ST. ANNE'S COLLEGE OF ENGINEERING AND TECHNOLOGY

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ANGUCHETTYPALAYAM, PANRUTI – 607 106.

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE 3009 - SPECIAL ELECTRICAL MACHINES

V SEMESTER

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1.1STEPPER MOTOR

Stepper Motors have revolutionized machinery in today's world. These motors are mostly used in 3D printers, CNC machines, Robotics etc. Stepper motor is nothing but a DC motor that moves in steps and each step can be controlled with precision. Therefore stepper Motors have high accuracy compared to other Motors also they have high torque which can handle heavy loads making it an ideal choice for machinery

CONSTRUCTION OF STEPPER MOTOR:

Stepper motor construction is quite similar to DC motor. It also has a permanent magnet as Rotor. Rotor will be in the center and will rotate when force is acts on it. This rotor is surrounded by a number of stator which is wound by magnetic coil all over it. Stator will be placed as close as possible to rotor so that magnetic fields in stators can influence rotor's movement. To control the stepper motor each stator will be powered one by one alternatively. In this case the stator will magnetize and act as an electromagnetic pole exerting repulsive force on the rotor and pushes it to move one step. Alternative magnetizing and demagnetizing of stators will move the rotor step by step and enable it to rotate with great control.

TYPES OF STEPPER MOTOR BASED ON CONSTRUCTION:

There are different types of stepper motor which varies with its complexity in construction and working. In this tutorial we will see some of the basic types and its construction.

PERMANENT MAGNET STEPPER MOTOR:

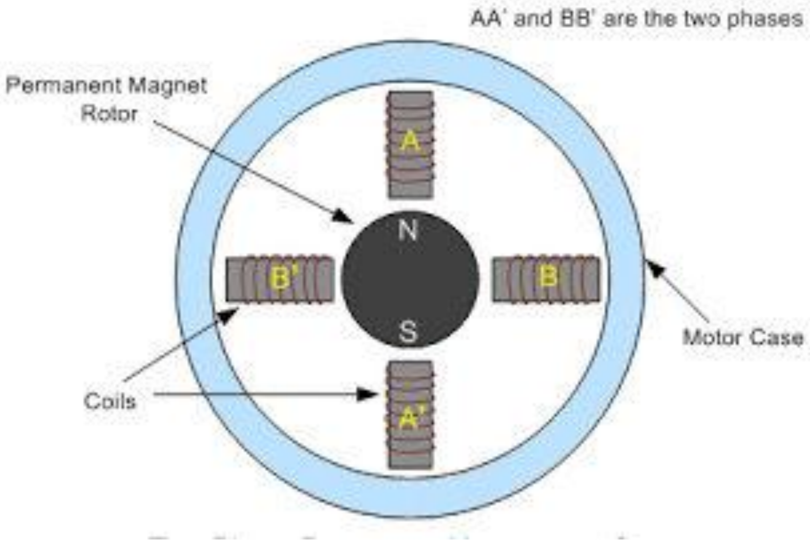


Figure 1.1.1 permanent magnet stepping motor

In this motor a permanent magnet is used as Rotor and electromagnetic stators around it. This is the motor we saw in above examples. Here the stator will be magnetized and demagnetized to move the rotor and set the motor to rotation.

VARIABLE RELUCTANCE STEPPER MOTOR:

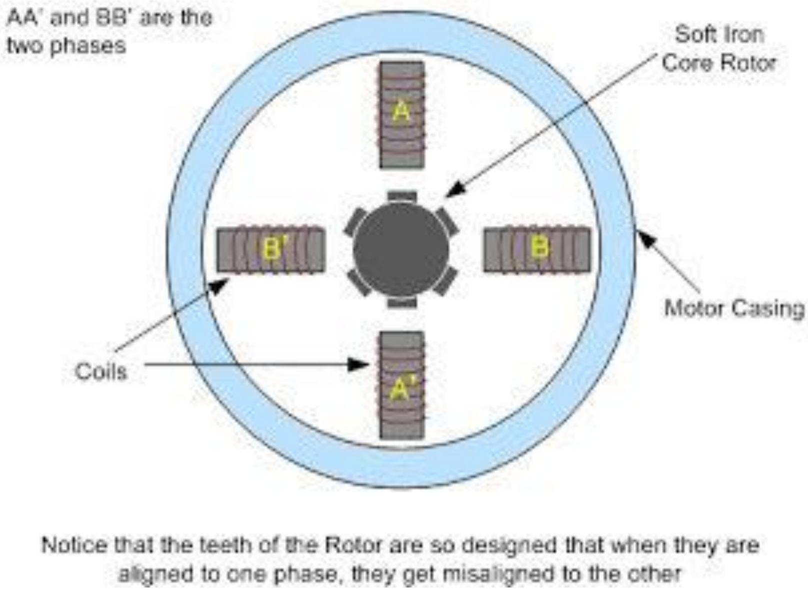


Figure 1.1.2 variable reluctance stepper motor

This motor is built using Ferromagnetic rotor and Electromagnetic stator with coil winding to magnetize them. Here the rotor will have multiple projections also called as teeth which will act like magnetic poles. This stepper motor works based on Magnetic reluctance hence got its name. When current passes through stator pole, it will magnetize and pulls the rotor's projecting poles in a way the distance between them is minimum and in full alignment. The driver circuit will continue to magnetize stators setting the rotor into rotation.

HYBRID SYNCHRONOUS STEPPER MOTOR:

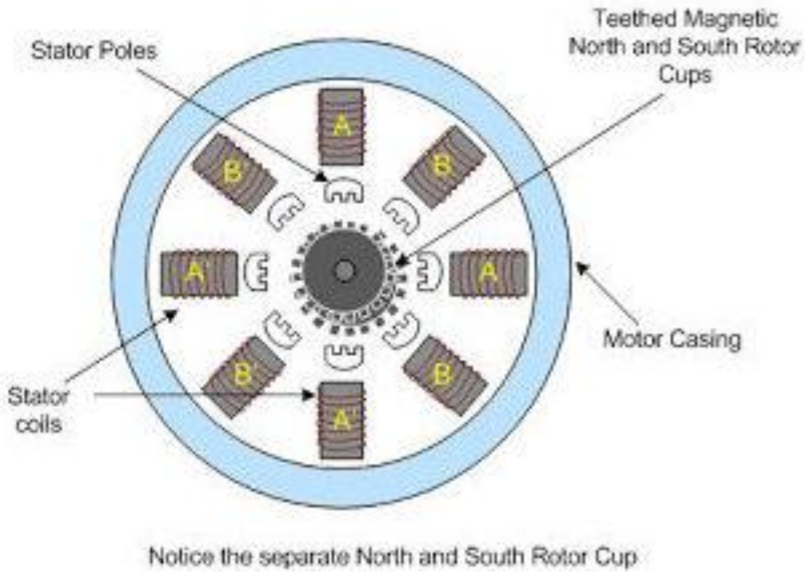


figure 1.1.3 Hybrid synchronous stepper motor

This is a combination of above two motor permanent and variable reluctance stepper motor. This motor consists of permanent magnetic toothed rotor like the ones in permanent magnet stepper motor with set of north and south poles in it. Also just like variable reluctant motor the stators have teeth in it. Few teeth of stator will be aligned to teeth of rotor while others will not be aligned to each other. When stator is magnetized by supplying current to it, magnetic flux drives the rotor to move by one step. The presence of teeth in both stator and rotor changes the magnetic flux and drives the motor by steps as intended.

The Hybrid synchronous motor is most popular since it has high torque and resolution. Driving modes like half step can even increase the resolution of this motor. While full step or micro stepping can be used to increase the torque, accuracy and smooth working. The hybrid motor is most popular because of the advantages it holds but comes with high cost due to its complex construction.

CHARACTERISTICS STEPPER MOTOR:

These are some of the important characteristics you need to look for in a stepper motor.

1. Resolution
2. Rotating angle
3. Operating voltage
4. Torque
5. Speed

APPLICATIONS OF STEPPER MOTOR:

1. Printers
2. CNC machines
3. 3D printers
4. Laser and optics
5. Industrial machinery

1.2 SINGLE STACK VARIABLE RELUCTANCE STEPPER MOTOR: CONSTRUCTION AND PRINCIPLE OF OPERATION

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 in figure1.2.1

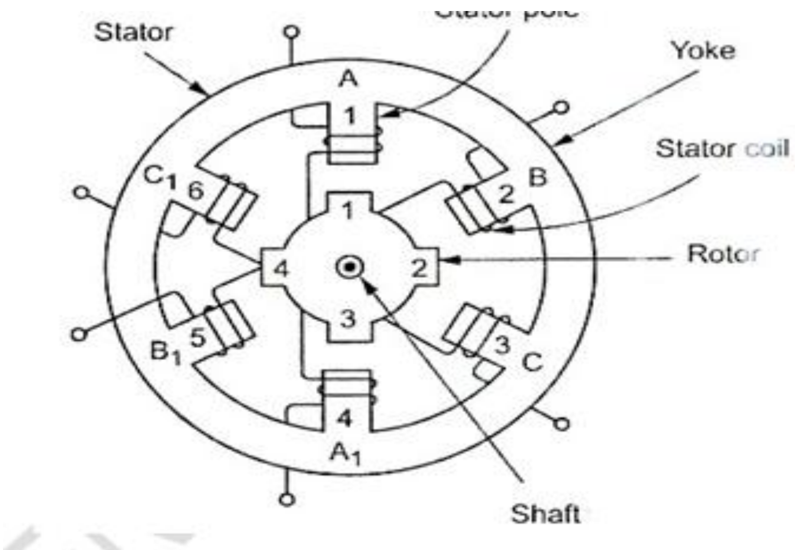


Figure 1.2.1 single stack variable reluctance stepping motor

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

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

Electrical Connection

Electrical connection of VR stepper as shown figure 1.2.2 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.

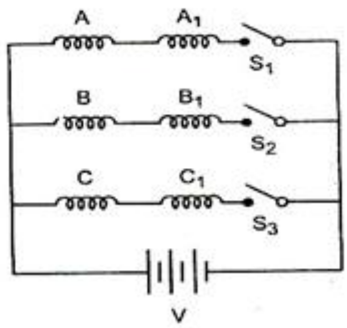


Figure 1.2.2 switching circuit

Principle of Operation

It works on the principle of variable reluctance. The principle of operation of VR stepper motor explained by referring figure1.2.3.

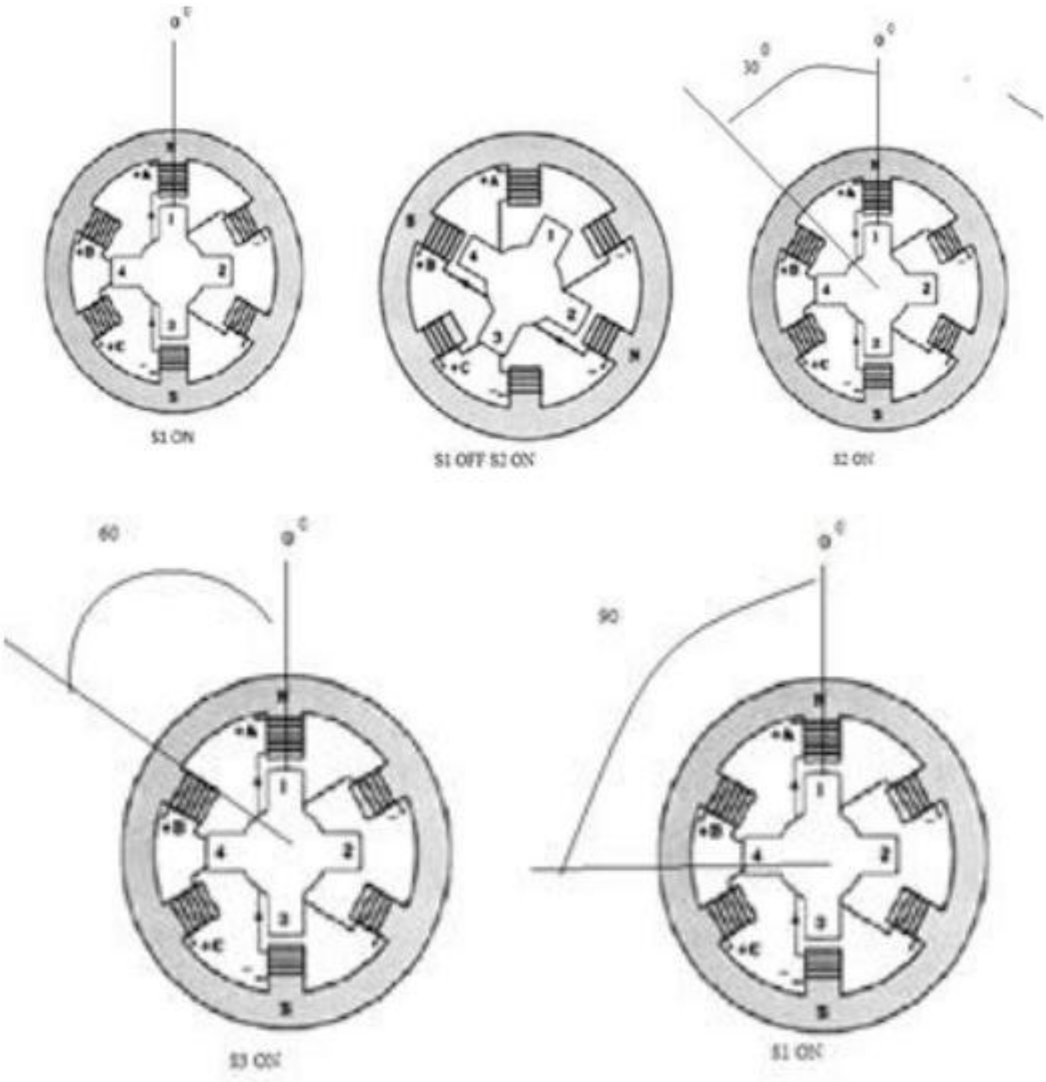


Figure 1.2.3 permanent magnet stepping motor

(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 counterclockwise direction so that B and B'and 2 and 4 in alignment. The truth table for mode I operation in counter and clockwise directions are given in the table 1.2.1

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

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

Table 1.2.1 Truth table for one phase on mode

(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.

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

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

Table 1.2.2 Truth table for two phase on mode

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.

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°

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°

Table 1.2.3 Truth table for Half step on mode

1.3 MULTI-STACKVRSTEPPERMOTOR

A Multi Stack or m stack variable reluctance stepper motor is made up of m identical single stack variable reluctance motor. The rotor is mounted on the single shaft. The stator and rotor of the Multi Stack Variable motor have the same number of poles and hence, the same pole pitch. All the stator poles are aligned in a Multi-Stack motor. But the rotor poles are displaced by 1/m of the pole pitch angle from each other. The stator windings of each stack forms one phase as the stator pole windings are excited simultaneously. Thus, the number of phases and the number of stacks are same.

Construction:

- M -stack VR stepper motor has m stacks on stator and m-stacks on rotor.
- Each m- stacks of stators and rotors have same no. of poles (teeth).
- Stator is mounted on a common outer casing.
- Rotor is mounted on a common shaft.
- m- Stacks of stator have same pole alignment.
- Each rotor pole is placed by1/m of pole pitch from one another.
- Each stack is excited by separate winding. So m-stack machine has m-phases.
- Consider, a 3-stack stepper motor having12 poles .It has, 3-stacks, 3-phase.
- Eachstackhas12statorand12rotorpoles.

Consider the cross-sectional view of the three stacks motor parallel to the shaft is shown below.

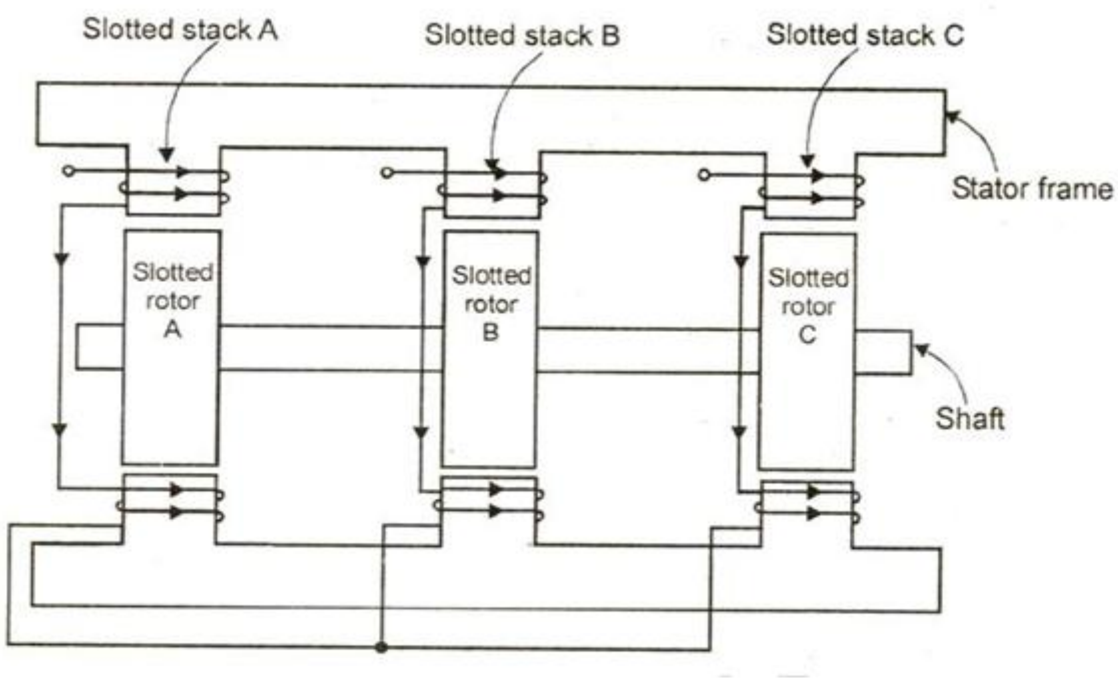


Figure 1.3.1 Multi stack variable reluctance stepping motor

Operation:

Phase-A excited:

- Stack–A gets excited.
- Rotor poles of stack-A gets aligned with stator poles.
- Due to offset, rotor poles of stack-B &C are not aligned.

Phase-B excited:

- Stack–B gets excited.
- Rotor poles of stack-B gets aligned with stator poles.
- Rotormovesby10˚ in anti-clockwise direction.
- Due to offset, rotor poles of stack-A&C are not aligned.

Phase-C excited:

- Stack–C gets excited.
- Rotor poles of stack-C gets aligned with stator poles.
- Rotormovesbyanother10° in anti-clockwise direction.
- Due to offset, rotor poles of stack-B &A are not aligned.

When the phase winding A is excited the rotor teeth of stack A are aligned with the stator teeth as shown in the figure below.

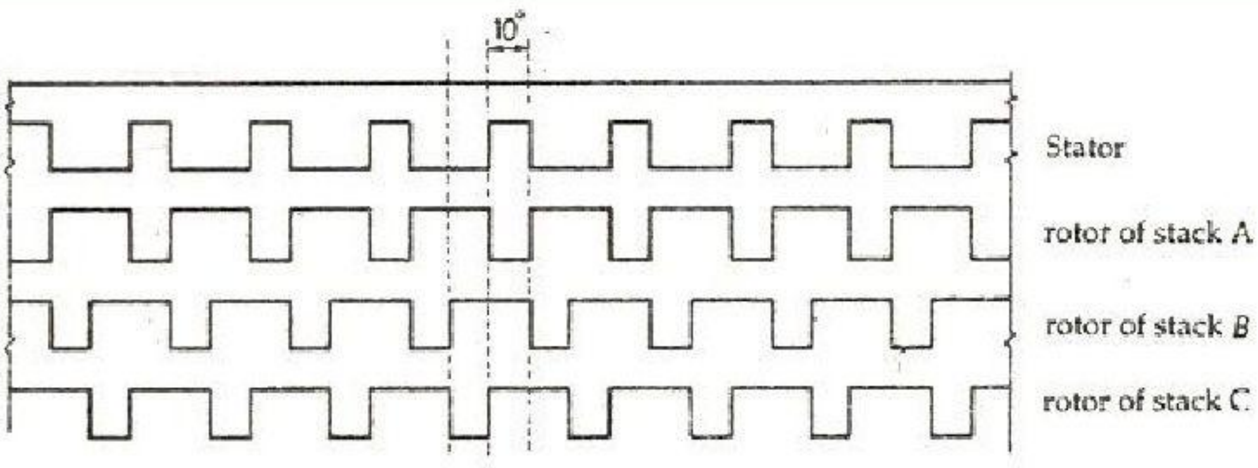


Figure 1.3.2 Relative positions of rotor and stator teeth after switching

When phase A is de-energized, and phase B is excited, rotor teeth of the stack B are aligned with the stator teeth. The rotor movement is about 10 degrees in the anticlockwise direction. The motor moves one step which is equal to ½ of the pole pitch due to change of excitation from stack A to stack B. The figure below shows the position of the stator and rotor teeth when the phase B is excited.

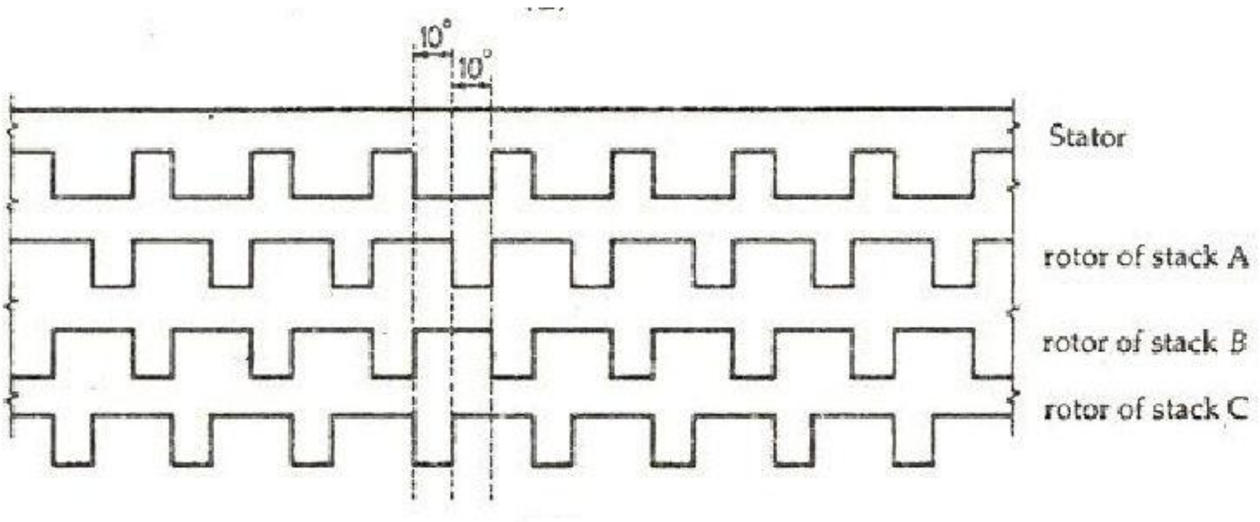


Figure 1.3.3 Relative positions of rotor and stator teeth after switching

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

Multi Stack Variable Reluctance Stepper Motors are widely used to obtain smaller step angles in the range of 2 to 15 degrees. Both the Variable reluctance motor Single Stack and Multi Stack types have a high torque to inertia ratio.

Advantages:

- Low rotor inertia
- High torque to inertia ratio
- Capable of high stepping rate
- High speed slewing capability
- Lightweight

- 3,4and5phase,singleandmulti-stackmodels available
- Ability to freewheel

Disadvantages:

- Normallyavailablein3.6˚step angles.
- No detent torque available with windings de-energized.
- Exhibits mid-range resonance at some stepping rated under some drive conditions.
- Low efficiencies at low voltages and stepping rates.

1.4 HYBRID STEPPER MOTOR

The word Hybrid means combination or mixture. The Hybrid Stepper Motor is a combination of the features of the Variable Reluctance Stepper Motor and Permanent Magnet Stepper Motor. In the center of the rotor, an axial permanent magnet is provided. It is magnetized to produce a pair of poles as North (N) and South (S)

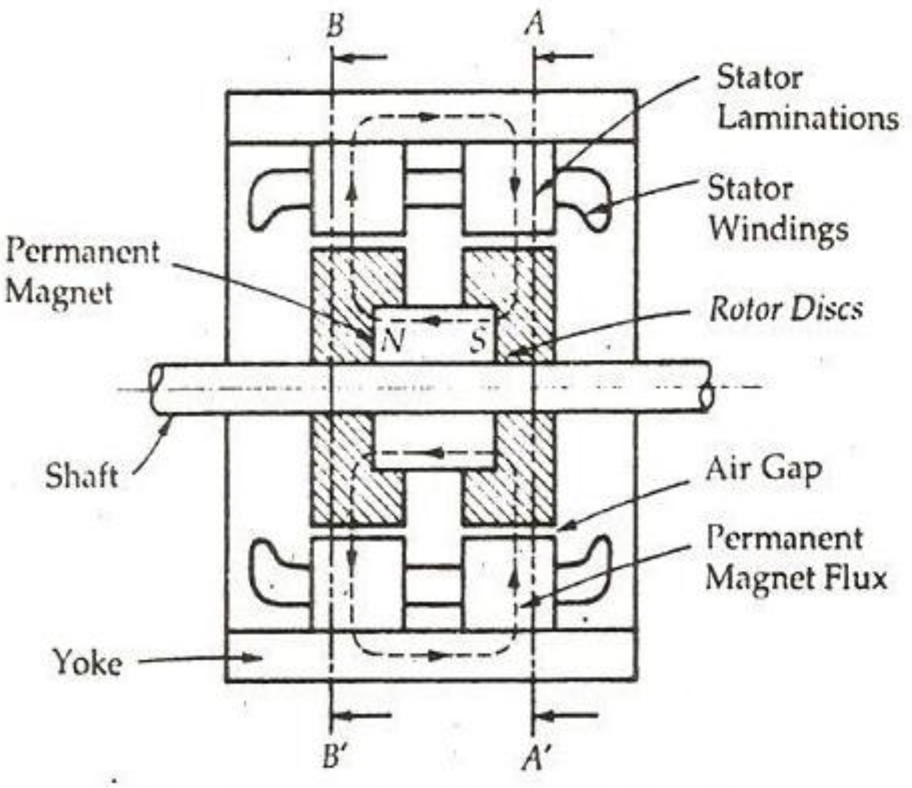


Figure 1.4.1 Hybrid stepping motor

[Source: "special electric machines" by R.srinivasan page:2.26]

At both the end of the axial magnet the end caps are provided, which contains an equal number of teeth which are magnetized by the magnet. The figure of the cross section of the two end caps of the rotor is shown below.

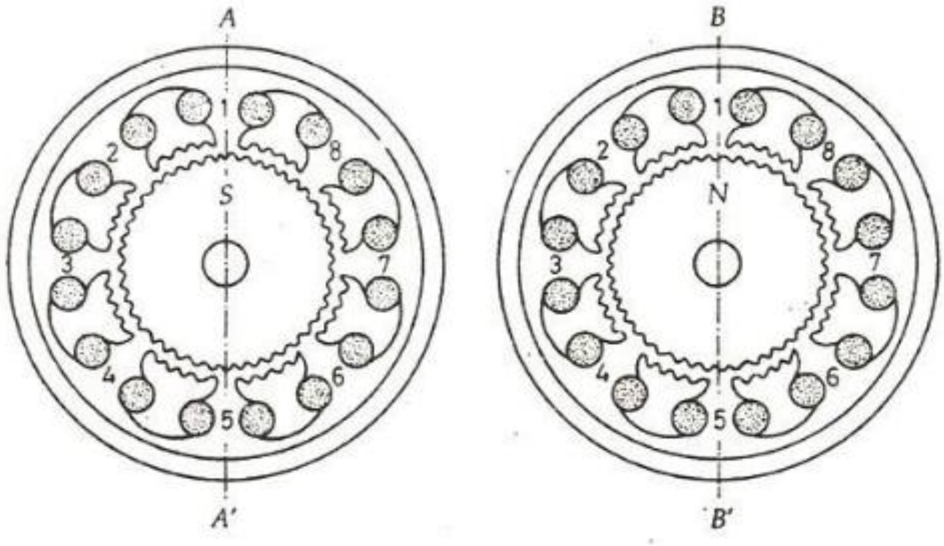


Figure 1.4.2 Hybrid stepping motor

The rotor teeth are perfectly aligned with the stator teeth. The teeth of the two end caps are displaced from each other by half of the pole pitch. As the magnet is axially magnetized, all the teeth on the left and right end cap acquire polarity as south and North Pole respectively.

The coils on poles 1, 3, 5 and 7 are connected in series to form phase A. Similarly, the coils on the poles 2, 4, 6 and 8 are connected in series to form phase B.

When Phase is excited by supplying a positive current, the stator poles 1 and 5 becomes South poles and stator pole 3 and 7 becomes north poles.

Now, when the Phase A is de-energized, and phase B is excited, the rotor will turn by a full step angle of 1.8⁰ in the anticlockwise direction. The phase A is now energized negatively; the rotor moves further by 1.8⁰ in the same anti-clockwise direction. Further rotation of the rotor requires phase B to be excited negatively.

Thus, to produce anticlockwise motion of the rotor the phases are energized in the following sequence +A, +B, -A, -B, +B, +A…….. For the clockwise rotation, the sequence is +A, -B, +B, +A……..

One of the main advantages of the Hybrid stepper motor is that, if the excitation of the motor is removed the rotor continues to remain locked in the same position as before the removal of the excitation. This is because of the Detent Torque produced by the permanent magnet.

Advantages of Hybrid Stepper Motor

The advantages of the Hybrid Stepper Motor are as follows:-

- The length of the step is smaller.
- It has greater torque.
- Provides Detent Torque with the de-energized windings.
- Higher efficiency at lower speed.
- Lower stepping rate.

Disadvantages of Hybrid Stepper Motor

- Higher inertia.
- The weight of the motor is more because of the presence of the rotor magnet.
- If the magnetic strength is varied, the performance of the motor is affected.
- The cost of the Hybrid motor is more as compared to the Variable Reluctance Motor.

1.5 THEORY OF TORQUE PREDICTION

According to Faradays laws of electromagnetic induction

Flux linkages $\lambda = N\upsilon$

$\lambda = Li$

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

Varying the reluctance $L = \frac{N}{S}$

By varying reluctance

mmf = Nυ

Reluctance = $\frac{1}{A\mu}$

Flux = $\frac{Ni}{S}$

Flux linkages $\lambda = \frac{N.Ni}{S} = \frac{N^2}{S}$

Inductance $L = \frac{\text{flux linkages}}{\text{Ampere}}$

$$L = \frac{N^2 i}{Si}$$

$$L = \frac{N^2}{S}$$

If the reluctance of magnetic circuit can be varied, inductance L and the flux linkages λ can also be varied.

Consider a magnetic circuit as shown in fig. 1.5.1

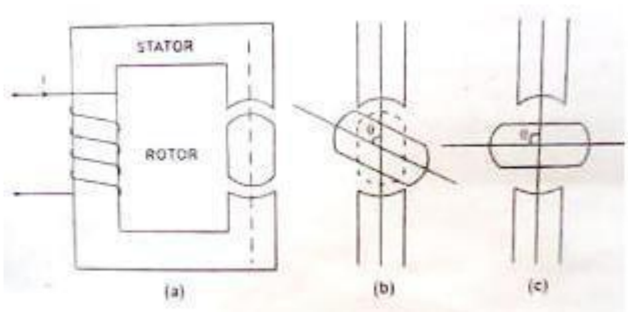


Figure 1.5.1 Magnetic circuit

The stator consists magnetic core with two pole arrangement. Stator core carries a coil. Rotor is also made up of ferrous material. The motor core is similar to a salient pole machine. Let the angle between the axis of stator pole and rotor pole be θ. let the angular displacement be illustrated using fig. 1.5.1 (a, b and c).

Case 1: θ = 0

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

Case 2 : θ = 45^0

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

Case 3: θ = 90^0

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

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

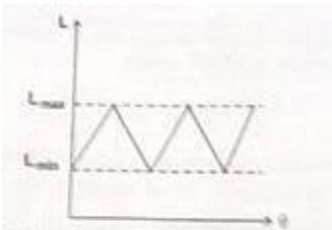


Figure 1.5.2 Magnetic circuit

Derivation for reluctance torque

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

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

Where λ = NΦ or λ = Li

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

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

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

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

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

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

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

$$We = \frac{1}{2} Li2$$

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

$$\frac{dWe}{dt} = \frac{1}{2} L.\, 2i\frac{\partial i}{\partial t} + = \frac{1}{2} i2 \frac{\partial L}{\partial t}$$

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

Power received from the electrical source = ei

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

Power due to change in stored energy

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

Mechanical power developed

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

Mechanical power developed

$$Pm = \frac{1}{2}\, \omega i2\frac{\partial L}{\partial \theta}$$

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

Pm = ωT

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 monitoring when $\frac{\partial L}{\partial \theta}$ is +ve.

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

* Torque is proportional to i2 : Therefore it does not depend upon the direction of the current.

1.6 CHARACTERISTICS OF STEPPER MOTOR

Stepper motor characteristics are

Static characteristics

Dynamic characteristics

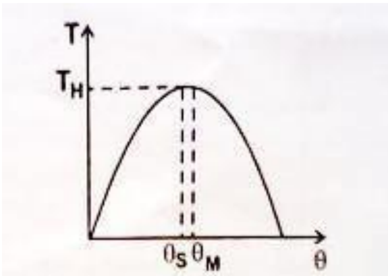
STATIC CHARACTERISTICS

(i) Torque Angle curve

(ii) Torque current curve

(i)Torque-Angle curve

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



Torque Angle

Figure 1.6.1 Torque-Angle curve

Holding Torque (TH)

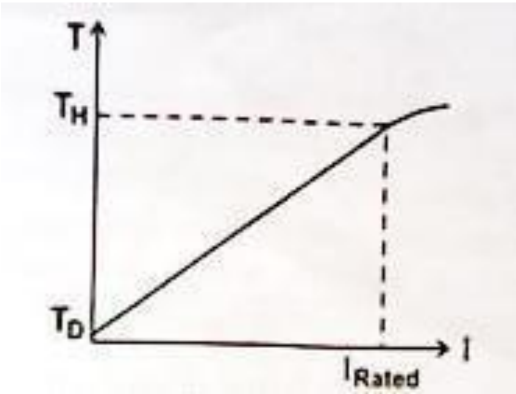
It is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the static equilibrium position.

DETENT TORQUE (TD):

It is the maximum load torque which the un-energized stepper motor can withstand slipping. Detent torque is due to magnetism, and is therefore available only in permanent magnet and hybrid stepper motor. It is about 5-10 % of holding torque.

TORQUE CURRENT CURVE

A typical torque curve for a stepper motor is shown in fig.1.6.2. It is seen the curve is initially linear but later on its slope progressively decreases as the magnetic circuit of the motor saturates.



Torque-current Curve

Figure 1.6.2 Torque-current curve

Torque constant (Kt)

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

Dynamic characteristics

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

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

Slewing mode

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

Start Stop mode

Start stop mode of operation of stepper motor is shown in figure1.6.3 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.

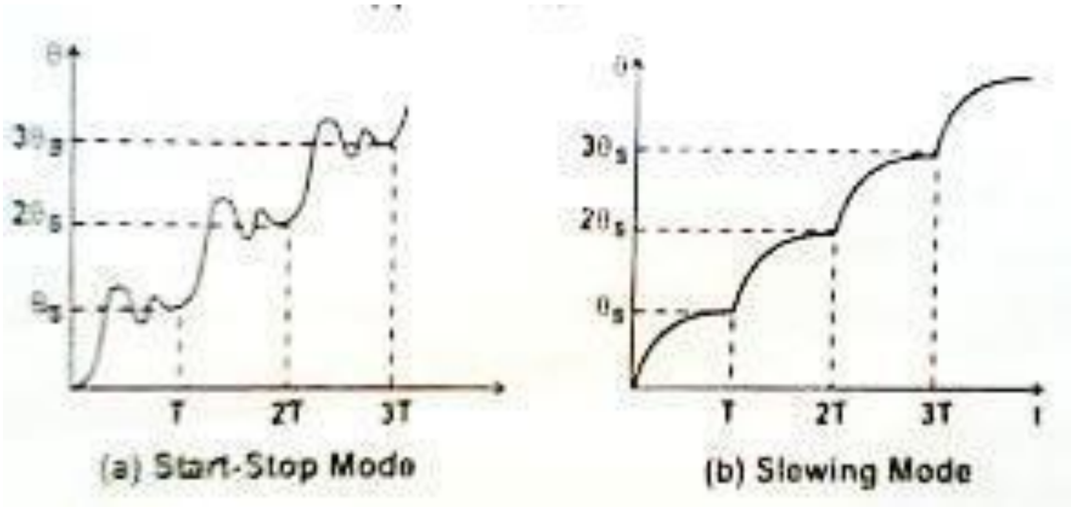


Figure 1.6.3 Dynamic Characteristics

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

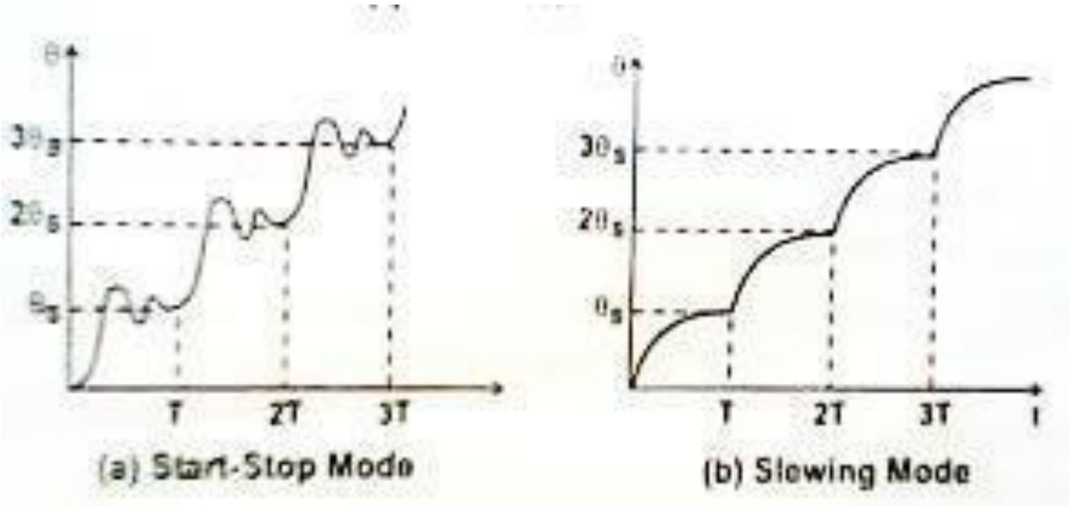


Figure 1.6.3 Dynamic Characteristics

TORQUE-SPEED CHARACTERISTICS

Torque developed by the stepper motor and stepping rate characteristics for both modes of operation are shown in fig.1.6.4.the curve ABC represents the "pull in" characteristics and the curve ADE represents the "pull-out" characteristics.

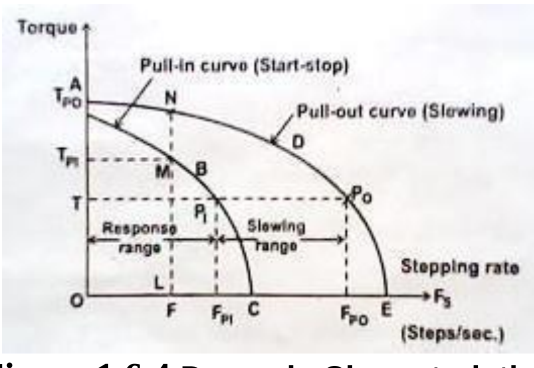


Figure 1.6.4 Dynamic Characteristics

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

Pull in torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the start-stop mode of operation without losing synchronism. In the fig.1.6.4 LM represents the pull in torque (i.e) TPI corresponding to the stepping rate F (i.e.) OL.

Pull out torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the slewing mode without losing synchronism. In fig.1.6.4 LN represents the pull in torque (i.e.) TPO corresponding to F (i.e.) OL.

Pull in range

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

Pull out range

It is the maximum stepping rate at which the stepper motor can operate in slewing mode developing a specified torque without losing synchronism. In fig.1.6.4 PIPO represents the pull out range for a torque of T. The range PIPO is known slewing range.

Pull in rate (FPI)

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

Pull out rate (FPO)

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

Synchronism

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

Mid frequency resonance

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

FIGURES OF MERIT (FM'S)

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

1. Electrical Time constant (Te)

Te=Lm/Rm

where Lm-Inductance of motor winding

Rm- resistance of motor.

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

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

2. Motor time constant (Tm)

Tm=J/(Ke.KtRm)=JRm/Ke

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

Rm-resistance of the motor winding (Ω)

Ke-back Emf constant (volt s/ rad)

Kt- torque constant (Nm/A)

Motor back Emf and torque constants are determined by magnetic circuit and phase winding design. Winding resistance also from winding design. Moment of inertia is determined by mechanical design. In this way motor time constant Tm combines all the three aspects of motor design viz, magnetic circuit, electrical circuit and mechanical design. Achieving a low Tm requires excellence in motor design. As a thumb rule the ratio of Te/Tm 0.1

Initial Acceleration (a0):A0=T/J(rad/S2)

Where T-rated torque (N-M)

J-moment of inertia (kg-m2)

A0 gives a quantitative idea of how fast the motor accelerates to its final velocity or position. Maximization of a0 calls for good magnetic circuit design to produce high torque in conjunction with good mechanical design to minimize rotor inertia. The moment of inertia of the load coupled to motor also determines a0

Motor Constant (km) Km=T/√ ω

Where T- rated motor torque

ω -rated power (w) of the motor

Km=√Kt Ke/Rm

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

1.7 DRIVE SYSTEM AND CONTROL CIRCUITRY FOR STEPPER MOTOR

DRIVE SYSTEM

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

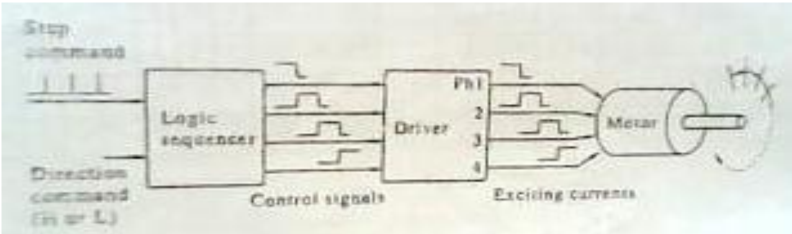


Figure 1.7.1 Block Diagram of the drive system of a stepping motor

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

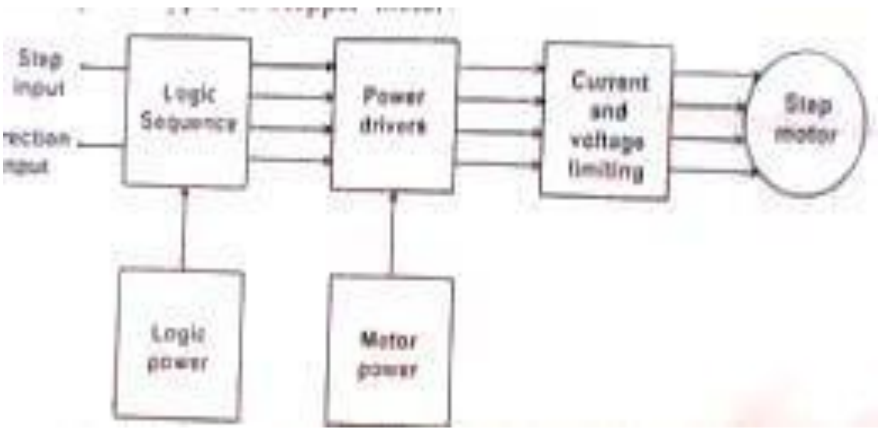


Figure 1.7.2 Block Diagram of a typical step motor control

LOGIC SEQUENCER

The logic sequencer is a logic circuit which control the excitation of the winding sequentially, responding to step command pulses. A logic sequencer is usually composed of a shifter register and logic gates such as NANDs, NORs etc. But one can assemble a logic sequencer for a particular purpose by a proper combination of JK flip flop, IC chips and logic gate chips. Two simple types of sequencer build with only two JK-FFs are shown in figure for unidirectional case. Truth tables for logic sequencer also given for both the directions.

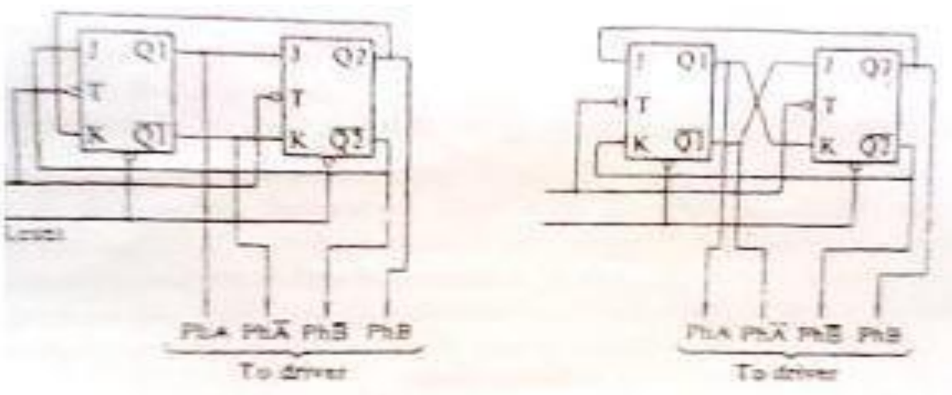


Figure 1.7.3 Logic Sequencer

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

	R	1	2	3	4	5	6	….
Ph A,Q1	0	0	1	1	0	0	1	….
Ph B,Q2	0	1	1	0	0	1	1	….
Ph $\bar{A}$,Q1	1	1	0	0	1	1	0	….
Ph B,Q2	1	0	0	1	1	0	0	….

A unidirectional logic sequencer for two phases on operation of a two phase hybridmotorThe corresponding between the output terminals of the sequencer and the phase windings to be controlled is as follows. If Q1 is on the H level the winding Ph A is excited and if Q1is on L level, Ph A is not excited. To reserve the rotational direction, the connection of the sequencer must be interchanged. The direction switching circuits shown in fig 2.40 may be used for this purpose. The essential functions being in the combination of three NAND gates or two AND gates and a NOR gate.

POWER DRIVER CIRCUIT

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

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

Where I=V/R – rated current and

Ʈ=L/R winding time constant.

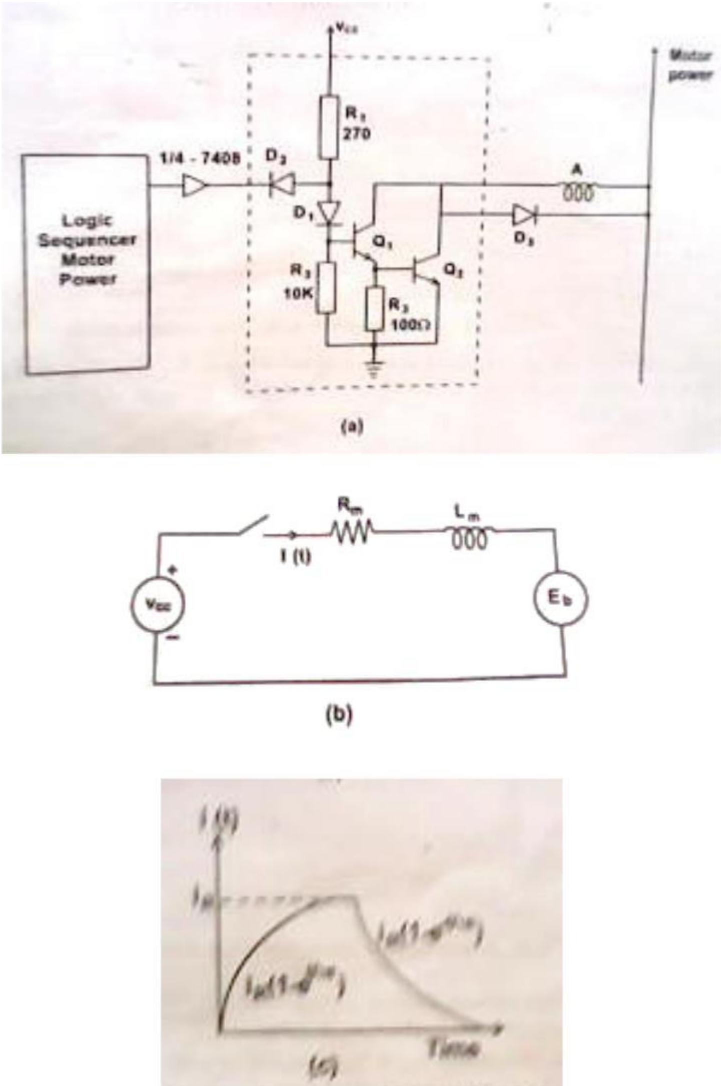


Figure 1.7.4 Power Driver Stage of Stepper Motor Controller

In practice, the time constant Ʈ limits the rise and fall of current in the winding. At low stepping rate the current rises to the rated value in each ON interval and falls to zero value in each OFF interval. However as the switching rate increases, the current is not able to rise to the steady state, nor fall down to zero value within the on/off time intervals set by the pulse waveform. This in effect, smoothens the winding current reducing the swing as shown in figure. As a result the torque developed by the motor gets reduced considerably and for higher frequencies, the motor just vibrates‘or oscillates within one step of the current mechanical position.

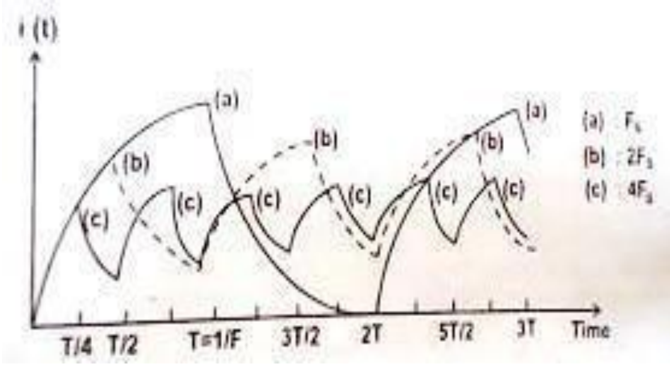


Figure 1.7.5 Effect of increasing Stepping Rate on Current Swing

In order to overcome these problems and to make improvement of current build up several methods of drive circuits have been developed. For example when a transistor is turned on to9 excite a phase, the power supply must overcome effect of winding inductances has tendency to oppose the current built up. As switching frequency increases the position that the buildup time takes up within the switching cycle becomes large and it results in decreased torque and slow response.

Improvement of current buildup/special driver circuit

(a) Resistance drive (L/R drive)

Here the initial slope of the current waveform is made higher by adding external resistance in each winding and applying a higher voltage proportionally. While this increases the rate of rise of the current, the maximum value remains unchanged as shown in figure1.7.5

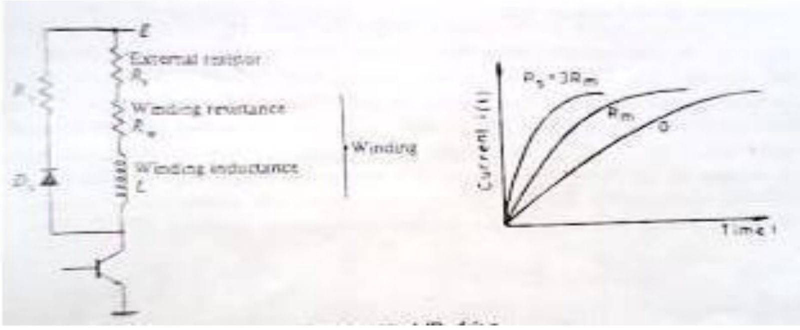


Figure 1.7.5Resistance L/R drive

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^2R losses and heating. This denotes wastage of power as far as the motor is concerned. In order to reach the same steady state current I_R as before, the voltage required To be applied is much higher than before. Hence this approach is suitable for small instrument stepper motor with current ratings around 100 mA, and heating is not a major problem.

(b) Dual voltage driver (or) Bi-level driver

To reduce the power dissipation in the driver and increase the performance of a stepping motor, a dual-voltage driver is used. The scheme for one phase is shown in fig. 1.7.6.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 both1 and2 are turned on, and the higher voltage E_H will be applied to the winding. The diode D_1 is now reverse biased to isolate the lower voltage supply. The current build up quickly due to the higher voltageE_H. The time constant of the monostable multivibrator is selected so that transistor1 is turned off when the winding current exceeds the rated current by a little. After the higher

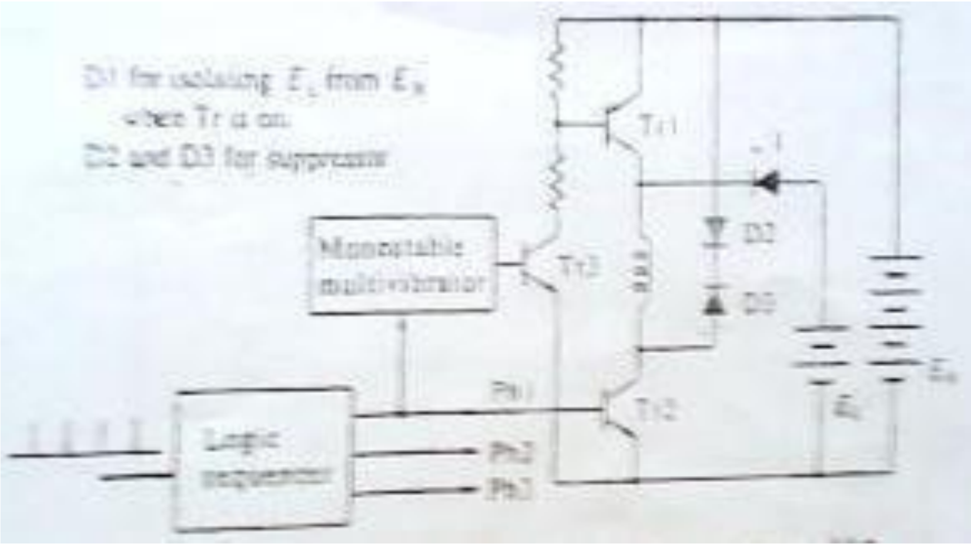


Figure 1.7.6 Dual voltage Drive

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

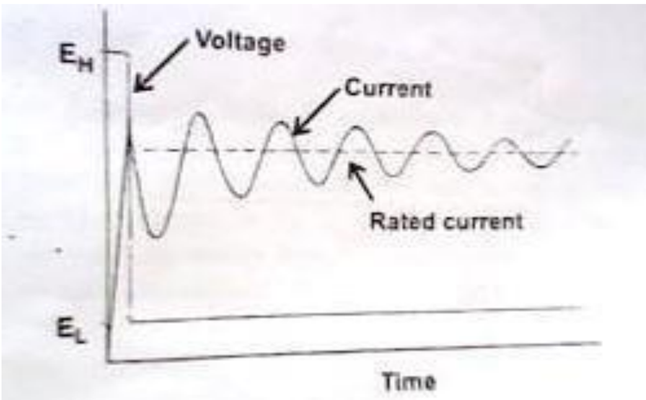


Figure 1.7.6 Voltage and current wave form in dual voltage driver

When the dual voltage method is employed for the two phase on drive of a two phase

T r

hybrid motor, the circuit scheme will de such as that shown in fig.1.7.7. Two transistor Tr1 &Tr2 and two diodes $D_1$and D_2 are used for switching the higher voltage. In dual voltage scheme as the stepping rate is increased, the high voltage is turned on for a greater percentage of time.

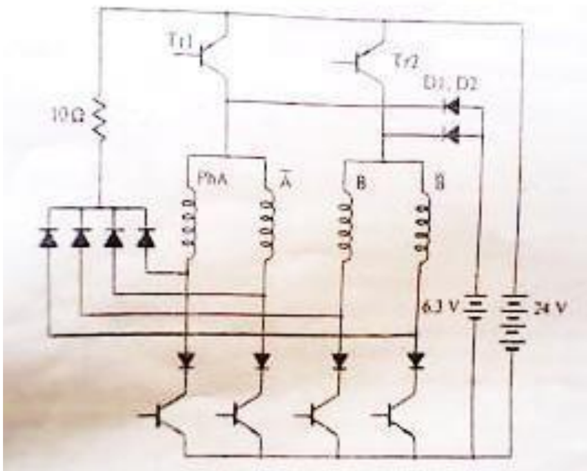


Figure 1.7.7 Dual voltage Driver circuit

It requires two regulated power supplies EH& EL end two power transistor switches Tr1 & Tr2 and complex switching logic. Hence it is not very popular.

(c) Chopper drive

Here a higher voltage 5 to 10 times the related value is applied to the phase winding as shown in fig.2.50(a) and the current is allowed to raise very fast. As soon as the current reaches about 2 to 5% above the rated current, the voltage is cut off, allowing the current to decrease exponentially. Again as the current reaches some 2 to 5% below the rated value, the voltage is applied again. The process is repeated some 5-6 times within the ON period before the phase is switched off. During this period the current oscillates about the rated value as shown in figure A minor modification is to chop the applied dc voltage at a high frequency of around 1khz, with the desired duty cycle so as to obtain the average on-state current equal to the rated value.

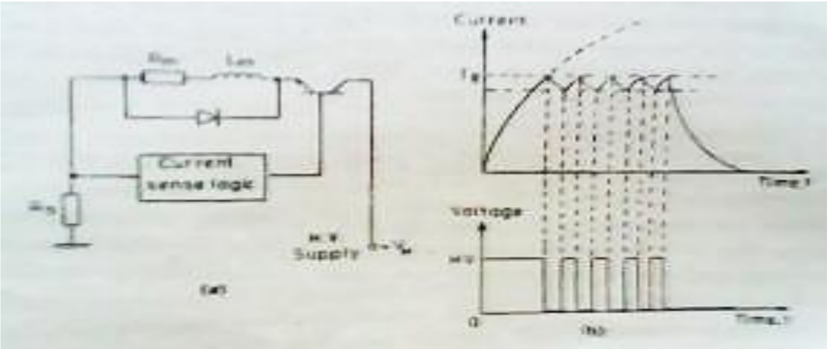


Figure 1.7.8 Oscillation of current in chopper drive

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

(d) Problems with driver circuits

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

25 per cent.

Suppressor circuits

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

(a) Diode suppressor

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

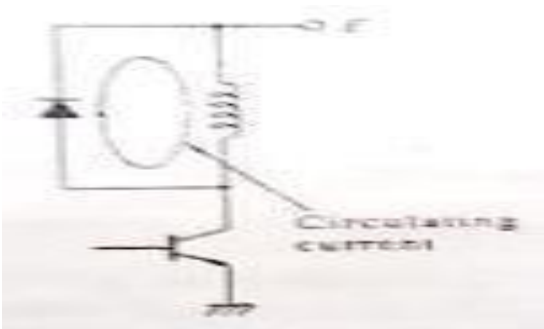


Figure 1.7.9 Diode Resistor suppressor

(b) Diode-Resistor suppressor

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

is VCE=E+IRS+VD

Where E= supply potential

I= Current before turning off

Rs-resistance of suppressor resistor

VD-forward potential of diode

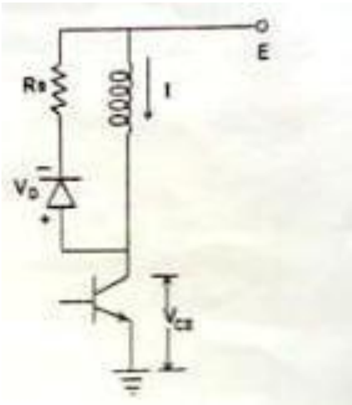


Figure 1.7.10 suppressor based on zener diode

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

Zener diode suppressor

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

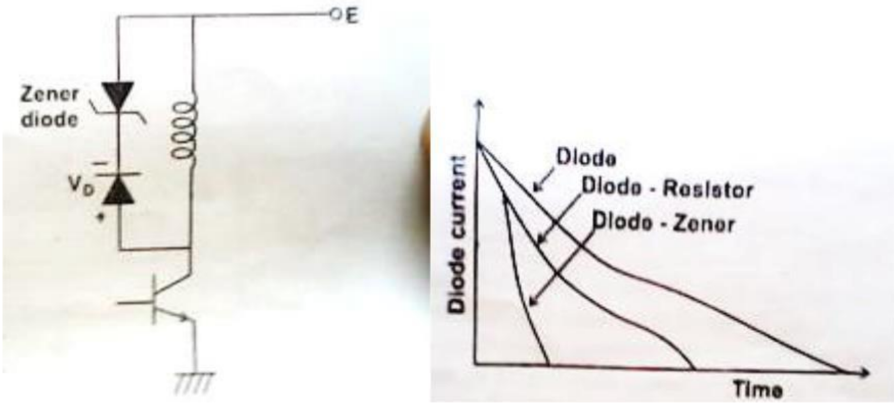


Figure 1.7.11 comparison of suppressor schemes

(d) Condenser suppressor

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

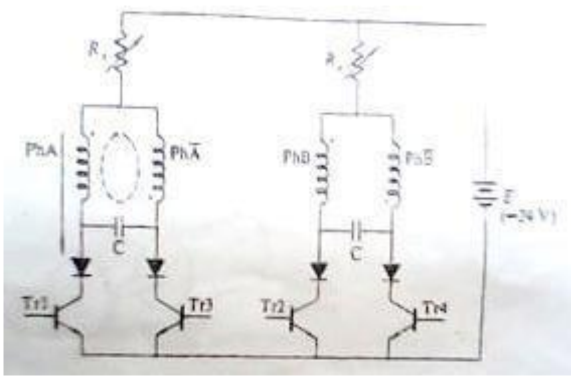


Figure 1.7.12 condenser suppressor

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

UNIT II - SWITCHED RELUCTANCE MOTORS

2.1 Construction of SRM

Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure 2.1.1. The stator is made up of silicon steel stampings with inward projected poles. The number of poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8). All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf�become 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.

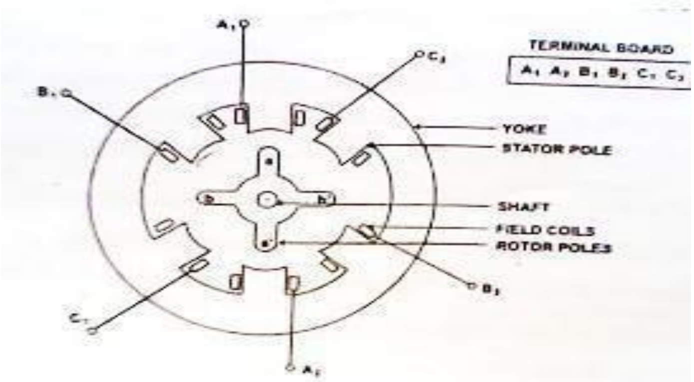


Figure 2.1.1 Cross sectional view of SRM

The rotor is also made up of silicon steel stampings with outward projected poles. Number of poles of rotor is different from the number of poles of the stator. In most of the available motors the number of poles of the rotor is 4 or 6 depending upon the number of poles.

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

BLOCK DIAGRAM OF SRM

Fig. 2 shows the block diagram of SRM. Dc supply is given to the power semiconductor switching circuitry which is connected to various phase windings of SRM. Rotor position sensor which is mounted on the shaft of SRM, provides signals to the controller about the position of the rotor with reference to reference axis. Controller collects this information and also the reference speed signal and suitably turns ON and OFF the concerned power semiconductor device to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.

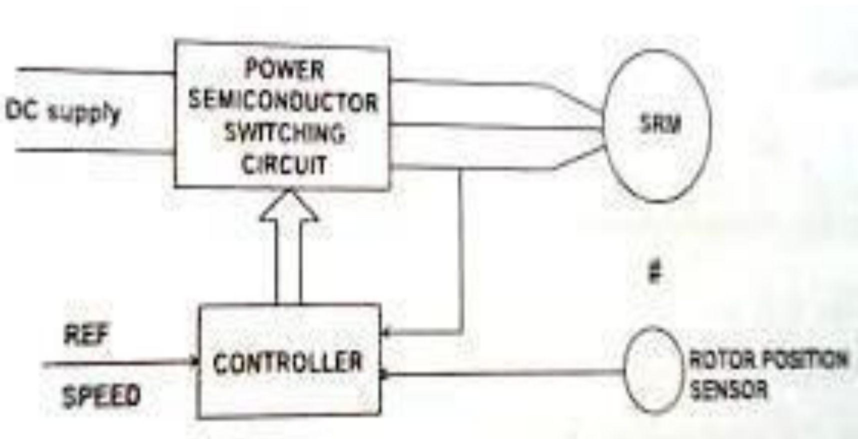


Figure 2.1.2 Block Diagram Of SRM

PRINCIPLE OF OPERATION

Fig. 2.1.3 represents the physical location of the axis stator poles and rotor poles of a 6/4 SRM.To start with stator pole axis AA‘ and rotor pole axis aa‘ are in alignment as shown in fig. 2.1.3 (a). They are in the minimum reluctance position so far as phase windings is concerned. Then $dL_a/d\theta=0$. At this position inductance of B windings is neither maximum nor minimum. There exists $dL_b/d\theta$ and $dL_c/d\theta$.

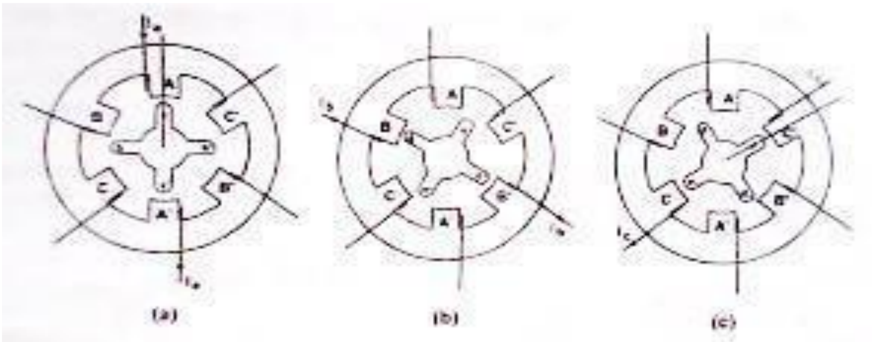


Figure 2.1.3 Physical location of the axis of stator and rotor poles of 6/4 SRM

Now if B phase is energized then the rotor develops a torque because of variable reluctance and existences of variation in inductance. The torque developed is equal to$(1/2)i_B^2(dL_B/d\theta)$. This direction is such that BB‘and bb‘ try to get aligned. If this torque is more than the opposing load torque and frictional torque the rotor starts rotating. When the shaft occupies the position such that BB‘and bb‘ are in alignment (i.e.,) $\theta=30°$, no torque is developed as in this position $dL_B/d\theta=0$. Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as $(dL_C/d\theta)$ exists. The rotor continues to rotate.

When the rotor rotates further 30°, the torque developed due to winding C is zero [vide fig. 2.1.3(c)]Then the phase winding C is switched off and phase winding A is energized. Then rotorExperiences a torque and rotates further step 30°. This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor.

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

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

2.2 POWER SEMICONDUCTOR SWITCHING CIRCUITS FOR SRM (POWER CONTROLLERS)

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

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

1. TWO POWER SEMICONDUCTOR SWITCHING DEVICES PER PHASE AND TWO DIODES

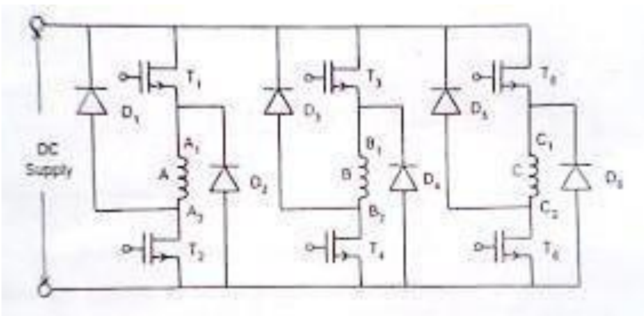


Figure 2.2.1 Two Power Semiconductor switching devices and two diodes

As shown in fig 2.2.1 phase winding A is connected to the dc supply through power semiconductor devices T1 and T2. 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 T_1 and T_2 are turned off .The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D_1 and D_2 to the supply. Thus the stored energy is fed back to the mains. Similarly phase winding B & C are also switched on to the supply and switched off from the supply in a cyclic manner. This circuit requires 2 power switching devices and 2 diodes for each phase winding. For high speed operation it is required to see that the stored energy can be fed back to the mains within the available period.

Usually the upper devices T_1, T_3 and T_5 are turned on and off from the signals obtained from the rotor position sensor .The duration of conduction or angle of conduction θ can be controlled by using suitable control circuitry .The lower devices T_2, T_4, T_6 are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical AND 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

1. Control of each phase is completely independent of the other phase.
2. 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.

3. The energy from the off going phase is feedback to the source, which results in utilization of energy

DEMERITS

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

2.(N+1) POWER SWITCHING DEVICES AND (N+1)DIODES

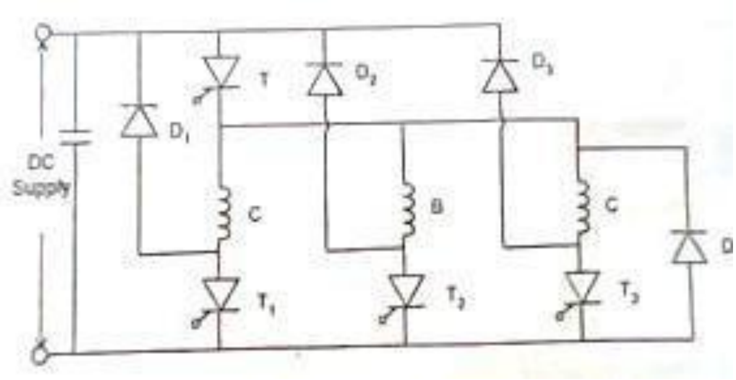


Figure 2.2.2 (n+1) power switching devices and (n+1) diodes
[Source: "special electric machines" by R.Srinivasan page:3.19]

This circuit makes use of less number of power switching devices and diodes as shown in fig 2. 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

1. The converter uses low number of switching devices, which reduces the cost of the converter.

2. The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses.

3. Voltage rating of all the switching devices and the diodes are V_{dc}, which is relatively low.

4. 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

1. Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.

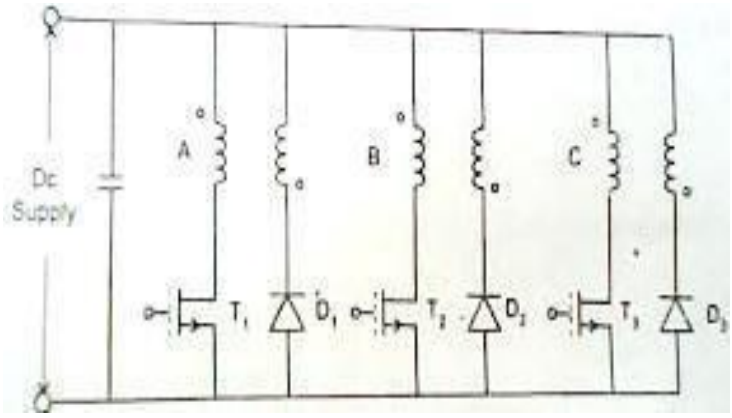
2. At higher speeds of the off going phase cannot be de-energized fast enough because the common switch ―T‖ keeps turnings on intermediately, disabling forced demagnetization.

3. The common switch conducts for all the phases and thus has higher switching stress.

3. PHASE WINDING USING BIFILAR WIRES

Each phase winding has two exactly similar phase windings as shown in fig2.2.3.For this bifilar wires are used .Each phase consists of two identical windings and are magnetically coupled when one of them are excited.

In stepper motor, the purpose of bifilar winding is for bipolar excitation



with a reduced number of switching elements.

Figure 2.2.3 Phase winding using bifilar wires

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

1. The converter uses lower number of switching devices thus reducing the cost on the converter.

2. The converter allows fast demagnetization of phases during commutation.

DEMERITS

1. Bifilar winding suffers from double number of connections.

2. A poor utilization of copper.

3. Freewheeling is not possible during chopping as the phases have -Vdc. this causes of higher ripples in current and torque during chopping.

4. The imperfection in the coupling between the two winding causes voltage spikes during turn off.

5. The copper loss associated with the auxiliary winding is unacceptable high for many applications.

4. SPLIT – LINK CIRCUIT USED WITH EVEN PHASE NUMBER

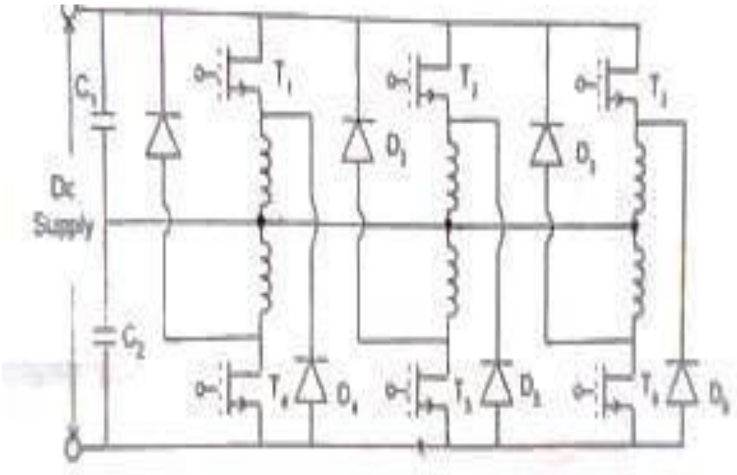


Figure 2.2.4 split link circuit used with even phase number

The circuit shown in fig.2.2.4 is used in a range of highly efficient drives (from 4-80kw).The main power supply is split into two halves using split capacitors. During conduction, energy is supplied to the phases by one half the power supply. During commutation period, the phases demagnetize into other half of the power supply.

When switch T1 is turned on, phase winding 1 is energized by capacitor c1. When switch T2 is turned off, the stored energy in the phase winding 1 is fed back to the capacitor c2 through diode D4.

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

Merits

1. It requires lower number of switching devices.

2. Faster demagnetization of phases during commutation.

Demerits

1. During chopping, freewheeling is not possible as the phaser have the voltage **V**dc/2. This causes higher switching frequency and more losses.

2. This is not feasible for low voltage application.

3. The converter is fewer faults tolerant as fault in any phase will unbalance the other phase that is connected to it.

C-DUMP CIRCUIT

In the C dump circuit shown in fig.2.2.5. the device count is reduced to n' plus one additional devices to bleed the stored energy from the dump capacitor C back to supply

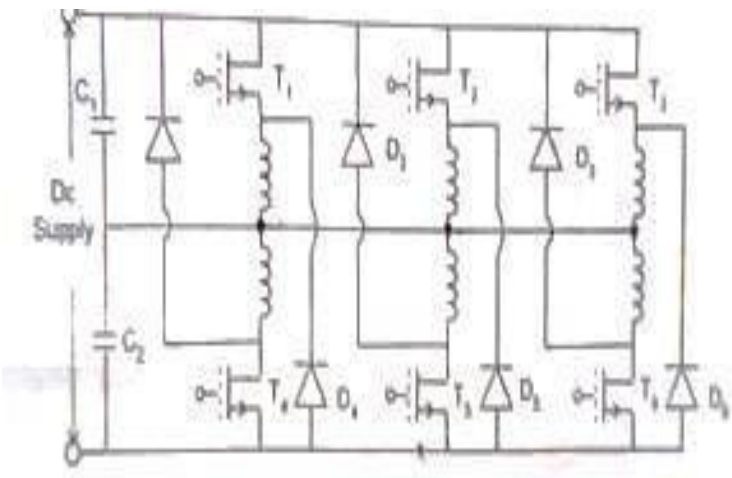


Figure 2.2.5 c dump circuit

via the step down chopper circuit. The mean capacitor voltage is maintained well above the supply to permit rapid defluxing after commutation.

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

DEMERITS

1.Dump capacitor voltage is maintained 2 Vdc to allow fast demagnetization. But use of a capacitor and an inductor in the dump circuit and also the voltage rating of other devices is twice the bus voltage

2. Monitoring of the dump capacitor voltage C‘and control of dump switch T makes the converter very complicated and also the converter does not allow freewheeling

2.4 CONTROL CIRCUITS FOR SRM

For motoring operation the pulses of phase current must coincide with a period of accuracy inductance. The timing and dwell (i.e.) period of conductance of the current pulse determine the torque, the efficiency and other parameters. With fixed firing angles, there is a monotonic relationship existing between average torque and rms phase current but generally it is not linear. This may present some complications in feedback-controlled systems. Although it is possible to achieve near servo-quality‘dynamic performance, particularly in respects of speed range torque/inertia and reversing capability. More complex controls are required for higher power drives, particularly where a wide speed range is required at constant power, and microprocessor controls are used. As high-speed operation, the peak current is limited by the self-emf of the phase winding. A smooth current waveform is obtained with a peak/rms ratio similar to that of a half sinewave.At low speed, the self-emf of the winding is small and the current must be limited by chopping or PWM of the applied voltage.

Two types of control circuits used are:

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

HYSTERISIS TYPE CURRENT REGULATION

As by this control circuit current is maintained more or less constant like ―hysteresis‖

throughout the conduction period in each phase it is known as hysteresis Fig2.4.1 (a) shows the current waveform controlled by the hysteresis type current regulator. The schematic arrangement of the control circuit is shown in fig 2.4.1

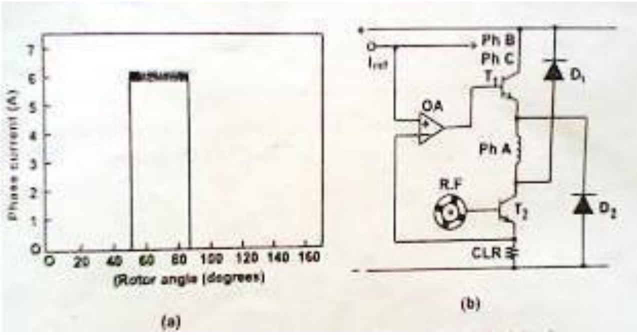


Figure 2.4.1 (a) Chopped current wave form, (b) Hysteresis type current regulation

Principle of operation

As shown in fig. 2.4.1(b) the transducer (a tachogenerator) is connected from the rotor and then the output signal from the transducer is given as a feedback signal at the base of transistor T2. From the emitter of transistor T2, the portion of the feedback signal (current) is fed at the input of the operational amplifier (O.A). There it is compared with the reference current and correspondingly after amplification the feedback signal is given at the base oftransistor T1. This signal in combination with collector current will flow from the emitter oftransistor T1 through A phase winding of the machine. Thus the current through A phase winding can be controlled depending on the requirement. CLR is the resistance for limiting the current as per the design. As the current reference increase the torque increases. At low currents the torque is roughly proportional to current squared but at higher current it becomes more nearly linear. At very high currents, saturation decreases the torque per ampere again. This type of control produces a constant-torque type of characteristics. With loads whose torque increases monotonically with speed, such as fans and blowers, speed adjustment is possible without tachometer feedback but general feedback is needed to provide accurate speed control. In some cases the pulse train from the soft position sensor may be used for speed feedback, but only at relative high speeds.

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

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

VOLTAGE PWM TYPE CURRENT REGULATION

The schematic arrangement of PWM type control circuit is shown in fig. 2.4.2

Principle of operation

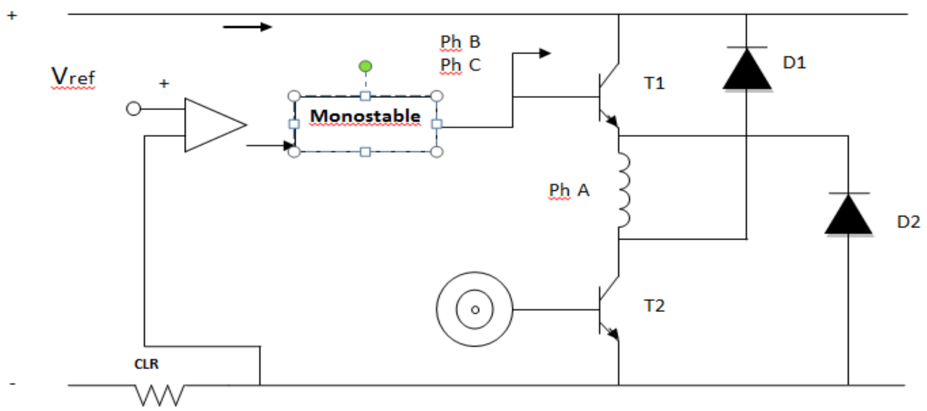


Figure 2.4.2 (a) voltage PWM type current regulator

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

CLR -Current limiting resistor R.F-Rotor feed back

OA -Operational Amplifier T1T2-Switching transistor

D1 D2-Diodes to return stored energy

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

2.5 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.

Figure represents the speed torque characteristics of SRM for constant ϴ and duty cycle. It is constant at low speeds and slightly droops as speed increases. For various other constant value of ϴ , the family of curves for the same duty cycle is shown in fig.1

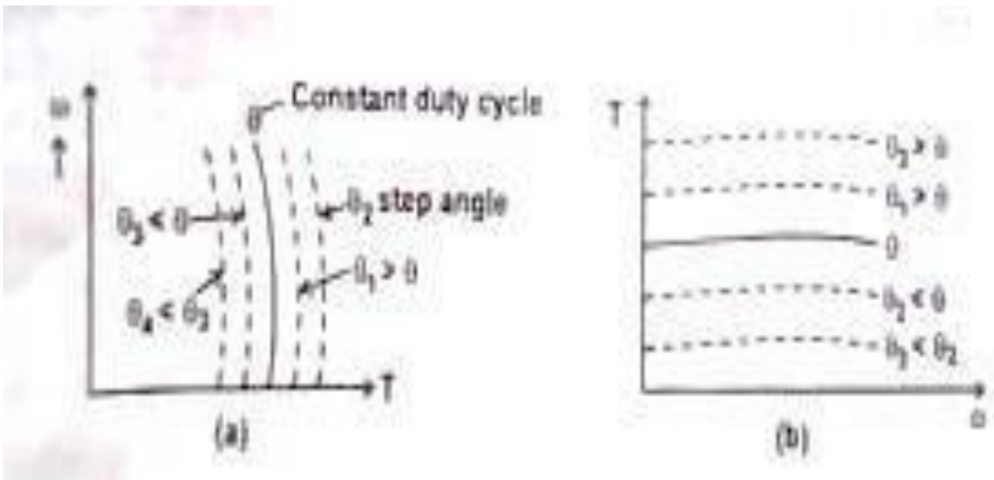


Figure 2.5.1 Torque speed characteristics of SRM

Torque speed characteristics for fixed ϴ and for various duty cycles are shown in fig. 2.5.1. ϴ and duty cycle are varied by suitably operating the semiconductor devices.

Torque Speed Capability Curve

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

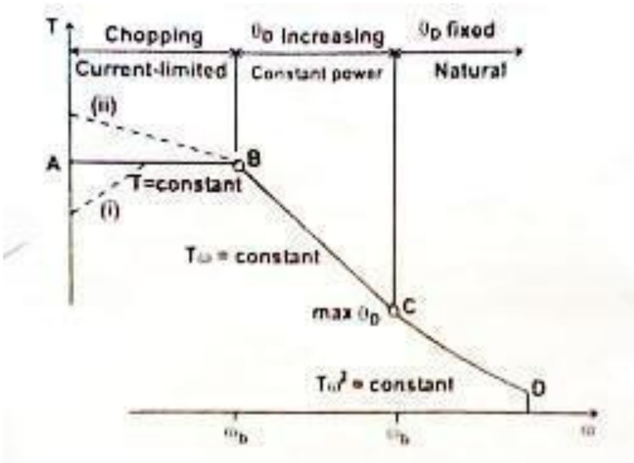


Figure 2.5.2 General Torque speed characteristics of SRM

[Source: "special electric machines" by R.Srinivasan page:3.56]

conduction angle the torque can be varied by varying the duty cycle of the chopper. However the maximum torque developed is restricted to definite value based on mechanical consideration.Fig2 Torque speed characteristic of switched reluctance motor AB in the fig.2 represents constant maximum torque region of operation. At very low speeds, the torque / speed capability curve may deviate from the clock torque characteristics. If the chopping frequency is limited or if the bandwidth of the current regulator is limited, it is difficult to limit the current without the help of self emf of the motor and the current reference may have to be reduced. If very low windage and core loss permit the chopper losses to be increased, so that with higher current a higher torque is obtained. Under intermittent condition of course very much higher torque can be obtained in any part of the speed range up to Ꞷ b.

The motor current limits the torque below base speed. The ‗corner point‘or base speed ‗Ꞷ b‘ is the highest speed at which maximum current can be supplied at rated voltage with fixed firing angles. If these angles are still kept fixed, the maximum torque at rated voltage decreases with speed squared. But if the conduction angle is increased,(i.e.)Ө on is decreased, there is a considerable speed range over which maximum current can be still be forced into the motor. This maintains the torque at a higher level to maintain constant power characteristic. But the core losses and windage losses increases with the speed.

Thus the curve BC represents the maximum permissible torque at each speed without exceeding the maximum permissible power transferred. This region is obtained by varying Ө D to its maximum value Ө D max. Ө D is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power; maximum permissible conduction angle

2.6 ROTOR POSITION SENSOR

Rotor position information is important for the operation of SRM.Rotor angle information must be accurate for the high speed drives. Inaccurate position sensing results in decreased torque &efficiency. In high speed motors, error in 1° decreases the torqueby8%.Position sensing sensor is enough.

Disadvantages of electro mechanical sensors are:

Unreliable due to dust, high temperature, humidity, vibration.

Cost increases with resolution.

Additional manufacturing expenses.

Extra electrical connections.

Need more space at the shaft.

To over come the above problems, sensor less rotor position estimation methods are developed. Sensor less methods employs motor electrical parameters for position detection.

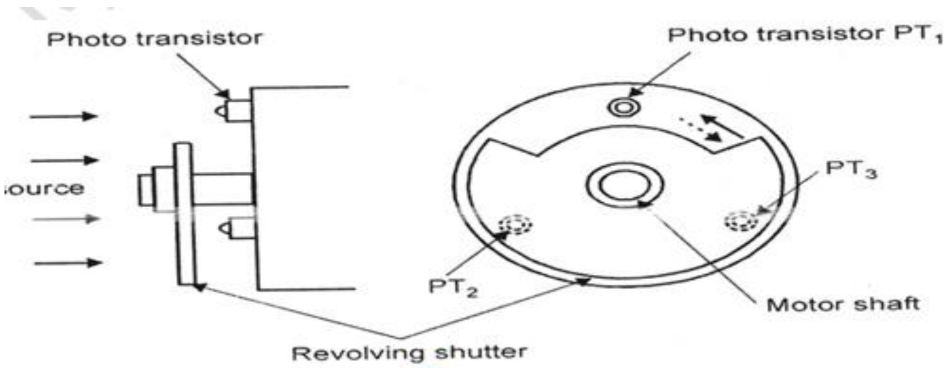


Fig.opticalposition sensor

1. **HALLPOSITION SENSOR:**

- Based on Hall principle.
- On rotor shaft, 3hall components, rotating plate with permanent magnet.
- Output of hall components indicates the rotor position.
    - Observer based sensing methods
    - Incremental inductance based sensing
    - Direct inductance based sensing
    - Intelligent control based sensing methods

Observer based sensing methods:

Use a state observer or a sliding mode observer

Depends on the inductances lope for their convergence and functioning.

Computationally intensive and have the problem of convergence

2.7 MICROPROCESSOR OR COMPUTER BASED CONTROL OF SRM DRIVE

Today in industrial places there is high demands on control accuracies, flexibility, ease of operation, repeatability of parameters for many drive applications.

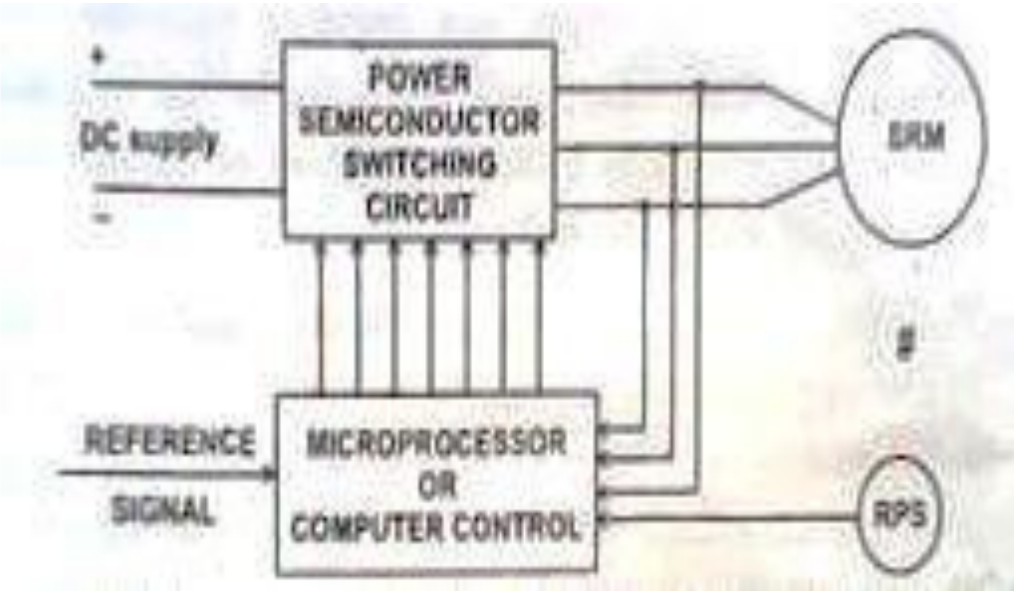


Figure 2.7.1 Block Diagram of the microprocessor control of srm

Nowadays switched reluctance motors are increasingly used in industries. To meet the above requirements, uses of microprocessor have become important.

Microprocessor or computer based control of SRM Fig.2.7.1 shows the block diagram of microprocessor based control of SRM drive. This control system consists of power semiconductor switching circuit, SRM with rotor position sensor and microprocessor system.

In this system microprocessor acts as a controller for the switched reluctance motor and generate control pulses to the power semiconductor switching circuits.

The input DC supply is fed to the power semiconductor switching circuits. Different types of power semiconductor switching circuits are used for different application. Normally the circuits are inverter circuit configuration.

The power semiconductor devices are turned on and off by controller circuit. Here the controller circuit is microprocessor or computer based control system. In the SRM drive shown in fig. 2.7.1, the rotor position sensor gives the information about the rotor with respect to the reference axis to the microprocessor or computer control. The controller also receives the status of current, flow through the phase winding and reference signal.

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

The microprocessor or computer controller can perform the following functions.

a) Control the feedback loops.

b) PWM or square wave signal generation to inverters.

c) Optimal and adaptive control.

d) Signal monitoring and warning.

e) General sequencing control.

f) Protection and fault overriding control.

g) Data acquisition.

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

3.1 Permanent Magnets Material

NdFeB – Neodymium – iron – boron has the highest energy product of all commercially available magnets at room temperature. It has high remanence and coercivity in the motor frame size for the same output compared with motors using ferrite magnets. But it is costlier. But both of the above stated magnets are sensitive to temperature and care should be taken for working temperature above 100˚.For very high temperature applications, alnico or rare earth cobalt magnets must be used.

B – H Loop

It is used for understanding characteristics hysteresis loop as shown.

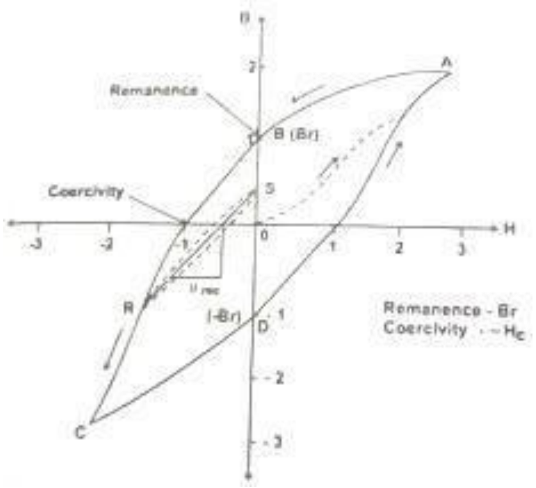


Figure 3.1.1 BH Hysteresis loop of hard permanent magnet

Material X – axis – Magnetizing force or field intensity H.

Y – axis – Magnetic flux density B in the material.

An un-magnetized sample has B = 0 and H = 0 and therefore starts out at the origin.

Curve OA

If it is subjected to a magnetic field, magnetic fixture (an electromagnetic with shaped pole pieces to focus flux into the magnet), then B and H in the magnet follow the curve OA as the external ampere – turns are increased.

Curve AB

If the external ampere – turns are switched off, the magnet relaxes along AB. The operating point (H, B) depends on the shape of the magnet and permanence of the surrounding magnetic circuit. If the magnet is surrounded by a highly permeable magnetic circuit, that is if it is keepered then its poles are effectively shorted together so that H = 0 and then the flux density is the value at point remanence Br.

Permanence: Maximum flux density that can be retained by the magnet at a specified temperature after being magnetized to saturation.

Curve BC

External ampere turns applied in the opposite direction cause the magnets operating point to follow the curve from B through the second quadrant to C.

Curve CD

If the ampere – turns are switched off at c the magnet relaxes along CD.

It is now magnetized in the opposite direction and the maximum flux density it can retain when keepered is – Br.

To bring B to zero from negative remanence point D, the field +Hc must be applied.

The entire loop is usually symmetrical and be measured using instruments such as hysteresis graph.

Soft PM

Soft PM materials have Knee in the second quadrant such as Alnico. Alnico magnets have very high remanence and excellent mechanical and thermal properties. But they are limited in the demagnetizing field they can withstand. These soft PM are hard when compared with lamination steels the hysteresis loop of typical non oriented electrical steel is very narrow when compared with Alnico.

Demagnetization curve

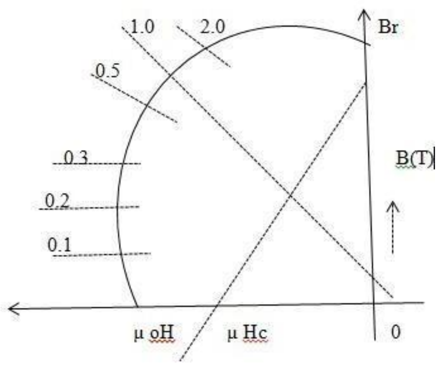


Figure 3.1.2 Demagnetization curve

In the absence of externally applied ampere – turn, the magnets operating point is at the intersection of the demagnetization curve and the load line. The slope of the load line is the product of μ0 and the permeance co efficient of the external circuit. In a permanent magnet, the relationship between B and H is

$$B=\mu_0 H+J$$

$\mu_0 H$ – flux density that would exist if the magnet were removed and the magnetizing force remain at the value H.

J – contribution of the magnet to the flux - density within its own volume.

If the demagnetization curve is a straight line, and therefore its relative slope and there by the μ_{rec} is unity, Then J is constant.

J – Magnetization of the magnet, unit T tesla

Hard magnets have $\mu_{rec} >= 1$,J decreases as the –Hc increases.

The magnet can recover or recoil back to its original flux density as long as the magnetization is constant. The coercive force required to permanently demagnetize the magnet is called the intrinsic coercivity and it is Hci.

3.2 PERMANENT MAGNET BRUSHLESS D.C. MOTORS

Conventional DC motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawbacks that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid state switches, maintenance free motors were realized. These motors are known as brushless DC motors. The function of magnets is the same in both brushless motor and the dc commutator motor. The motor obvious advantage of brushless configuration is the removal of brushes. Brush maintenance is no longer required, and many problems associated with brushes are removed.

An advantage of the brushless configuration in which the rotor inside the stator is that more cross sectional area is available for the power or armature winding. At the same time conduction of heat through the frame is providing greater specific torque. The efficiency is likely to be higher that of a commutator motor of equal size and the absence of brush friction help further in this regard.

CONSTRUCTIONAL FEATURES OF BLPM MOTORS

Construction

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).

Figure 2.1.1 construction of BLPMDCmotor

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.

Merits and Demerits

There is no field winding. Therefore there is no field cu loss. The length of the motor is less as there is no mechanical commutator.

Size of the motor becomes less.

It is possible to nave very high speeds.

It is self-starting motor. Speed can be controlled.

Motor can be operated in hazardous atmospheric condition. Efficiency is better.

Demerits

Field cannot be controlled.

Power rating is restricted because of the maximum available size of permanent magnets.

A rotor position sensor is required.

A power electronic switch circuitry is required.

Comparison of brushless dc motor relative to induction motor drives

In the same frame, for same cooling, the brushless PM motor will have better efficiency and p.f and therefore greater output. The difference may be in the order of 20 – 50% which is higher.

Power electronic converter required is similar in topology to the PWM inverters used in induction motor drives.

In case of induction motor, operation in the weakening mode is easily achieved providing a constant power capability at high speed which is difficult in BLPM dc motor.

PM excitation is viable only in smaller motors usually well below 20 kw also subject to speed constraints, In large motors PM excitation does not make sense due to weight and cost.

Commutator and brushes arrangement

Because of the hetropolar magnetic field in the air gap of dc machine the emf induced in the armature conductors is alternating in nature. This emf is available across brushes as unidirectional emf because of commutator and brushes arrangement.

The dc current passing through the brushes is so distributed in the armature winding that unidirectional torque is developed in armature conductor.

A dc current passing through the brushes because of commutator and brushes action, always sets up a mmf whose axis is in quadrature with the main field axis, irrespective of the speed of the armature.

PRINCIPLE OF OPERATION OF BRUSHLESS PM DC MOTOR

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. Then the power drawn from the mains V *I is equal to the mechanical power delivered $\frac{2\pi NT}{60}$ Pm =ωT and the various losses in the motor and in the electronic switching circuitry

CLASSIFICATION OF BLPM DC MOTOR

BLPM dc motors can be classified on the basis of the flux density distribution in the air gap of the motor. They are

(a). BLPM Square wave dc motor [BLPM SQW DC Motor]

(b).BLPM sinusoidal wave dc motor [BLPM SINE WAVE DC Motor]

BLPM Square wave motor

These are two types: 180Degree pole arc.

120Degree pole arc.

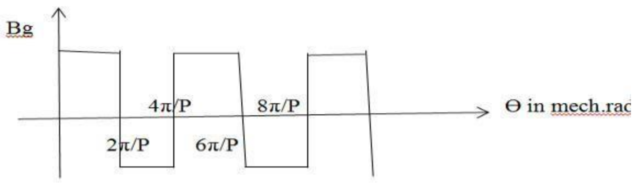


Figure 3.2.2 Air gap flux density distribution in 180 degree BLPM SQW motor.

Air gap density distribution of BLPM DC SQW motor with 120 degree pole arc, as shown

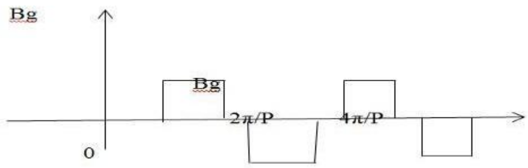


Figure 3.2.3 Air gap flux density distribution in 120 degree BLPM SQW motor.

BLPM Sine wave DC Motor

Air gap density distribution of BLPM dc sine wave motor as shown in fig.3.2.3

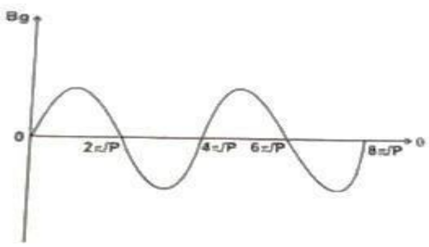


Figure 3.2.3 Air gap flux density distribution in 120 degree BLPM SW motor.

3.3 CONSTRUCTION OF MECHANICAL COMMUTATOR

COMMUTATOR SEGMENT

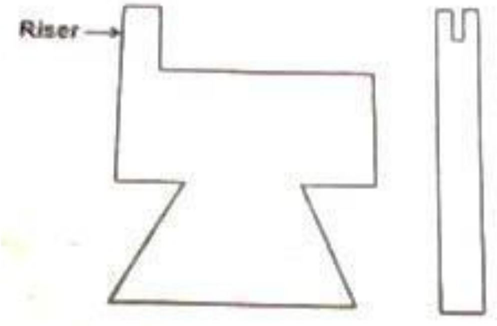


Figure 2.1.1 Commutator Segment

Commutator is made up of specially shaped commutator segments made up of copper. These segments are separated by thin mica sheets (ie) Insulation of similar shape. The commutator segments are tapered such that when assembled they form a cylinder.

These segments are mechanically fixed to the shaft using V – shaped circular steel clamps, but are isolated electrically from the shaft using suitable insulation between the clamps and the segment.

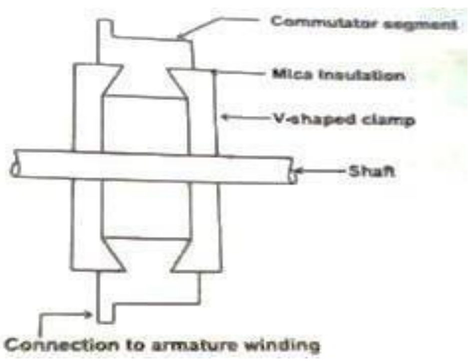


Figure 3.3.2 connection of commutator segments to shaft

MECHANICAL COMMUTATOR AND BRUSHES ARRANGEMENT

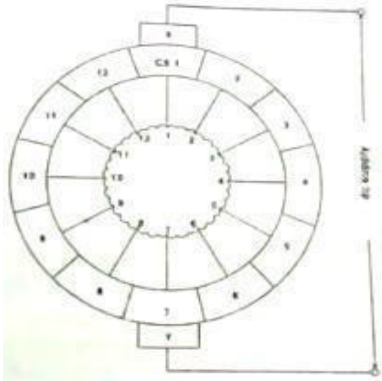


Figure 3.3.3 Mechanical Commutator and Brushes

It represents a case with 2poles and 12 commutator segments. To start with the brush X contacts with CSI and brush Y with 7.A dc supply is connected across the brushes X and Y. The dc current I passes through brush X, CSI, tapping 1,tapping 7and brush Y. There are two armature parallel paths between tapping‘s 1 and 7.the current passing through the armature winding sets up a magneto motive force whose axis is along the axes of tapping 7 and 1 of the brush axes Y and X.

Allow the armature to rotate by an angle in a counter clockwise direction. Then the brush X contacts CS2 and the tapping‘s a and the brush Y. Contact CS8 and tapping 8.The dc current passes through the tapping‘s 2 and 8 there are two parallel paths.

(i) 2–3–4–5–6–7–8

(ii) 2–1–12–11–10–9–8

Now the mmf set up by the armature winding is form tapping 8 to 2 along the brush axis YX Thus the armature mmf direction is always along the brush axis YX, even though the current distribution in the armature winding gets altered. In a normal dc machine brushes are kept in the interpolar axis. Therfore, the axis of the armature mmf makes an angle 90˚elec with the main field axis.The function of commutator and brushes arrangement in a conventional dc machine is to set up an armature mmf always in quadrature with the main field mmf respectively of the speed of rotation of the rotor.

ELECTRONIC COMMUTATOR

The armature winding which is in the stator has 12 tapping's. Each tapping is connected to the positive of the dc supply node and through 12 switches designate as S1,S2,….S12 and negative of the supply at node Y through switches S'1,S'2,…….S'12.

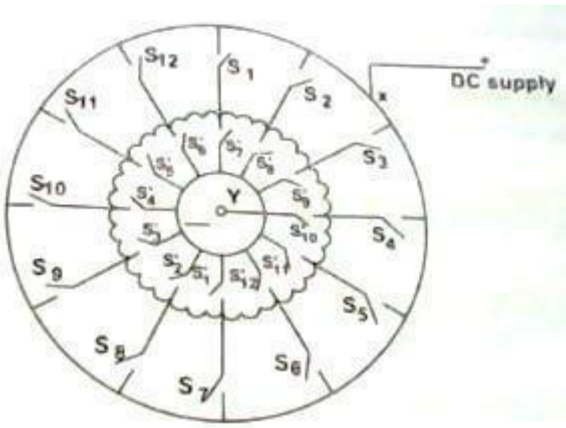


Figure 3.3.4 Electronic Commutator

When S1 and S'1 are closed the others are in open position, the dc supply is given to The trappings 1 and 7.there are two armature parallel path.

(i) 1–2–3–4–5–6–7

(ii) 1–12–11–10–9–8–7

They set up armature mmf along the axis 7 to 1.After a small interval S1 and S‘1 are kept open and S2 and S‘2 are closed. Then dccurrent passes from tapping 2 to 8 sets up mmf in the direction 8 – 2.

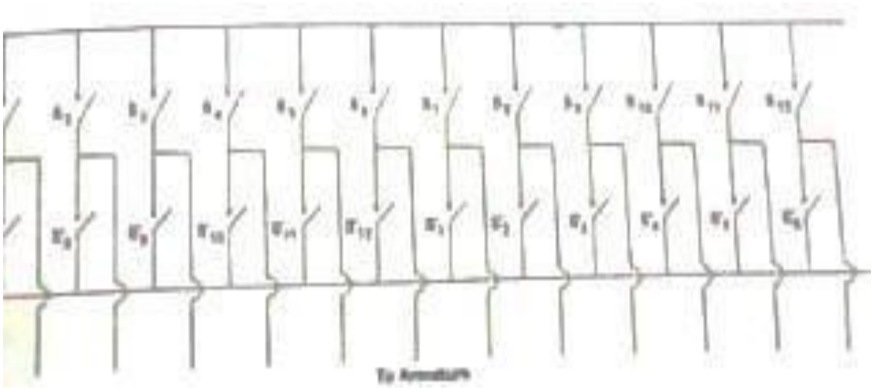


Figure 3.3.5 switching circuit of Electronics commutator

Thus by operating the switch in a sequential manner it is possible to get a revolving mmf in the air gap. The switches S1 to S12 and S‘1 to S‘12 can be replaced by power electronic switching devices such as SCR‘s MOSFET‘s IGBT‘s, power transistor etc.

When SCR‘s are used suitable commutating circuit should be included. Depending upon the type of forced commutated employed, each switch requires on or two SCRs and other commutating devices. As number of devices is increased, the circuit becomes cumbersome.

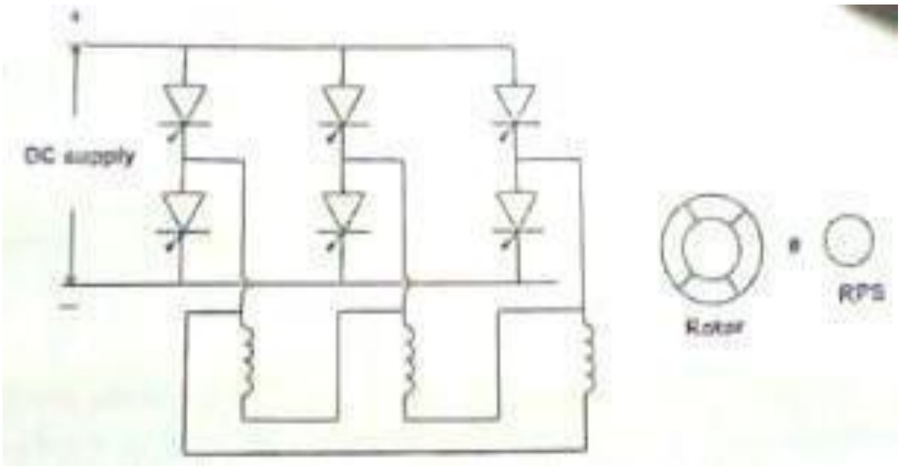


Figure 3.3.6 Delta Connected Stator Armature Winding

For normal electronic commutator, usually six switching devices are employed. Then the winding should have three tapping's. Therefore the winding can be connected either in star or in delta.

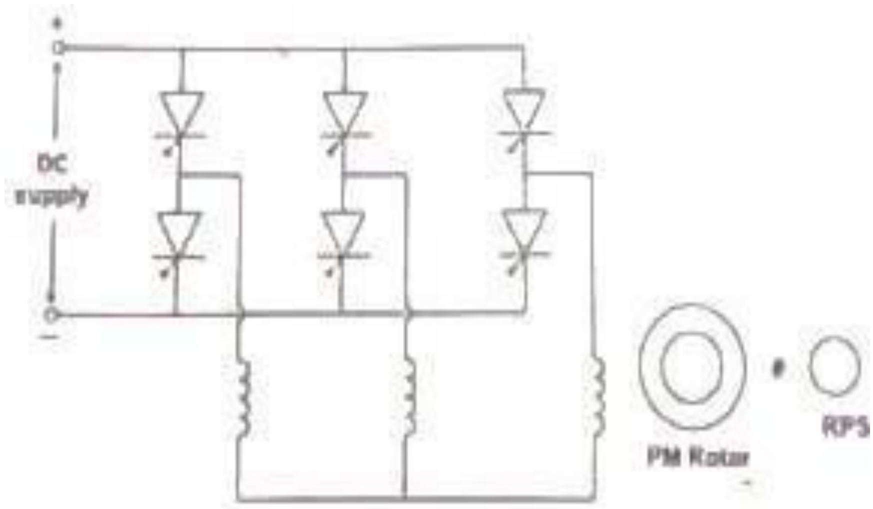


Figure 3.3.7 Star Connected Armature Winding

COMPARISON BETWEEN MECHANICAL COMMUTATOR AND BRUSHES AND ELECTRONIC COMMUTATOR

S. No	Mechanical Commutator	Electronic Commutator
1.	Commutator is made up of copper segment and mica insulation. Brushes are of carbon or graphite.	Power electronic switching device is used in the commutator.it requires a position sensor.
2.	Commutator arrangements are located in the rotor.	It is located in the stator.
3.	Shaft position sensing is inherent in the arrangement	Separate rotor position sensor is required.
4.	Numbers of commutator segments are very high.	Number of switching devices is limited to 6.
5.	Highly reliable.	Reliability is improved by specially designing the devices and protective circuits.
6.	Difficult to control the voltage available across the tappings.	The voltage available across armature tappings can be controlled by employing PWM techniques.
7.	Interpole windings are employed to have sparkles commutation.	By suitable operating the switching devices, better performance can be achieved.

3.4 TORQUE- SPEED CHARACTERSISTICS OF BLPM SQM DC MOTOR

Let the supply voltage V be constant. A family of torque speed characteristics for various constant supply voltages is as shown in figure 3.4.1

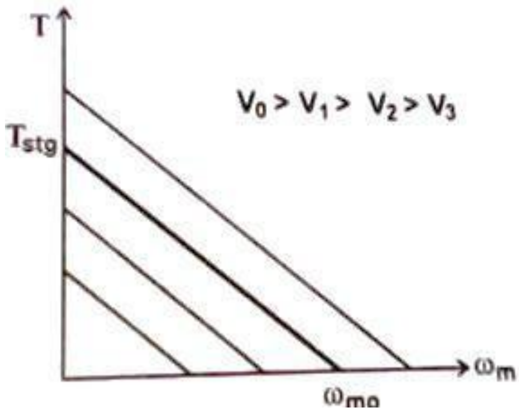


Figure 3.4.1 T-ωm curve for various supply voltages

Permissible region of operation in T-ωm plane

Torque speed characteristics of BLPM square wave motor is shown in fig.3.4.1. The constraints are

1. The continues current should not exceed the permissible current limit I_n (i.e) Torques should not exceed K_t I_n.
2. The maximum permissible supply voltage = V_n.
3. The speed should not exceed ω_{mn}.

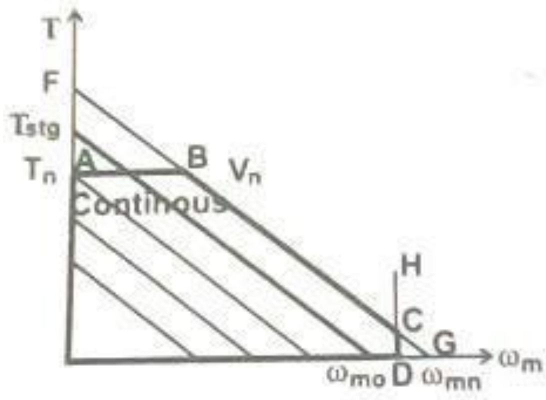


Figure 3.4.2 Torque-speed characteristics

LINE AB

Parallel to X-axis represents maximum permissible torque line which corresponds to maximum permissible current I_n.

Line FG

It represents T-ω_m characteristics corresponding to the maximum permissible V_n. B and C are points in Fg. B is the point of intersection between AB and FG.

Line DH

It represents constant maximum permissible speed line (i.e) ω_{mn} is constant. DH intersects FG and x axis at D.

The area OABCDO is the permissible region of operation. To obtain a particular point P corresponding to given load-torque and speed condition the only way to operate the motor at P is by suitably adjusting the supply voltage fed to the motor.

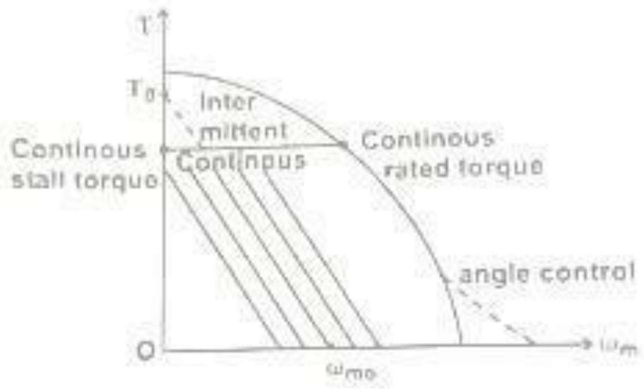


Figure 2.1.1 Torque speed characteristics of ideal brushless DC motor

If the phase resistance is small as it should be in an efficient design, then the characteristics to that of a shunt dc motor. The speed is essentially controlled by the voltage V and may be changed by changing the supply voltage. Then the current drawn just to drive the torque at its speed. As the load torque is increased, the speed drops and the drop is directly proportional to the phase resistance and the torque. The voltage is usually controlled by chopping or PWM.

This gives rise to a family of torque speed characteristics as shown in fig. 4.5.8. The boundaries of continuous and intermittent limits are shown. Continuous limit - determined by the heat transfer and temperature rise. Intermittent limit – determined by the maximum ratings of semiconductor devices in circuit. In practice the torque speed characteristics deviates from the ideal form because of the effects of inductance and other parasitic influences. Also the speed range can be extended by increasing the dwell of conduction period relative to the rotor position.

3.5 POWER CONTROLLER FOR BLPM SQUARE WAVE DC MOTOR

POWER CIRCUIT

Power Circuit of BLPM dc motor is as shown fig3.5.1 consists of six power semiconductor switching device connected in bridge configuration across a dc supply. A suitable shunt resistance is connected in series to get the current feedback. Feedback diodes are connected across the device. The armature winding is assumed to be star connected. Rotor has a rotor position sensor and a tacho-generator is coupled to the shaft to get feedback signal.

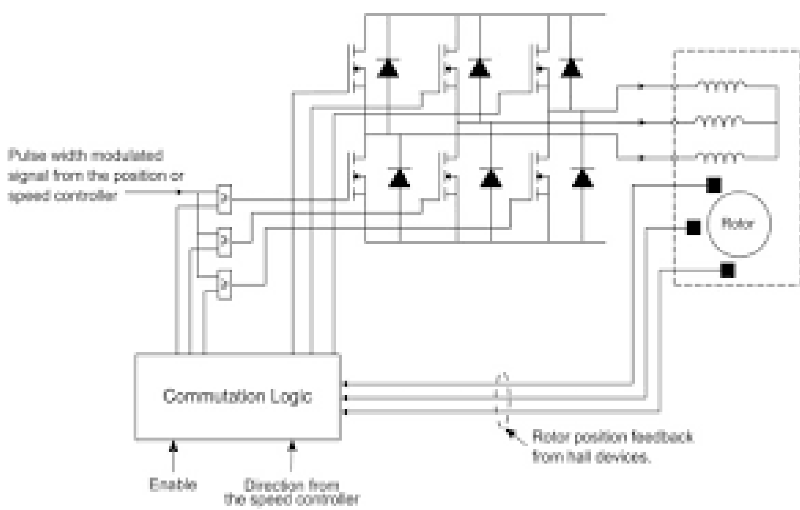


Figure 3.5.1 structure of controller for brushless PM DC Motor

CONTROL CIRCUIT

The control circuits consist of a commutation logic unit. Which get the information about the rotor shaft position and decides which switching devices are to be turned on and which devices are to be turned off. This provides six output signals out of which three are used as the base drive for the upper leg devices. The other three output signal are logically AND with the high frequency pulses and the resultant signals are used to drive the lower leg devices.

A comparator compares the tachogenerator output with reference speed and the output signal is considered as the reference current signal for the current comparator which compares the reference current with the actual current and the error signal output is fed to the monostable multivibrator which is excited by high frequency pulses. The duty cycle of the output of monostable is controlled by error signal. This output signal influences the conduction period and duty cycle of lower leg devices.

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.

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.3.5.2

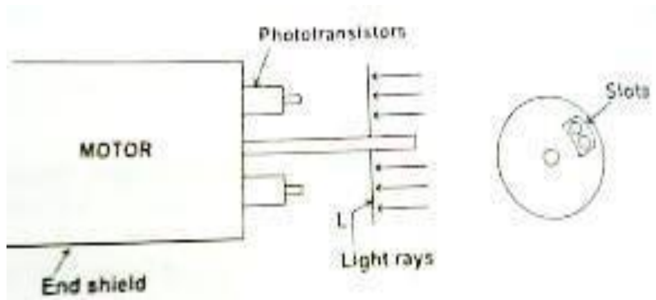


Figure 3.5.2 Optical position sensor

The phototransistors are fixed at the end shield cover such that they are mutually displaced by 60 degree electrical by a suitable light source. The shaft carries a circular disc which rotates along the shaft. The disc prevents the light ray falling on the devices. Suitable slot are punched in the disc such turned into on state suitably turns the main switching devices of electronic commutation circuitry into on state. As the shaft rotates, the devices of electronic commutation which are turned into ON are successively changed.

HALL EFFECT POSITION SENSOR

Consider a small pellet of n-type semiconducting material as shown in fig 4.36.

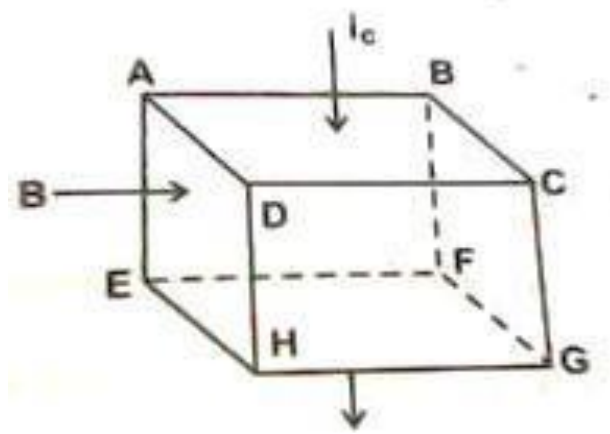


Figure 3.5.3 Hall Effect sensor

A current is allowed to pass from the surface ABCD to the surface EFGH. Let the surface ABEF be subjected to a North pole magnetic field of flux density B tesla. As per Fleming left hand rule, the positive charge in the pellet get concentrated near surface ADHE and negative charges near the surface BCFG. Since type material has free negative charges, there electrons gets concentrated near the surface BCGF.This charge in distribution makes the surface ADHE more positive than the surface BCGF. This potential known as Hall emf or emf due to Hall Effect.

It has been experimentally shown that Emf due to Hall Effect is V_H is given by

$V_H = R_H(i_c / d)$ volts

Where i_c current through the pellet in amps

B- Flux density in tesla

d- Thickness of the pellet in m.

R_H – Constant which depends upon the physical dimensions or physical properties of the pellet. If the polarity of B is changed from North Pole to South Pole the polarity of the emf due to Hall Effect also get changed.

HALL EFFECT POSITION SENSOR

Hall effect position sensor can be advantageously used in a BLPM motor. Consider a 2 pole BLPM motor with two winding w1 and w2 as shown in fig.

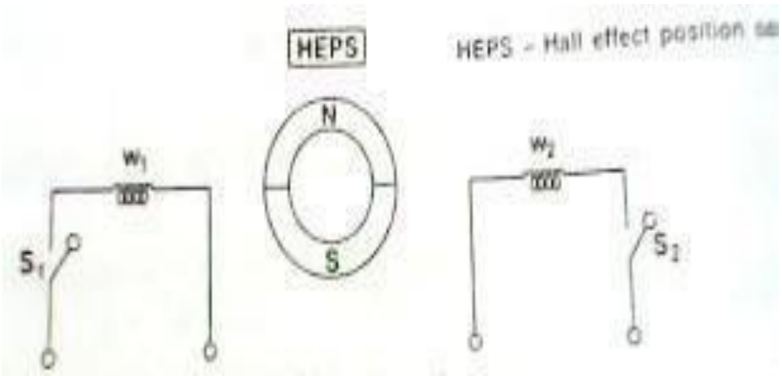


Figure 3.5.4 2 pole BLPM motor

When w1 carries a current on closing S1 it set up a North Pole flux in the air gap. Similarly when s2 is closed w2 is energized and sets up a North Pole flux.w1 and w2 are located in the stator such that their axes are 180 degree apart. A Hall Effect position sensor is kept in an axis of the winding.

When Hall Effect position sensor is influenced by North Pole flux the hall Emf is made to operate the switch S1. Then w1 sets up North Pole flux. The rotor experiences a torque and South Pole of the rotor tends to align with the axis of w1.because of interia.it overshoot the rotor hence rotates in clockwise direction. Now HEPS is under the influence of S pole flux of the rotor. Then the polarity of hall emf gets changed. This make the switch S1 in off state and S2 is closed. Now w2 sets up N pole flux in the air gap, the rotor rotates in clockwise direction. So that the s pole gets aligned with w2 axis. Then this process continuous. The rotor rotates continuously.

3.7MAGNETIC CIRCUIT ANALYSIS ON OPEN CIRCUIT

Cross section of a 2 pole brushless dc motor having high energy rare earth magnets on the rotor and the demagnetization curve are as shown in fig 3.7.1

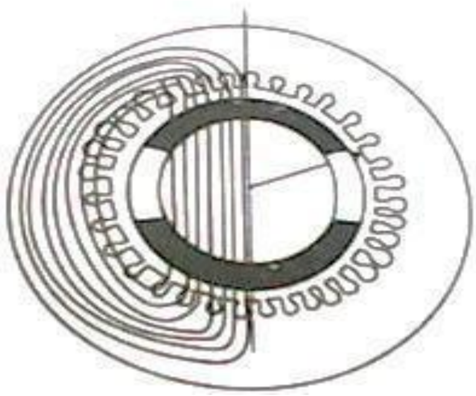


Figure 3.7.1 Motor cross section and flux pattern

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 fig 3.7.1.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.

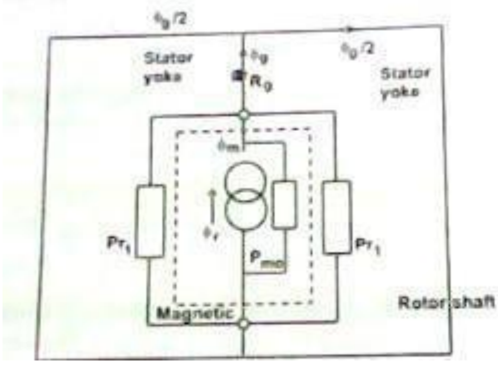


Figure 3.7.2 magnetic equivalent circuit.

The steel cores of the stator and rotor shaft are assumed to be infinitely permeable.

Each magnet is represented by a Norton'equivalent circuit consisting of a flux generator in parallel with an internal leakage permeance pmo.

$\Phi r = BrAm$

$Pmo = \mu 0 \mu rec Am/lm$

where Am – pole area the magnet

lm – length of the magnet in the direction of magnetization (in this case its radial thickness)

Br- remanent flux density

μrec- relative recoil permeability (the slope of the demagnetization curve)

In this case the outer pole area is larger than the inner pole area but to keep the analysis simple average pole area is considered.

With a magnet arc of 120°

$Am=2/3\ \Pi\ [r1-g-lm/2]\ l$

r1- radius of the rotor

g- air gap length

Most of the magnet flux crosses the air gap via the air gap reluctance Rg

$R_g = g'/\mu_0 A_g$

g'- equivalent air gap length allowing for slotting.

the slotting can be taken into account by means of carter's coefficient, which case,

$g' = K_c\, g$

Ag- air gap area through which the flux passes as it crosses he gap . the precise boundary of this area is uncertain because of fringing both at the edges of the magnet and at the ends of the rotor. An approximate allowance for fringing can be made by adding g' at each of the four boundaries ,giving

$$A_g = [2/3\,(r_1 - g/2) + 2g](l + 2g)$$

the remaining permeance in the magnetic circuit I the rotor leakage permeance ρrl, which represents the paths of the magnet flux components that fails to cross the air gap. this can be conveniently included in a modified magnet internal permeance by writing

$$P_m = P_{mo} + P_{rl}$$

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

Prl-normalized rotor leakage permeance

UNIT IV - PERMANENT MAGNET SYNCHRONOUS MOTORS

4.1 CONSTRUCTION AND OPERATION OF A PERMANENT MAGNET SYNCHRONOUS MOTOR

INTRODUCTION

A permanent magnet synchronous motor is also called as brushless permanent magnet sine wave motor. A sine wave motor has a

1. Sinusoidal or quasi-sinusoidal distribution of magnetic flux in the air gap.
2. Sinusoidal or quasi-sinusoidal current wave forms.
3. Quasi-sinusoidal distribution of stator conductors (i.e.) short-pitched and distributed or concentric stator windings.

The quasi sinusoidal distribution of magnetic flux around the air gap is achieved by tapering the magnet thickness at the pole edges and by using a shorter magnet pole arc typically 120º.

The quasi sinusoidal current wave forms are achieved through the use of PWM inverters and this may be current regulated to produce the best possible approximation to a pure sine wave. The use of short pitched distributed or concentric winding is exactly the same as in ac motors.

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

Fig. 4.1.1 shows a cross section of simple permanent magnet synchronous machines. It 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.

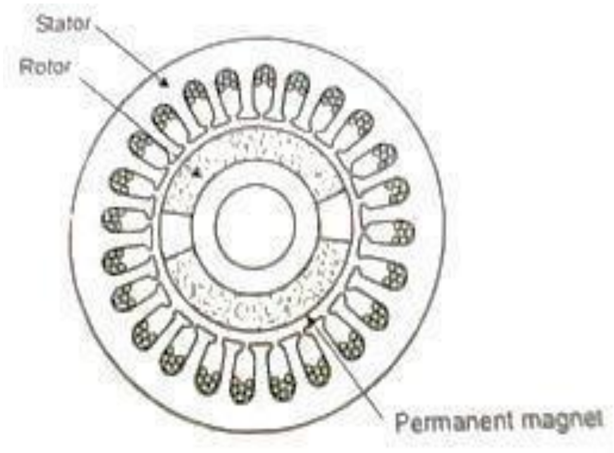


Figure 4.1.1 Permanent magnet synchronous motor

In a permanent magnet machines the air gap serves an role in that its length largely determines the operating point of the permanent magnet in the no-load operating condition of the machines .Also longer air gaps reduce machines windage losses.

The permanent magnets form the poles equivalent to the wound field pole of conventional synchronous machines. Permanent magnet poles are inherently salient and there is no equivalent to the cylindrical rotor pole configurations used in many convectional synchronous machines.

Many permanent magnet synchronous machines may be cylindrical or smooth rotor physically but electrically the magnet is still equivalent to a salient pole structure. Some of the PMSM rotors have the permanent magnets directly facing the air gap as in fig. 2.1.1.

Rotor yoke is the magnetic portion of the rotor to provide a return path for the permanent magnets and also provide structural support. The yoke is often a part of the pole structure

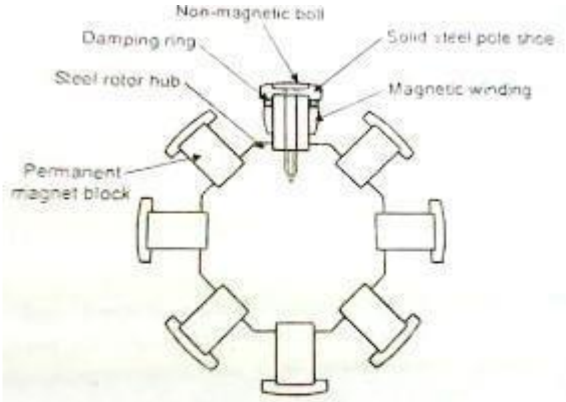


Figure 2.1.1 PMSM Rotor

Damper winding is the typical cage arrangement of conducting bars, similar to induction motor rotor bars and to damper bars used on many other types of synchronous machines. It is not essential for all permanent magnet synchronous machines applications, but is found in most machines used in power applications.

The main purpose is to dampen the oscillations about synchronous speed, but the bars are also used to start synchronous motors in many applications. The design and assembly of damper bars in permanent magnet machines are similar to the other types of synchronous machines.

Synchronous machines are classified according to their rotor configuration. There are four general types of rotors in permanent magnet synchronous machines. They are

- Peripheral rotor
- Interior rotor
- Claw pole or lundell rotor.
- Transverse rotor.

Peripheral rotor

The permanent magnets are located on the rotor periphery and permanent magnet flux is radial.

Interior rotor

The permanent magnets are located on the interior of the rotor and flux is generally radial.

Claw pole or Lund ell

The permanent magnets are generally disc shaped and magnetized axially. Long soft iron extensions emanate axially from periphery of the discs like claws or Lund ell poles. There is set of equally spaced claws on each disc which alternate with each other forming alternate north and south poles.

Transverse rotor

In this type the permanent magnets are generally between soft iron poles and the permanent magnet flux is circumferential. In this soft iron poles at as damper bars. Magnetically this configuration is similar to a reluctance machine rotor, since the permeability of the permanent magnet is very low, almost the same as that of a non-magnetic material. Therefore, reluctance torque as well as torque resulting from the permanent magnet flux is developed. Thus BLPM sine waves (SNW) motor is construction wise the same as that of BLPM square wave (SQW) motor. The armature winding and the shape of the permanent magnet are so designed that flux density distribution of the air gap is sinusoidal(i.e.) .The magnetic field setup by the permanent magnet in the air gap is sinusoidal

4.2 MICROPROCESSOR BASED CONTROL OF PMSM

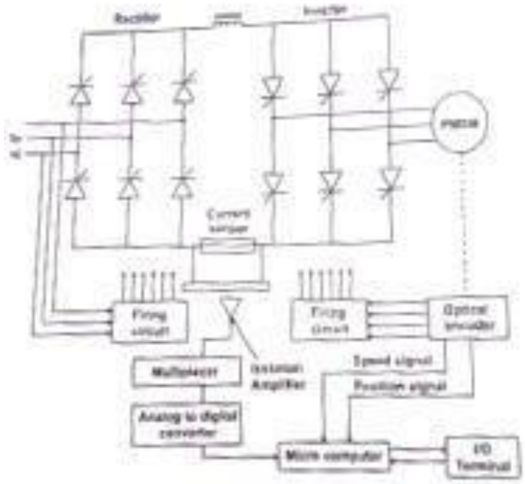


Figure 4.2.1 Microprocessor Based control of PMSM motor

Fig 4.2.1 shows the block diagram of microprocessor based permanent magnet synchronous motor drive. 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. In the block diagram of the microprocessor controller PMSM shown in fig 5.15, the permanent magnet synchronous motor is fed from a current source d.c link converter system, which consists of a SCR invertor 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 invertor triggering pulses are synchronized to the rotor position reference signals with a delay angle determined by an 8-bit control input.

4.3 SELF CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

As the rotor speed changes the armature supply frequency is also change proportionally so that the armature field always moves (rotates) at the same speed as the rotor. The armature and rotor field move in synchronism for all operating points. Here accurate tracking of speed by frequency is realized with the help of rotor position sensor.

When the rotor makes certain predetermined angle with the axis of the armature phases the firing pulses to the converter feeding the motor is also change. The switches are fired at a frequency proportional to the motor speed. Thus the frequency of the voltage induced in the armature is proportional to the speed.

Self-control ensures that for all operating points the armature and rotor fields move exactly at the same speed. The torque angle is adjusted electronically hence there is an additional controllable parameter passing greater control of the motor behavior by changing the firing of the semi-conductor switches of an inverter.

The torque angle is said electronically hence the fundamental component of phase A needs $\Phi f/\beta$, it lies along the direct axis that rotates at a synchronous speed. The switches must be triggered by phase A current component when Φf axis is β electrical degrees behind the phase A axis. This is achieved by firing the switch when direct axis is $\delta+\beta$ behind axis of A as show shown in fig.

Self-control is applicable to all variable frequency converters, the frequency being determined by machine.

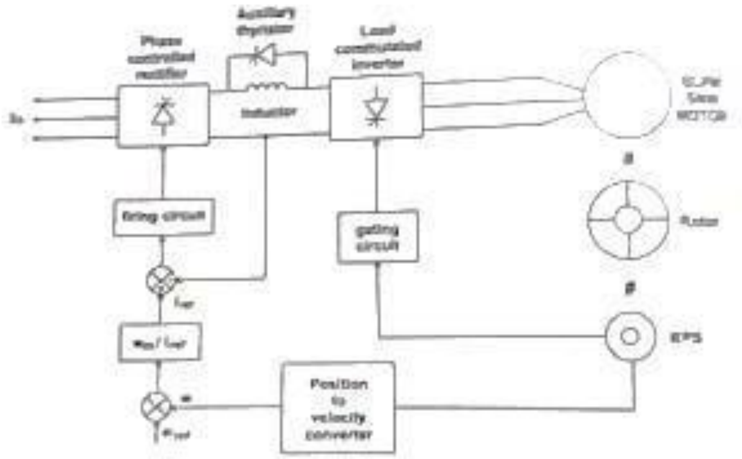


Figure 4.2.1 Self control of PMSM

At high power levels the most common power converter configuration is the current fed DC link converter which is shown in fig. 4.3.1

Inner current and outer speed loop

The phase controlled thyristor rectifier on the supply side of the DC link has the current regulating loop and operate as a control current source. The regulated DC current is delivered to the DC link inductor to the thyristor of load commutator inverter which supplies line current to the synchronous motor.

The inverter gating signals are under the control of shaft-position sensor giving a commutator less dc motor with armature current controlled. The thyristor of these inverters utilize load commutation because of the generated emf appearing at the armature. It is ensured by the over excitation of synchronous motor, so that it operates at leading power factor hence it reduces commutating circuitry, low losses and is applicable to power levels of several megawatts.

The shaft position is sensed by the position sensor. The shaft speed is obtained by converting the position information. This speed is compared with the reference speed signal which provides the speed error. This is the current reference signal for the linear current loop.

This reference current is compared with the sensed dc link current which provides control signals for the rectifier thyristor. The sensed shaft position is used as gating signal for inverter thyristor.Commutation at low speed Load commutation is ensured only at high speeds. Whereas at low speeds the Emf generated is not sufficient for load commutation. The inverter can be commutated by supplying pulsating on and off dc link current. This technique produces large pulsating torque but this is not suitable for drives which require smooth torque at low speed.

The DC link current is pulsed by phase shifting the gate signal of the supply side converter from rectification to inversion and back again. When the current is zero the motor side converter is switched to a new conduction period and supply side converter is then turned on. Time required for the motor current to fall to zero can be significantly shortened by placing a shunt thyristor in parallel with a DC link inductor. When the current zero is needed the line side converter is phased back to inversion and the auxiliary thyristor is gated.

The DC link inductor is then short circuited and its current can supply freely without affecting the motor. When the line side converter is turned on the auxiliary thyristor is quickly blocked. This method of interruption of the motor current reduces the effect of pulsating torque.

Four Quadrant Operations

The drive characteristics are similar to those of a conventional DC motor drive. Motor speed can be increased to a certain base speed corresponding to the maximum voltage from the supply. Further, increase in speed is obtained by reducing the field current to give a field weakening region of operation.

Regenerative braking is accomplished by shifting the gate signal, so that machine side inverter acts as a rectifier and supply side rectifier as a inverter, hence the power is return to the ac utility network. The direction of rotation Of the motor is also reversible by alternating the gate sequence of the motor side converter. Thus four quadrant operations are achieved, without additional circuitry.

4.4 VECTOR CONTROL OF BLPM SNW MOTOR

Electromagnetic torque in any electrical machine is developed due to the interaction of current carrying armature conductors with the air gap flux. Consider a two machine whose armature conductor currents and air gap flux are as shown in fig. 5.12. Here the flux is in quadrature with the armature mmf axis.

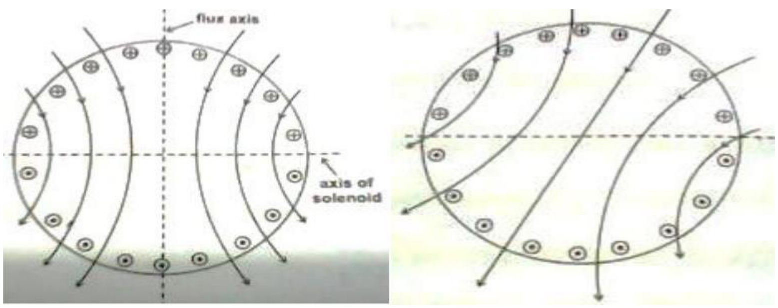


Figure 4.4.1 Vector control of PMSM motor

Each and every armature conductor experiences a force which contributes the torque. The torque contributed by various armature conductors have the same direction even through their magnitude may vary. It is observed that the steady state and dynamic (behaviors) performance of a most of such an arrangement are better.

Consider a second case wherein the armature conductor current distribution and air gap flux distribution are as shown in fig. 6.26. In this case the angle between the axis of the air gap flux and the armature mmf axis is different from 90° elec.

In this case also each and every armature conductor experiences a force and contributes to the torque. But in this case the direction of the torque experienced by the conductors is not the same. Since conduction develops torque in one direction while the others develop in the opposite direction. As a result, the resultant torque gets reduced; consequently it is observed that both the steady state and dynamic performance of such a motor is poorer. For a BLPM motor to have better steady state and dynamic performance, it is essential that the armature Mmf axis and the axis of PM are to be in quadrature for all operating condition.

PRINCIPLE OF VECTOR CONTROL

BLPM SNW motor is usually employed for variable speed applications. For this we keep V/f constant and vary V and f to get the desired speed and torque.

From the theory of BLPM SNW motor it is known that as the speed is varied from a very low value upto the corner frequency, the desired operating point of current is such that $I_d = 0$ and I is along the q-axis. Such a condition can be achieved by suitably controlling the voltage by PWM technique after adjusting the frequency to a desired value.

When the frequency is more than the corner frequency it is not possible to make $I_d = 0$, due to the voltage constraints. In such a case a better operating point for current is obtained with minimum I_d value after satisfying the voltage constraints. Controlling BLPM SNW motor taking into consideration the above mentioned aspects is known as vector Control‖ of BLPM SNW motor.

SCHEMATIC DIAGRAM OF VECTOR CONTROL

The schematic block diagram of vector control is as shown in figure 4.4.2 knowing the value of the desired torque and speed and also the parameters and the voltage to which the motor is subjected to, it is possible to complete the values of id .ref and iq .ref for the desired dynamic and steady state performance.

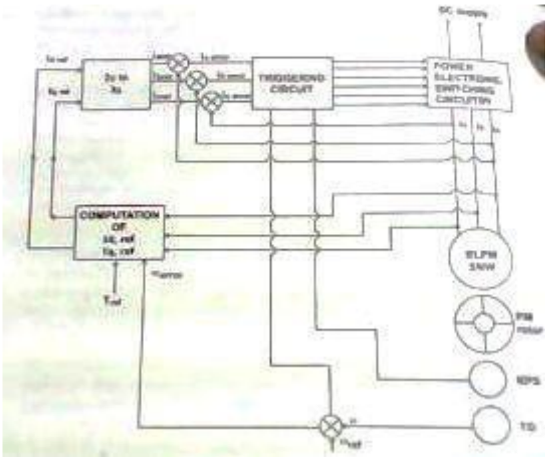


Figure 4.4.2 Vector control of PMSM motor

RPS – Rotor position sensor, TG – Tachogenerator

The reference values of id and iq are transformed into reference values of currents namely ia ref, ib ref an d ic ref. These currents are compared with the actual currents and the error values actuate the triggering circuitry which is also influenced by the rotor position sensor and speed. Thus the vector control of BLPM SNW motor is achieved.

4.5 TORQUE-SPEED CHARACTERISTICS OF BLPM

The torque-speed characteristics of BLPM sine wave motor is shown in fig. 4.5.1

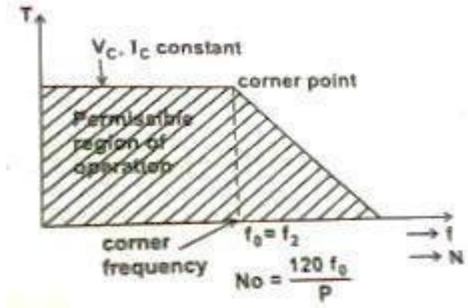


Figure 4.5.1 Torque-speed characteristics of BLPM sine wave (SNW) motor

For a given and (i.e) V_c I_c maximum permissible voltage and maximum permissible current, maximum torque remains constant from a low frequency to f_c (i.e) corner frequency.

Any further increase in frequency decreases the maximum torque. At $f_m = f_D$ (i.e.) the torque Developed is zero. Shaded pole represents the permissible region of operation in torque speed characteristics.

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 E_q 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 the short-circuit $\frac{E_q}{X_s}$ 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.

4.6 PHASOR DIAGRAM OF A BRUSHLESS PM SNW OR BLPB SYNCHRONOUS MOTOR:

Consider a BLPM SNW motor, the stator carries a balanced 3υ winding .this winding is connected to a dc supply through an electronic commutator whose switching action is influenced by the signal obtained from the rotor position sensor.

Under steady state operating condition, the voltage available at the input terminals of the armature winding is assumed to be sinusoidally varying three phase balanced voltage. The electronic commutator acts as an ideal inverter whose frequency is influenced by the rotor speed. Under this condition a revolving magnetic field is set up in the air gap which is sinusoidally distributed in space, having a number of poles is equal to the rotor. It rotates in air gap in the same direction as that of rotor and a speed eq1ual to the aped of the rotor

Rotor carries a permanent magnet. Its flux density is sine distributed. It also revolved in the air gap with as particular speed

It is assumed that the motor acts as a balanced 3υsystem. Ther4efore it is sufficient to draw the phasor diagram for only one phase. The armature winding circuit is influenced by the following emfs.

1. V - Supply voltage per phase across each winding of the armature.

   The magnitude of this voltage depends upon dc voltage and switching techniques adopted.

2. E_f - Emf induced in the armature winding per phase due to sinusoidally varying permanent magnetic field flux.

   Magnitude of $E_f=4.44 υ_m f K_{w1} T_{ph}= |E_f|$

   As per Faradays law of electromagnetic induct5ion, this emf lags behind $υ_{mf}$- permanent magnet flux enclosed by armature phase winding by 90°.

3. E_a - emf induced in the armature phase winding due to the flux $υ_a$ set up by resultant armature mmf $υ \infty I_a$

   $|E_a| = 4.44 f υ_a K_{w1} T_{ph}$

   $= 4.44 f (K I_a) K_{w1} T_{ph}$

   $|E_a| = |I_a X_a|$ where $X_a = 4.44 f K K_{w1} T_{ph}$

   This lags behind $υ_a$ by 90° or in other words E_a lags behind I_a by 90°.

   Therefore $E_a=-jX_aI_a$

4. E_{al} - emf induced in the same armature winding due to armature leakage flux.

$|E_{al}| = 4.44 \, f \, \emptyset_{al} \, K_{w1} T_{ph}$

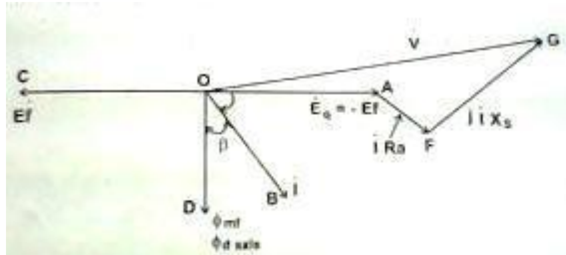


Figure 4.6.1 phasor diagram of BLPM sine wave motor

ϕ_{mf} be the mutual flux set up by the permanent magnet, but linked by the armature winding.

Ef lags behind $\phi_{mf} = \phi_d$

AF represents IaRa

FG represents Ia Xs; FG is perpendicular to I phasor

OG represents V

Angle between the I and is β the torque or power angle.

Power input = 3VI

= 3 (Eq +Ia Ra + j I Xs).I

= 3 Eq.Ia+3 I^2 Ra+O

3Eq I – electromagnetic power transferred as mechanical power.

3I^2Ra – copper losss.

Mechanical power developed = 3 Eq.I

= 3 Eq I cos(90-β)

= 3 Eq I sin β

= 3 Ef I sin β

The motor operates at Ns rpm or 120f/2p rpm

Therefore electromagnetic torque developed =60/2 Ns × 3Eq I sin β

The same phasor diagram can be redrawn as shown in fig with Φ_d or fm as the reference phasor.

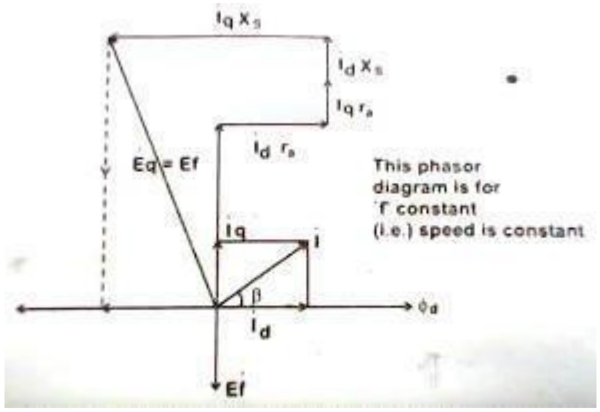


Figure 4.6.2 Phasor Diagram of BLPM sine wave motor with ϕ d or ϕ mf as reference axis

Further the current I phasor is resolved into two components Id and Iq Id

set up mmf along the direct axis (or axis of the permanent magnet)

Iq sets up mmf along quadrature axis (i,e) axis perpendicular to the axis of permanent magnet.

V = Eq +I Ra + j I Xs

I = Iq + Id

Therefore V =Eq+Id r_a +Iq r_a + j Id Xs +j Iq Xs

V can be represented as a complex quantity.

V = (V_r + j V_{IP})

From the above drawn phasor.

V=(Id r_a - Iq Xs)+j (Eq+ Iq r_a + Id Xs)

I can also be represented as a complex quantity

I = Id + j Iq

Power input = Re ($3VI^*$) I^* - conjugate

= Re(3((Id r_a - Iq Xs)+j (Eq+ Iq r_a + Id Xs)) ((Id-j IQ))) (i,e) power input = Re(3(I_d ra – Id Iq Xs) + (-j Id Iq ra + j Xs) + j (Eq Id + Iq Id ra+ Xs) + (Eq Iq +I_q ra + Id Iq Xs))

= 3(I_u^2 ra – Id Iq Xs) + 3 (Eq Iq + I_q^2 ra + Id Iq Xs)

= 3 Eq Iq + 3(I_u^2 + I_q^2) r_u

= 3 Eq Iq + 3$I^2 r_a$

Electromagnetic power transferred = 3 Eq Iq

= 3 EI sin β

Torque developed = 60/2πNs . 3 EI sin β

Note:

In case of salient pole rotors the electromagnetic torque developed from the electrical power.

From eqn. (5.43)

$$\frac{p}{\omega m} = 3[I_d^2 r_a \; I_d I_q X_s] + 3[E_q I_q \; + \quad + I_d I_q X_s]$$

$$=3[I_d^2 r_a \; I_d I_q (X_d + X_q)] + 3[E_q I_q + I_q^2 r_a + I_d I_q (X_d + X_q)]$$

Power input = $R_e \, 3[(I_d r_a - I_q X_s) + j(E_q + I_d X_s + I_q r_a)(I_d - jI_q)]$

$$= R_e \, 3[((I_d r_a - I_q (X_d + X_q))) + j(E_q + I_d (X_d + X_q) + I_q r_a)(I_d - jI_q)]$$

$$= R_e \, 3[I_d^2 r_a - I_q (X_d + X_q) I_d + E_q I_q + I_d I_q \quad + \quad + I_q^2 r_a]$$

$$=3 \; E_q I_q + 3I^2 R_a$$

Torque developed for a salient pole machine is given by

$$T = \frac{3p}{\omega_m} [E_q I_q + (X_d - X_q) I_d I_q] N - m$$

$\frac{3p}{\omega_m} E_q I_q$ = magnet alignment torque.

$\frac{3p}{\omega_m} (X_d - X_q) I_d I_q$ = reluctance torque.

In case of surface – magnet motors, the reluctance torque becomes zero.

Therefore, torque developed = $\frac{3E_q I_q}{\omega_m}$ N-m

Or = $\frac{3P}{\omega} E_q I_q$ N-m

At a given speed, E_q is fixed as it is proportional to speed. Then torque is proportional to q-axis current I_q

The linear relationship between torque and current simplifies the controller design and makes the dynamic performance more regular and predictable. The same property is shared by the square wave motor and the dc permanent commutator motor.

In the phasor diagram shown in fig. 5.10.

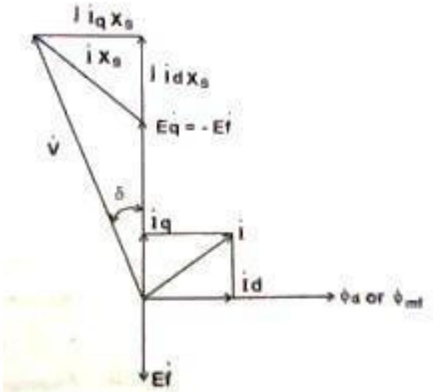


Figure 4.6.2 Phasor Diagram neglecting the effect of resistance Neglecting the effect of resistance, the basic voltage equation

As the effect of resistance is neglected

$$\frac{\dot{V}}{jX_s} = \frac{\dot{E}_q}{jX_s} + \dot{I}$$

$$\dot{I} = \frac{\dot{V} \quad \dot{E}_q}{jX_s}$$

4.7 EMF EQUATION OF PRACTICAL BLPM SINE WAVE MOTOR

In a practical BLPM sine wave motor at the time of design it is taken care to have the flux density is sinusoidal distributed and rotor rotates with uniform angular velocity. However armature winding consists of short chorded coils properly distributed over a set of slot. These aspects reduce the magnitude of E_{ph} of an ideal winding by a factor K_{w1} which is known as the winding factor the fundamental component of flux.

$e = -N\, d\phi/dt$

$-d\phi/dt$ as $N=1$

$= -\, d\phi/dt \; ((2 B\square\, lr/p) \cos p\theta\, \omega_{mt})$

$= (2 B\square\, lr/p)\, p\, \omega_m \sin p\, \omega_{mt}$

$e = 2 B\square\, lr\, \omega_m \sin p\, \omega_{mt}$ ……..(5.2)

$K_{w1} = K_{s1} K_{p1} K_{b1}$ ……..(5.8)

K_{s1} =slew factor

$K_{s1} = (\sin \sigma/2)/ (\sigma/2)$

$K_{s1} = 1$ (slightly less than 1)

σ – Skew angle in elec. Radians.

K_{p1} = pitch factor (or) short chording factor

$= \sin m\pi/2$ or $\cos \rho/2$

Where m = coil span/pole pitch

$= \text{fraction} < 1$

$\pi(1 - m) = \rho$

[Coil span = τ

$= \pi$ elec rad

$= \pi/\rho$ mech. Rad]

$K_{p1}=\sin\frac{m\pi}{2}$ or $\cos\frac{\rho}{2}$

[$m\pi$ *is elec rad* $\frac{m\pi}{p}$ mech. Rad.]

K_{b1} = Distribution factor or width factor

$K_{b1} = \frac{\sin q\frac{v}{2}}{q\sin\frac{v}{2}}$

Where v = slot angle in elec. Radians

$= \frac{2\pi\rho}{n_s}$; n_s = no. of slots (total)

q = slots/pole/phase for 60° phase spread

= slots/pair of poles/phase

$K_{b1} < 1$; $K_{p1} < 1$; $K_{s1} < 1$

Therefore $K_{w1} = K_{p1} K_{b1} K_{s1} < 1$ (winding factor)

Thus rms value of the per phase emf is

$$\mathbf{E_{ph} = 4.44\, f\, \emptyset_m\, T_{ph}\, K_{w1}\ volts.}$$

4.8 TORQUE EQUATION OF PERMANENT MAGNET SYNCHRONOUS MOTOR

5.7.1 Torque equation of ideal PMSM

When a balanced three phase voltage is applied to the armature, a three phase current flows through the conductors. This current produces armature flux for deriving the torque equation, the concept of armature ampere conductor density is used. A sinusoidally distributed ampere conductor density is assumed as shown in figure 5.9

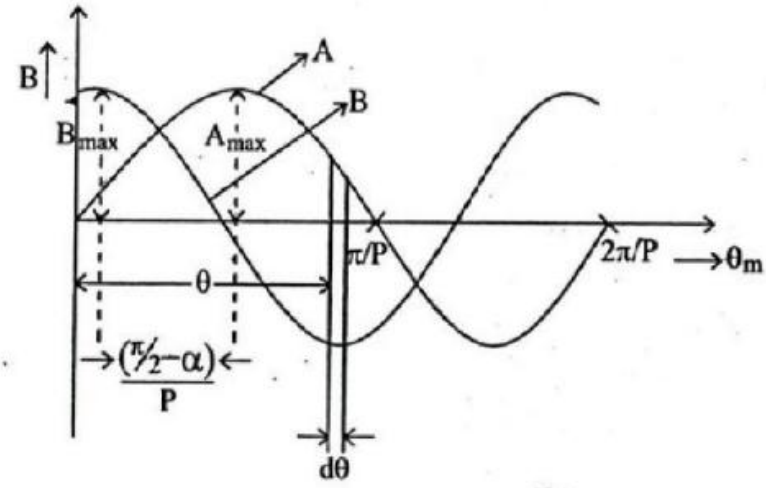


Figure 5.9 Ampere conductor and flux density distribution

Let the operation point of PMSM is such that the ampere conductor density and the flux density are as shown in figure5.9 In figure 5.9 the angle between the axes of ampere conductor and flux density is $\left(\frac{\pi}{2} - \alpha\right)$. A strip of width $d\theta$ is considered at θ

From figure 5.9,

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

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

$$\therefore \quad B = B_{max} \cos(P\theta - \alpha) \qquad \text{... (5.21)}$$

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

Force experinced by the armature conductors in $d\theta$ is

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

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

Torque experienced by the armature conductors in $d\theta$ is

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

Torque experienced by armature conductors/pole $= \int_{\theta=0}^{\theta=\pi/P} dT$

$$= A_{max} B_{max} rl \int_0^{\pi/P} \sin P\theta \cos(P\theta - \alpha) d\theta$$

$$= \frac{A_{max} B_{max}}{2} rl \int_0^{\pi/P} [\sin(P\theta + P\theta - \alpha) + \sin\alpha] d\theta$$

$$= \frac{A_{max} B_{max}}{2} rl \left[\frac{-\cos(2P\theta - \alpha)}{2P} + \theta \sin\alpha\right]_0^{\pi/P}$$

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

$$= \frac{A_{max} B_{max} rl}{2}\left[\frac{-\cos\alpha}{2P} + \frac{\cos\alpha}{2P} + \frac{\pi}{P}\sin\alpha\right]$$

$$= \frac{A_{max} B_{max} rl}{2}\ \frac{\pi}{P}\sin\alpha \qquad \text{... (5.22)}$$

Total electromagnetic torque developed by all the armature conductors = 2P × Torque per pole

$$= 2P\ \frac{\pi}{P}\ \frac{A_{max} B_{max} rl \sin\alpha}{2}$$

$$= \pi A_{max} B_{max} rl \sin\alpha \qquad \text{... (5.23)}$$

As armature is stationary, this torque is experienced by the rotor and rotor rotates

$$T = -\pi A_{max} B_{max} rl \sin\alpha \qquad \text{... (5.24)}$$

Since $\beta = -\alpha$

$$\Rightarrow T = \pi A_{max} B_{max} rl \sin\beta \qquad \text{... (5.25)}$$

Where β is the torque angle or power angle

5.7.2 Ampere conductor density distribution

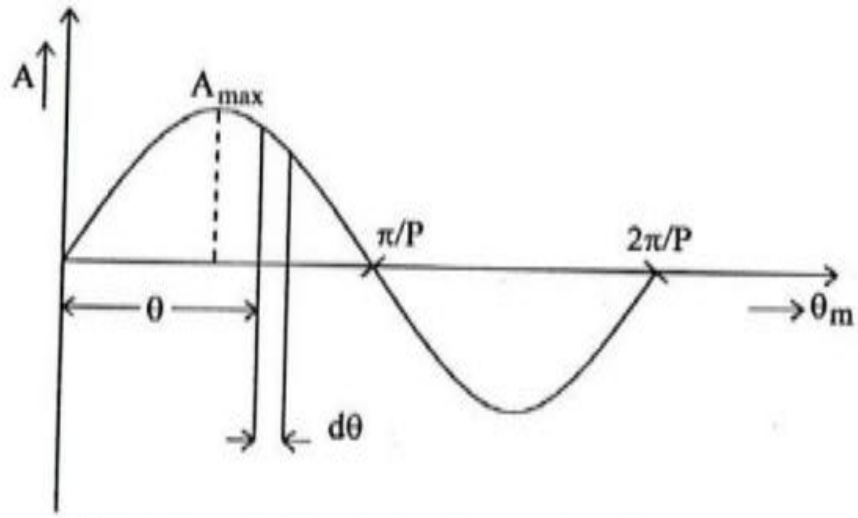


Figure: 5.10 Ampere conductor density

The above figure shown the ampere conductor density distribution in the air gap due to current carrying armature winding

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

Where A $\rightarrow$ ampere conductor density

consider a strip of width $d\theta$ at angle θ from the reference axis.

Ampere conductors in the strip $d\theta$ is $A\,d\theta$.

$$A d\theta = A_{max} \sin P\theta \, d\theta \quad \text{... (5.26)}$$

$$\text{Ampere conductors per pole} = \int_{0}^{\pi/P} A d\theta$$

$$= \int_{0}^{\pi/P} A_{max} \sin P\theta \, d\theta$$

$$= A_{max} \left[\frac{\cos P\theta}{P} \right]_{0}^{\pi/P}$$

$$= \frac{A_{max}}{P} (-1 - 1)$$

$$= \frac{2A_{max}}{P} \quad \text{... (5.27)}$$

Let T_{ph} be the number of full pitched turns per phase

i be the current

Total ampere conductiors $= 2iT_{ph}$

$$\text{Sinusoidally distributed ampere conductors /pole} = \frac{2iT_{ph}}{2P}$$

$$= \frac{iT_{ph}}{P} \quad \text{... (5.28)}$$

equating eqations (5.27) & (5.28)

$$= \frac{2A_{max}}{P} = \frac{iT_{ph}}{P}$$

$$A_{max} = \frac{iT_{ph}}{2} \quad \text{...(5.29)}$$

For a PMSM supplied by balanced three phase sinusoidal voltage, the phase currents are given by

$$i_R = I_{max} \cos \omega t$$

$$i_y = I_{max} \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$i_B = I_{max} \cos\left(\omega t - \frac{4\pi}{3}\right)$$

The turns are given by

$$T_{phR} = T_{ph} \cos \theta$$

$$T_{phy} = T_{ph} \cos\left(\theta - \frac{2\pi}{3}\right)$$

$$T_{phB} = T_{ph} \cos\left(\theta - \frac{4\pi}{3}\right)$$

Ampere turns at any instant is given by

$$iT_{ph} = i_R T_{phR} + i_y T_{phy} + i_B T_{phB}$$

$$= I_{max} T_{ph} \cos \omega t \cos \theta + I_{max} T_{ph} \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$\cos\left(\theta - \frac{2\pi}{3}\right) + I_{max} T_{ph} \cos\left(\omega t - \frac{4\pi}{3}\right) \cos\left(\theta - \frac{4\pi}{3}\right)$$

By simplifying the above equation

$$iT_{ph} = \frac{3}{2} I_{max} T_{ph} \cos(\omega t - \theta)$$

$$= \frac{3}{2} \sqrt{2}\, I_{ph} T_{ph} \cos(\omega t - \theta)$$

$$A_{max} = \frac{iT_{ph}}{2}$$

$$A_{max} = \frac{3\sqrt{2}}{2} I_{ph} T_{ph} \qquad \text{... (5.30)}$$

In practical motor, the armature turns are short pitched and distributed further they may and be accommodated in skewed slots in such case for getting slots fundamental component of ampere turn distribution, the turns per phase is modified as $K_{\omega 1} T_{ph}$

Where $K_{\omega 1} = K_{s1} K_{c1} K_{d1}$

$K_{s1} \rightarrow$ skew factor

$$K_{s1} = \frac{\sin \sigma/2}{\sigma/2} \qquad \text{where } \sigma \rightarrow \text{skew angle}$$

$$K_{c1} = \frac{\cos \delta}{2}; \; K_{c1} \rightarrow \text{chording factor}$$

$K_{d1} \rightarrow$ distribution factor

$$K_{d1} = \frac{\sin q V/2}{q \sin V/2}$$

Fundamental component of ampere turns per phase of a practical motor

$$= \frac{4}{\pi} i T_{ph} K_{\omega 1} \qquad ...(5.31)$$

When a balanced sinusoidally varying three phase ac current pass through a balanced three phase winding, it can be shown that total sinussoidally distributed ampere turns is equal to

$$= \frac{3}{2} \frac{4}{\pi} I_{max} K_{\omega 1} T_{ph}$$

$$= \frac{3 \cdot 2\sqrt{2}}{\pi} I_{ph} K_{\omega 1} T_{ph} \qquad ...(5.32)$$

The amplitude of ampere conductor density distribution is equal to the total sinusoidally distributed ampere turns divided by 2

$\therefore A_{max}$ in practical 3ϕ motor

$$= \frac{3\cdot 2\sqrt{2}}{\pi}\frac{I_{ph}K_{\omega 1}}{2}T_{ph}$$

$$= \frac{3\sqrt{2}}{\pi}I_{ph}K_{\omega 1}T_{ph} \qquad \text{... (5.33)}$$

elictromagnetic torque developed in practical PMSM is

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

$$= \pi\left[\frac{3\sqrt{2}}{\pi}I_{ph}K_{\omega 1}T_{ph}\right]B_{max}rl\sin\beta$$

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

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

$$T = 3\frac{E_{ph}}{\omega_m}I_{ph}\sin\beta \qquad \text{... (5.34)}$$

5.1 CONSTRUCTIONAL FEATURES OF SYNCHRONOUS RELUCTANCE MOTOR

CONSTRUCTION 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 .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

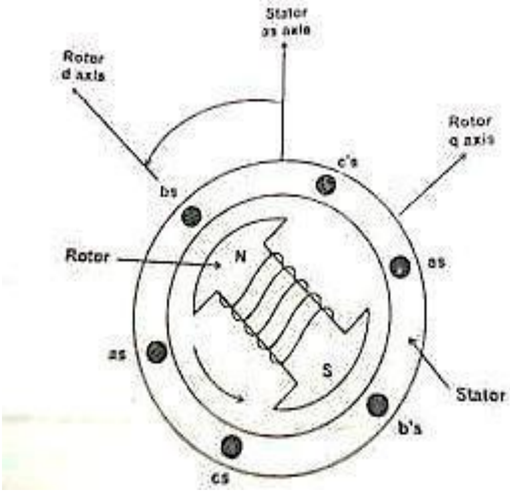


Figure 5.1.1 Idealized Three Phase Four Pole Synchronous Machine (Salient Pole)

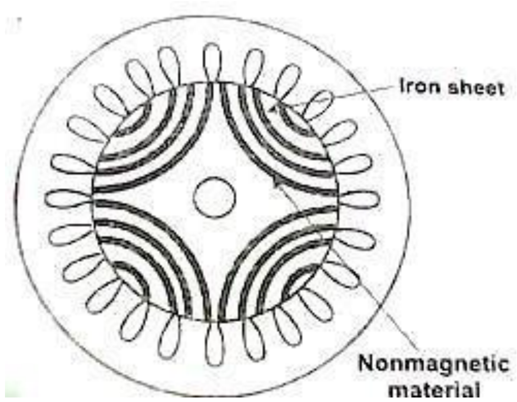


Figure 5.1.2 cross section of synchronous reluctance motor

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. Synchronous reluctance motor is designed for high power applications. It can broadly be classified into Axially laminated and Radially laminated.

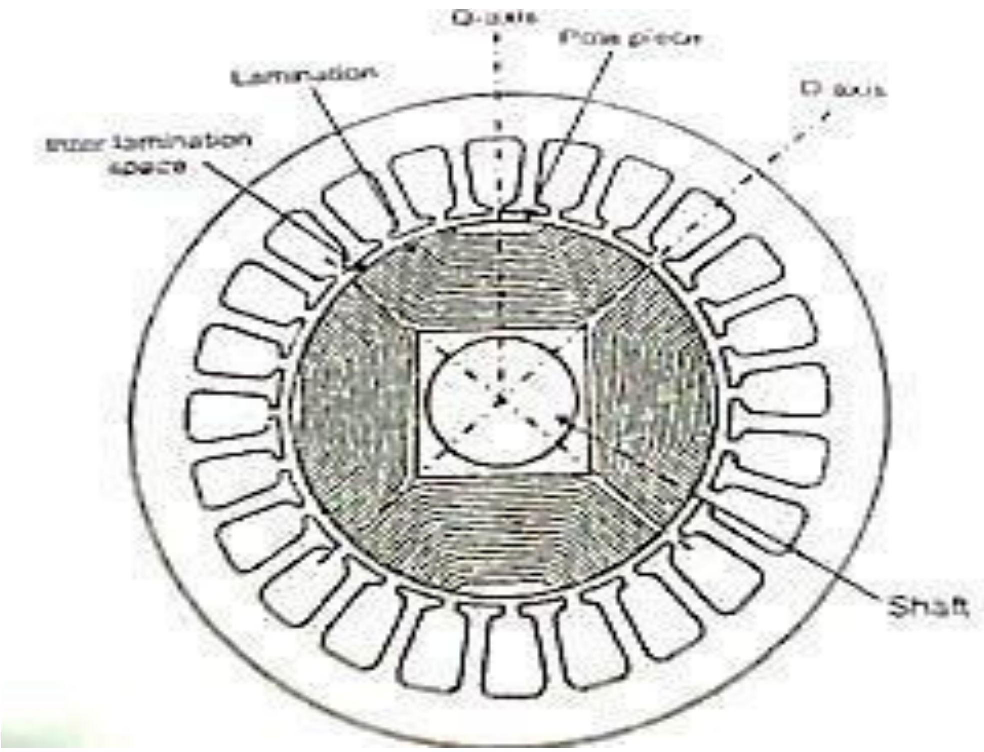


Figure 5.1.3 cross section of axially laminated

Reluctance motors can deliver very high power density at low cost, making them ideal for many applications. Disadvantages are high torque ripple (the difference between maximum and minimum torque during one revolution) when operated at low speed, and noise caused by torque ripple. Until the early twenty-first century their use was limited by the complexity of designing and controlling them.

These challenges are being overcome by advances in the theory, by the use of sophisticated computer design tools, and by the use of low-cost embedded systems for control, typically based on microcontrollers using control algorithms and real-time computing to tailor drive waveforms according to rotor position and current or voltage feedback. Before the development of large-scale integrated circuits the control electronics would have been prohibitively costly.

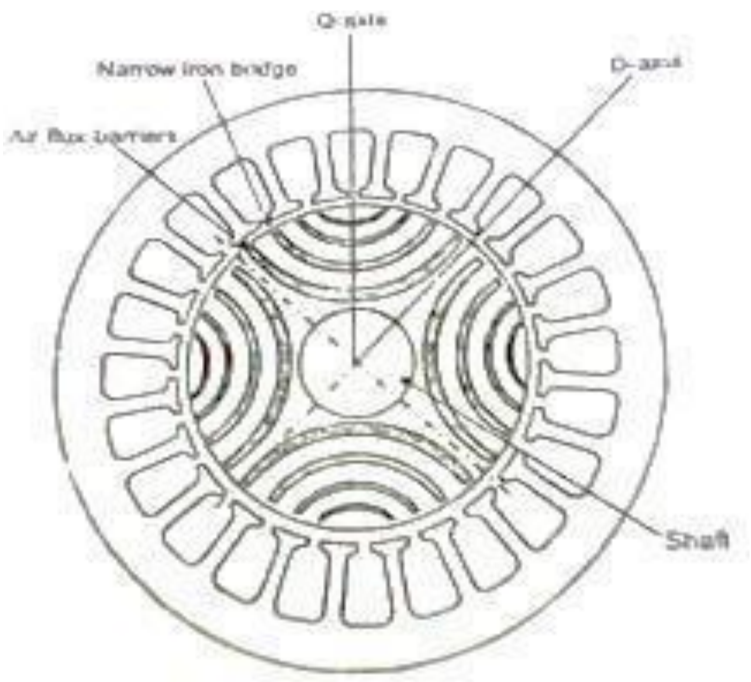


Figure 5.1.3 cross section of radially laminated

The stator consists of multiple projecting (salient) electromagnet poles, similar to a wound field brushed DC motor. The rotor consists of soft magnetic material, such as laminated silicon steel, which has multiple projections acting as salient magnetic poles through magnetic reluctance. The number of rotor poles is typically less than the number of stator poles, which minimizes torque ripple and prevents the poles from all aligning simultaneously—a position which cannot generate torque.

When a rotor pole is equidistant from the two adjacent stator poles, the rotor pole is said to be in the "fully unaligned position". This is the position of maximum magnetic reluctance for the rotor pole. In the "aligned position", two (or more) rotor poles are fully aligned with two (or more) stator poles, (which mean the rotor poles completely face the stator poles) and is a position of minimum reluctance.

When a stator pole is energized, the rotor torque is in the direction that will reduce reluctance. Thus the nearest rotor pole is pulled from the unaligned position into alignment with the stator field (a position of less reluctance). (This is the same effect used by a solenoid, or when picking up ferromagnetic metal with a magnet.) In order to sustain rotation, the stator field must rotate in advance of the rotor poles, thus constantly "pulling" the rotor along. Some motor variants will run on 3-phase AC power (see the synchronous reluctance variant below).

Most modern designs are of the switched reluctance type, because electronic commutation gives significant control advantages for motor starting, speed control, and smooth operation (low torque ripple).

Dual-rotor layouts provide more torque at lower price per volume or per mass. The inductance of each phase winding in the motor will vary with position, because the reluctance also varies with position. This presents a control systems challenge.

Applications

1. Some washing machine designs.
2. Control rod drive mechanisms of nuclear reactors.
3. The Dyson Digital Motor used in some products produced by the Dyson company.

ROTOR DESIGN

Salient rotor (Segmental)

Salient rotor shape such that the quadrature air gap is much larger than the direct air gap. This yields reactively small L_d/L_qrations in the range of.5.1.4

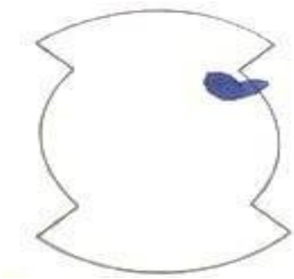


Figure 5.1.4 cross section of salient rotor

Salient rotor design is as shown. The low L_d. /$L_q$ratios are largely the result of circulating flux in the pole faces of the rotor. However the ruggedness and simplicity of the rotor structure has encouraged for high speed applications.

Radially Laminated Rotor (Flux Barrier)

Another approach is to use laminations with flux barriers punched into the steel for a 4 pole machine. The flux barriers and the central hole of the lamination required for the shaft weaken the rotor structurally and thus make this approach a poor choice for high speed design.

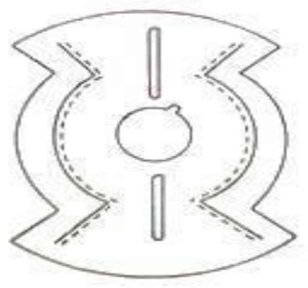


Figure 5.1.5 cross section of Radially laminated Rotor

Axially Laminated Rotor

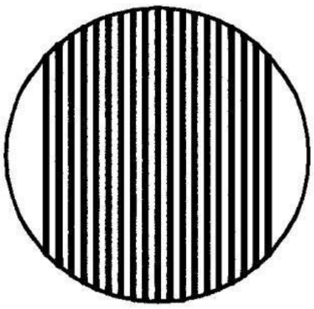


Figure 5.1.6 cross section of axially laminated Rotor

Fig.5.1.6 Axially Laminated Rotor Two pole phase axially laminated rotor with a L_d. /$L_q$ratio of 20, the maximum efficiency is 94% has been reported in the literature. It is observed that torque ripple and iron losses are more axially laminated rotor than radially laminated rotor. Another rotor design as shown in fig. The rotor consists of alternating layers of ferromagnetic and non-magnetic steel. If choose the thickness of the steel such that the pitch of the ferromagnetic rotor segments matched the slot pitch of the stator. The ferromagnetic rotor segments always see a stator tooth pitch regardless of the angle of rotation of the rotor. This is done to maximize flux variations and hence iron losses in the rotor.

Special rotor laminations make it possible to produce the same number of reluctance path as there are magnetic poles in the stator. Synchronous speed is achieved as the poles lock in step with magnetic poles of the rotating stator field and cause the stator to run at the same speed as the rotating fields. The rotor is pressures with end rings similar to induction motor .Stator winding are similar to squirrel cage induction motor.

ROTOR CONSTRUCTION

Explosion bonding technique as shown in fig. Other joining techniques such as brazing roll bonding, or diffusion bonding may also appropriate for rotor construction.

First sheets of ferromagnetic and non-ferromagnetic steel are bonded. The bonded sheets are then cut into rectangular blocks h\which are machined into the desired rotor. The rotor shaft can also be machined out of the same block as the rotor.

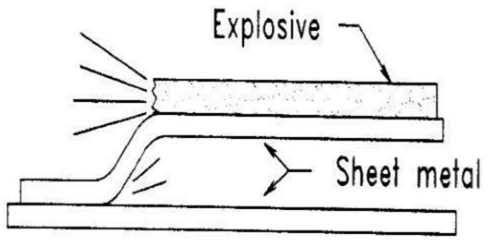


Figure 5.1.7 Explosion bonding

The rotor joining technique known as explosion bonding. Explosion bonding uses explosive energy to force two or more metal sheets together at high pressures. Conventionally the high pressure causes several atomic layers on the surface of each sheet to behave as a fluid. The angle of collision between the two metals forces this fluid to jet outward. Effectively cleaning the metal surface, these ultra clean surfaces along with the high pressure forcing the metal plates together provide the necessary condition for solid phase welding.

Experimental tests on a stainless steel/mild steel bond indicate that the tensile and fatigue strengths of the bond are greater than those of either of the component materials due to the shock hardening which occurs during the process. The bond was also subjected to 10 cycles of temperature variation from 20° C - 70°C, with no significant reduction in tensile strength.

WORKING OF SYNCHRONOUS RELUCTANCE MOTOR

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. 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.

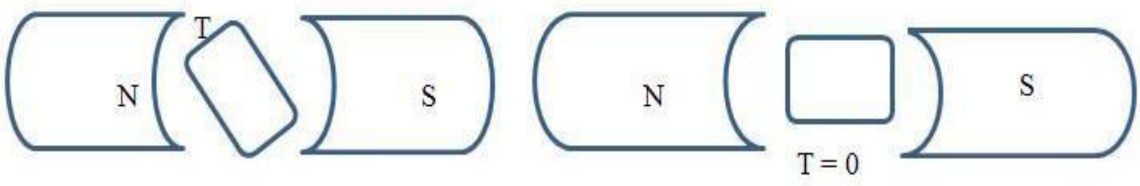
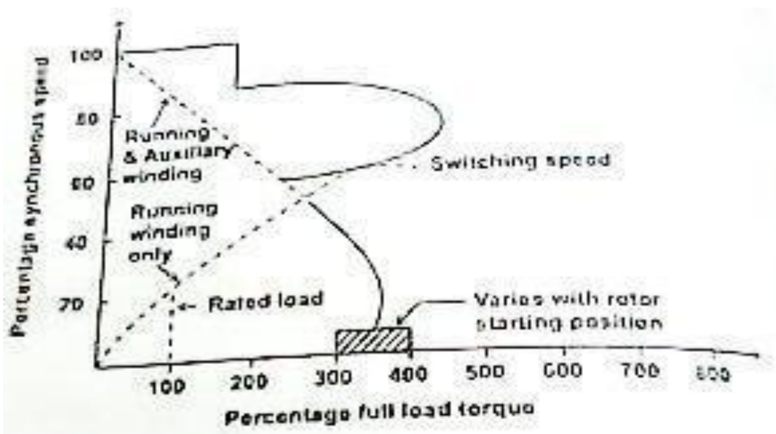


Figure 5.1.7 Rotor position due to revolving magnetic field

5.2 TORQUE – SPEED CHARACTERISTICS

The torque speed characteristic of synchronous reluctance motor is shown in fig. The motor starts at anywhere from 300 to 400 percent of its full load torque (depending on the rotor position of the unsymmetrical rotor with respect to the field winding) as a two phase motor. As a result of the magnetic rotating field created by a starting and running winding displaced 90° in both space and time.

At about ¾th of the synchronous speed a centrifugal switch opens the starting winding and the motor continues to develop a single phase torque produced by its running winding only. As it approaches synchronous speed, the reluctance torque is sufficient to pull the rotor into synchronism with the pulsating single phase field. The motor operates at constant speed up to a little over 20% of its full load torque. If it is loaded beyond the value of pull out torque, it will continue to operate as a single phase induction motor up to 500% of its rated speed.



APPLICATION

1. Comparable power density but better efficiency than induction motor.
2. Slightly lower power factor than induction motor.
3. Slightly small field weakening range than induction motor.
4. High cost than induction motor but lower than any type of PM motors.
5. Need speed synchronization to inverter out frequency by rotor position sensor sensor less control.
6. Sensor less control is much easier due to motor saliency.
7. By adding squirrel cage induction motor to synchronous reluctance motor one obtains line starting reluctance moors.
8. Line started reluctance motors can be parallel with open loop control if the load does not change suddenly.
9. Other combinations are possible such as adding PM for improved performance
10. Rotor design for best manufacturability is still being optimized especially for high speed applications.

5.3 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

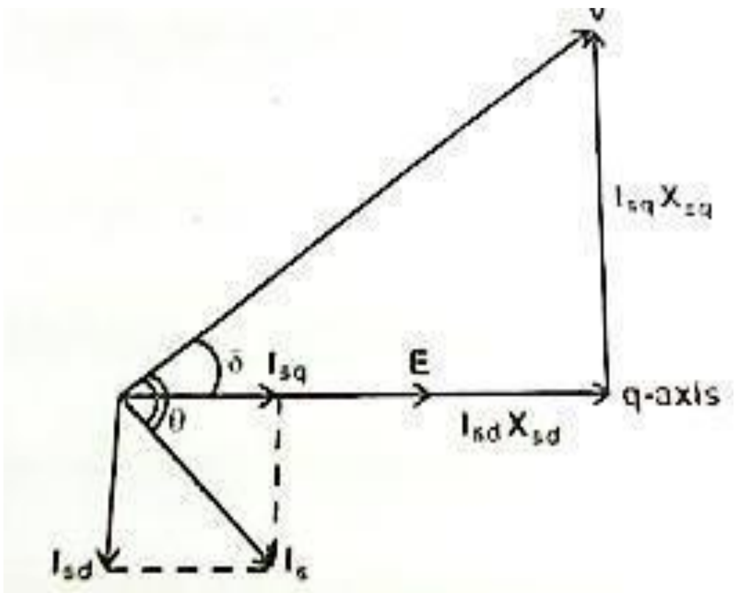


Figure 5.3.1 Phasor diagram of synchronous reluctance motor

– j IsdXsd – j Isq ……..(1.1)

Where

V is the Supply Voltage Is is the stator current

E is the excitation emf

8 is the load angle

ɸ is 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 … .... (1.2)

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

V = E – j IsdXsd – j IsqXsq From phasor diagram
V cosẟ = E + Isd + Xsd .... (1.3)

Isd = $\frac{Vcos-E}{Xsd}$

IsqXsq = V sinẟ

Isq =$\frac{V\ sin}{Xsq}$ ....(1.4)

Is cos = Isq cosẟ - Isd sin .... (1.5)

Where

Xsd and Xsq are synchronous reactance of d and q axis.

Sub (3) and (4) in Equ (5)

Is cos ϕ = $\frac{E}{Xsd}$ sin + 2 $\frac{Xsd-Xsq}{2\ Xsd\ Xsq}$ .... (1.6)

P = 3 Vis cos ϕ . . . . (1.7)

Sub equ (6) in equ (7)

Pm = 3 [$\frac{VE}{Xsd}$ sin +V ^{2} $\frac{(Xsd}{2\ Xsd\ Xsq}$ $-Xsq$) sin2 ẟ]

Pm = T ω_S

T = Pm/ω_S

= $\frac{3}{ws}$ [$\frac{VE}{Xsd}$ sinẟ + $\frac{v2(Xsd-Xsq)}{2\ Xsd\ Xsq}$ sin 2ẟ] ....(1.8)

Sub E = 0

T = $\frac{3}{\omega s}$V^2 [$\frac{Xsd-xsq}{2Xsd\ Xsq}$] sin 2ẟ ....(1.9)

Equation (9) is the torque equation of synchronous reluctance motor.

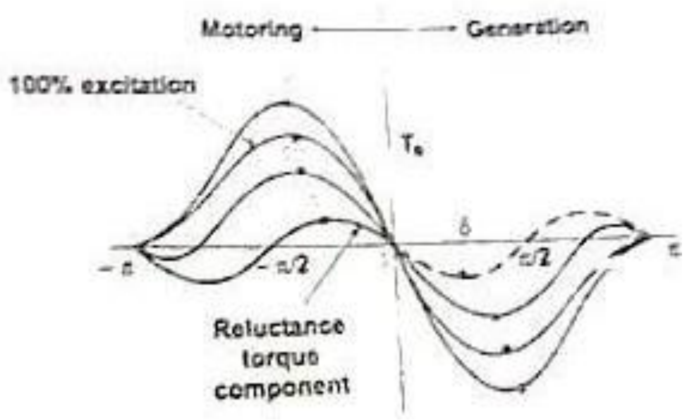


Figure 5.3.2 Torque Angle characteristics of salient pole

Plotting the equation (9) as shown in fig indicates that the stability limit is reached at δ =± π /4

And by increasing g load angle torque also increases.

$$V^2 \left[\frac{Xsd}{2\,XsdXsq} - Xsq\right] \sin 2\,\delta = \text{reluctance Power}$$

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

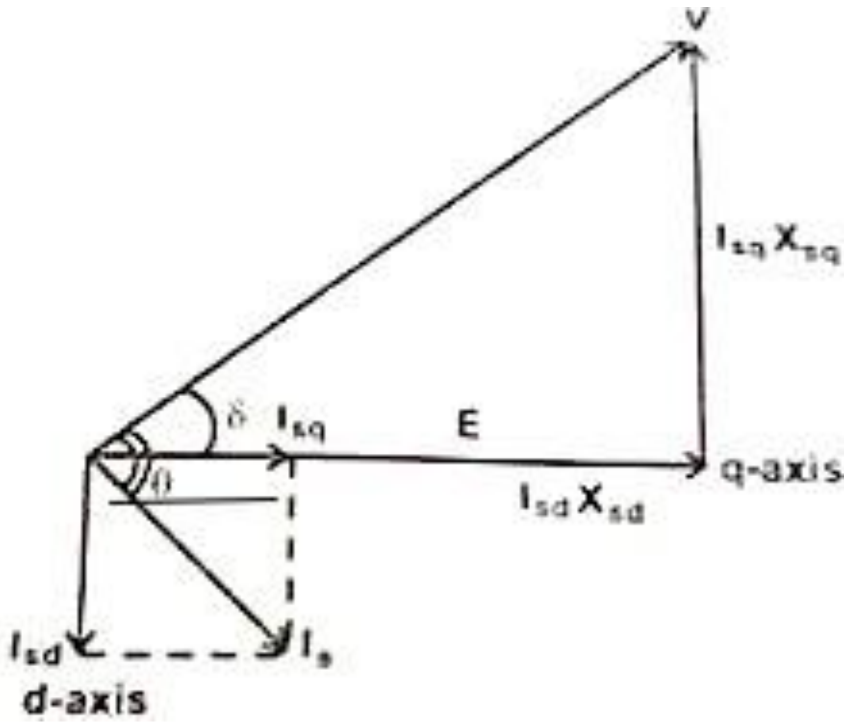


Fig 1.14 Phasor Diagram of Synchronous Reluctance Motor with E=0

ADVANTAGES AND DISADVANTAGES OF SYNCHRONOUS RELUCTANCE MOTOR

Advantages

1. There is no concern with demagnetization; hence synchronous reluctance machines are inherently more reliable than PM machines.
2. There need not be any exciting field as torque is zero, thus eliminating electromagnetic spinning losses.
3. Synchronous reluctance machine rotors can be constructed entirely from high strength, low cost materials.

Disadvantages

1. High cost than induction Motor.
2. Need Speed synchronization to inverter output frequency by using rotor position sensor and sensor less control.
3. Compared to induction motor it is slightly heavier and has low power factor.
4. By increasing the saliency ratio L_{ds}/L_{qs}, the power factor can be improved.

5.4 CONSTRUCTION FEATURES OF STATOR OF HYSTERESIS MOTOR

A Hysteresis Motor is a synchronous motor with a uniform air gap and without DC excitation. It operates both in single and three phase supply. The Torque in a Hysteresis Motor is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.

The working of the motor depends on the working of the continuously revolving magnetic flux. For the split phase operation, the stator winding of the motor has two single phase supply. This stator winding remains continuously connected to the single phase supply both at the starting as well as the running of the motor.

The rotor of the motor is made up of smooth chrome steel cylinder and it has no winding. It has high retentivity and because of this, it is very difficult to change the magnetic polarities once they are caused by the revolving flux of the rotor. The rotor of the hysteresis motor moves synchronously because the pole of the motor magnetically locks with the stator which has opposite polarities.

Construction of Stator of Hysteresis Motor

The stator of the hysteresis motor produces a rotating magnetic field and is almost similar to the stator of the induction motor. Thus, the stator of the motor is connected either to single supply or to the three phase supply. The three phase motor produces more uniform rotating field as compared to that of the single phase supply.

The stator winding of the single-phase hysteresis motor is made of permanent split capacitor type or shaded pole type. The capacitor is used with an auxiliary winding in ordertoproduceauniformfield.

Construction of Rotor of Hysteresis Motor

The rotor of the hysteresis motor consists of the core of aluminium or some other non-magnetic material which carries a layer of special magnetic material. The figure below shows the rotor of the hysteresis motor.

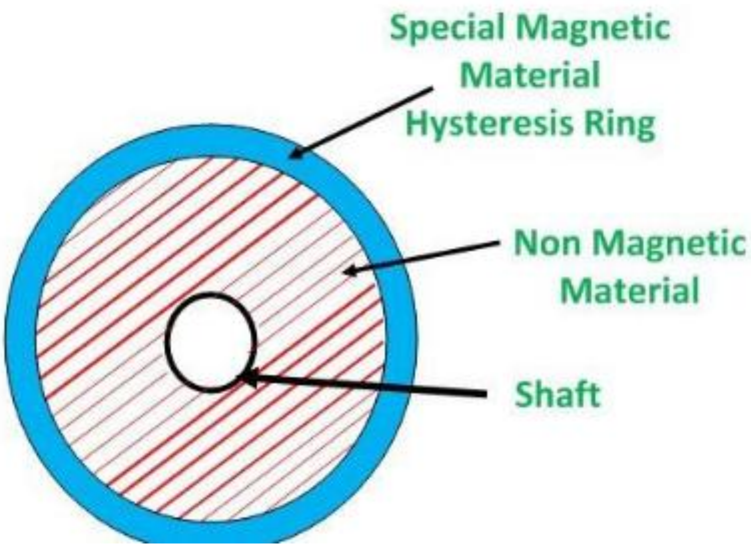


Figure 5.4.1 cross section of Hysteresis motor

The outer layer has a number of thin rings forming a laminated rotor. The rotor of the motor is a smooth cylinder, and it does not carry any windings. The ring is made of hard chrome or cobalt steel having a large hysteresis loop as shown in the figure below.

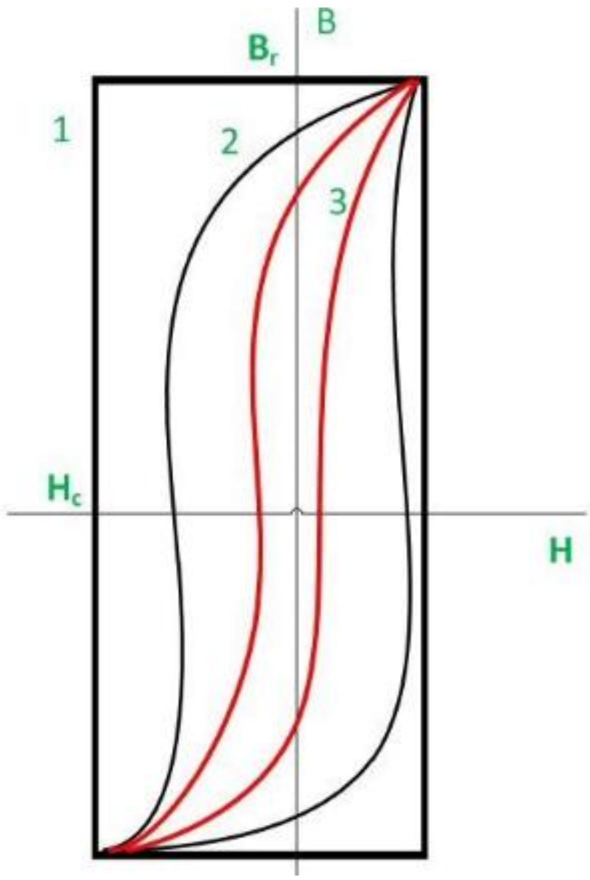


Figure 5.4.2 B-H loop of Hysteresis motor

OPERATION OF A HYSTERESIS MOTOR

The following illustration shows the basic functioning of a hysteresis motor.

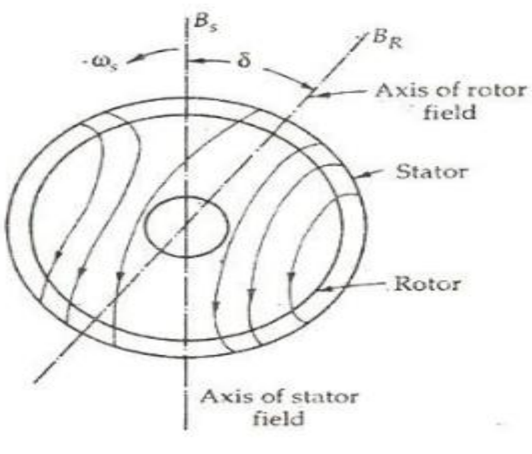


Figure 5.4.2 B-H loop of Hysteresis motor

When supply is given applied to the stator, a rotating magnetic field is produced. This magnetic field magnetises the rotor ring and induces pole within it. Due to the hysteresis loss in the rotor, the induced rotor flux lags behind the rotating stator flux. The angle δ between the stator magnetic field B_S and the rotor magnetic field B_R is responsible for the production of the torque. The angle δ depends on the shape of the hysteresis loop and not on the frequency.

Thus, the value of Coercive force and residual flux density of the magnetic material should be large. The ideal material would have a rectangular hysteresis loop as shown by loop 1 in the hysteresis loop figure. The stator magnetic field produces Eddy currents in the rotor. As a result, they produce their own magnetic field.

The eddy current loss is given by the equation shown below.

Where,

- k_e is a constant
- f_2 is the eddy current frequency
- B is the flux density

As we know,

$$f_2 = sf_1$$

Where s is the slip and f1 is the frequency of the stator.

Therefore,

$$\tau_e = \frac{p_e}{s\,\omega_s} \quad \text{or}$$

$$\tau_e = k's \quad \dots\dots\dots (1)$$

Where,

$$k' = \frac{k_e f_1^2 B^2}{\omega_s} = \text{constant}$$

$$p_h = k_h f_2 B^{1.6} \quad \text{or}$$

$$p_h = k_h s f_1 B^{1.6} \quad \dots\dots\dots (2)$$

torque is given by

$$\tau_h = \frac{p_h}{s\,\omega_s} \quad \text{or}$$

$$\tau_h = \frac{k_h f_1 B^{1.6}}{\omega_s} = k'' = \text{constant} \quad \dots\dots\dots.(3)$$

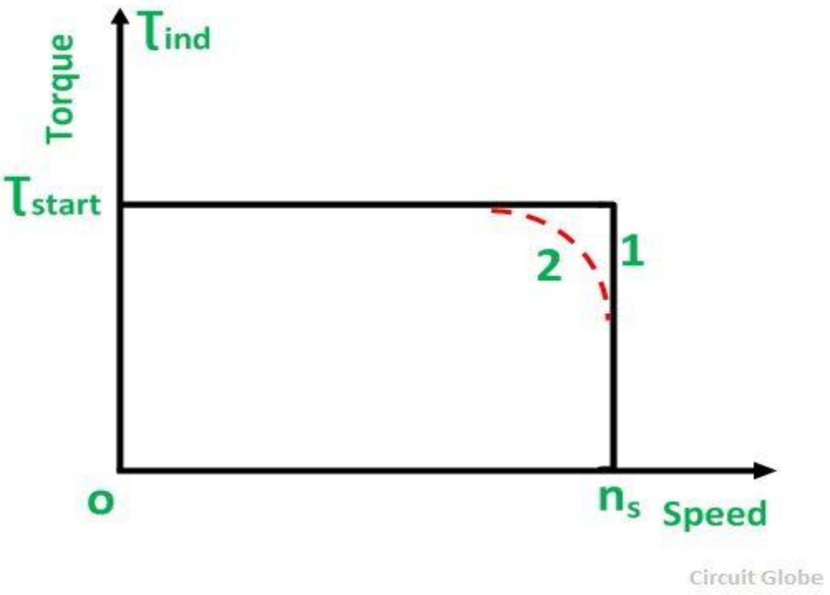
Now, the torque due to hysteresis loss is given by the equation shown

From the equation (1) it is clear that the torque is proportional to the slip. Therefore, as the speed of the rotor increases the value of τ_e decreases. As the speed of the motor reaches synchronous speed, the slip becomes zero and torque also become zero.

As the electromagnet torque is developed by the motor is because of the hysteresis loss and remains constant at all rotor speed until the breakdown torque. At the synchronous speed, the eddy current torque is zero and only torque due to hysteresis loss is present.

Torque Speed characteristic of Hysteresis Motor

The speed torque curve of the motor is shown below.



Curve 1 is the ideal curve, and the curve 2 is the practical hysteresis motor curve. The torque-speed characteristic of the hysteresis motor is different from an induction motor. Since, at the synchronous speed, the torque developed by an induction motor becomes zero, whereas in the hysteresis motor the torque is constant at all the speed even at the synchronous speed. Thus, from the curve, it is seen that the locked rotor, starting and pull out torque is equal.

The noise level of the hysteresis motor is very low as compared to the induction motor because it operates at a constant speed and its rotor is smooth. This type of motor is smoothest running, quietest single phase motor and is used for quality sound reproduction equipment like record players, tape recorders, etc. It is also employed in electric clocks and other timing devices.