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(Accredited by NAAC, Approved by AICTE, New Delhi. Affiliated to Anna University, Chennai)
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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE8005 – SPECIAL ELECTRICAL MACHINES- HANDOUTS

UNIT - I
STEPPING MOTOR

- 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).
- 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.

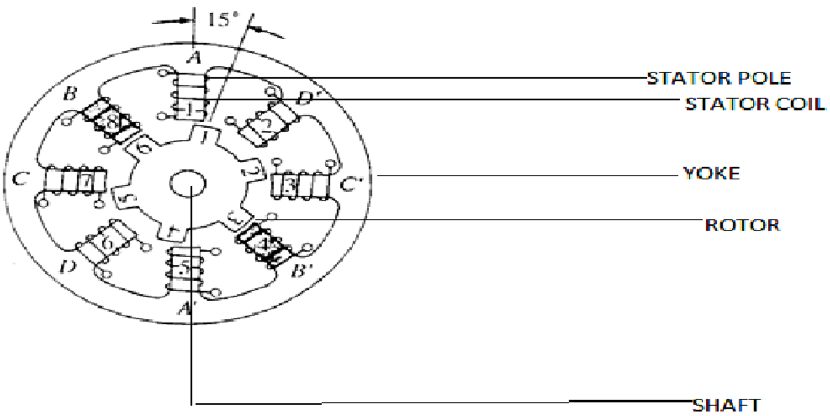
CLASSIFICATION OF STEPPER MOTORS

- 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.



Single Stack Variable Reluctance Stepper Motor

Stator:

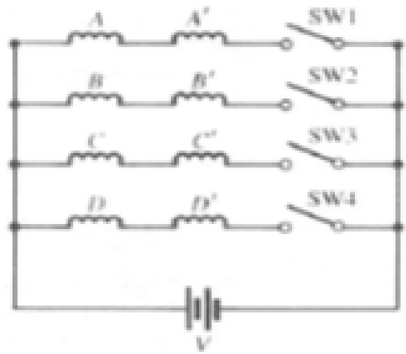
- ➢ The Stator is made up of silicon steel stampings with inward projected even or odd number of poles or teeth.
- ➢ Each and every stator poles carries a field coil an exciting coil. In case of even number of poles the exciting coils of opposite poles are connected in series.
- ➢ The two coils are connected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

Rotor:

- ➢ 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.Similary 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

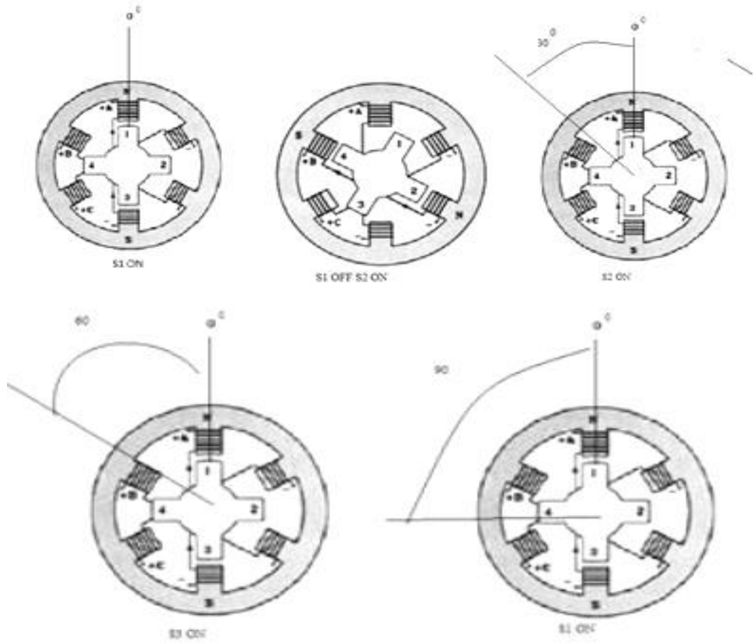
It works on the principle of variable reluctance. The principle of operation of VR stepper motor explained by referring fig.

(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 θ = 0° 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 counter clockwise 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 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

Counter Clockwise Rotation (CCW)

S1	S2	S3	θ
*	-	-	0
-	*	-	30
-	-	*	60
*	-	-	90
-	*	-	120
-	-	*	150
*	-	-	180
-	*	-	210
-	-	*	240
*	-	-	270
-	*	-	300
-	-	*	330
*	-	-	360

Clockwise Rotation (CW)

S1	S2	S3	θ
*	-	-	0
-	-	*	30
-	*	-	60
*	-	-	90
-	-	*	120
-	*	-	150
*	-	-	180
-	-	*	210
-	*	-	240
*	-	-	270
-	-	*	300
-	*	-	330
*	-	-	360

(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

Counter Clockwise Rotation (CCW)

S1	S2	S3	θ°	
*	*	-	15°	AB
-	*	*	45°	BC
-	*	-	75°	CA
*	*	-	105°	AB
-	*	*	135°	BC
-	*	-	165°	CA
*	*	-	195°	AB
-	*	*	225°	BC
-	*	-	255°	CA
*	*	-	285°	AB

Clockwise Rotation (CW) **(C)**

	S1	S2	S3	θ
AC	-	*	-	15°
CB	-	*	*	45°
BA	*	*	-	75°
AC	-	*	-	105°
CB	-	*	*	135°
BA	*	*	-	165°
AC	-	*	-	195°
CB	-	*	*	225°
BA	*	*	-	255°
AC	-	*	-	285°

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.

Counter Clockwise Rotation (CCW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	*	-	15°	AB°
-	*	-	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
*	-	*	75°	CA°
*	-	-	90°	A°
*	*	-	105°	AB°
-	*	-	120°	B°
-	*	*	135°	BC°
-	*	-	150°	C°
*	-	*	165°	CA°

Clockwise Rotation (CW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	-	*	15°	AB°
-	-	*	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
-	*	-	75°	CA°
*	*	-	90°	A°
*	-	-	105°	AB°
*	-	*	120°	B°
-	-	-	135°	BC°
-	*	*	150°	C°
-	*	-	165°	CA

MICRO STEPPING CONTROL OF STEPPING MOTOR

- Stepping motor is a digital actuator which moves in steps of θs in response to input pulses.

  such incremental motion results in the following limitations of the stepper motor

Limited resolution:

- As θs 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 accuracy finer than θs.

Mid frequency Resonance:

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

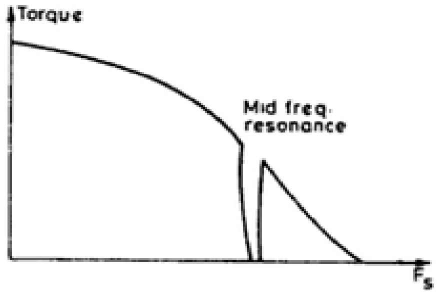


Fig 1.4 Mid frequency Resonance

- 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 Δ θs << θs full step angle is response to input pulses.

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 θ = 0° 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® in counter clockwise direction as show in fig (a).

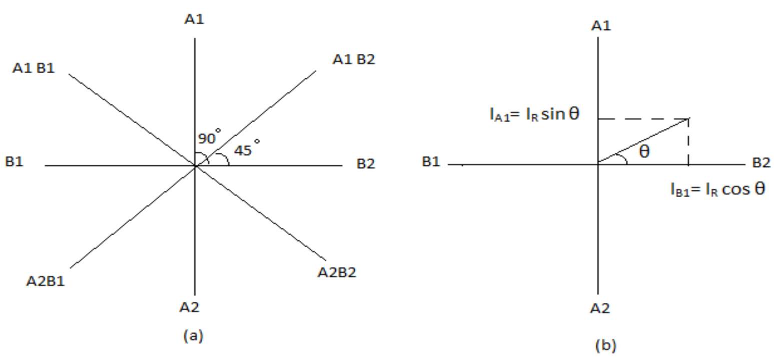
- The rotor follows suit by rotating through 90° in the process of aligning itself with stator magnetic field. Thus with a conventional controller the stator magnetic field rotates through 90° when a new input pulse is received causing the rotor to rotate full step.

- However in micro stepping we want the stator magnetic field to rote through a small angle θs << 90° in respect to input pulse. This is achieved by modulating the current through B2 and A1 winding as show in fig (b) such that

IA1= IR sin θ

IB1= IR cos θ

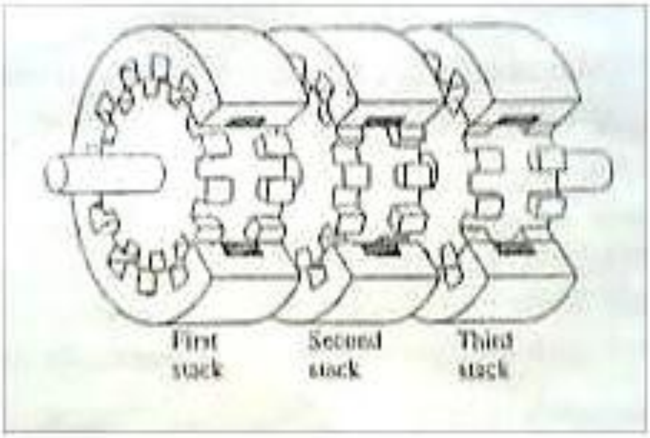
- Then the resulting stator magnetic field will be at an angle θ ° with respect to the positive real axis. Consequently the rotor will rotate through an angle θs << 90°.
- This method of modulating current through stator winding so as to obtain rotation of stator magnetic field through a small angle θ °



Principle of micro stepping

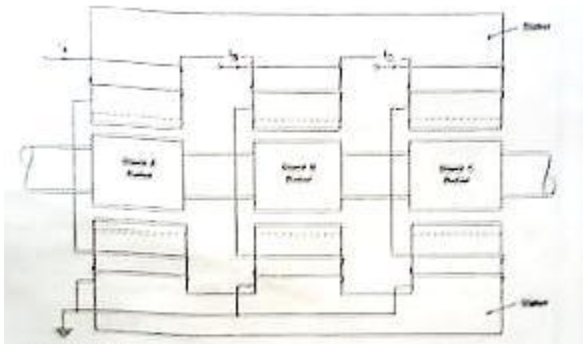
MULTISTACK VARIABLE RELUCTANCE STEPPER MOTOR

- These are used to obtain smaller step sizes, typically in the range of 2° to 15°. Although three stacks are common a multi-stack 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.



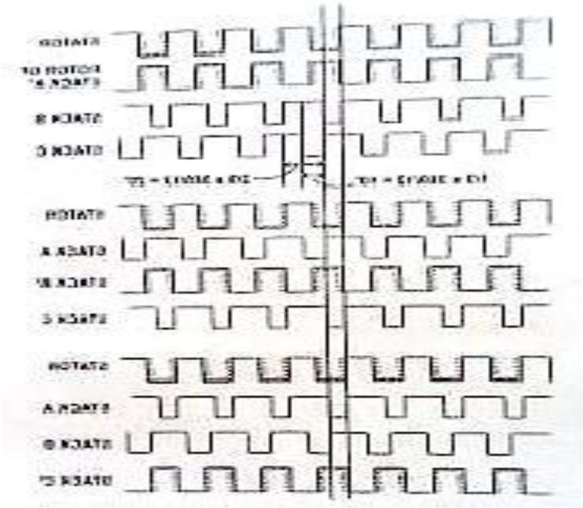
Construction of multi-stack VR motor.

- A multi-stack (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.



Cross-section of a 3-stack, VR stepper motor parallel to the shaft.

- Figure 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.
- 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.



Position of stator & rotor teeth of 3 stack VR motor

- Let Nr be the number of rotor teeth and ‗m‘ the number of stacks or phases, then

Tooth pitch Tp= 360/Nr

Step Angle α= 360°/mNr

PERMANENT MAGNET STEPPER MOTOR:

Construction:

Stator:

- PM stepper motor consists of stator poles with stator windings. When supply given to the stator winding it act as electromagnets and generates the north and south poles.
- Normally 4 pole stators are used. It is similar to the VR stepper motor.(A-A', B-B' are coil pairs or two phases)

Rotor:

- The PM stepper motor consists of cylindrical rotor which is made by permanent magnet. It consists always a north pole and a south pole permanently.
- Rotor has no windings. Rotation direction depends the polarity of stator current.
- Manufacturing cost is low for PM stepper motor.
- For 4 stator poles 2 rotor poles are used.

$$\text{Step angle } \beta = \frac{360}{m*Nr}$$

Principle of operation:

1. One Phase ON Mode:

- One stator winding is energized, the rotor poles move into alignment with energized stator poles. Stator can excited with positive or negative current. The excited stator pole creates north and south poles in opposite coils .
- First A energized with positive current I_A. Here the angle of rotation is 0^o. The north pole of A coil attracts the south pole of rotor. Similarly south pole of stator is attracts by rotor north pole. So stator and rotor poles are aligned each other.
- Then A-A' phase de-energized and B-B' are energized with positive current I_B . Now B coils creates north pole and rotor pole attracts by B pole. So the rotor rotates 90^o Clock wise direction. Excitation sequence is (A-A', B-B',A-A')
- Similarly A and B are excited with negative currents I_A and I_B. Each excitation gives 90^o rotation of rotor. Finally for one full rotation 4 steps are needed in one phase ON operation. Angles are 0^o, 90^o, 180^o, 270^o, 360^o.

2. Two Phase ON Mode:

- In this mode at the same time two phases are ON with positive current and the negative current alternately. By this method step angle is reduced in stepper motor. The motor resolution is increased.
- Excitation sequence is (A-B, B-A', A'-B', B'-A) for clock wise rotation vice-versa.

3. Alternate Phase ON Mode:

- In this mode first only one phase is ON and two phases are ON sequentially. In this mode step angle is decrease to small value.
- First A phase is ON with positive current and A and B phase is ON. So the rotor attracted by A pole first and then both A and B in second mode finally stay between two poles. The step angle is 45^o for each step rotation. The excitation sequence is (A, A-B, B, B-A', A', A'-B', B', B'-A) for clock wise rotation.

Advantages:

- Low power requirement.
- High detent torque compare than VR motor.
- Rotor no need of external exciting current.
- It produces more torque per ampere stator current.

Disadvantages:

- Motor has higher inertia.
- Slower acceleration.
- Step size is large only between 30^o to 90^o.

Hybrid stepper motor

Construction:

- This motor combines both PM and VR stepper motor. It used to achieve small step angle with high torque and small size.

Stator:

- The stator is most similar to the VR motors. It consists of salient pole with windings.

Rotor:

- The rotor consists of an axial PM at the two ends of which are attached two identical ferromagnetic stacks. These two stacks consist of equal number of teeth. The rotor made by cylindrical or disk shaped PM with end stacks. It can create North Pole one side and South Pole another side of the rotor. Two stacks have angular displacement of one half of the rotor teeth pitch.
- The tooth of North Pole is aligned between the two teeth (Slot) of South Pole.

Principle of operation:

- Most widely used hybrid motor is the two phase type. This model has four poles and operates on one phase on excitation.

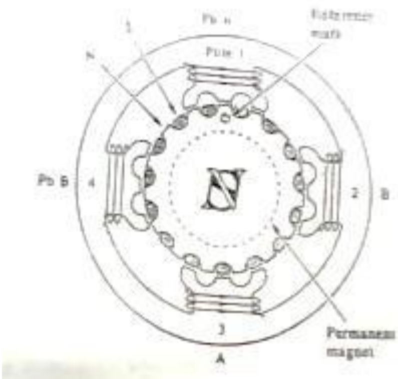


Fig cross-section of a two phase hybrid motor

- 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. shows the process of rotor journey as the winding currents are switched in one phase ON excitation.

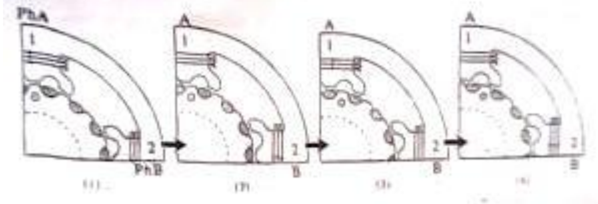


Fig one-phase on operation of a two-phase hybrid motor.

- 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.

Two-phase hybrid motor with 8 stator poles.

Advantages:

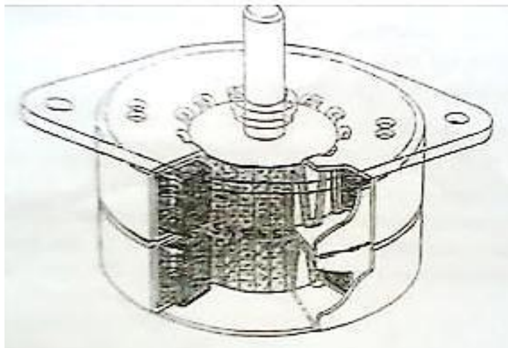
- Provide detent torque with windings de-energized.
- Less tendency to resonate.
- High stepping rate capability.
- High efficiency at low speed and low stepping rates.
- Higher holding torque capability.

Disadvantages:

- Higher inertia and weight due to PM in rotor.
- Performance affect by magnetic property loss of magnet.

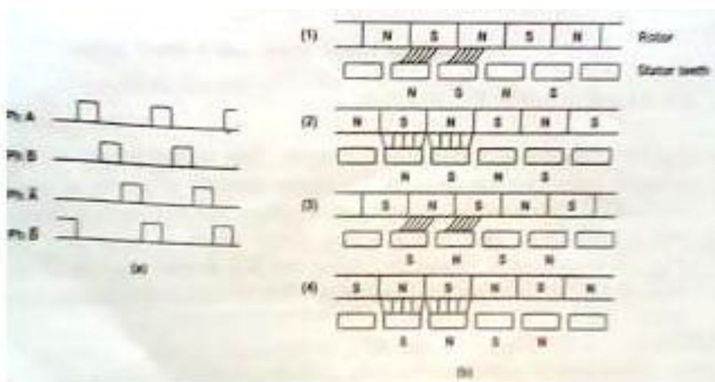
CLAW TOOTH PM MOTOR

- 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 toroidal coil is contained within them.
- This type of motor has usually 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.



Cutaway diagram of a claw-tooth PM motor

- 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 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.



Current waveform supplied to a claw-tooth PM motor

Torque equation of stepper motor

As per faradays law,

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

$$\text{where } \lambda = N\phi \text{ or } \lambda = Li$$

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

$$= -L\frac{\partial i}{\partial t} - i\frac{\partial L}{\partial t}$$

$$= -L\frac{\partial i}{\partial t} - L\frac{\partial L}{\partial \theta} \times \frac{\partial \theta}{\partial t}$$

$$= -L\frac{\partial i}{\partial t} - i\,\omega\frac{\partial L}{\partial \theta}$$

- Stored energy in a magnetic field

$$We = \frac{1}{2} Li^2$$

- Power due to stored energy (Rate of change of energy transfer)

$$\frac{d\,We}{dt} = \frac{1}{2} L \cdot 2i \frac{\partial i}{\partial t} + \frac{1}{2} i^2 \frac{\partial L}{\partial t}$$

- Power received from electrical source = ei
- Mechanical Power developed = {Power received from the electrical source – Power due to stored energy}= { ei – (dWe/dt) }

$$\therefore\ ei = i L \frac{\partial i}{\partial t} + \omega i^2 \frac{\partial L}{\partial \theta}$$

Power due to change in stored energy

$$= Li \frac{\partial i}{\partial t} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta}$$

Mechanical power developed

$$= \left[i L \frac{\partial i}{\partial t} + \omega i^2 \frac{\partial L}{\partial \theta} \right] - \left[Li \frac{\partial i}{\partial t} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \right]$$

Mechanical power developed

$$P_m = \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta}$$

$$P_m = \frac{2 \pi NT}{60}$$

$$P_m = \omega T$$

where $\omega = \frac{2 \pi N}{60}$

Therefore reluctance torque $T = \frac{P_m}{\omega}$

Reluctance Torque $T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta}$

Note:

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

Static and dynamic characteristics of stepper motor

Stepper motor characteristics are divided into two groups

- Static characteristics
- Dynamic characteristics

Static characteristics

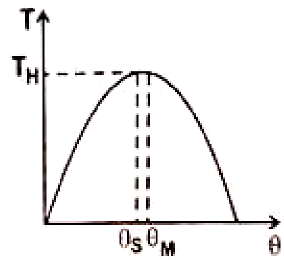
It is divided into two charteristics.

(i)Torque Angle curve

(ii)Torque current curve.

(i)Torque-Angle curve:

- Torque angle curve of a step motor is shown in fig. it is seen that the torque increases almost sinusoid ally, with angle Θ from equilibrium.



Holding Torque (TH)

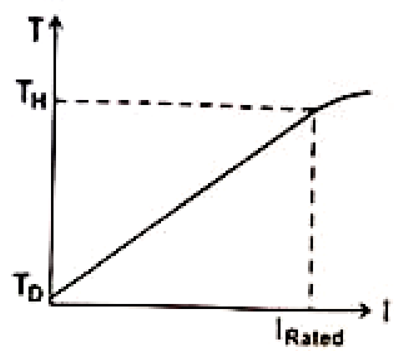
- It is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the static equilibrium position.

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.

ii) Torque current curve

- A typical torque curve for a stepper motor is shown in fig. 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

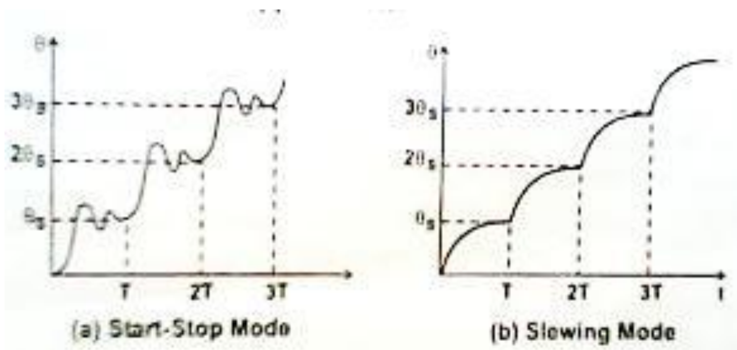
- Also called as pull in curve or single stepping mode.

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:

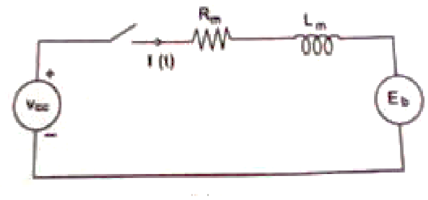
- In this second pulse is given to the stepper motor only after the rotor attained a steady or rest position due to first pulse.
- The region of start-stop mode of operation depends on the operation depends on the torque developed and the stepping rate or stepping frequency of stepper motor.



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.
- This simplest possible circuit of one phase consisting of a Darlington pair current amplifier and associated protection circuits.
- The switching waveform 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.

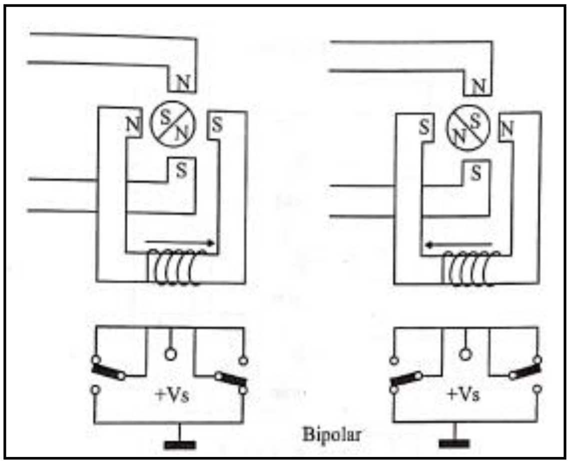
- There are some problems with this simple power circuit. They can be understood by considering each phase winding subject to repetitive switching. On application of a positive step voltage, the current rises exponentially as

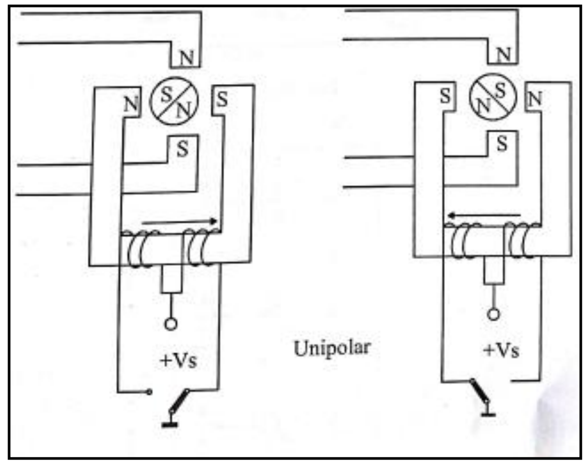


$$i(t)=I(1- \; e^{t/\tau})$$

Where I=V/R – rated current and

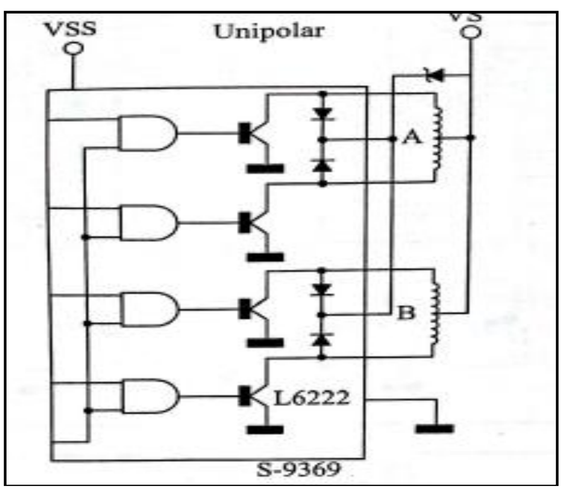
Ƭ =L/R winding time constant.

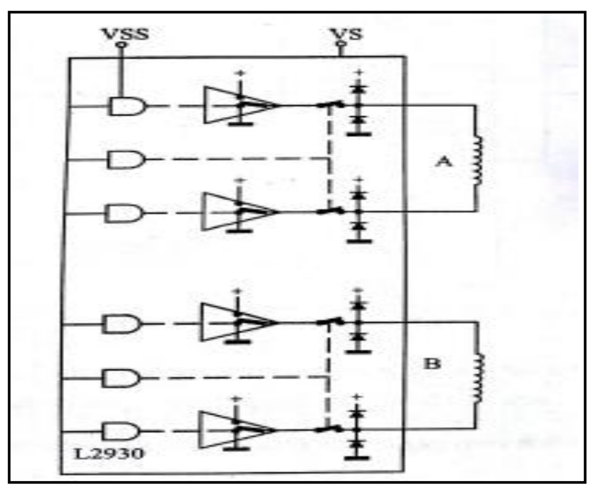




Unipolar driver circuit is only produce less torque but the bipolar driver circuit is produce high Torque.

(1)

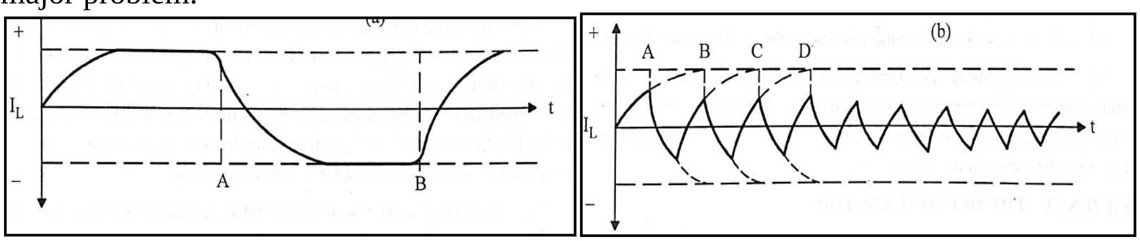




Resistance drive (L/R drive)

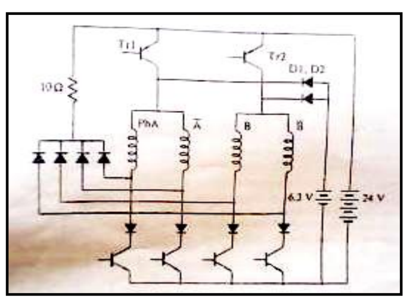
- Here the initial slope of the current waveform is made higher by adding external resistance in each winding and applying a higher voltage proportionally.
- While this increases the rate of rise of the current, the maximum value remains unchanged.

- 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 $I^2 R$ 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.



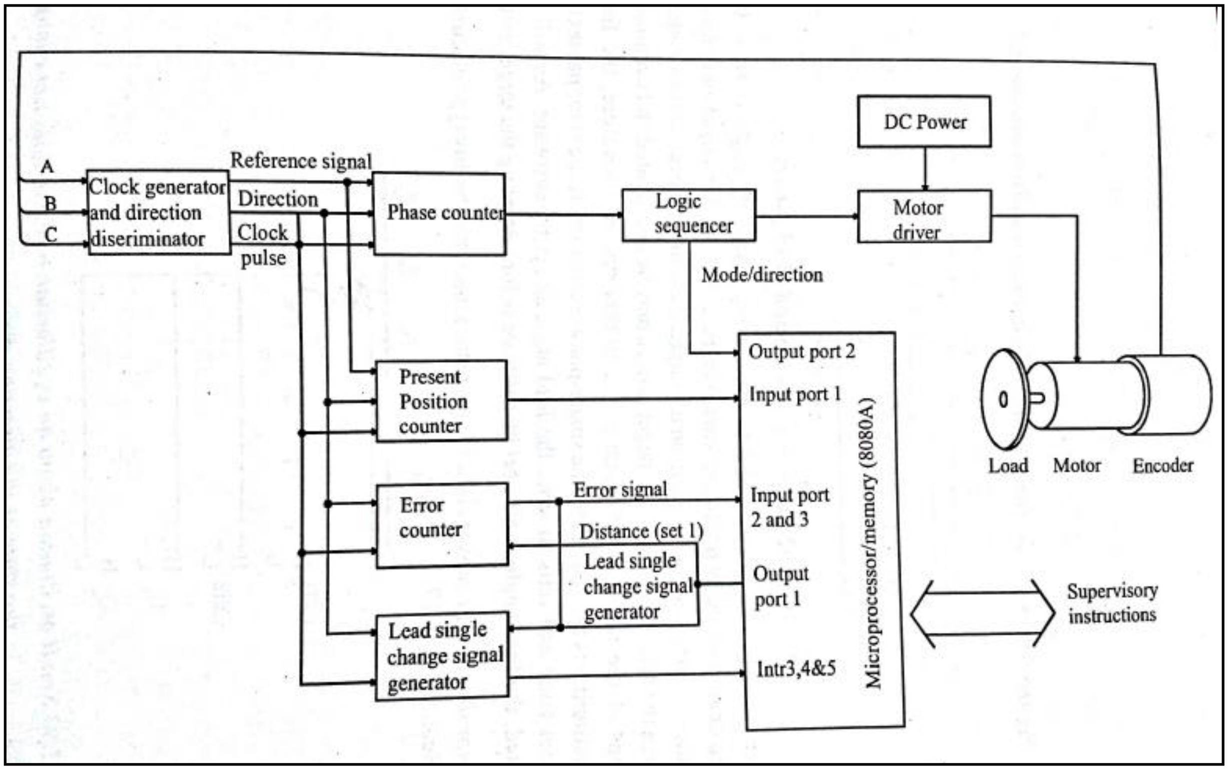
Dual voltage driver (or) Bi-level driver

- To reduce the power dissipation in the driver and increase the performance of a stepping motor, a dual-voltage driver is used.
- 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 Tr1 and Tr2 are turned on, and the higher voltage EH will be applied to the winding. The diode D1 now reverse biased to isolate the lower voltage supply.



- The current build up quickly due to the higher voltage EH. The time constant of the mono-stable multi-vibrator is selected so that transistor Tr1 is turned off when the winding current exceeds the rated current by a little. After the higher
- Voltage source is cut off the diode is forward biased and the winding current is supplied from the lower voltage supply.
- This drive is good and energy efficient. However it is more complex as it requires two regulated power supplies EH and EL end two power transistor switches Tr1 & Tr2 and complex switching logic. Hence it is not very popular.

Block diagram of Microprocessor based closed loop system of stepper motor



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

  Tm 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 θ
- According to rotor dynamics
- Tm=—J*dω/dt+Dω+Tf
- Also θs=θ=ωt=step angle
- ω=θs/t=f θs

  where f=1/t

  By putting ω=f θs
- Tm=J *d/dt(f θs)+D(f θs)+Tf
- θs=360/mNr is fixed for a particular type of motor
- S o θs can be considered as constant
- Therefore Tm=J θs* d/dt(f)+D θs(f)+Tf
- ω=((Tm-Tf)/J)dt+ω1

Where

- $\omega 1$=Integration constant

- Substituting ω and $\omega 1$ in equation 2.50
- $((T_m-T_f)/J)t+ \theta_s f_1= \theta_s f$
- Dividing throughout by θ_s we get
- $((T_m-T_f)/J\ \theta_s)t+ f_1=f$
- Therefore stepping rate $f=((T_m-T_f)/J\ \theta_s)$

Applications of stepper motor

- Floppy disc drives
- Quartz watch
- Camera shutter operation
- Dot matrix and line printers
- Small tool application
- Robotics
- Instrumentation applications.
- Computer peripherals & Office equipment's.
- Numerical control of machine tools and robotics.
- Applications in semiconductor technology.
- Space vehicles and satellites

UNIT-II

SWITCHED RELUCTANCE MOTORS (SRM)

Construction of SRM

Rotary Type

Stator:

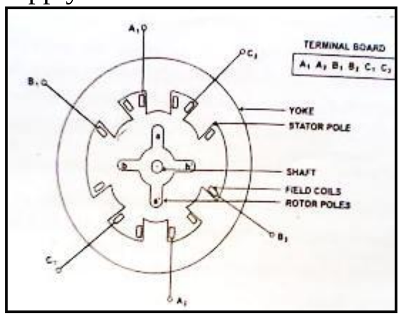
- The Stator is made up of silicon steel stampings with inward projected even or odd number of poles or teeth.
- Each and every stator poles carries a field coil an exciting coil. In case of even number of poles the exciting coils of opposite poles are connected in series.
- The two coils are connected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

Rotor:

- 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.

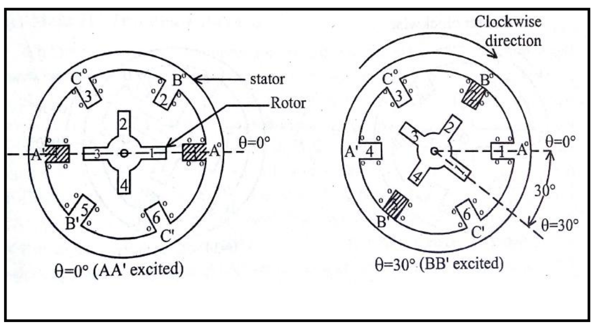
- Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure. The stator is made up of silicon steel stampings with inward projected poles.
- The number of poles of the stator can be either an even number or an odd number. Most 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.



Working:

- Below shown figure 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. They are in the minimum reluctance position so far as phase windings is concerned. Then dLa/dθ=0. At this position inductance of B windings is neither maximum nor minimum. There exists dLb/dθ and dLc/dθ.

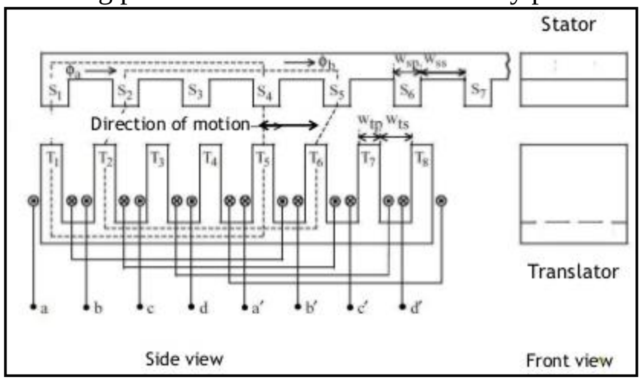


- Now if B phase is energized then the rotor develops a torque because of variable reluctance and existences of variation in inductance.
- The torque developed is equal to (1/2)iB2(dLB/dθ). This direction is such that BB‘ and bb‘ try to get aligned. If this torque is more than the opposing load torque and frictional torque the rotor starts rotating.
- When the shaft occupies the position such that BB‘ and bb‘ are in alignment (i.e.,) θ=30°, no torque is developed as in this position dLB/dθ=0. Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as (dLC/dθ) exists.
- The rotor continues to rotate. When the rotor rotates further 30°, the torque developed due to winding C is zero. Then the phase winding C is switched off and phase winding A is energized. Then rotor experiences a torque and rotates further step 30°. This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor

Liner Type SRM

The concept of an LSRM stems from its predecessor: the rotary switched reluctance motor (RSRM). The only difference between the two configurations is that the RSRM produces a rotational torque, and an LSRM produces a linear force.

- An LSRM is a linear electric motor, in which, translational force production occurs by the tendency of the moving part to move towards a separate stationary point where the inductance of the excited winding is maximized.
- The switched aspect describes the switching of winding excitations at different phases to achieve a continual linear motion. Consider Figure which depicts an 8/6 RSRM design. The numbers 8 and 6 represent the number of poles on the stator and the rotor respectively. In an LSRM system, the translator is the moving part and the stator is the stationary part.



Torque equation of SRM

As per faradays law,

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

$$\text{where } \lambda = N\phi \text{ or } \lambda = Li$$

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

$$= -L\frac{\partial i}{\partial t} - i\frac{\partial L}{\partial t}$$

$$= -L\frac{\partial i}{\partial t} - L\frac{\partial L}{\partial \theta} \times \frac{\partial \theta}{\partial t}$$

$$= -L\frac{\partial i}{\partial t} - i\omega\frac{\partial L}{\partial \theta}$$

- Stored energy in a magnetic field

$$We = \frac{1}{2}Li^2$$

- Power due to stored energy (Rate of change of energy transfer)

$$\frac{d\,We}{dt} = \frac{1}{2}L \cdot 2i\frac{\partial i}{\partial t} + \frac{1}{2}i^2\frac{\partial L}{\partial t}$$

- Power received from electrical source = ei
- Mechanical Power developed = {Power received from the electrical source -Power due to stored energy}= { ei – (dWe/dt) }

$$\therefore\ ei = i\,L\frac{\partial i}{\partial t} + \omega i^2 \frac{\partial L}{\partial \theta}$$

Power due to change in stored energy

$$= Li\frac{\partial i}{\partial t} + \frac{1}{2}\omega i^2 \frac{\partial L}{\partial \theta}$$

Mechanical power developed

$$= \left[i\,L\frac{\partial i}{\partial t} + \omega i^2 \frac{\partial L}{\partial \theta} \right] - \left[Li\frac{\partial i}{\partial t} + \frac{1}{2}\omega i^2 \frac{\partial L}{\partial \theta} \right]$$

Mechanical power developed

$$P_m = \frac{1}{2}\omega i^2 \frac{\partial L}{\partial \theta}$$

$$P_m = \frac{2\pi NT}{60}$$

$$P_m = \omega T$$

where $\omega = \frac{2\pi N}{60}$

Therefore reluctance torque $T = \frac{P_m}{\omega}$

Reluctance Torque $T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta}$

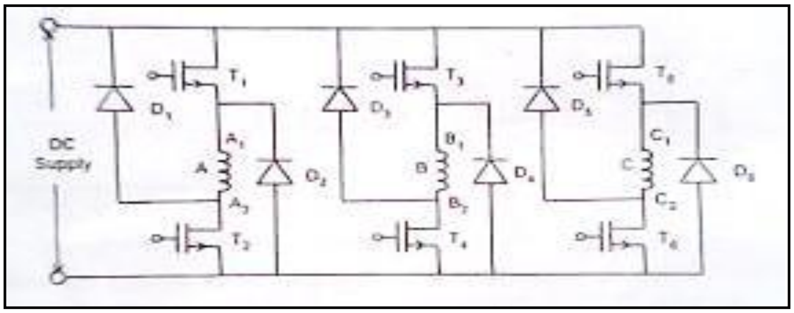
Note:

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

Power converters and configuration used for the control of switched reluctance motor with neat diagram

Two Power Semiconductor Switching Devices per phase and two diodes

- Depending upon the rotor position, when the phase winding A is to be energized the devices T1 and T2 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 T1 and T2 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 D1 and D2 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 T1, T3 and T5 are turned on and off from the signals obtained from the rotor position sensor .The duration of conduction or angle of conduction θ can be controlled by using suitable control circuitry .
- The lower devices T2, T4, T6 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.

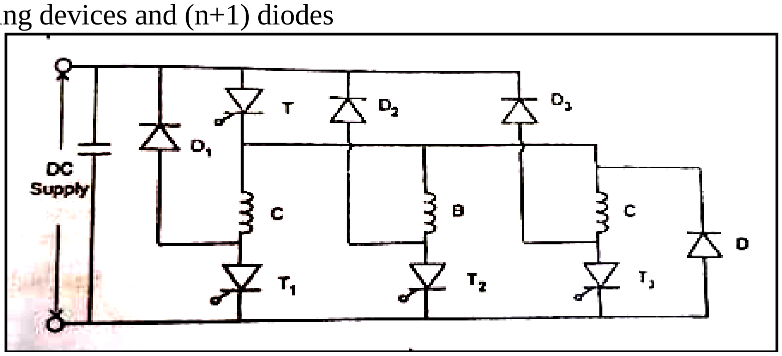
Merits

- 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 reduce the switching frequency and thus the switching losses of the converter.

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



- When the (SCRs) switching devices T and T1 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 D1. When devices T and T2 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.

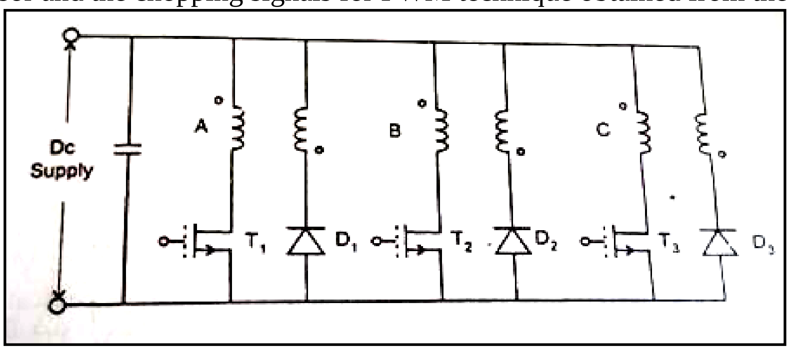
Demerits

- Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.
- At higher speeds , the off going phase cannot be de-energized fast enough because the

common switch T‖ keeps turnings on intermediately, disabling forced demagnetization. Higher switching stress for T1

Phase winding using bifilar wires:

- 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 T1 is turned on the dc current passes through the phase winding A.
- when the devices T1 is turned off the stored energy in the magnetic field is fed back to the dc source through the winding A‘ and D1 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 -Vdc. this causes of higher ripples in current and torque during chopping.

Hysteresis type and PWM type current regulator

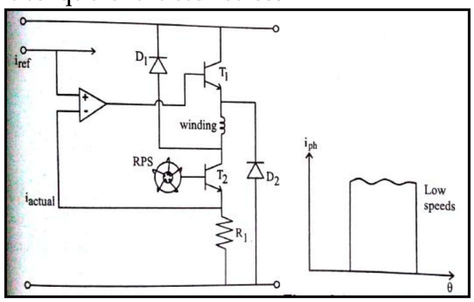
Necessity:

- For higher power drivers more complex controls are required.
- When a wide speed range is required at constant power means digital or microprocessor controls are used.
- At high speed the phase current is limited by its self emf of winding.
- At low speed the current is cannot limit by emf because emf is small only. Current is limited by two methods.
- Hysteresis type current controller.
- Voltage PWM duty cycle control.

Hysteresis type current controller:

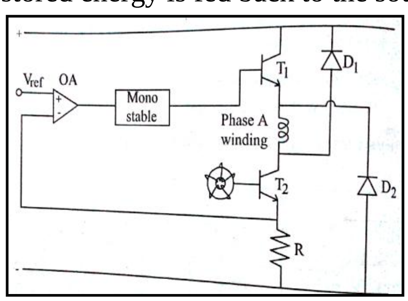
- This type of controller maintain more or less constant current throughout conduction period in each phase.

- The rotor position sensor is connected to rotor and its output is given to the T2 transistor switch.
- From the emitter of the T2 switch a position of current signal is fed at the input to the operational amplifier.
- The output of the operational amplifier is fed to the T1 switch base.
- This signal is combine with collector current and passed to the phase winding A.
- The current flow is controlled by ON and OFF of the T1 and T2.
- A resistor is connected between the T2 and ground. It is used to limit the current. This type control gives constant torque characteristics.

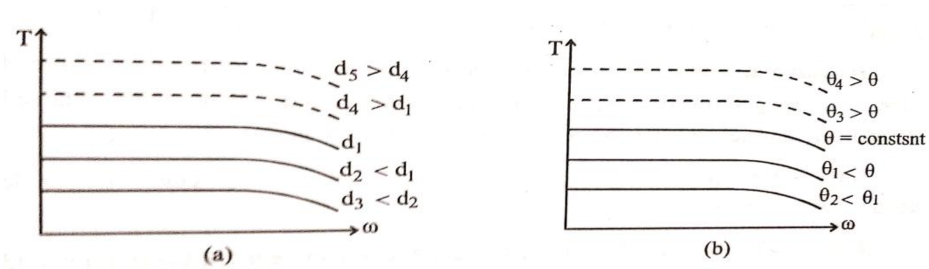


Voltage PWM duty cycle control

- This circuit is consists of two transistors T1 and T2, two Energy feedback diodes D1,D2, operational amplifier, RPS and Monostable vibrator.
- When RPS signal is given to the T2 Base the T2 is turn ON.
- Then the actual voltage is given the op-amp and it compares with the Reference voltage signal.
- The output error signal is given the mono-stable vibrator. This output is fed to the T1 base. This signal combines with collector current and flows through the phase winding. Then the current is controlled by PWM or rotor feedback.
- When the T1 and T2 off the stored energy is fed back to the source through D1,D2.

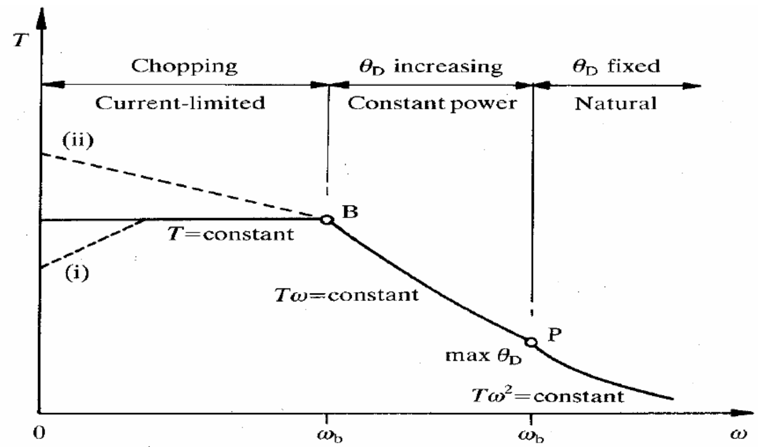


Torque speed characteristics

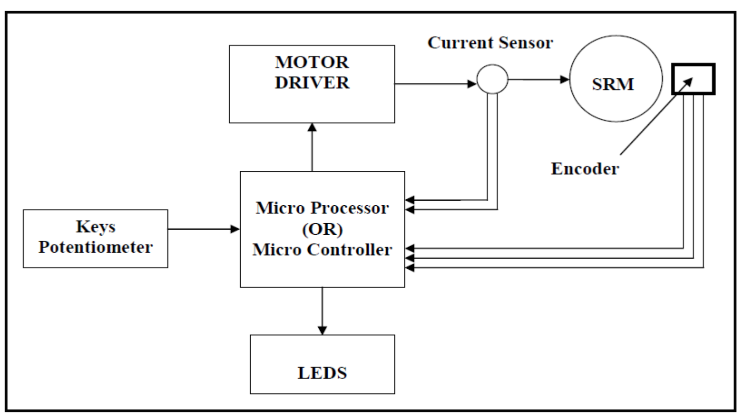


Torque developed (i.e.) average torque developed but SRM depends upon the current wave form of SRM phase winding. Current waveform depends upon the conduction period and chopping details. It also depends upon the speed.

Consider a case that conduction angle θ 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.



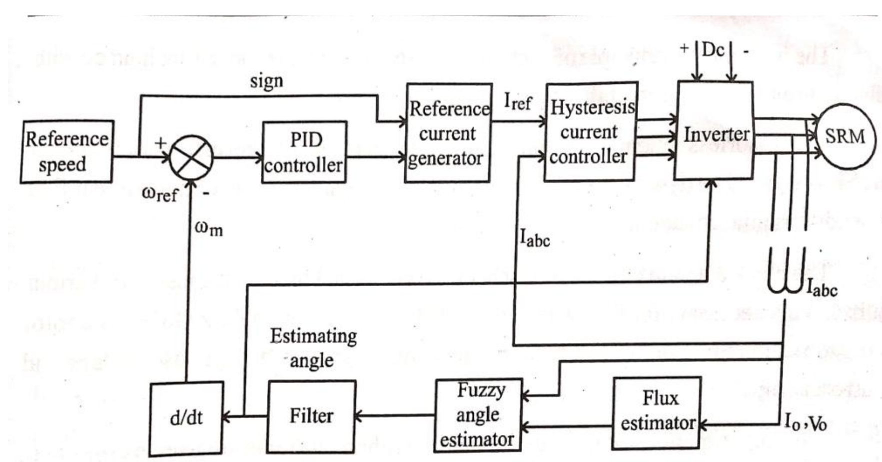
Micro processor control of Switched reluctance motor



- This section describes a general purpose microprocessor controlled closed loop switched reluctance motor (SRM) drive system.
- The system is designed to drive a four phase SRM with minimum number of switches, while achieving maximum flexibility.

- This section also describes the hardware for driving the motor, the techniques used to measure control parameters and how they are fed to the microprocessor.
- The operation of the microprocessor software to provide the user interface and control on the operation is given in detail.
- The main objective of this microprocessor based control of SRM is to develop Software controllability of various modes of operation; here a microprocessor based control philosophy is adopted to achieve flexibility of adapting the controller-driver for various applications. This system can be designed to drive a SR motor. The application should meet the following performance specifications:
  - Speed control of SR motor with encoder position sensor.
  - Variable line voltage up to rated 42V DC.
  - Control techniques incorporates.
    - Voltage SRM control with speed closed loop.
    - Motor starts from any position with rotor alignment.
    - Two directions of rotation.
    - Motoring mode.
    - Minimal speed 600 rpm (can be set by user).
    - Maximal speed depended on line voltage 4320 rpm (can be set by user).
  - User Interface (start/stop switch, right/left switch, potentiometer for speed adjustment, LED indicators).
  - DC-Bus over current protection.

SENSORLESS CONTROL OF SRM DRIVE



- The switched reluctance motor (SRM) has concentrated stator windings and a rotor which does not have windings nor permanent magnets, see Figure .This leads to a low-cost and extremely robust construction, which gives the motor the capability to be operated at ultra-high speeds and in harsh environments.
- Although the machine has a robust structure and simple design, the control is quite complicated compared to the case of classical AC machines.
- An essential aspect in the control of the machine is that the rotor position is needed in order to guarantee proper commutation of the current between the different phases of the machine. In many cases, the rotor position is provided by means of a sensor mechanically mounted on the motor shaft.
- The presence of a sensor leads to a reduced reliability of the drive, especially in harsh environments, and to a higher cost of the drive. For small motors, the cost of the sensor may be as

large as the cost of the motor itself. Worldwide a lot of research has been done in ways to provide the rotor position without the need of a mechanical position sensor.

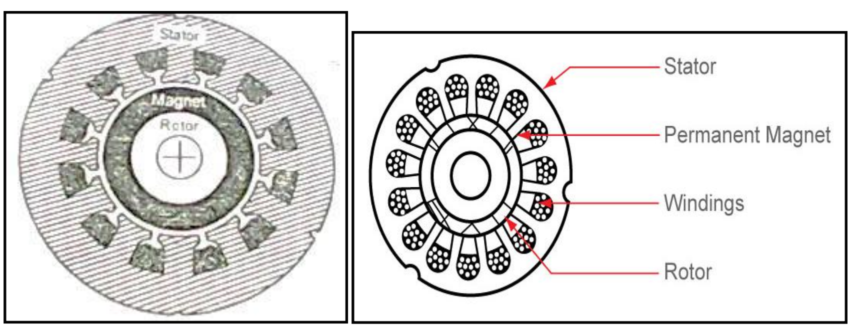
Switched Reluctance Motor Applications

- Domestic appliances such as washing machines, vacuum cleaners, fans, etc.
- Machine tools: Planers, vertical lathes, drilling machines
- General machinery: fans, pumps, compressors
- Food mixing machinery
- Lifting machines: lifts, winches, conveyors
- Power generation equipment: wind turbine rotor blade load control
- Plastic manufacturing: extrusion machinery, injection molding machines
- Paper mill machinery
- Metal rolling mill
- Coil winding and unwinding machinery.

UNIT III
PERMANENT MAGNET BRUSHLESS D.C. MOTORS

Construction and working principle of PMBLDC motor
Construction
Stator

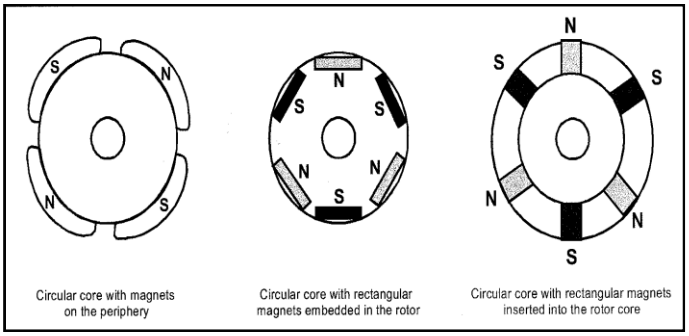
- The stator of the BLPM dc motor is made up of silicon steel stampings with slots in its interior surface.
- These slots accommodate either a closed or opened distributed armature winding usually it is closed.
- This winding is to be wound for a specified number of poles. This winding is suitably connected to a dc supply through a power electronic switching circuitry (named as electronic commutator).



Arrangement of permanent magnet in the rotor

Rotor

- Rotor is made of forged steel. Rotor accommodates permanent magnet.
- Number of poles of the rotor is the same as that of the stator. The rotor shaft carries a rotor position sensor.
- This position sensor provides information about the position of the shaft at any instant to the controller which sends suitable signals to the electronic commutator.
- **Surface mounted type.**
- **Interior type.**



Principle of operation:

Starting

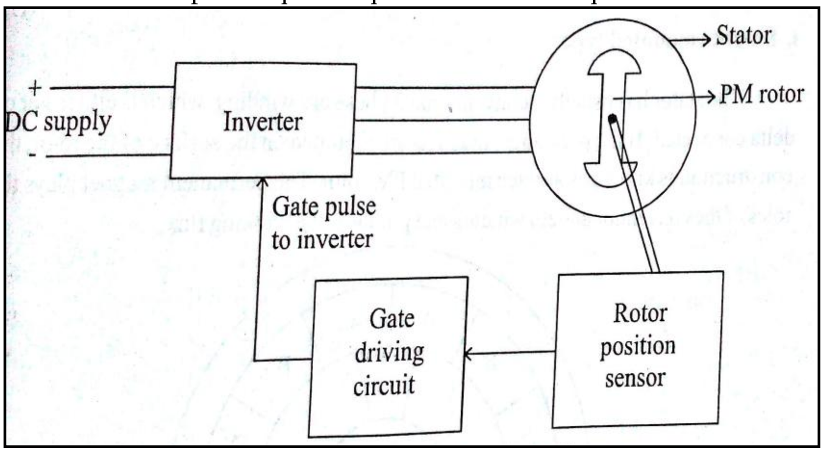
- When dc supply is switched on to the motor the armature winding draws a current. The current distribution within the stator armature winding depends upon rotor position and the devices turned on.
- An emf perpendicular to the permanent magnet field is set up. Then the armature conductors experience a force.
- The reactive force develops a torque in the rotor. If this torque is more than the opposing frictional and load torque the motor starts. It is a self- starting motor.

Demagnetization curve

- As the motor picks up speed, there exists a relative angular velocity between the permanent magnet field and the armature conductors.
- As per faradays law of electromagnetic induction, an emf is dynamically induced in the armature conductors. This back emf as per len‘s law opposes the cause armature current and is reduced.
- As a result the developed torque reduces. Finally the rotor will attain a steady speed when the developed torque is exactly equal to the opposing frictional load torque. Thus the motor attains a steady state condition.

Electromechanical transfer

- When the load – torque is increased, the rotor speed tends to fall. As a result the back emf generated in the armature winding tends to get reduced.
- Then the current drawn from the mains is increased as the supply voltage remains constant.
- More torque is developed by the motor. The motor will attain a new dynamic equilibrium position when the developed torque is equal to the new torque.



Torque equation of PMBLDC

Power input $P = VI$

$$V = 2e_{ph} + 2IR_{ph} + 2vdd$$
$$P = [2e_{ph} + 2IR_{ph} + 2vdd]I$$

Where

$2e_{ph}$ I is the power converted as mechanical

2 I^2Rph is the copper loss in armature winding

2Vdd I is the power loss in device

Mechanical power developed $= 2e_{ph} I$

$$= 2\ (2B_g rl\ T_{ph}\ \omega_m)I$$
$$= 4\ B_g\ rl\ Tph\ \omega_m\ I$$

$$\text{Mechanical power} = \frac{2\pi N}{60} T$$
$$= \omega_m . T$$
$$\therefore\ T = 4B_g\ rl\ T_{ph}\ I$$
$$T = K_t I$$

Where $K_t = 4B_g\ rl\ T_{ph}$

a. Case I : Starting Torque

$$w_m = 0$$
$$I_{st} = V/2\ R_{ph}$$
$$T_{st} = 4B_g\ rl\ T\ ph. V/2\ R_{ph}$$
$$T_{st} = K_t . V/2\ R_{ph}$$

b. Case II: ON load condition:

$$T = K_t I$$
$$= 4B_g\ rl\ T_{ph}\ I$$
$$I = \frac{V - 2e_{ph}}{2R_{ph}}$$
$$2e_{ph} = V - 2IR_{ph}$$
$$4\ B_g\ rl\ T_{ph}\ \omega_m = V - 2IR_{ph}$$
$$K_e\ \omega_m = V - 2IR_{ph}$$
$$\omega_m = \frac{V - 2IR_{ph}}{Ke}$$
$$\omega_o = V/Ke$$
$$\frac{\omega_m}{\omega_{mo}} = \frac{V - 2IR_{ph}}{Ke}\frac{ke}{V} = \frac{V - 2IR_{ph}}{V}$$

$$\frac{\omega_m}{\omega_{mo}} = 1 - \frac{2 I R_{ph}}{V}$$

$$\frac{I}{I_{st}} = \frac{K_t I}{K_t I_{st}} = I . \frac{2 R_{ph}}{V}$$

$$\frac{T}{T_{st}} = \frac{2 I R_{ph}}{V}$$

$$\frac{\omega_m}{\omega_{m0}} = 1 - T/T_{st}$$

$$\frac{\omega_m}{\omega_{m0}} = 1 - \frac{I}{I_{st}}$$

Mechanical characteristics of ideal PMBLDC motor

- The torque cure of the ideal brushless motor can be derived from the foregoing equations. If the commutation is perfect and if the converter is supplied from ideal voltage source V, then at any instant the following equation can be written for DC terminal voltage.

V= E+ RI

R- sum of two series resistance
E- sum of two series phases emf.
The equations same as the commutator DC motor.

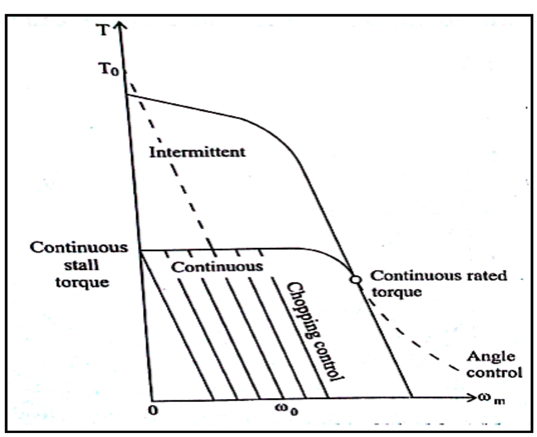
$$\omega = \omega_0 [1 - T/T_0]$$

Where no load speed is

$$\omega_0 = V/k\phi \text{ rad / sec.}$$

and stall torque is given by

$$T_0 = k\phi I_0$$



- The above torque is stall torque To. Then the current at stall condition is Io = V/R

The characteristic is similar to the DC shunt motor.

- Speed is controlled by supply voltage V. then the motor draws enough current to drive the torque at this speed. if the load torque is increased then the speed drops and it is directly proportional to the resistance and torque.
- Voltage is controlled by chopping or PWM. Continuous region is determined by temperature raise and heat transfer. The intermittent region is determined by maximum rating of switching devices used in controller.

The T - ω_m constraints are

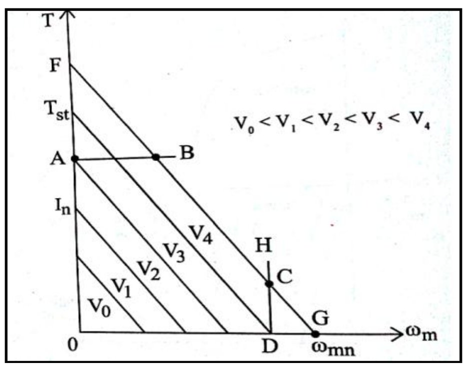
- Continuous current should not exceed the permissible limit. Torque also should not exceed the permissible limit. (Kt In)
- The maximum permissible supply voltage is Vn.
- The speed is not exceeding the ω_m.

Line AB:

- This line represents the permissible current limit In.

Line FG:

- It represents the permissible voltage limit Vn. The point B is the intersection of AB and FG.



Line DH:

- It represents the permissible speed limit ω_m. The region OABCDO is permissible operating region. The resistance is very low then the characteristics is similar to DC shunt motor.

Types of PMBLDC motors based on the flux density distribution in the airgap.

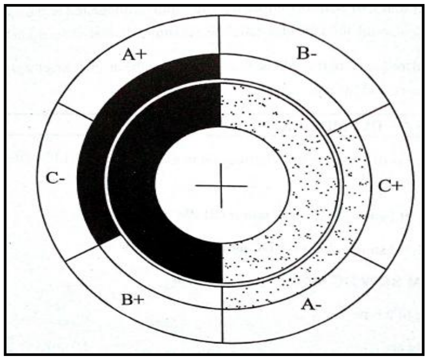
Two modes are

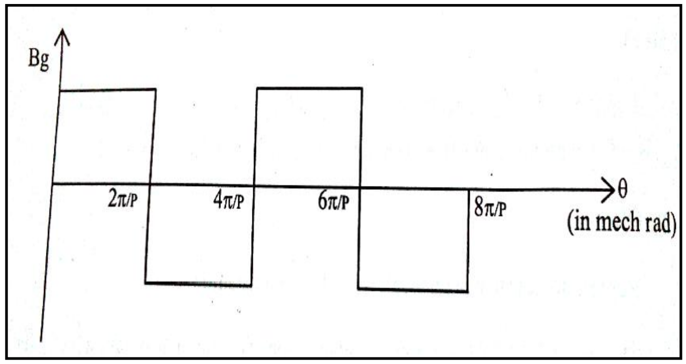
- 120 degree mode.
- 180 degree mode.
- These modes corresponding to the period of the switches in the voltage source inverter. Each switch conducts 120 deg or 180 deg as per mode. Commutation from one switch to another is takes place in 60 deg.

180 degree mode:

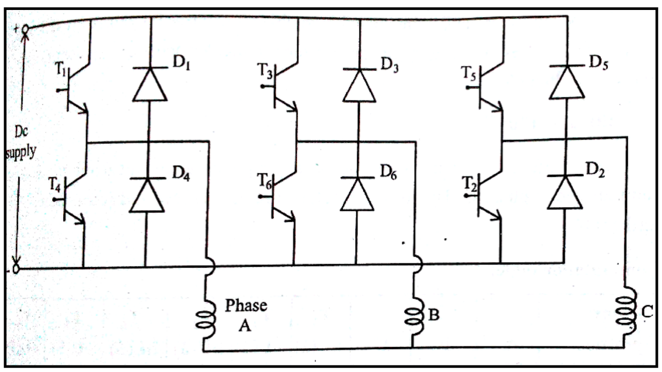
- The air gap distribution is 180 deg for PMBL square wave DC motor.
- The rotor magnet poles are shaded to differentiate the N S poles. The phase belts are shaded for complete 60 deg sector of the stator.

- There are two slots and each having identical currents. The conductors are connected between the rotor ring and stator phase belts. Third ring is mmf. It represents the mmf distribution of the stator currents at a particular instant.





Case i: (wt=0)
A- positive current.
C- negative current.
The mmf of stator is same as the rotor N S poles. Then the polarity of mmf distribution same as the flux density distribution of the rotor. The positive torque is developed. If the mmf and flux shadings are unlike the negative torque produced.



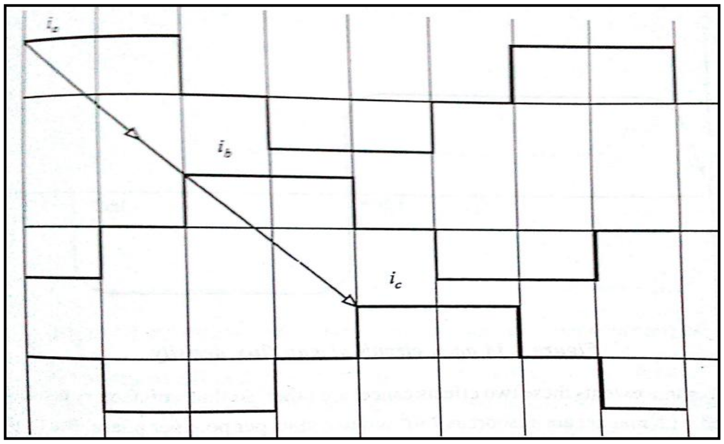
Commutation table:

Rotor position	A	B	C	T_1 aU(1)	T_4 aL(4)	T_3 bU(3)	T_6 bL(6)	T_5 cU(5)	T_2 cL(2)
0 – 60°	1	0	– 1	1	0	0	0	0	1
60° – 120°	1	–1	0	1	0	0	1	0	0
120° – 180°	0	–1	1	0	0	0	1	1	0
180° – 240°	–1	0	1	0	1	0	0	1	0
240° – 360°	–1	1	0	0	1	1	0	0	0
300° – 360°	0	1	–1	0	0	1	0	0	1

Case ii (wt=60) The negative current changed from C to B by T2 off and T6 on. The motor rotates continuously. For further 60 deg.

A-is positive current.

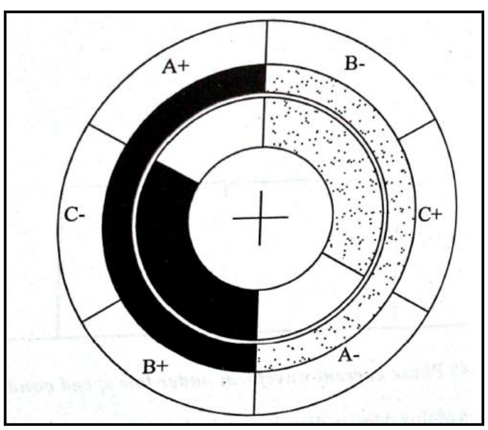
Case iii (wt =120)
The positive current changed from A to C. then the rotor rotates further 60 deg.
B- is negative current.

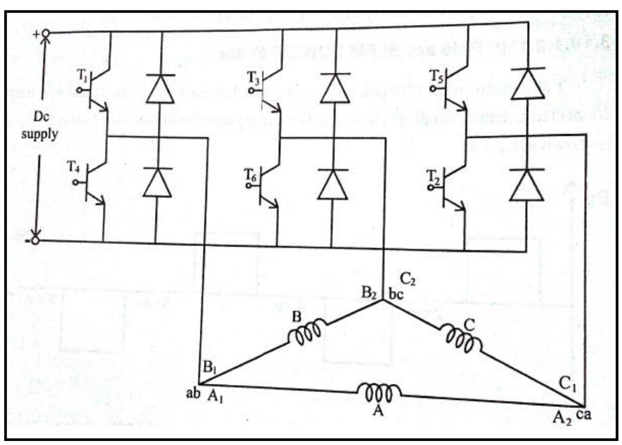


120 degree mode

It is similar to the delta connected armature winding operation.

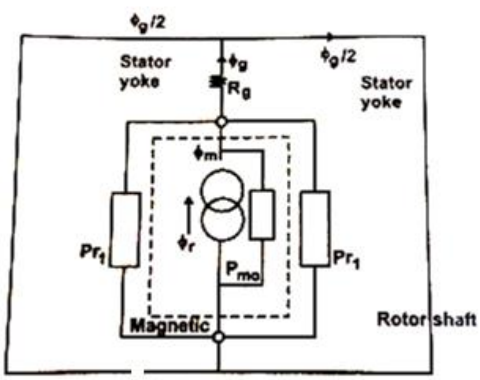
- The air-gap flux density distribution is 120 deg.
- The phase C is remains covered and phase A coverage is increases equal to phase B phase coverage is degrease. So the total torque is constant.
- Similarly emf also constant. Two paths are created one is by C and another one is by A and B phases. Current is divided into two equal.
- Torque constant cannot possible due to resistance and inductances. But current should be constant. Otherwise torque ripples and losses increase.



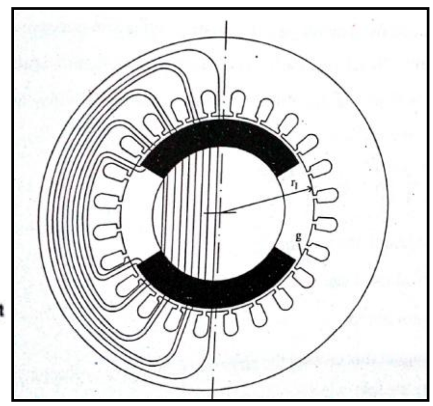


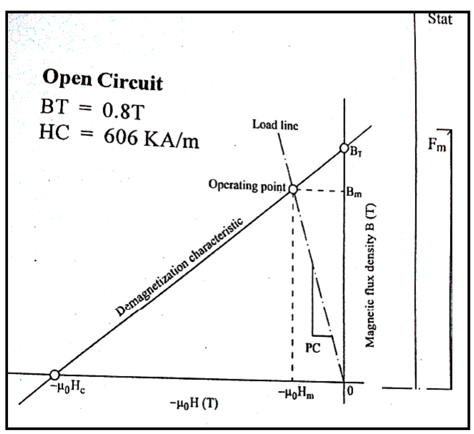
Rotor position	A	B	C	T_1 abU (1)	T_4 abL (4)	T_3 bcU (3)	T_6 bcL (6)	T_5 caU (5)	T_2 caL (2)
0 – 60°	1	1	−1	0	0	1	0	0	1
60° – 120°	1	−1	1	1	0	0	0	0	1
120° – 180°	1	−1	1	1	0	0	1	0	0
180° – 260°	−1	−1	1	0	0	0	1	1	0
240° – 360°	−1	1	1	0	1	0	0	1	0
300° – 360°	−1	1	−1	0	1	1	0	0	0

Magnetic circuit of PMBLDCM



Magnetic equivalent circuit.





- First step to analyze a magnetic circuit is to identify the main flux paths and the reluctance or permeances assigned to them.
- The equivalent magnetic circuit is shown in figure. Only half of the equivalent circuit is shown & the lower half is the mirror image of the upper half about the horizontal axis, which is at equipotential.

- This assumption is true only if the two halves are balanced. If not the horizontal axis might still be an equipotential but the fluxes and the magnetic potentials in the two halves would be different and there could be residual flux in the axial direction along the shaft. The axial flux is undesirable, because it can induce current to flow in the bearing.

$P_m = P_{mo} + P_{r1}$ (∵ parallel permeance are added to obtain equivalent permear

$P_m = P_{mo}(1 + P_{r1})$

Where p_{r1} is the normalised rotor leakage permeance ie normalised to P_{mo}

Thus the various circuit parameters can be determined.

Let us equate the total mmf to that of the airgap

$$F = \frac{\phi_r \phi_g}{P_m} = \phi_g R_g$$

$$\phi_r - \phi_g = \phi_g P_m R_g$$

$$\phi_R = \phi_g + \phi_g P_m R_g$$

$$\phi_R = \phi_g (1 + P_m R_g)$$

$$\phi_g = \frac{\phi_R}{1 + P_m R_g}$$

CONTROLLERS

Rotor Position sensors for BLPM motor

It converts the information of rotor shaft position into suitable electrical signal. This signal is utilized to switch ON and OFF the various semiconductor devices of electric switching and commutation circuitry of BLPM motor.

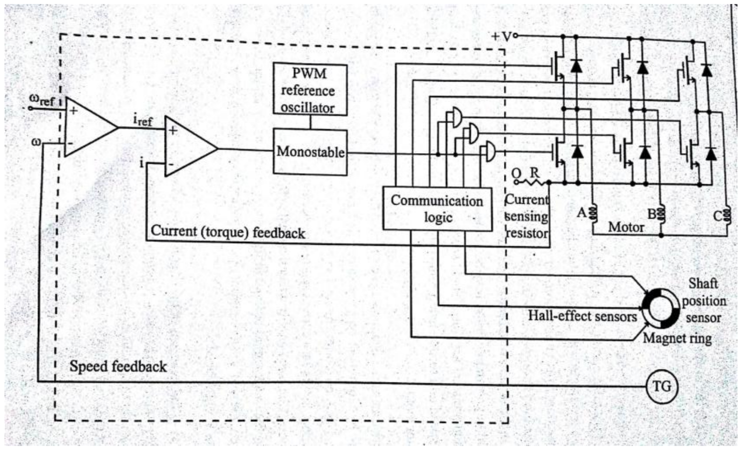
Two popular rotor sensors are

Optical Position Sensor.

Hall Effect Position Sensor.

(a) Optical position sensor

This makes use of six photo transistors. This device is turned into ON state when light rays fall on the devices. Otherwise the device is in OFF state the schematic representation is shown in fig.



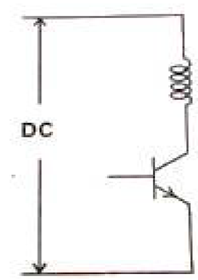
Types of BLPM motor

BLPM motor is classified on the basis of number of phase windings and the number of pulses given to the devices during each cycle.

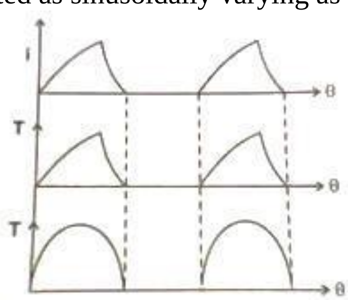
One phase winding one pulse BLPM motor

The stator has one phase winding as shown in fig.

It is connected to the supply through a power semiconductor switch. When the rotor position sensor is influenced by say n pole flux, the stator operates and the rotor developed a torque. When the RPS is under the influence of S pole, the transistor is in off state. The rotor gets torque whenever the rotor position is under the influence of n pole.



The current and torque are approximated as sinusoidally varying as shown in fig.

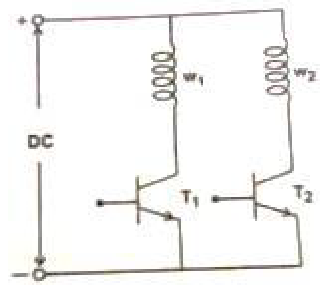


Advantage

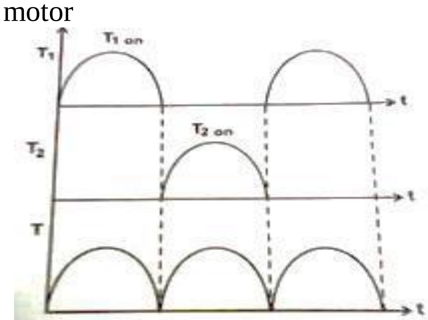
- One transistor and one position sensor is sufficient.
- Inertia should be such that the rotor rotates continuously.
- Utilization of transistor and winding are less than 50%.

Two phase winding and two pulse BLPM motor

Stator has two phase windings which are displaced y 180° electrical. Electrical connections are as shown in fig. It makes use of two semiconductor switches.



two phase winding and two pulse motor



Performance of this type is similar to one phase 2 pulse BLPM motor. Torque waveform are as shown in fig. However it requires two independent phase windings.

Merit

Better torque waveform.

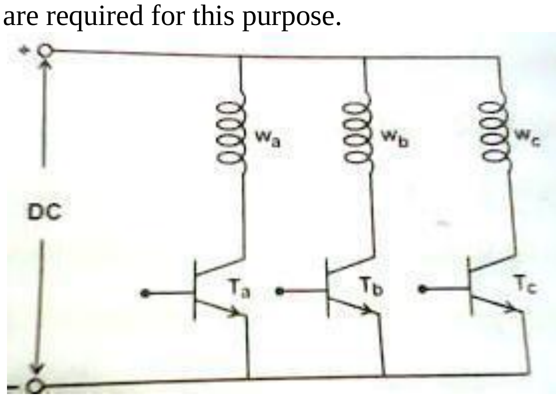
Demerit

Their utilization is only 50% which is less.

Cabling with rotor position sensor should be made proper.

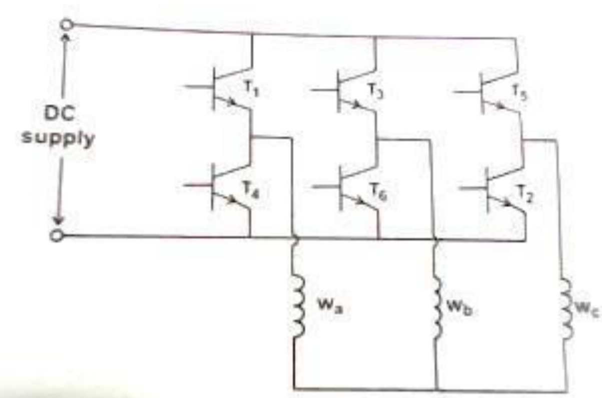
Three phase winding and three pulse BLPM motor

The stator has 3Φ windings as shown in fig. Whose areas are displaced by 120°elec. apart. Each phase windings is controlled by a semiconductor switch which is operated depending upon the position of the rotor. Three position sensors are required for this purpose.



Three phase six pulse BLPM motor

Most commonly used. It has 3 phase windings and six witching devices as shown in fig.



Applications

- Aerospace
- military
- Automotive
- office automation
- household equipment industries

UNIT IV

PERMANENT MAGNET SYNCHRONOUS MOTORS (PMSM)

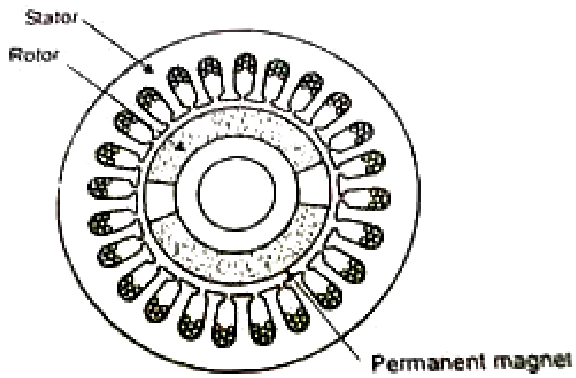
CONSTRUCTION AND PRINCIPLE OF OPERATION

- Permanent magnet synchronous machines generally have same operating and performance characteristics as synchronous machines.
- A permanent magnet machine can have a configuration almost identical to that of the conventional synchronous machines with absence of slip rings and a field winding.

Construction

Stator:

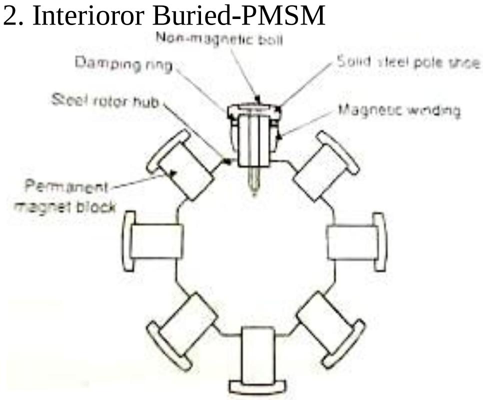
- A simple permanent magnet synchronous machine consists of the stationary member of the machine called stator.
- Stator laminations for axial air gap machines are often formed by winding continuous strips of soft steel.
- Various parts of the laminations are the teeth slots which contain the armature windings.
- Yoke completes the magnetic path. Lamination thickness depends upon the frequency of the armature source voltage and cost.
- Armature windings are generally double layer (two coil side per slot) and lap wound. Individual coils are connected together to form phasor groups.
- Phasor groups are connected together in series/parallel combinations to form star, delta, two phase (or) single windings.
- AC windings are generally short pitched to reduce harmonic voltage generated in the windings.
- Coils, phase groups and phases must be insulated from each other in the end-turn regions and the required dielectric strength of the insulation will depend upon the voltage ratings of the machines.

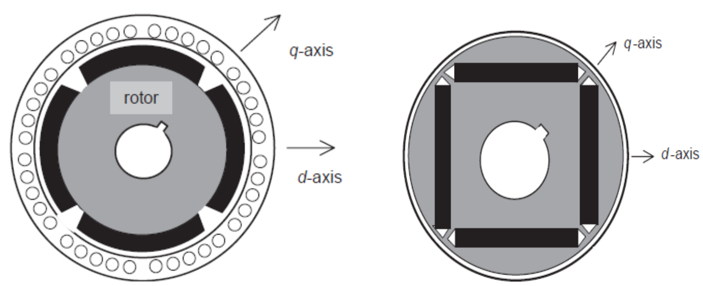


Rotor:

It is made by permanent magnets in different configurations.

1. Surface Mounted-PMSM
   - Projecting type
   - Inset type
2. Interioror Buried-PMSM





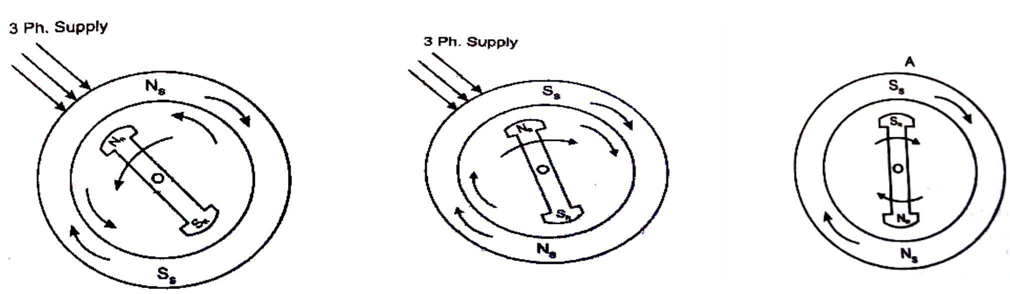
Principle of Operation

- It is one type of AC motors which can operate at a constant speed from no load to full load. (2)
- It is similar to AC generation construction. It has revolving field and it should excited by DC source separately.
- By changing DC field excitation we can change the power factor from lagging to leading values.
- It is mostly used motors because of its constant speed, high efficiency, and low initial cost.
- It is also used to improve the power factor of 3 phase AC circuits.

Principle and operation: (3)

- When a three phase Ac supply given to the three phase windings, it produce resultant pulsating fields.
- Direction of the field also changes with respect to time continuously.
- It values is 1.5 Φm (here Φm is the maximum flux of single phase).
- The speed of rotating field is

Ns = 120f/ P



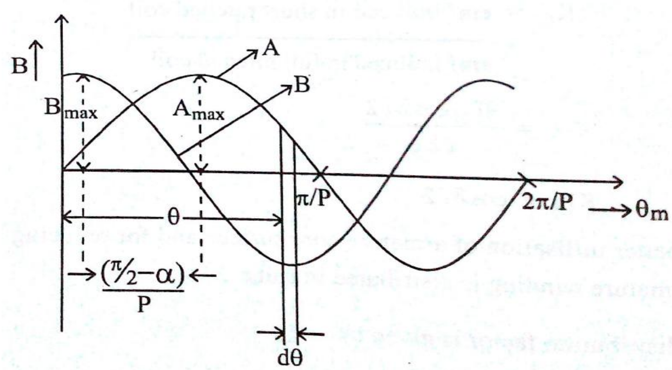
- Ns is the constant speed of rotating field.
- Ns and Ss are stator poles,
- Nr and Sr are rotor poles. It creates by DC supply given to rotor winding.
- In first half cycle condition Ns and Nr are ripple each other similarly for Ss and Sr. So rotor rotates anti clock wise direction.
- In second half cycle condition Ns and Ss are changed. So Ss and Nr are attracted similarly for Ns and Sr. Now rotor rotates in clockwise direction.
- At result rotor just oscillate only not rotate.
- So synchronous motor is not self start motor. It needs starting methods.
- By using prime movers first rotor rotated near Ns speed then Ns and Sr are interlocked (stator and rotor poles are interlocked. So motor starts continuously rotates in constant Ns speed.

Based on nature of voltage induced in the stator classified as

1. Sinusoid ally excited PMSM:
   - Stator has distributed winding.
   - Stator induced voltage has sinusoidal waveform.
2. Trapezoid ally excited PMSM:
   - Stator has concentrated winding.
   - Stator induced voltage has trapezoidal waveform.

Torque equation of ideal and practical PMSM motor

- The torque of the PMSM mainly depending the flux density B and ampere conductor A.



$$B = B_{max}\sin\left(P\theta + \left(\frac{\pi}{2} - \alpha\right)\right)$$

$$= B_{max}\sin\left(\frac{\pi}{2} + P\theta - \alpha\right)$$

$$B = B_{max}\cos(P\theta - \alpha)$$

$$A = A_{max}\sin P\theta$$

Force experienced by the armature conductors is,

$$dF = B\,l\,A\,d\theta$$

$$= A_{max}\; B_{max}\, l \sin P\theta \cos(P\theta - \alpha)\, d\theta$$

Torque in the armature conductors is,

$$dT = A_{max} B_{max} rl \sin P\theta \cos(P\theta - \alpha) d\theta$$

Torque in armature conductor per pole,

$$= A_{max} B_{max} rl \int_{o}^{\pi/P} \sin P\theta \cos(P\theta - \alpha) d\theta$$

$$= \frac{A_{max} B_{max}}{2} rl \int_{o}^{\pi/P} [\sin(P\theta + P\theta - \alpha) + \sin\alpha] d\theta$$

$$= \frac{A_{max} B_{max}}{2} rl \left[\frac{-\cos(2P\theta - \alpha)}{2P} + \theta \sin\alpha \right]_{o}^{\pi/P}$$

$$T = -\pi A_{max} B_{max} rl \sin\alpha$$

$$\text{Since } \beta = -\alpha$$

$$\Rightarrow T = \pi A_{max} B_{max} rl \sin\beta$$

Torque experienced in practical PMSM,

$$T = (3\sqrt{2} K_{\omega 1} T_{ph} B_{max} rl) I_{ph} \sin\beta$$

$$T = 3 \frac{E_{ph}}{\omega_m} I_{ph} \sin\beta$$

phasor diagram

- The flux line is reference .Then the Emf Eb 90 deg lagging with flux.
- -Eb drawn apposite 180 deg to Eb.
- The two current components are Iq and Id 90 phase difference to each other and the sum of these currents is I vector
- Then the resistive loss IR is drawn parallel to I.
- The Reactive loss jIX drawn perpendicular to resistive loss line. The voltage V is draw from reactive loss line and origin O.

$$\phi_a \; \alpha \; I_a$$

$$\phi_a = K_a I_a$$

$$E_a = 4.44 f K_\omega N_{ph} K_a I_a = I_a X_a$$

$$X_a = 4.44 f K_\omega N_{ph} K_a$$

- Ea drawn apposite 90 deg to jIX.

$$\overline{E}_a = -j I_a X_a$$

$$\overline{E}_{al} = 4.44 f K_{\omega} N_{ph} \phi_{al}$$

$$\because \phi_{al} \propto I_{al}$$

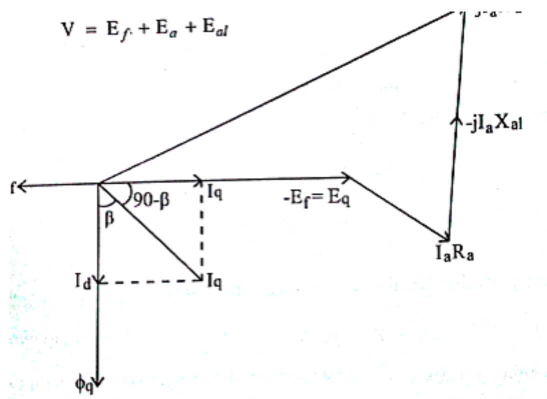
$$\phi_{al} = K_{al} I_{al}$$

$$\overline{E}_{al} = 4.44 f K_{\omega} N_{ph} K_{al} I_{al}$$

$$= I_{al} X_{al}$$

$$X_{al} = 4.44 f K_{\omega} N_{ph}$$

The Voltage is, $V = E_f + E_a + E_{al}$



$$\text{Voltage } \overline{V} = E_q + I_a R_a + [-j\, I_{al} X_{al} - j\, I_a X_a]$$

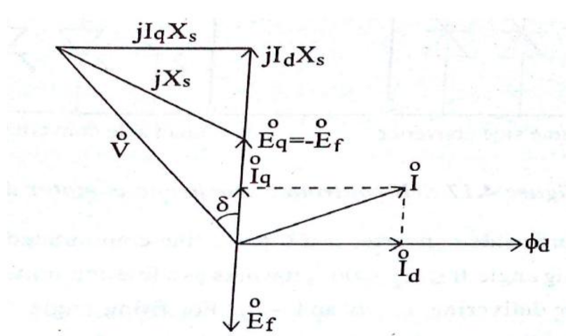
$$= E_q + I_a R_a - j\, I_a [X_{al} + X_a]$$

$$X_{al} + X_a = X_s$$

$$\overline{V} = E_q + I_a R_a - j I_a X_s$$

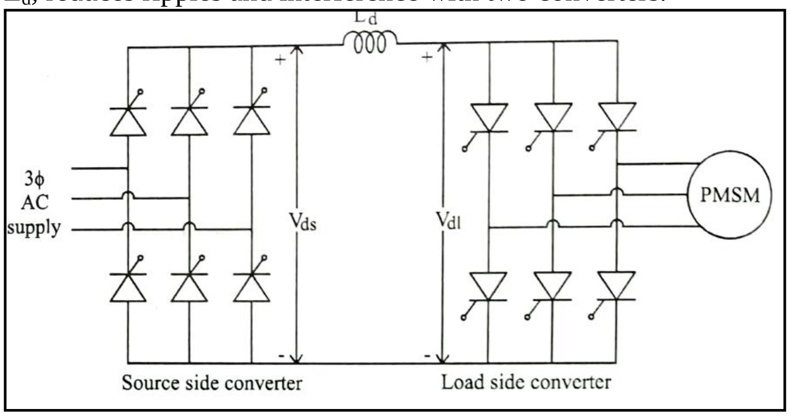
$$= E_q + I_a [R_a - j X_s]$$

$$\overline{V} = E_q + I_a Z_s$$



Self controlled PMSM driver with load commutated thyristor inverter

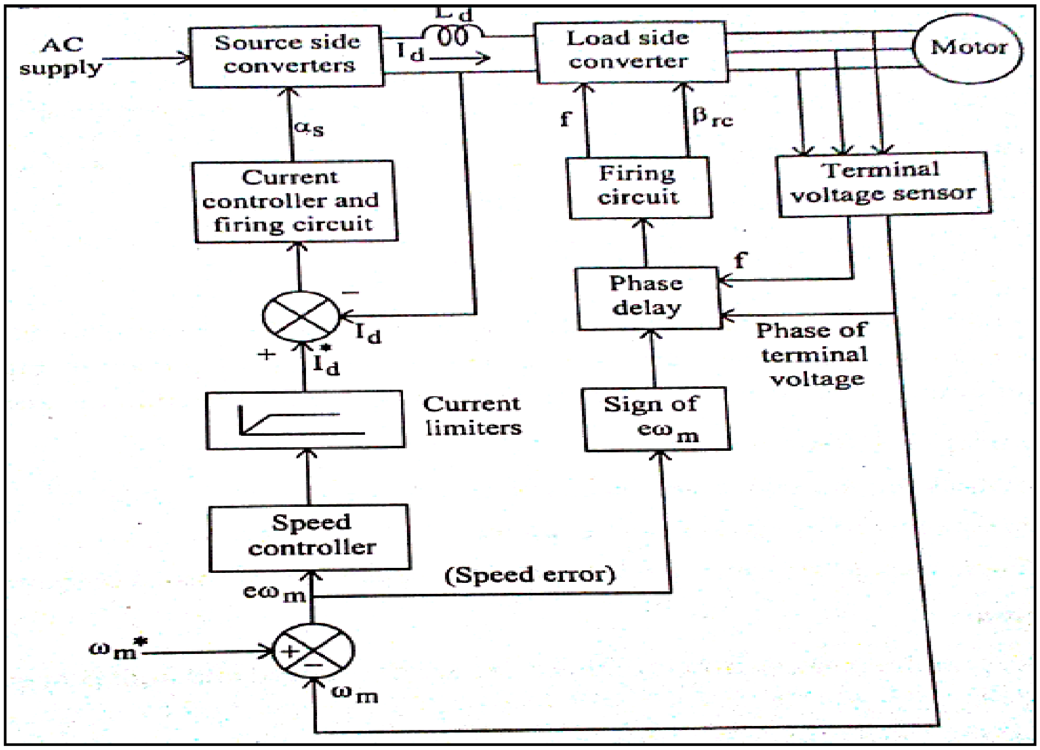
- Self control ensures that for all operating points the armature and rotor field moves exactly at the same speed. The torque angle is adjusted electronically.
- Hence there is an additional controllable parameter causing greater control of the motor behavior. By varying the firing of the semiconductor switches of an inverter the torque angle is set electronically.
- Self control is applicable to all variable frequency converters, frequency being determined by machine speed.
- The drive employs two converters, termed as source side converter and load side converter. Inductance L_d, reduces ripples and interference with two converters.



- The source side converter is a 6 pulse line commutated thyristor inverter. For firing angle 0 <= α_s<= 90°, it works as a line commutated fully controlled rectifier delivering + V_{ds} and +Id. For firing angle 90° <= α_s<= 180°, it works as line commutated inverter delivering Negative V_{ds} & Positive I_d
- When synchronous motor operates at a leading power factor, thyristors of the load side converter can be commutated by motor induced voltages in the same way as thyristors of line commutated converter are commutated by line voltages commutation of thyristors by induced voltages of load is known as “load commutation"
- Load side converter operates as an inverter producing Negative V_{dl}, & Positive I_{dl}, for 90° <= α_s<= 180° and for 0 <= α_s<= 90° it works as a rectifier producing Positive I_{dl}
- For 0 <= α_s<= 90°, 90° <= α_s<= 180º and with Vds > Val. the source side converter works as rectifier and load side converter as an inverter causing power flow from source to motor thus giving motoring operation.
- For 90° <= α_s<= 180º, <= α_s<= 90° load side converter acts as rectifier and source side converter acts as an inverter, delivering power flow to the source and thus operates in regenerative braking.
- The magnitude of torque depends on (Vds - Vai). Speed can be changed by control of line side firing angle. DC link current Id flows through the machine phase for 120° in each half circle It is fundamental component of phase current I, is,

$$I_S = (\sqrt{6}/\pi)I_d$$

- For machine operation in self controlled mode, rotating field speed should be the same as rotor speed. This condition is realized by making frequency of load side converter output voltage equal to the frequency of voltage induced in the armature.



Advantages of load commutation:

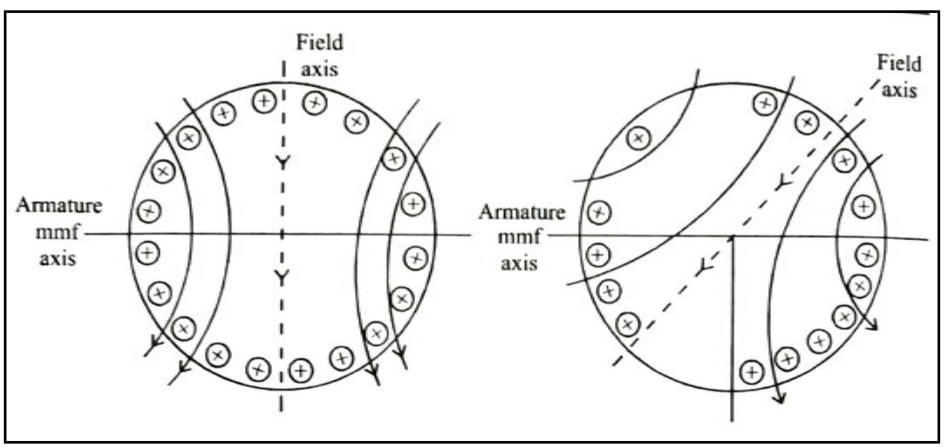
- It does require commutation circuits
- Frequency of operation can be higher
- It can operate at power levels beyond the capability of forced commutation.

Applications:

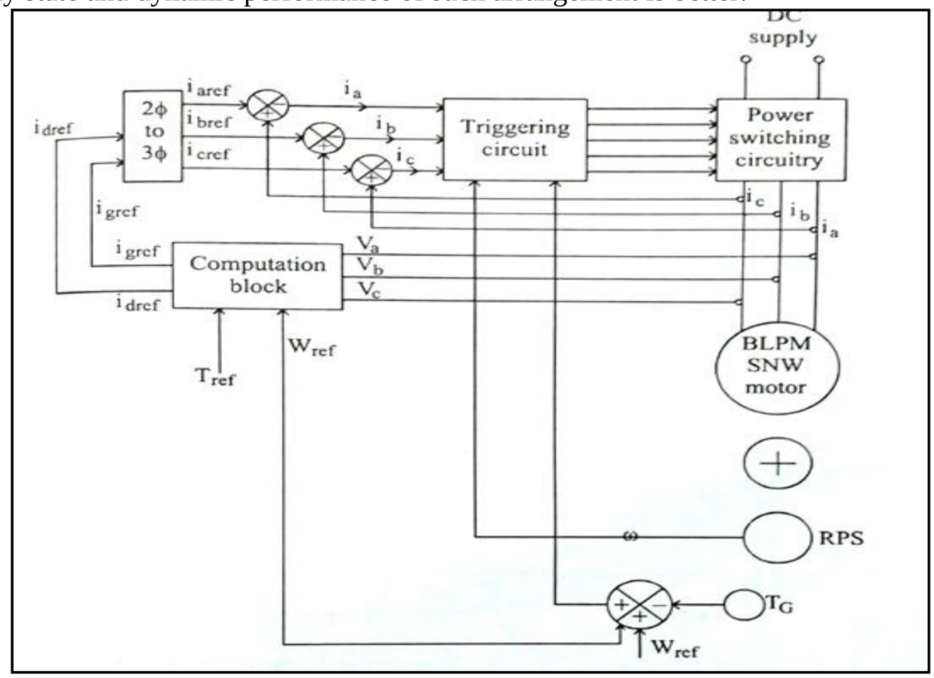
Some prominent applications of this drive are high speed and high power drives for

- Compressors
- Blowers
- Conveyers
- Steel rolling mills
- Main line traction
- Aircraft test facilities

vector control of BLPM square wave motor



- Electromagnetic torque developed due to the interaction of the current carrying conductor and magnetic field.
- In diagram flux axis is in quadrature with armature mmf axis. Each and every armature conductor experiences a force which contributes the torque.
- The torque contributed by armature conductors has the same direction. It is observed that the steady state and dynamic performance of such arrangement is better.



- In diagram angle between the axis of flux and armature mmf axis is different from 90°. In this case some conductors develop torque in one direction whiles the other in the opposite direction.
- It is observed that both the steady state and dynamic performance of such a motor poor. Thus for a BLPM SNM motor to have better steady state and dynamic performance it is essential that the armature mmf axis and field axis are to be in quadrature in all operating conditions.

$$\dot{I} = \dot{I}\, d + \dot{I}q,$$

Where

$\dot{I}$ d → Direct axis current

$\dot{I}$ q → quadrature axis current

- Desired operating point of current is such that $\dot{I}$ d = 0.
- I is along 'q' axis.
- Controlling the BLPM SNW motor taking into consideration above mentioned aspect is known as “Vector control of BLPM SNW motor".

mechanical characteristics of PMSM motor

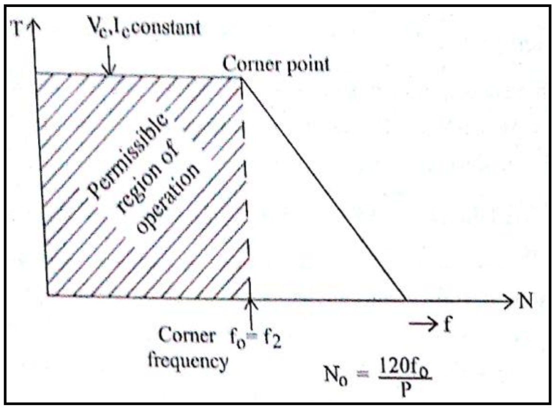
- It is a graph between the speed and torque of the PMSM. Both are mechanical paramentes. So it is called as mechanical characteristics.
- At low speed the frequency increases the torque remains constant only. This region is constant torque region. it is with in the permissible torque and speed limit.
- At high speed and frequency increases torque decreases. In this region motor cannot run long time. It comes to zero speed at above critical soeed.

Effect of over speed

- In the torque speed characteristics, if the speed is increased beyond the point D, there is a risk of over current because the back emf continues to increase while the terminal voltage remains constant.

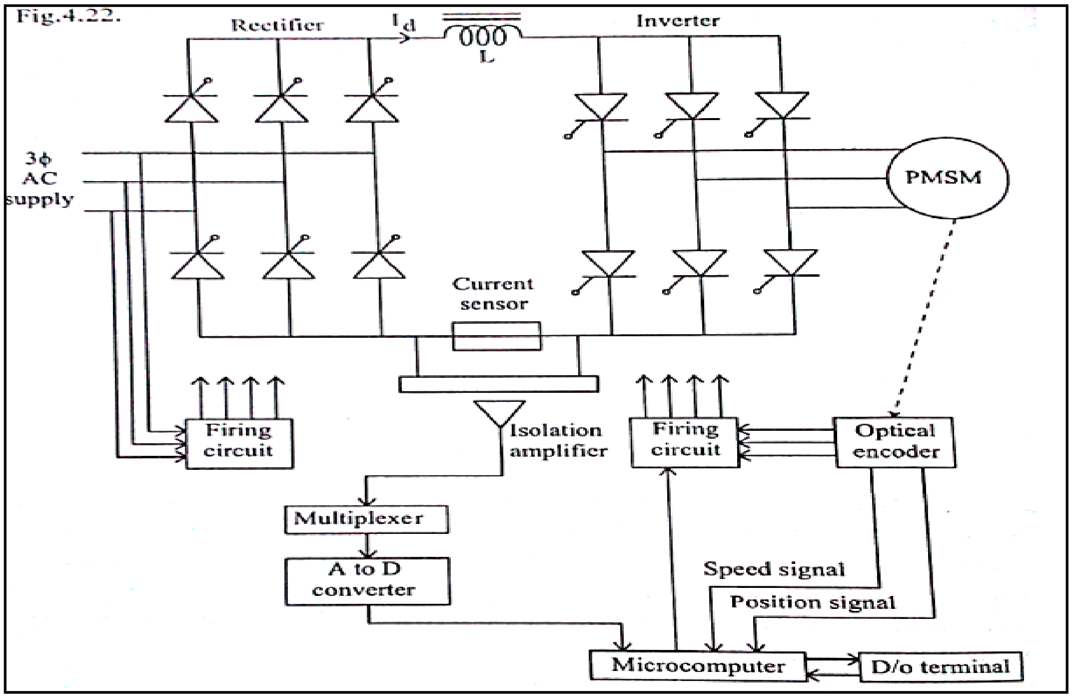
- The current is then almost a pure reactive current flowing from the motor back to the supply. There is a small q axis current and a small torque because of losses in the motor and in the converter. The power flow is thus reversed.
- This mode of operation is possible only if the motor _over runs' the converter or is driven by an external load or prime mover.

- In such a case the reactive current is limited only by the synchronous reactance. As the speed increase further, it approaches short circuit current, which is many times larger than the normal current rating of the motor winding or the converter.
- This current may be sufficient to demagnetize the magnets particularly if their temperature is high.
- Current is rectified by the freewheeling diodes in the converter and there is a additional risk due to over voltage on the dc side of the converter, especially if a filter capacitor and ac line rectifiers are used to supply the dc. But this condition is unusual, even though in the system design the possibility should be assessed.



Microcontroller based control for PMSM

- The advent of microprocessor has raised interest in digital control of power converter systems and electronics motor drives since the microprocessor provides a flexible and low cost alternative to the conventional method.
- For permanent magnet synchronous motor drive systems, microprocessor control offers several interesting features principally improved performance and reliability, versatility of the controller, reduced components and reduced development and manufacturing cost.
- The permanent magnet synchronous motor is fed from a current source d.c link converter system, which consists of a SCR inverter through rectifier and which is operated from three phase a.c supply lines, and its gating signals are provided by digitally controlled firing circuit.
- The optical encoder which is composed of a coded disk attached to the motor shaft and four optical sensors, providing rotor speed and position signals.
- The inverter triggering pulses are synchronized to the rotor position reference signals with a delay angle determined by an 8-bit control input.



- The inverter SCR's are naturally commutated by the machines voltages during normal conditions. The speed signals, which is a train of pulses of frequency, proportional to the motor speed, is fed to a programmable counter used for speed sensing.
- The stator current is detected by current sensor and amplified by optically isolated amplifier. The output signals are multiplexed and converted to digital form by a high speed analog to digital converter.
- The main functions of the microprocessor are monitoring and control of the system variables for the purpose of obtaining desired drive features.
- It can also perform various auxiliary tasks such as protection, diagnosis and display.
- In normal operation, commands are fetched from the input-output terminals, and system variables (the dc link current, the rotor position and speed) are sensed and fed to the CPU.
- After processing, the microprocessor issues control signal to the input rectifier, then the machine inverter, so as to provide the programme.

Advantages:

Higher accuracy.

- Continuous monitoring of operation.

Disadvantages:

- More components needed. So complexity is increased.
- Sensor less operation is difficult.

Advantages of Permanent Magnet Synchronous Motors

- Elimination of field cooper loss.
- High power density.
- Low rotor inertia.
- High efficiency.

Disadvantages:

- Loss of flexibilities of field flux control.
- Demagnetization effect.
- High cost.

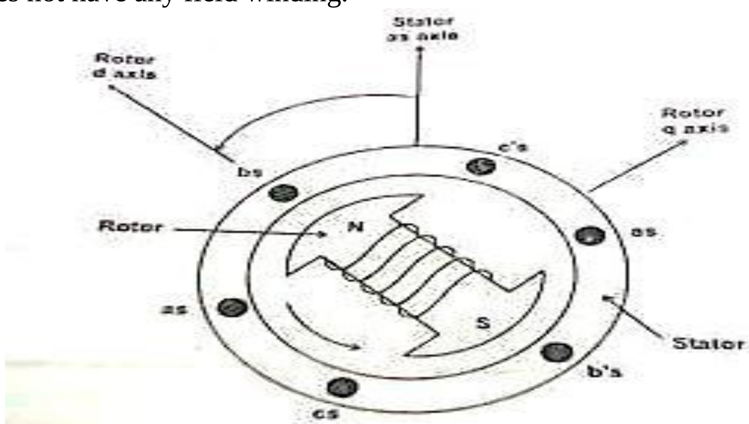
Applications

- Air conditioners.
- Refrigerators.
- AC compressors.
- Washing machines, which are direct-drive.
- Automotive electrical power steering.
- Machine tools.
- Large power systems to improve leading, and lagging power factor.
- Control of traction.

UNIT V
OTHER SPECIAL MACHINES

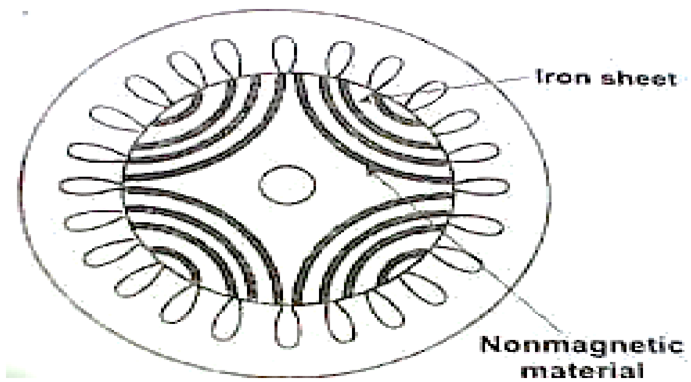
Constructional and working principal of synchronous reluctance motor

- The structure of reluctance motor is same as that of salient pole synchronous machine as shown in fig. The rotor does not have any field winding.



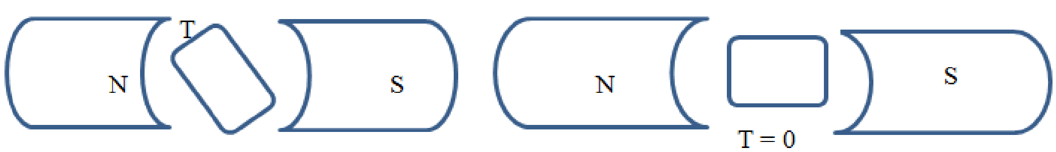
Idealized Three Phase Four Pole Synchronous Machine (Salient Pole)

- The stator has three phase symmetrical winding, which creates sinusoidal rotating magnetic field in the air gap, and the reluctance torque is developed because the induced magnetic field in the rotor has a tendency to cause the rotor to align with the stator field at a minimum reluctance position.
- The rotor of the modern reluctance machine is designed with iron laminations in the axial direction separated by non-magnetic material.
- The performance of the reluctance motor may approach that of induction machine. With high saliency ratio a power factor oh 0.8 can be reached.
- The efficiency of a reluctance machine may be higher than an induction motor because there is no rotor copper loss. Because of inherent simplicity, robustness of construction and low cost.
- The synchronous reluctance motor has no synchronous starting torque and runs up from stand still by induction action. There is an auxiliary starting winding. This has increased the pull out torque, the power factor and the efficiency.



Cross Section of Synchronous Reluctance Motor.

- Synchronous reluctance motor is designed for high power applications.
  It can broadly be classified into
  Axially laminated and
  Radially laminated.
- In order to understand the working of synchronous reluctance motor, when a piece of magnetic material is located in a magnetic field, a force acts on the material tending to bring it into the desert portion of the field.
- The force tends to align the specimen of the material in such a way that the reluctance of the magnetic path that passes through the material will be minimum.
- When supply is given to the stator winding, the revolving magnetic field will exert reluctance torque on the unsymmetrical rotor tending to align the salient pole axis of the rotor with the axis of the revolving magnetic field, because in this position, the reluctance of the magnetic path would be minimum.
- If the reluctance torque is sufficient to start the motor and its load, the rotor will pull into step with the revolving field and continue to run at the speed of the revolving field.
- Actually the motor starts as an induction motor and after it has reached its maximum speed as an induction motor, the reluctance torque pulls its rotor into step with the revolving field, motor now runs as synchronous motor by virtue of its saliency.
- Reluctance motors have approximately one third the HP rating they would have as induction motors with cylindrical rotors.



Rotor Position due to Revolving Magnetic Field

- Although the ratio may be increased to 9one half by proper design of the field windings, power factor and efficiency are poorer than for the equivalent induction motor.
- Reluctance motors are subject to cogging, since the locked rotor torque varies with the rotor position, but the effect may be minimized by skewing the rotor bars and by not having the number of poles.

phasor diagram of synchronous reluctance motor

The synchronous reluctance machine is considered as a balanced three phase circuit, it is sufficient to draw the phasor diagram for only one phase. The basic voltage equation neglecting the effect of resistance is

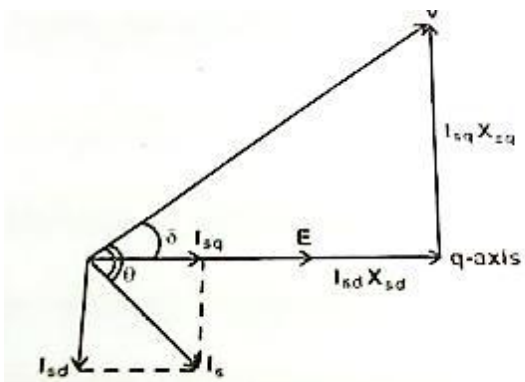


Fig Phasor Diagram of Synchronous Reluctance Motor

$V = E - j\, IsdXsd - j\, Isq$

Where V is the Supply Voltage Is is the stator current

E is the excitation emf

ϑ is the load angle

ϕis the phase angle

Xsd and Xsq are the synchronous reactance of direct and quadrature axis

Isd and Isq are the direct and quadrature axis current

$I = Isd + Isq$

Isd is in phase quadrtur with E and Isq is in phase with E.

$V = E - j\, IsdXsd - j\, IsqXsq$

From phasor diagram

$V \cos\vartheta = E + Isd + Xsd$

$Isd = \frac{V cos - E}{Xsd}$

$IsqXsq = V \sin\vartheta$

$Isq = \frac{V\, sin}{Xsq}$

$Is \cos = Isq \cos\vartheta - Isd\, sin\ldots$

$$Pm = 3\,[\frac{VE}{Xsd}\sin\ +V^{2}\frac{(Xsd-Xsq)}{2\,Xsd\,Xsq}\sin 2\ 8\,]$$

$$Pm = T\,\omega_s$$

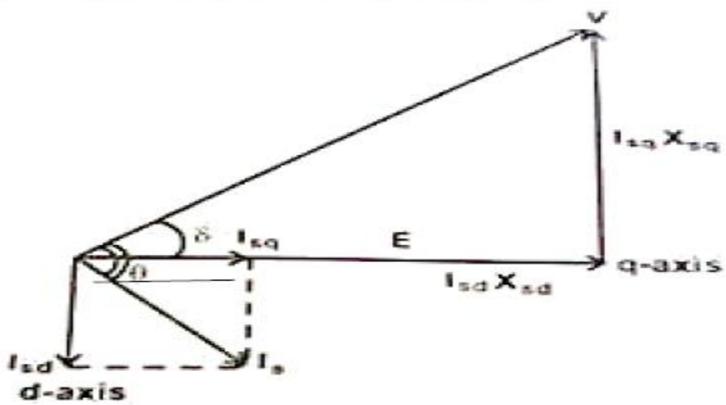
$$T = Pm/\omega_s$$

$$= \frac{3}{ws}\,[\frac{VE}{Xsd}\sin 8\ + \frac{v2(Xsd-Xsq)}{2\,Xsd\,Xsq}\sin 28\,]\ldots$$

Sub E = 0

$$T = \frac{3}{\omega s}V^{2}\,[\frac{Xsd-xsq}{2Xsd\,Xsq}]\,\sin 28$$

In synchronous reluctance motor, the excitation emf(E) is zero.

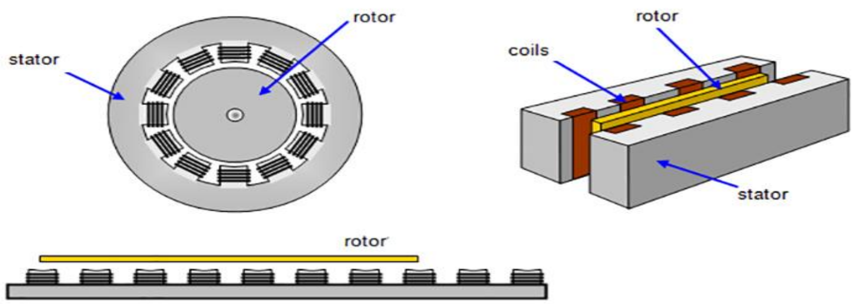


Phasor Diagram of Synchronous Reluctance Motor with E=0

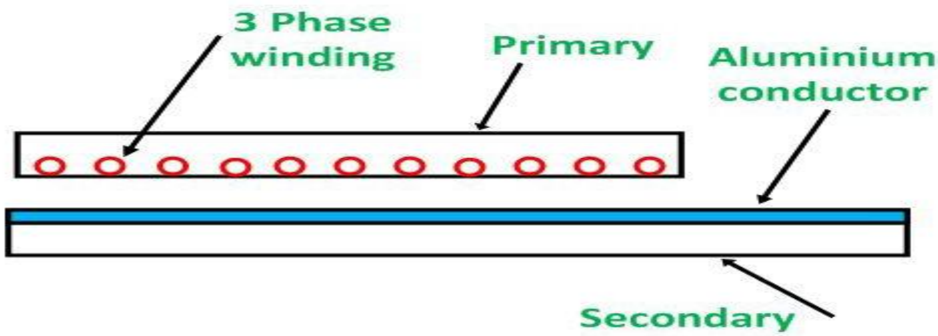
Applications of synchronous reluctance motor

- Fiber spinning mills
- Industrial process equipment
- Metering pumps
- Wrapping and folding machines.

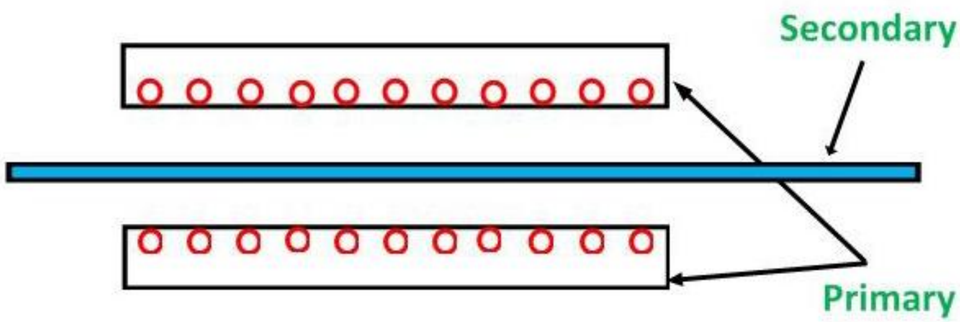
linear induction motor



- A Linear Induction Motor is a special type of induction motor used to achieve rectilinear motion rather than rotational motion as in the case of conventional motors.
- An induction motor is one in which the current in the rotor is induced by the electromagnetic field in the stator, eliminating the use of magnets.
- A linear induction motor is a type of linear motor based on a rotary AC induction motor.
- The secondary consists of what is commonly referred to as a “reaction plate” — a conducting aluminum or copper plate, typically with a steel backing.



- When power is supplied to the primary, magnetic flux develops and travels across the length of the primary. Eddy currents are induced in the conducting material of the secondary. The magnetic flux of the primary and the induced currents of the secondary interact to produce a linear force.
- Linear bearings are necessary in linear induction motors to maintain the proper air gap between the primary and secondary parts. The linear bearings also support the attractive forces that occur between the primary and secondary when the motor is powered.
- A common variation is the double-sided linear induction motor (DSLIM or DLIM), in which the reaction plate passes between two primaries that face each other. For DLIM designs, the reaction plate is only made of conductive material and does not include steel backing.
- The double-sided design produces higher thrust forces and eliminates the attractive forces between the primary and secondary parts.



Double-sided linear induction motors can produce higher thrust forces.

- The linear speed of the primary is proportional to the frequency of supply voltage and the pole pitch of the primary part laminations.

$$V_s = 2 \cdot t \cdot f_s$$

Where:
Vs = velocity of stator (primary) (m/s)
t = pole pitch (m)

fs = frequency of power supply (Hz)

- But linear induction motors are asynchronous, which means the secondary travels at a speed slower than the magnetic field of the primary. The difference in speed is referred to as "slip."

$$V_r = (1-s)\cdot V_s$$

Advantages

- Low initial cost.
- Low maintenance cost due to the absence of rotating parts.
- No limitation of maximum speed due to centrifugal forces.
- No overheating of the rotor.

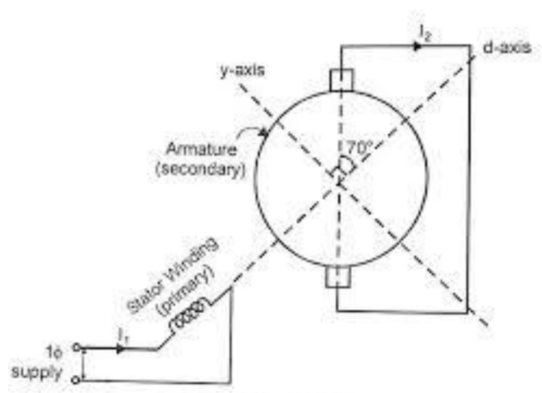
Disadvantages

- The construction of LIM devices is somewhat complicated as they require sophisticated control algorithms.
- These have increased attractional forces at the time of operation.
- Shows no force at the time of standstill.
- The enhanced physical size of the device means that the packaging size is more.
- Requires more power for functionality. When compared with permanent magnets linear motors, the efficiency is less and generates more heat. This further needs water cooling devices to be included in the construction.

Applications

- Automatic sliding doors in electric trains.
- Metallic conveyor belts.
- Pumping of liquid metal, material handling in cranes

Construction of repulsion motor



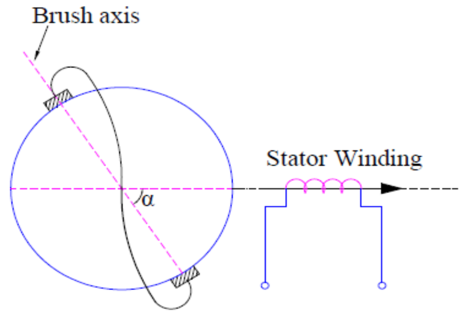
Repulsion Motor

- The repulsion motor is equipped with the stator, rotor, and commutator brush assembly.
- The stator carries a single-phase exciting winding similar to the main winding of a single-phase induction motor.
- The rotor has distributed DC winding connected to the commutator at one end just like in the DC motor.
- The carbon brushes are short-circuited on themselves and find a use for conducting current using the armature.

Working principle of repulsion motor

- The basic principle behind the working of repulsion motor is that "similar poles repel each other."

- This means two North poles will repel each other. Similarly, two South poles will repel each other.
- When the repulsion motor winding is supplied with single-phase AC, it produces a magnetic flux along the direct axis.
- When T this magnetic flux links with the rotor winding, it creates an EMF. Due to this EMF, a rotor current is produced.

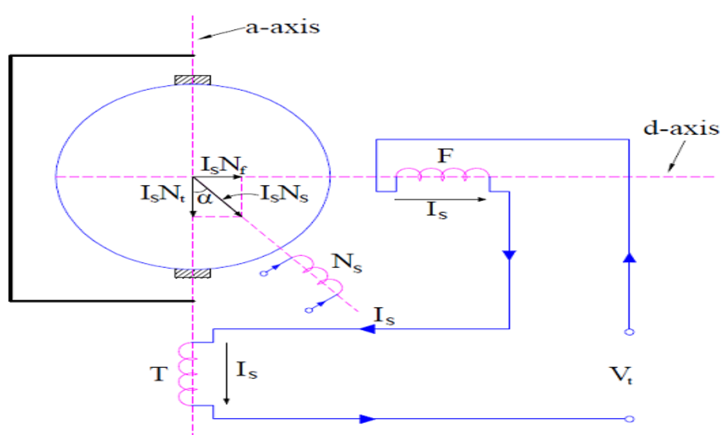


Types of repulsion motors

- There are three types of repulsion motor they are
- Compensated repulsion motor
- Repulsion-start induction motor
- Repulsion induction motor
- They differ in construction, operating characteristics, and industrial applications.
- These three kinds of repulsion motor are available in the market which works under the principle of repulsion like the following.

Torque equation of repulsion motor

- Production of electromagnetic torque in repulsion motor, the brush position must not be along the direct axis or quadrature axis. In general, the brush occupies some intermediate position.
- But for the sake of simplicity, we will assume bush axis vertical and will shift stator field axis at some intermediate position as shown in figure below. This has no effect on the operation and calculation of motor but greatly reduces the calculation effort.



- In the above figure, the field axis is making an angle of α with the brush axis. If Is and Ns are the stator filed current and effective number of stator turns then stator mmf, IsNs is directed along its axis as shown in above figure.
- This stator field is now replaced by two fictitious stator coils F and T such that stator mmfIsNs remain unchanged in magnitude as well as direction.
  The number of turns Nt of coil T can be found as below.
  Mmf of coil T = IsNt

Component of stator mmf along the brush axis = IsNsCosα

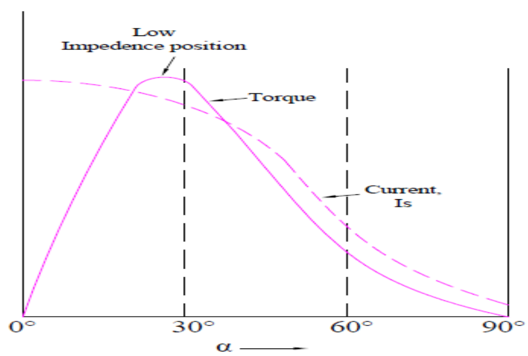
IsNt = IsNsCosα

Nt = NsCosα

Similarly, the number of turns of coil F is given as

Nf = NsSinα

- Since the magnetic axis of rotor winding and coil T coincides, all the flux produced by coil T will link with the rotor winding. This means that the rotor mmf will be equal to the mmf of coil T as per lenz's law. Therefore,
  Rotor mmf = mmf of coil T
  = IsNt
  = IsNsCosα
  Now, the electromagnetic torque
  Te = k (Stator Field Strength) (Rotor Field Strength) Sinα
  where is k is a constant.
  = k (IsNs)(IsNsCosα)Sinα
  = (k/2)(IsNs)2(2CosαSinα)
  = (k/2)(IsNs)2Sin2α …. [Sin2α = 2CosαSinα]
  Therefore, the torque in repulsion motor is given as
  Te = (k/2)(IsNs)2Sin2α
- The variation of current and torque with respect to different positions of brush is shown below.



- Rotor current is maximum when the brush axis and direct axis coincides.
- Rotor current is zero when the brush occupies a position in quadrature with the direct axis.
- Maximum torque in repulsion motor is achieved when stator and rotor field axis are 45° apart.
- Uses:
  Repulsion motor is used for loads requiring high starting torque such as hoists, lifts etc.

Hysteresis Motor:

- Hysteresis Motor is a synchronous motor with a cylindrical rotor and does not require any dc excitation to the rotor and it uses non-projected poles. It is a single phase motor with rotor made up of ferromagnetic material.

Construction of Hysteresis Motor:

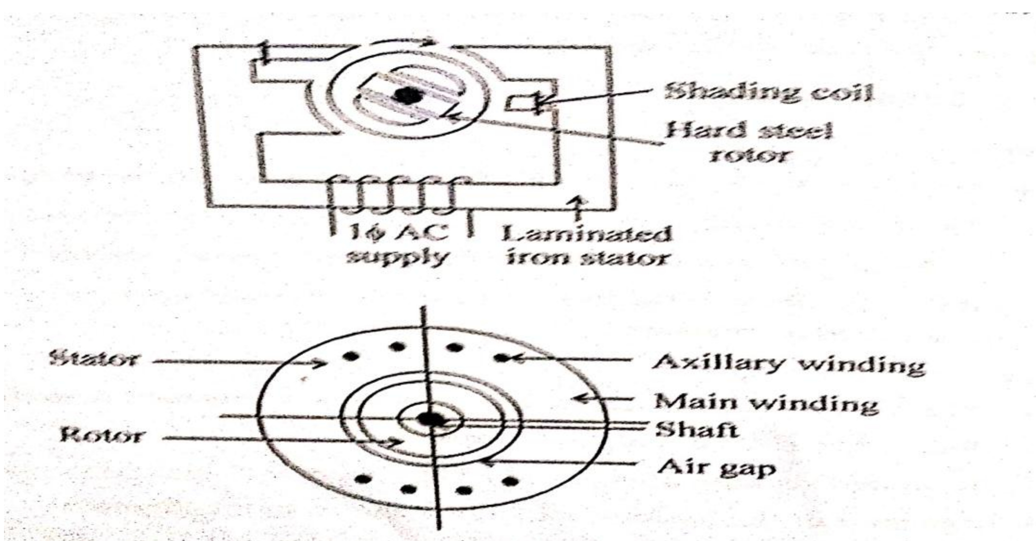
Hysteresis Motor consists of
(i)Stator
(ii)Rotor
(iii)Main windings
(iv)Auxiliary windings
(v)Shaft

Stator:

The stator is wounded with main and auxiliary windings so as to produce rotating magnetic field. In some hysteresis motor designs, the stator can also be shaded pole type. To develop synchronizing revolving field from single phase supply, the stator of hysteresis motor is designed accordingly.

Rotor: The rotor is smooth cylindrical type made up of hard magnetic material like chrome steel or alnico for high retentivity. This requires selecting a material with high hysteresis loop area. The rotor does not carry any winding or teeth.

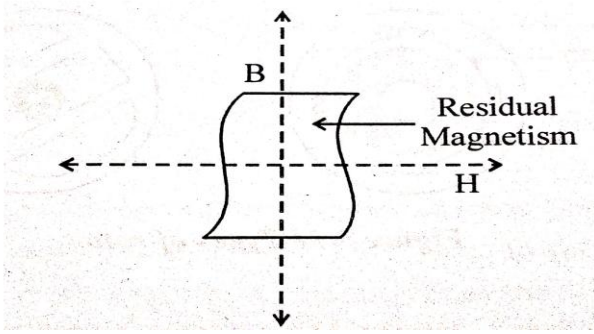
- The rotor of hysteresis motor has high resistance to reduce eddy current loss. This cylindrical rotor is mounted on the shaft through arbour made up of aluminium.
- The construction of hysteresis motor is shown in the figure(a) below while nature of hysteresis loop required for rotor material is shown in the below figure(b).



- The hysteresis phenomenon is dominant for the rotor material chosen and due to which rotor pole axis lag behind the axis of rotating magnetic field. Due to this, rotor poles get attracted towards the moving stator field poles.

- Thus rotor gets subjected to torque called hysteresis torque. This torque is constant at all speeds. When the stator field axis moves forward, due to high retentivity the rotor pole strength remains maintained. So higher the retentivity, higher is the hysteresis torque.

- Initially, rotor starts rotating due to the combined effect of hysteresis torque as well as torque due to eddy currents induced in the rotor. Once the speed is near about the synchronous, the stator pulls rotor into synchronism.



Advantages of Hysteresis ‘Motor:

- As rotor has no teeth, no winding, there are no mechanical vibrations
- Due to the absence of vibrations, the operation is quiet and noiseless

Disadvantages of using Hysteresis Motors:

- Low efficiency
- Available in very small size
- Poor output

Applications of Hysteresis Motor:

- Sound recording instruments
- Sound producing equipment
- High-quality record players
- Tape recorders