mode of operation of stepper motor is shown in fig.2.35 (a). 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.

Fig. 2.20 Torque-current Curve

Fig. 2.21 Modes of operation
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 torque developed and the stepping rate or stepping frequency of stepper motor.

![Fig. 2.21 Modes of operation](image)

**2.12. TORQUE-SPEED CHARACTERISTICS**

Torque developed by the stepper motor and stepping rate characteristics for both modes of operation are shown in fig.2.36. the curve ABC represents the "pull in" characteristics and the curve ADE represents the "pull-out" characteristics.

![Fig. 2.22 Torque-Speed Characteristics](image)

The area OABCO represents the region for start stop mode of operation. At any operating point in the region the motor can start and stop without losing synchronism. The area ABCEDA refers to the region for slewing mode of operation. At any operating point without losing synchronism to attain an operating point in the slewing mode at first the motor is to operate at a point in the start-stop mode and then stepping rate is increased to operate in slewing mode, similarly while switching off it is essential to operate the motor from slewing mode to start-stop mode before it is stopped.
Pull in torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the start-stop mode of operation without losing synchronism. In the fig.2.36 LM represents the pull in torque (i.e.) TPI corresponding to the stepping rate F (i.e.) OL.

Pull out torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the slewing mode without losing synchronism. In fig.2.36 LN represents the pull in torque (i.e.) TPO corresponding to F (i.e.) OL.

Pull in range

It is the maximum stepping rate at which the stepper motor can operate in start-stop mode developing a specific torque (without losing synchronism). In fig. 2.36 PIT represents pull in range for a torque of T (i.e.) OP. This range is also known as response range of stepping rate for the given torque T.

Pull out range

It is the maximum stepping rate at which the stepper motor can operate in slewing mode developing a specified torque without losing synchronism. In fig.2.36 PIPO represents the pull out range for a torque of T. The range PIPO is known slewing range.

Pull in rate (FPI)

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

Pull out rate (FPO)

It is the maximum stepping rate at which the stepper motor will slew, without missing steps, against load torque T.

Synchronism

This term means one to one correspondence between the number of pulses applied to the stepper motor and the number of steps through which the motor has actually moved.

Mid frequency resonance

The phenomenon at which the motor torque drops to a low value at certain input pulse frequencies.

FIGURES OF MERIT (FM'S)

Figures of merit (FM'S) are performance indices which give quantitative information on certain aspects of performance and design of actuators such as stepper motors, DC or AC servomotors etc.
1. Electrical Time constant (Te)

\[ Te = \frac{Lm}{Rm} \quad \ldots \ldots \quad (2.26) \]

where \( Lm \) - Inductance of motor winding

\( Rm \) - resistance of motor.

\( Te \) governs the rate at which current rises when the motor winding is turned on. It also determines how quickly the current decays when the winding is turned off.

In motion control, the speed of response is of importance. Hence electrical time constant \( Te \) must be minimized.

\( Te \) dependent upon inductance and resistance of the motor winding. Inductance is determined by magnetic circuit. (i.e.) magnet iron volume as well as volume of copper used in the motor design. Once these have been designed, neither reducing conductor size nor increasing the number of turns will reduce \( Te \). Otherwise magnetic circuit itself has to be redesigned.

2. Motor time constant (Tm)

\[ Tm = \frac{J}{(Ke.KtRm)} = \frac{JRm}{Ke} \quad \ldots \ldots \quad (2.27) \]

\( J \) - moment of inertia of motor (kg-m²)

\( Rm \) - resistance of the motor winding (Ω)

\( Ke \) - back emf constant (volts/ rad)

\( Kt \) - torque constant (Nm/A)

Motor back emf and torque constants are determined by magnetic circuit and phase winding design. Winding resistance also from winding design. Moment of inertia is determined by mechanical design.

In this way motor time constant \( Tm \) combines all the three aspects of motor design viz, magnetic circuit, electrical circuit and mechanical design. Achieving a low \( Tm \) requires excellence in motor design. As a thumb rule the ratio of \( Te/Tm \) 0.1

Initial Acceleration (a0):

\[ A0 = \frac{T}{J}(rad/S^2) \]

Where \( T \) - rated torque (N-M)

\( J \) - moment of inertia (kg-m²)

\( a0 \) gives a quantitative idea of how fast the motor accelerates to its final velocity or position. Maximization of \( a0 \) calls for good magnetic circuit design to produce high torque in conjunction with good mechanical design to minimize rotor inertia. The moment of inertia of the load coupled to motor also determines \( a0 \).
**Motor Constant (km)**

\[ \text{km} = \frac{T}{\sqrt{\omega}} \]

where \( T \)- rated motor torque

\[ \omega \] - rated power(w) of the motor

\[ \text{km} = \sqrt{\frac{Kt}{Ke/Rm}} \]

This shows that maximizing \( \text{km} \) causes minimizing \( R \), maximizing \( Ke \) and \( Kt \). Maximizing \( Ke \) and \( Kt \). Call for optimization of magnetic circuit design, decreasing electrical time constant \( Te \) which is undesirable. A trade off between electrical and magnetic circuit design is necessary to achieve a good \( \text{km} \).

Power rate \((dP/dt)\):

\[ \text{Power rate is } (dP/dt) = (d/dt)(T.(d\omega /dt)) = T.(d2\omega /dt^2) = T.(T/J) = (T^2/J) \quad \ldots ..(2.28) \]

Now \( T = Kt I \) so

**DRIVE SYSTEM AND CONTROL CIRCUITRY FOR STEPPER MOTOR**

**DRIVE SYSTEM**

The stepper motor is a digital device that needs binary (digital) signals for its operation. Depending on the stator construction two or more phases have to be sequentially switched using a master clock pulse input. The clock frequency determines the stepping rate, and hence the speed of the motor. The control circuit generating the sequence is called a translator or logic sequencer.

![Block Diagram of the drive system of a stepping motor.](image)

The fig 2.38 shows the block diagram of a typical control circuit for a stepper motor. It consists of a logic sequencer, power driver and essential protective circuits for current and voltage limiting. This control circuit enables the stepper motor to be run at a desired speed in either direction. The power driver is essentially a current amplifier, since the sequence generator can supply only logic but not any power. The controller structure for VR or hybrid types of stepper motor
LOGIC SEQUENCER

The logic sequencer is a logic circuit which control the excitation of the winding sequentially, responding to step command pulses. A logic sequencer is usually composed of a shifter register and logic gates such as NANDs, NORs etc. But one can assemble a logic sequencer for a particular purpose by a proper combination of JK flip flop, IC chips and logic gate chips.

Two simple types of sequencer build with only two JK-FFs are shown in fig 2.39 for unidirectional case. Truth tables for logic sequencer also given for both the directions.
TABLE 2.7 Logic Sequencer

| R | 1 | 2 | 3 | 4 | 5 | 6 | …  
|---|---|---|---|---|---|---|---
| Ph A,Q1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | …  
| Ph B,Q2 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | …  
| Ph A,Q1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | …  
| Ph B,Q2 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | …  

Fig.2.25 A unidirectional logic sequencer for two phase on operation of a two phase hybrid motor

The corresponding between the output terminals of the sequencer and the phase windings to be controlled is as follows.

Q1----Ph A  
Q1----Ph A  
Q2----Ph B  
Q2----Ph B

If Q1 is on the H level the winding Ph A is excited and if Q1 is on L level, Ph A is not excited.

To reserve the rotational direction, the connection of the sequencer must be interchanged. The direction switching circuits shown in Fig 2.40 may be used for this purpose. The essential functions being in the combination of three NAND gates or two AND gates and a NOR gate.

2.14.3. Power Driver Circuit

The number of logic signals discussed above is equal to the number of phases and the power circuitry is identical for all phases. Fig. 2.44(a) shows the simplest possible circuit of one phase consisting of a Darlington pair current amplifier and associated protection circuits. The switching waveform shown in fig. 2.44(c) is the typical R-L response with an exponential rise followed by decay at the end of the pulses.

In view of the inductive switching operation, certain protective elements are introduced in the driver circuit. These are the inverter gate 7408, the forward biased diode D1 and the freewheeling diode D. The inverter IC provides some sort of isolation between the logic circuit and the power driver.
There are some problems with this simple power circuit. They can be understood by considering each phase winding as a R-L circuit shown in fig. 2.44(b) subject to repetitive switching. On application of a positive step voltage, the current rises exponentially as

\[ i(t) = I(1 - e^{-t/T}) \]  

Where \( I = V/R \) – rated current and

\[ T = L/R \]  

winding time constant.

Fig. 2.26 Power Driver Stage of Stepper Motor Controller

In practice, the time constant \( T \) limits the rise and fall of current in the winding. At low stepping rate the current rises to the rated value in each ON interval and falls to zero value in each OFF interval. However as the switching rate increases, the current is not able to rise to the steady state, nor fall down to zero value with in the on/off time intervals set by the pulse waveform. This in effect, smoothens the winding current reducing the swing as shown in fig. 2.45. As a result the torque developed by the motor gets reduced considerably and for higher frequencies, the motor just ‘vibrates’ or oscillates within one step of the current mechanical position.
In order to overcome these problems and to make improvement of current build up several methods of drive circuits have been developed.

For example when a transistor is turned on to excite a phase, the power supply must overcome effect of winding inductances has tendency to oppose the current built up. As switching frequency increases the position that the buildup time takes up within the switching cycle becomes large and it results in decreased torque and slow response.

### 2.14.4 Improvement of current buildup/special driver circuit

**a) Resistance drive (L/R drive)**

Here the initial slope of the current waveform is made higher by adding external resistance in each winding and applying a higher voltage proportionally. While this increases the rate of rise of the current, the maximum value remains unchanged as shown in fig. 2.46.

The circuit time constant is now reduced and the motor is able to develop normal torque even at high frequencies. The disadvantage of this method is

Flow of current through external resistance causes $I R$ losses and heating. This denotes wastage of power as far as the motor is concerned.

In order to reach the same steady state current $I R$ as before, the voltage required to be applied is much higher than before. Hence this approach is suitable for small instrument stepper motor with current ratings around 100 mA, and heating is not a major problem.
(b) Dual voltage driver (or) Bi-level driver

To reduce the power dissipation in the driver and increase the performance of a stepping motor, a dual-voltage driver is used. The scheme for one phase is shown in fig. 2.47.

When a step command pulse is given to the sequencer, a high level signal will be put out from one of the output terminal to excite a phase winding. On this signal both $T_1$ and $T_2$ are turned on, and the higher voltage $E_H$ will be applied to the winding. The diode $D_1$ is now reverse biased to isolate the lower voltage supply. The current build up quickly due to the higher $E_H$. The time constant of the monostable multivibrator is selected so that transistor $T_1$ is turned off when the winding current exceeds the rated current by a little. After the higher

![Fig. 2.29 Improvement of current buildup by dual voltage drive](image)

Voltage source is cut off the diode is forward biased and the winding current is supplied from the lower voltage supply. A typical current wave form is shown in fig. 2.48.

![Fig. 2.30 Voltage and current wave form in dual voltage driver](image)

When the dual voltage method is employed for the two phase on drive of a two phase hybrid motor, the circuit scheme will de such as that shown in fig.2.49. Two transistor $T_1$ & $T_2$ and two diodes $D_1$ and $D_2$ are used for switching the higher voltage. In dual voltage
scheme as the stepping rate is increased, the high voltage is turned on for a greater percentage of time.

Fig. 2.31 A dual-voltage driver for the two-phase-on drive of a two-phase hybrid motor

This drive is good and energy efficient. However, it is more complex as it requires two regulated power supplies EH & EL and two power transistor switches Tr1 & Tr2 and complex switching logic. Hence it is not very popular.

(c) Chopper drive

Here a higher voltage 5 to 10 times the related value is applied to the phase winding as shown in fig. 2.30(a) and the current is allowed to raise very fast. As soon as the current reaches about 2 to 5% above the rated current, the voltage is cut off, allowing the current to decrease exponentially. Again as the current reaches some 2 to 5% below the rated value, the voltage is applied again. The process is repeated some 5-6 times within the ON period before the phase is switched off. During this period the current oscillates about the rated value as shown in fig. A minor modification is to chop the applied dc voltage at a high frequency of around 1kHz, with the desired duty cycle so as to obtain the average on-state current equal to the rated value.

Fig. 2.32 Chopper drive
The chopper drive is particularly suitable for high torque stepper motors. It is ener4gy efficient like the bi-level drive but the control circuit is simpler.

(d) Problems with driver circuits

A winding on a stepping motor is inductive and appears as a combination of inductance and resistance in series. In addition, as a motor revolves a counter emf is produced in the winding. The equivalent circuit to a winding is hence, such as that shown for designing a power driver one must take into account necessary factors and behavior of this kind of circuit. Firstly the worst case3 conditions of the stepping motor, power transistors, and supply voltage must be considered. The motor parameters vary due to manufacturing tolerance and operating conditions. Since stepping motors are designed to deliver the highest power from the smallest size, the case temperature can be as high as about 100°C and the winding resistance therefore increases by 20 to 25 per cent.

Suppressor circuits

These circuits are needed to ensure fast decay of current through the winding when it is turned off. When the transistor in the above fig is turned off a high voltage builds up to Ldi/dt and this voltage may damage the transistor. There are several methods of suppressing this spike voltage and protecting the transistor as shown in the following.

(a) Diode suppressor

If a diode is put in parallel with the winding in the polarity as shown in fig. a circulating current will flow after the transistor is turned off, and the current will decay with time. In this scheme, no big change in current appears at turn off, and the collector potential is the supply potential E plus the forward potential of the diode. This method is very simple but a drawback is that the circulating current lasts for a considerable length of time and it produces a braking torque.

![Diode suppressor](image)

Fig. 2.33 Diode suppressor

(b) Diode-Resistor suppressor

A resistor is connected in series with the diode as shown in fig to damp quickly the circulating current. The voltage VCE applied to the collector at turn-off in this scheme is

\[ VCE = E + IRS + VD \]

Where E= supply potential
\[ I = \text{Current before turning off} \]

Rs - resistance of suppressor resistor

VD - forward potential of diode

Fig. 2.34 Diode-resistor suppressor

A high resistance RS is required to achieve a quick current decay, but this also results in a higher collector potential VCE, thus a transistor with a high maximum voltage rating is necessary.

**(a) Zener diode suppressor**

In this zener diode are often used to connect in series with the ordinary diode as shown in fig. Compared with preceding two cases zener diode which provides negative bias causes the current to decay more quickly after turn off. In addition to this, it is a merit of this method that the potential applied to the collector is the supply potential plus the zener potential, independent of the current. This makes the determination of the rating of the maximum collector potential easy. However zeners are signal diodes, rather than power diodes. Their power dissipation is limited to 5w. Consequently, this suppressor can be used for very small instrument stepper motors of typical size 8 to 11.

Comparison of effects of various suppressor schemes of various suppressor schemes
(d) Condenser suppressor

This scheme is often employed for bifilar-wound hybrid motor. An explanation is given for the circuit shown in fig:

![Condenser suppressor circuit](image)

Fig. 2.37 Condenser suppressor

A condenser is put between ph A and ph A\(\Box\) and between ph B and ph B\(\Box\). These condensers serve two fold purposes.

1. When a transistor is turned off, the condenser connected to it via a diode absorbs the decaying current from the winding to protect the transistor.

   Let us see the situation just after the Tr 1 is turned off in the one phase on mode. Either Tr 2 or Tr 4 will turn on, but Tr 3 will still be in the turned off state. Since the winding of ph A & ph A\(\Box\) are wound in the bifilar fashion, a transient current will circulate in loop. If Tr 3 is turned on when the transient current becomes zero and the charge stored in the condenser becomes maximum, a positive current can easily flow through phase A winding. By this resonance mechanism, currents are used efficiently in this scheme. This feature remains in the two phase on mode too. The condenser suppressor is suited to drives in which stepping rate is limited in a narrow range.

2. Another utility of condensers is as an electrical damper, a method of damping rotor oscillations is to provide a mechanism to convert kinetic energy to joule heating. If a rotor having a permanent magnet oscillates, an alternating emf is generated in the winding. However if a current path is not provided or a high resistance is connected, no current will be caused by this emf. When the condenser is connected between phases an oscillatory current will flow in the closed loop and joule heat is generated in the windings, which means that the condenser works as an electrical damper.

2.15. LINEAR AND NON LINEAR ANALYSIS

The linear and nonlinear analysis of the motor performance with respect to the torque produced by the rotor of the motor is explained.

Let

\[ T_m \] be the motor torque produced by the rotor in Nm
J be the inertia of the rotor and load combination in kgm²

ω be the angular velocity of the rotor

D be the damping coefficient or viscous frictional coefficient

Tf be the frictional load torque independent of the speed

θs be the step angle in radians

F be the stepping rate in steps/sec or pps

Frictional load torque Tf = K

According to rotor dynamics

\[ T_m = -J \frac{d\omega}{dt} + D\omega + Tf \]  \hspace{1cm} (2.30)

Also \( \theta_s = \theta = \omega t = \text{step angle} \)

\[ \omega = \theta_s / t = f \theta_s \]  \hspace{1cm} (2.31)

where \( f = 1/t \)  \hspace{1cm} (2.32)

By putting \( \omega = f \theta_s \)

\[ T_m = J \frac{d}{dt}(f \theta_s) + D(f \theta_s) + Tf \]  \hspace{1cm} (2.33)

\( \theta_s = 360 / mN_r \) is fixed for a particular type of motor

So \( \theta_s \) can be considered as constant

Therefore \[ T_m = J \theta_s \frac{d}{dt}(f \theta_s) + D(f \theta_s) + Tf \]  \hspace{1cm} (2.34)

In equation 2.47 if viscous friction constant is neglected the equation will be a linear equation, the corresponding acceleration will be nonlinear and the equation will be nonlinear which given rise to nonlinear analysis.

Linear acceleration on linear analysis

If the damping coefficient is neglected \( D = 0 \)

The expression for motor torque becomes

\[ T_m = -J \frac{d\omega}{dt} + Tf \]  \hspace{1cm} (2.35)

\[ T_m - Tf = J \frac{d\omega}{dt} \]

\[ (T_m - Tf)/J = \frac{d\omega}{dt} \]

\[ d\omega = (T_m - Tf)/J \]  \hspace{1cm} (2.36)

Integrating
\[ \omega = \frac{(T_m - T_f)}{J} \]dt + \omega_1 \quad \text{ .................. (2.37)}

Where

\[ \omega_1 = \text{Integration constant} \]

Mathematically \( \omega_1 \) is the constant of integration but it indicates the initial angular velocity of the motor before the occurrence of acceleration.

Therefore \( \omega = 0 \) s f and \( \omega_1 = 0 \) s f1

Substituting \( \omega \) and \( \omega_1 \) in equation 2.50

\[ \left( \frac{(T_m - T_f)}{J} \right) t + 0s f1 = 0sf \quad \text{ ..................(2.38)} \]

Dividing throughout by 0s we get

\[ \left( \frac{(T_m - T_f)}{J} \right) t + f1 = f \]

Therefore stepping rate \( f = \left( \frac{(T_m - T_f)}{J} \right) t + f1 \quad \text{ ..................(2.39)} \)

And \( T_f = K \theta \)

Figure 2.38 shows the linear acceleration from \( \omega_1 \) to \( \omega_2 \)

Nonlinear (exponential) acceleration on Nonlinear analysis

Considering the torque produced by the motor

\[ T_m = j0s \frac{df}{dt} + D0sf + T_f \quad \text{ ......(2.40)} \]

\[ (T_m - T_f) = j0s \frac{df}{dt} + D0sf \]

Dividing throughout by \( j0s \) We get

\[ (\frac{df}{dt}) + (\frac{D}{j})f - (\frac{T_m - T_f}{j0sf}) = 0 \]

(\text{or}) \quad (\frac{df}{dt}) + (\frac{D}{j})f = (\frac{T_m - T_f}{j0sf}) \quad \text{ .... (2.41)}

The above eqn. 2.54 is of the form

\[ (\frac{dy}{dx}) + py = Q \text{ Which have the solution of} \]

\[ ye^{\int pdx} = \int Q e^{\int pdx} + C \quad \text{ .................(2.42 )} \]
Here y=f; x=t; p=(D/j) and Q=(Tm-Tf)/j and s =constant

\[
\frac{fe[D/J dt]=[(Tm-Tf)/j0se[D/J dt]+C}{s e[D/J t]=(Tm-Tf)/j0se[D/J t+(D/J)]+C}
\]

\[
\frac{fe[D/J t]=[(Tm-Tf)/j0se[D/J t/(D/J))]+C}{s e[D/J t]=[(Tm-Tf)/j0se[D/J t/(D/J))]+C}
\]

where C is the integration constant

To find C substituting initial condition at t=0; f=f(0)=f1f1e0==((Tm-Tf)/j0se[D/J dt]+C)

\[
\frac{f1===(Tm-Tf)/j0se[D/J dt]+C}{f1===(Tm-Tf)/j0se(D/J)+C}
\]

\[
\frac{f1=(Tm-Tf)/D0s+C}{f1=(Tm-Tf)/D0s+C}
\]

\[
C= f1-(Tm-Tf)/D0s
\]

Substituting eqn. (2.62) in eqn. (2.58)

\[
\frac{f e(D/J)t==((Tm-Tf)/j0se(D/J)e(D/J)t++(f1-(Tm-Tf)/D0s))}{f e(D/J)t==((Tm-Tf)/D0se(D/J)t++(f1-(Tm-Tf)/D0s))}
\]

Dividing throughout by e(D/J)t we get

\[
F=(Tm-Tf)/D0s +(f1-(Tm-Tf)/D0s)e-D/j t
\]

Stepping frequency f= (Tm-Tf)/D0s +((f1-(Tm-Tf)/D0s)e-D/j t

The above equation is a nonlinear exponential equation which gives rise to nonlinear acceleration of the rotor of the motor.

**APPLICATION OF STEPPER MOTOR:**

The main application of stepper motor may be divided into the following groups.

1. Instrumentation applications.
2. Computer peripherals & Office equipment's.
3. Numerical control of machine tools and robotics.
4. Applications in semiconductor technology.
5. Space vehicles and satellites.
6. Electro medical and

7. Miscellaneous applications.

1. **Instrumentation application:**

This involve low torque applications such as

- Quartz watches.
- Synchronized clocks.
- Camera shutter operations.

2. **Stepper motor application in computer peripherals:**

This involve medium torque, high performance and high volume application such as

- Dot matrix and line printers.
- Graph plotters.
- Floppy disk drives
- Digital X-Y plotters.
- Magnetic tape drives.
- Paper tape drives.

3. **Application is office equipment:**

- Electronic typewriters.
- Copiers
- Facsimile machines.

4. **Machine tool applications:**

- This involve high torque application such as
- Numerical control system for milling machine
- X-Y tables and index table.
- Home use and industrial sewing machines.

5. **Application in semiconductor technology:**

- Stepper motors used in high vacuum.
- Goniometer-An instrument used to determine crystalline structure.
Electron beam micro fabricator.

6. Stepper motor used in space vehicles and satellites.

7. Robotics.

8. **Electro medical applications:**

   This involve high torque applications such as
   
   X-ray machines.

   Radiation therapy units.

   Ultra sound scanner.

9. **Miscellaneous applications:**

   Nuclear reactors.

   Heavy industry applications.

   Automatic focusing mechanism in camera
**Glossary**

1. **Stepper motor** -- Stepper motor is a brushless DC motor whose rotor rotates in discrete displacements when its stator windings are energized in a programmer manner. The rotor has no winding, magnets or case winding.

2. **Full step operation** -- Single phase on mode is the one in which at time only one phase winding is energized.

3. **Step Angle** -- It is the angular displacement of the rotor of the stepper motor for every pulse of excitation given to the stator windings of the motor.

4. **Resolution** -- It is number of steps per revolution.

5. **Stepping rate/frequency** -- The number of steps per second.

6. **Hold Position** -- It is corresponds to the rest position when the stepper motor is excited or energized.

7. **Stepping Error** -- Actual step angle is slightly different from the theoretical step angle.

8. **Positional Error** -- The maximum range of cumulative percentage of error taken over a complete rotation of stepper motor.

9. **Holding torque** -- It is the maximum load torque which the energized stepper motor can withstand slipping from equilibrium position.

10. **Detent torque** -- It is the maximum load torque which the un-energized stepper motor can withstand without slipping.

11. **Static stiffness** -- The ability of the actuator to resist disturbing torques and forces and thereby to maintain position.

12. **Band width** -- It is a measure of the frequencies up to which the actuator or servo system can respond.

13. **Synchronism** -- It is the one to one correspondence between the numbers of pulses applied to the stepper motor and the number of steps through which the motor has actually moved.

14. **Half step operation** -- It is alternate one phase on and two phase on mode operation. Here the rotor rotates through half of the full step angle.

15. **Slewing** -- Stepper may operate at high steeping rates, 25,000 steps per second.
UNIT III
SWITCHED RELUCTANCE MOTOR

INTRODUCTION
Switched reluctance motor (SRM) is electromagnetic and electrodynamics equipment which converts the electrical energy into mechanical energy. The electromagnetic torque is produced on variable reluctance principle. SRM makes use of

- Power semiconductor switching circuitry and
- Rotor position sensor.

SRM is singly excited and doubly salient electrical motor. This means that it has salient poles on both the rotor and the stator but the only one member carries winding. The rotor has no winding, magnets and cage winding but it is build from a stack of salient pole laminations.

- Its construction is simple and robust
- It requires less maintenance
- Its overall efficiency is better
- It is flexible control driving motor as motoring mode generating mode of operations of the machine can be easily achieved.

In the light of above it is a competitive motor variable speed dc motor and variable speed 3 – phase cage induction motor.

CONSTRUCTION AND OPERATION OF SRM

Construction of SRM
Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure 3.1

The stator is made up of silicon steel stampings with inward projected poles. The number of poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8). All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf’s are additive and they are called phase windings. Individual coil or a group of coils constitute phase windings. Each of the phase windings are connected to the terminal of the motor. These terminals are suitably connected to the output terminals of a power semiconductor switching circuitry, whose input is a d.c. supply.
The rotor is also made up of silicon steel stampings with outward projected poles. Number of poles of rotor is different from the number of poles of the stator. In most of the available motors the number of poles of the rotor is 4 or 6 depending upon the number of stator poles 6 or 8.

The rotor shaft carries a position sensor. The turning ON and turning OFF operation of the various devices of the power semiconductor circuitry are influenced by the signals obtained from the rotor position sensor.

**Block Diagram Of SRM**

Fig. 3.2 shows the block diagram of SRM. Dc supply is given to the power semiconductor switching circuitry which is connected to various phase windings of SRM. Rotor position sensor which is mounted on the shaft of SRM, provides signals to the controller about the position of the rotor with reference to reference axis. Controller collects this information and also the reference speed signal and suitably turns ON and OFF the concerned power semiconductor device to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.
3.2.3. Principle of operation

Fig. 3.3 represents the physical location of the axis stator poles and rotor poles of a 6/4 SRM.

To start with stator pole axis AA’ and rotor pole axis aa’ are in alignment as shown in fig. 3.3(a). They are in the minimum reluctance position so far as phase windings is concerned. Then \( \frac{dL_B}{d\theta} = 0 \). At this position inductance of B windings is neither maximum nor minimum. There exists \( \frac{dL_A}{d\theta} \) and \( \frac{dL_C}{d\theta} \).

![Fig. 3.3 Physical location of the axis of stator and rotor poles of 6/4 SRM](image)

Now if B phase is energized then the rotor develops a torque because of variable reluctance and existences of variation in inductance. The torque developed is equal to \((1/2)i_B^2\left(\frac{dL_B}{d\theta}\right)\). This direction is such that BB’ and bb’ try to get aligned. If this torque is more than the opposing load torque and frictional torque the rotor starts rotating. When the shaft occupies the position such that BB’ and bb’ are in alignment (i.e.,) \( \theta = 30^\circ \), no torque is developed as in this position \( \frac{dL_B}{d\theta} = 0 \). [Vide fig. 3.3(b)]

Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as \( \left(\frac{dL_C}{d\theta}\right) \) exists. The rotor continues to rotate. When the rotor rotates further \( 30^\circ \), the torque developed due to winding C is zero [vide fig. 3.3(c)] Then the phase winding C is switched off and phase winding A is energized. Then rotor experiences a torque and rotates further step \( 30^\circ \). This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor.

As the speed increases, the load torque requirement also changes. When the average developed torque is more than the load torque the rotor accelerates. When the torques balance the rotor attains dynamic equilibrium position. Thus the motor attains a steady speed. At this steady state condition power drawn from the mains is equal to the time rate of change of stored energy in magnetic circuit and the mechanical power developed.

When the load torque is increased, the speed of the motor tends to fall, so that the power balance is maintained. If the speed is to be develop at the same value, the develop
torque is to be increased by increasing the current. Thus more power is drawn from the mains. Vice-versa takes place when the load is reduced. Thus electrical to mechanical power conversion takes place.

**POWER SEMICONDUCTOR SWITCHING CIRCUITS FOR SRM (POWER CONTROLLERS)**

The selection of controller (converter) depends upon the application. One of the main aspects of the research in SRM drives has been the converter design. The main objectives of the design of the converter are performance of the drive and cost of the drive.

The power semiconductor switching circuits used are

1. Two power semiconductor switching devices per phase and two diodes.
2. (n+1) power semiconductor switching devices (n+1) diodes.
3. Phase winding using bifilar wires.
4. Split-link circuit used with even-phase number.
5. C-dump circuit.

**Two Power Semiconductor Switching Devices per phase and two diodes**

![Fig. 3.4 Two Power Semiconductor switching devices and two diodes.](image)

As shown in fig 3.4 phase winding A is connected to the dc supply through power semiconductor devices T_1 and T_2. Depending upon the rotor position, when the phase winding A is to be energized the devices T_1 and T_2 are turned ON. When the phase winding is to be disconnected from the supply (this instant is also dependent on the position of the shaft) the devices T_1 and T_2 are turned off. The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D_1 and D_2 to the supply. Thus the stored energy is fed back to the mains.

Similarly phase winding B & C are also switched on to the supply and switched off from the supply in a cyclic manner. This circuit requires 2 power switching devices and 2 diodes for each phase winding. For high speed operation it is required to see that the stored energy can be fed back to the mains within the available period.
Usually the upper devices $T_1$, $T_3$ and $T_5$ are turned on and off from the signals obtained from the rotor position sensor. The duration of conduction or angle of conduction $\theta$ can be controlled by using suitable control circuitry. The lower devices $T_2$, $T_4$, $T_6$ are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical AND ing of the rotor position sensor and chopping frequency. As a result it is possible to vary the effective phase current from a very low value to a high value. For varying the following methods are available.

1. By varying the duty cycle of the chopper.
2. By varying the conduction angle of the devices.

**Merits**

- Control of each phase is completely independent of the other phase.
- The converter is able to free wheel during the chopping period at low speeds which helps to reduce the switching frequency and thus the switching losses of the converter.
- The energy from the off going phase is feedback to the source, which results in utilization of energy.

**Demerits**

- Higher number of switches required in each phase, which makes the converter expensive and also used for low voltage applications.

**$(n+1)$ power switching devices and $(n+1)$ diodes**

![Fig. 3.5 (n+1) power switching devices and (n+1) diodes](image)

This circuit makes use of less number of power switching devices and diodes as shown in fig 3.5. When the (SCRs) switching devices $T$ and $T_1$ are turned on phase winding $A$ is energized from the dc supply. When these devices are turned off the stored energy in the phase winding is fed back to the mains through diodes $D$ and $D_1$. When devices $T$ and $T_2$ are
turned on the phase winding B is energized. When they are turned off, the stored energy in B phase winding C is switched on and off from the mains. The cycle gets repeated.

This circuit makes use of (n+1) power switching devices and (n+1) diodes where n is equal to the number of phases.

**Merits**

- The converter uses low number of switching devices, which reduces the cost of the converter.
- The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses.
- Voltage rating of all the switching devices and the diodes are $V_{dc}$, which is relatively low.
- The energy for the off going phase is transferred back into the source, which results in useful utilization of the energy and also improves the efficiency.

**Demerits**

- Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.
- At higher speeds of the off going phase cannot be de-energized fast enough because the common switch $T_1$ keeps turnings on intermediately, disabling forced demagnetization.
- The common switch conducts for all the phases and thus has higher switching stress.

**Phase winding using bifilar wires**

Each phase winding has two exactly similar phase windings as shown in fig 3.6. For this bifilar wires are used. Each phase consists of two identical windings and are magnetically coupled when one of them are excited.

In stepper motor, the purpose of bifilar winding is for bipolar excitation with a reduced number of switching elements.
When $T_1$ is turned on the dc current passes through the phase winding $A$. When the devices $T_1$ is turned off the stored energy in the magnetic field is fed back to the dc source through the winding $A'$ and $D_1$ to the supply.

The three devices operate in a sequential way depending upon the signals obtained from the rotor position sensor and the chopping signals for PWM technique obtained from the controller.

**Merits**
- The converter uses lower number of switching devices thus reducing the cost on the converter.
- The converter allows fast demagnetization of phases during commutation.

**Demerits**
- Bifilar winding suffers from double number of connections.
- A poor utilization of copper.
- Freewheeling is not possible during chopping as the phases have $-V_{dc}$, this causes of higher ripples in current and torque during chopping.
- The imperfection in the coupling between the two winding causes voltage spikes during turn off.
- The copper loss associated with the auxiliary winding is unacceptable high for many applications.

**Split – link circuit used with even phase number**

![Split link circuit used with even phase number](image)

The circuit shown in fig.3.7 is used in a range of highly efficient drives (from 4-80kw).

The main power supply is split into two halves using split capacitors. During conduction, energy is supplied to the phases by one half the power supply. During commutation period, the phases demagnetize into other half of the power supply.
When switch T1 is turned on, phase winding 1 is energized by capacitor c1. When switch T2 is turned off, the stored energy in the phase winding 1 is fed back to the capacitor c2 through diode D4.

When T4 is turned on by capacitor C2 and phase winding 4 is energized. When switch T4 is turned off, stored energy in the winding 4 is feedback to the capacitor C1 through diode D1. The similar operation takes place in the remaining winding also.

**Merits**

- It requires lower number of switching devices.
- Faster demagnetization of phases during commutation.

**Demerits**

- During chopping, freewheeling is not possible as the phaser have the voltage \(V_{dc}/2\).
  This causes higher switching frequency and more losses.
- This is not feasible for low voltage application.
- The converter is fewer faults tolerant as fault in any phase will unbalance the other phase that is connected to it.

**C-Dump circuit**

In the C dump circuit shown in fig. 3.8, the device count is reduced to \(n'\) plus one additional devices to bleed the stored energy from the dump capacitor C back to supply via the step down chopper circuit. The mean capacitor voltage is maintained well above the supply to permit rapid defluxing after commutation.

![Fig. 3.8 C dump circuit](image)

A control failure in the energy-recovery circuit would result in the rapid build-up of charge on the capacitor and if protective measures were not taken the entire converter could fail from over voltage.

**Demerits**

- Dump capacitor voltage is maintained \(\sim 2 V_{dc}\) to allow fast demagnetization. But use of a capacitor and an inductor in the dump circuit and also the voltage rating of other devices is twice the bus voltage.
3.4 VOLTAGE AND TORQUE EQUATIONS OF SRM

3.4.1 Basic voltage equation of SRM

From fig. 3.9

\[ V = iR + \frac{d\lambda}{dt} \]

\[ V = iR + \frac{d(\lambda L)}{dt} \]

\[ V = iR + L \frac{di}{dt} + i \frac{d\lambda}{dt} \]

\[ V = iR + L \frac{di}{dt} + i \frac{d\lambda}{dt} \times \frac{d}{dt} \]

\[ V = iR + L \frac{di}{dt} + i \frac{d\lambda}{dt} \]

Fig. 3.9 Basic R-L circuit of SRM.

where \( \lambda \) is a function of \( \Phi \) and \( L \)

\[ \frac{d\lambda}{dt} = \frac{d}{dt} i + \frac{di}{dt} \Phi \]

\[ V = iR + \frac{d(\lambda L)}{dt} \]

where \( iR \) is ohmic drop

\( L \frac{di}{dt} \) is Emf due to incremental inductance

\( i \omega \frac{d\lambda}{dt} \) is self induced emf or self emf

\[ V = iR + L \frac{di}{dt} + e \]

Self-induced emf \( e \) is proportional to current speed and rate of change of inductance with rotor angle.

If flat topped current is assumed \( L \frac{di}{dt} = 0 \) on the other hand if the inductance is constant, self emf is zero. So the first term \( L \frac{di}{dt} \) absorbs all the applied voltage.

\[ Vi = i^2R + L \frac{di}{dt} + i^2 \omega \frac{d\lambda}{dt} \]
Energy stored in the magnetic circuit = \( \frac{1}{2} L i^2 \)

Rate of change of energy stored in the magnetic circuit:

\[
\frac{d}{dt} \left[ \frac{1}{2} L i^2 \right] = \frac{1}{2} L \frac{di}{dt} + \frac{1}{2} i^2 \frac{di}{dt} \]

\[
= L \frac{di}{dt} + \frac{1}{2} i^2 \frac{di}{dt} \times \frac{d}{dt} \]

\[
\frac{dW_{\text{mag}}}{dt} = LI \frac{di}{dt} + \frac{1}{2} i^2 \omega \frac{di}{dt} \]

Mechanical energy transferred = electrical energy input + \( \frac{dW_{\text{mag}}}{dt} \) rate of change of energy stored in the magnetic circuit.

\[
\text{Mechanical energy transferred} = Vi L i^2 + \frac{dW_{\text{mag}}}{dt} \]

\[
= i^2 R + LI \frac{di}{dt} + i^2 \omega \frac{di}{dt} \]

\[
P_m = \frac{1}{2} i^2 \omega \frac{di}{dt} \]

\[P_m = \omega T\]

\[\therefore \text{Torque } T = \frac{1}{2} i^2 \frac{di}{dt}\]

**CONTROL CIRCUITS FOR SRM**

For motoring operation the pulses of phase current must coincide with a period of accuracy inductance. The timing and dwell (i.e.) period of conductance of the current pulse determine the torque, the efficiency and other parameters. With fixed firing angles, there is a monotonic relationship exist between average torque and rms phase current but generally it is not linear. This may present some complications in feedback-controlled systems. Although it is possible to achieve _near servo-quality_ dynamic performance, particularly in respects of speed range torque/inertia and reversing capability.

More complex controls are required for higher power drives, particularly where a wide speed range is required at constant power, and microprocessor controls are used. As high-speed operation, the peak current is limited by the self-emf of the phase winding. A smooth current waveform is obtained with a peak/rms ratio similar to that of a half sinewave.

At low speed, the self-emf of the winding is small and the current must be limited by chopping or PWM of the applied voltage.

Two types of control circuits used are:

1. Hysteresis type to maintain constant current
2. Voltage pulse width modulation control (or) duty cycle control.
HYSTERESIS TYPE CURRENT REGULATION

As by this control circuit current is maintained more or less constant like —hysteresis— throughout the conduction period in each phase it is known as hysteresis type control. Fig 3.10 (a) shows the current waveform controlled by the hysteresis type current regulator. The schematic arrangement of the control circuit is shown in fig 3.10 (b).

![Fig 3.10 (a) Chopped current waveform, (b) Hysteresis type current regulator](image)

**Principle of operation**

As shown in fig. 3.10(b) the transducer (a tachogenerator) is connected from the rotor and then the output signal from the transducer is given as a feedback signal at the base of transistor T₂. From the emitter of transistor T₂, the portion of the feedback signal (current) is fed at the input of the operational amplifier (O.A). There it is compared with the reference current and correspondingly after amplification the feedback signal is given at the base of transistor T₁. This signal in combination with collector current will flow from the emitter of transistor T₁ through A phase winding of the machine. Thus the current through A phase winding can be controlled depending on the requirement. CLR is the resistance for limiting the current as per the design.

As the current reference increase the torque increases. At low currents the torque is roughly proportional to current squared but at higher current it becomes more nearly linear. At very high currents, saturation decreases the torque per ampere again. This type of control produces a constant-torque type of characteristics.

With loads whose torque increases monotonically with speed, such as fans and blowers, speed adjustment is possible without tachometer feedback but general feedback is needed to provide accurate speed control. In some cases the pulse train from the soft position sensor may be used for speed feedback, but only at relative high speeds.

As low speeds, a larger number of pulses per revolution are necessary and this can be generated by an optical encoder or resolver for alternatively by phase-locking a high
frequency oscillator to the pulses of the commutation sensor. System with resolver-feedback or high-resolution optical encoders can work right down to zero speed.

The –hysteresis type current regulator may require current transducers of wide bandwidth, but the SR drive has the advantage that they can be grounded at one end with the other connected to the negative terminal of the lower phase leg switch. The sensors used are shunts or hall-effect sensors or sensefets with in build current sensing.

**VOLTAGE PWM TYPE CURRENT REGULATION**

The schematic arrangement of PWM type control circuit is shown in fig. 3.11

**Principle of operation**

Through transducer (tachogenerator) the mechanical signal (speed) is converted into electrical signal (current), which is fed from at the base of transistor T2. Thos base current combining with collector current flows the emitter of transistor T2 through CLR to the negative of the supply. Based on the feedback signal, the voltage at phase A changes. This feedback voltage is given as one input to the operational amplifier where it is compared with the reference voltage, correspondingly the difference is amplified and fed to the mono stable circuit. This circuit modulates the pulse width of the incoming signal based on the requirement and the modulated signal is given at the base of T1. This signal combines with collector current of T1 and flows through phase A as modulated current based on the

**Fig.3.11 Voltage PWM type current regulator**

- CLR - Current limiting resistor
- R.F - Rotor feedback
- OA - Operational Amplifier
- T1 T2 - Switching transistor
- D1 D2 - Diodes to return stored energy
requirement. Thus the current is regulated or controlled using pulse width modulation and rotor feedback.

A desirable future of both control methods is that the current wave form tends to retain the same shape over a wide speed range.

When the PWM duty cycle reaches 100%, the motor speed can be increased by increasing the conduction period. These increases eventually reach maximum values after which the torque becomes inversely proportional to speed squared but they can typically double the speed range at constant torque. The speed range over which constant power can be maintained is also quite wide and very high maximum speeds can be achieved, as in the synchronous reluctance motor and induction motor, because there is not the limitation imposed by fixed as in PM motors.

**TORQUE-SPEED CHARACTERISTICS**

Torque developed (i.e.) average torque developed but SRM depends upon the current wave form of SRM phase winding. Current waveform depends upon the conduction period and chopping details. It also depends upon the speed.

Consider a case that conduction angle $\Theta$ is constant and the chopper duty cycle is 1.(i.e.) it conducts continuously. For low speed operating condition, the current is assumed to be almost flat shaped. Therefore the developed torque is constant. For high speed operating condition, the current wave form gets changed and the average torque developed gets reduced.

Fig. 3.12(a) represents the speed torque characteristics of SRM for constant $\Theta$ and duty cycle. It is constant at low speeds and slightly droops as speed increases. For various other constant value of $\Theta$, the family of curves for the same duty cycle is shown in fig.3.12.

![Fig. 3.12 Torque speed characteristics at constant conduction angle $\theta$ and duty cycle](image)

Torque speed characteristics for fixed $\theta$ and for various duty cycles are shown in fig. 3.12. $\theta$ and duty cycle are varied by suitably operating the semiconductor devices.

### 3.8.1 Torque Speed Capability Curve

Maximum torque developed in a motor and the maximum power that can be transferred are usually restricted by the mechanical subsystem design parameters.

For given conduction angle the torque can be varied by varying the duty cycle of the chopper. However the maximum torque developed is restricted to definite value based on mechanical consideration.

![Diagram of Torque Speed Capability Curve](image)

Fig. 3.13 Torque speed characteristic of switched reluctance motor

AB in the fig.3.13 represents constant maximum torque region of operation.

At very low speeds, the torque / speed capability curve may deviate from the clock torque characteristics. If the chopping frequency is limited or if the bandwidth of the current regulator is limited, it is difficult to limit the current without the help of self emf of the motor and the current reference may have to be reduced.

If very low windage and core loss permit the chopper losses to be increased, so that with higher current a higher torque is obtained. Under intermittent condition of course very much higher torque can be obtained in any part of the speed range up to $\theta_b$.

The motor current limits the torque below base speed. The corner point $\theta_b$ is the highest speed at which maximum current can be supplied at rated voltage with fixed firing angles. If these angles are still kept fixed, the maximum torque at rated voltage decreases with speed squared. But if the conduction angle is increased, (i.e.)$\Theta$ on is decreased, there is a considerable speed range over which maximum current can be still be forced into the motor. This maintains the torque at a higher level to maintain constant power characteristic. But the core losses and windage losses increases with the speed. Thus the curve BC represents the maximum permissible torque at each speed without exceeding the
maximum permissible power transferred. This region is obtained by varying $\Theta D$ to its maximum value $\Theta D_{\text{max}}$. $\Theta D$ is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power; maximum permissible conduction angle $\Theta D_{\text{max}}$ and duty cycle of the chopper is unity.

Curve CD represents $T_2^2$ constant. The conduction angle is kept maximum and duty cycle is maximum by maintaining $T_2^2$ constant. D corresponds to maximum permissible. The region between the curve ABCD and X axis is the permissible region of operation of SRM.

**DISTINCTION BETWEEN SWITCHED RELUCTANCE MOTOR AND THE VARIABLE RELUCTANCE STEPPER MOTOR**

The conduction angle for phase currents is controlled and synchronized with the rotor position, usually by means of a shaft position sensor.

Thus SR motor is exactly like a brushless dc motor. But the stepper motor is usually fed with a square-wave of phase current without rotor position feedback.

SR motor is designed for efficient power conversion at high speeds comparable with those of the PM brushless dc motor. The stepper motor is usually designed as a torque motor with a limited speed range. SR motor is more than a high-speed stepper motor. Its performance and low manufacturing cost make it a competitive motor to PM brushless dc system.

**Merits of SRM**

1. Construction is simple and robust, as there is no brush.
2. Rotor carries no windings, no slip rings and brush-less maintenance.
3. No permanent magnet, neither in the stator nor in the rotor.
4. Ventilating system is simpler as losses takes place mostly in stator.
5. Power semiconductor switching circuitry is simpler.
6. No shoot-through fault is likely to happen in power semiconductor circuits.
7. Torque developed does not depend upon the polarity of the current in the phase winding.
8. The operation of the machine can be easily changed from motoring mode to generating mode by varying the region of conduction.
9. It is impossible to have very high speeds.
10. Depending upon the requirement, the desired torque speed characteristics can be tailor made.
11. It is a self-starting machine.
12. Starting torque can be very high without excessive inrush currents.

**Demerits of SRM**

1. Stator phase winding should be capable of carrying the magnetizing current also, for setting up the flux in the air gap.

2. For high speed operations, the developed torque has undesirable ripples. As a result it develops undesirable acoustic losses (noise).

3. For high speeds, current waveform also has undesirable harmonics. To suppress this effect a large size capacitor is to be connected.

4. The air gap at the aligned axis should be very small while the air gap at the inter-polar axis should be very large. It is difficult to achieve. No standardized practice is available.

5. The size of the motor is comparable with the size of variable speed induction motor drive.

6. Number of power wires between power semiconductor circuitry and the motor and the number of control cables from one controller to the power semiconductor circuitry are more and all to be properly connected.

7. It requires a position sensor.

**Application of SRM**

1. Washing machines

2. Vacuum cleaners

3. Fans

4. Future automobile applications

5. Robotic control applications

**SHAFT POSITION SENSING**

- Commutation requirement of the SR motor is very similar to that of a PM brushless motor.

- The shaft position sensor and decoding logic are very similar and in some cases it is theoretically possible to use the same shaft position sensor and the same integrated circuit to decode the position signals and control PWM as well.

- The shaft position sensors have the disadvantage of the associated cost, space requirement and possible extra source of failure. Reliable methods are well established. In position sensors or speed sensors, resolvers or optical encoders may be used to perform all the functions of providing commutation signals, speed feedback and position feedback.
Operation without position sensor is possible. But to have good starting and running performance with a wide range of load torque and inertias, sensor is necessary.

When the SR motor is operated in the "open-loop" mode like a stepper motor in the slewing range, the speed is fixed by the reference frequency in the controller as long as the motor maintains "step integrity". (i.e) stay in synchronism. Therefore like an ac synchronous motor, the switched reluctance motor has truly constant speed characteristics.

This open-loop control suffers from two dis-advantages.

(a) To ensure that synchronism is maintained even though the load torque may vary.
(b) To ensure reliable starting.

Because of the large step angle and a lower torque/inertia ratio, the SR motor usually does not have reliable "starting rate" of the stepper motor.

Also some form of inductance sensing or controlled current modulation (i.e) such as sine wave modulation may be necessary in the control at low speeds.

MICROPROCESSOR OR COMPUTER BASED CONTROL OF SRM DRIVE

Today in industrial places there is high demands on control accuracies, flexibility, ease of operation, repeatability of parameters for many drive applications. Nowadays switched reluctance motors are increasingly used in industries. To meet the above requirements, uses of microprocessor have become important.

Fig. 3.14 Microprocessor or computer based control of SRM

Fig. shows the block diagram of microprocessor based control of SRM drive. This control system consists of power semiconductor switching circuit, SRM with rotor position sensor and microprocessor system. In this system microprocessor acts as a controller for the switched reluctance motor and generate control pulses to the power semiconductor switching circuits.

The input DC supply is fed to the power semiconductor switching circuits. Different types of power semiconductor switching circuits are used for different application. Normally the circuits are inverter circuit configuration.
The power semiconductor devices are turned on and off by controller circuit. Here the controller circuit is microprocessor or computer based control system.

In the SRM drive shown in fig. 3.14, the rotor position sensor gives the information about the rotor with respect to the reference axis to the microprocessor or computer control. The controller also receives the status of current, flow through the phase winding and reference signal.

The microprocessor or computer compares the signals obtained from the RPS and reference and generate square pulses to the power semiconductor devices. This signal is fed to the inverter circuit. The phase winding of the SRM is energized depending upon the turning on and off of the power semiconductor switching circuit.

The microprocessor or computer controller can perform the following functions.

a) Control the feedback loops.
b) PWM or square wave signal generation to inverters.
c) Optimal and adaptive control.
d) Signal monitoring and warning.
e) General sequencing control.
f) Protection and fault overriding control.
g) Data acquisition.

The superiority of microprocessor or computer control over the conventional hardware based control can be easily recognized for complex drive control system. The simplification of hardware saves control electronics cost and improves the system reliability. The digital control has inherently improves the noise immunity which is particularly important because of large power switching transients in the converters.