1.6 CHARACTERISTICS OF STEPPER MOTOR

Stepper motor characteristics are Static characteristics

Dynamic characteristics

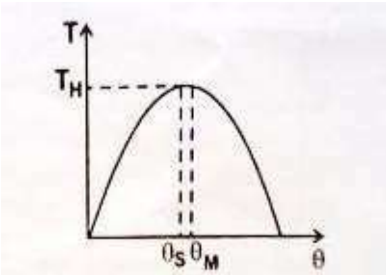
STATIC CHARACTERISTICS

(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

[Source: "special electric machines" by R.Srinivasan page:2.52]

Holding Torque (TH)

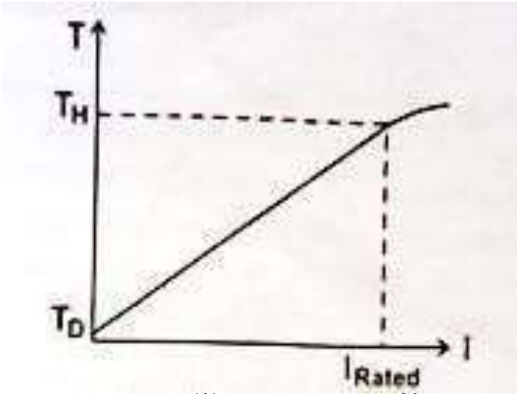
It is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the static equilibrium position.

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

[Source: "special electric machines" by R.Srinivasan page:2.54]

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.

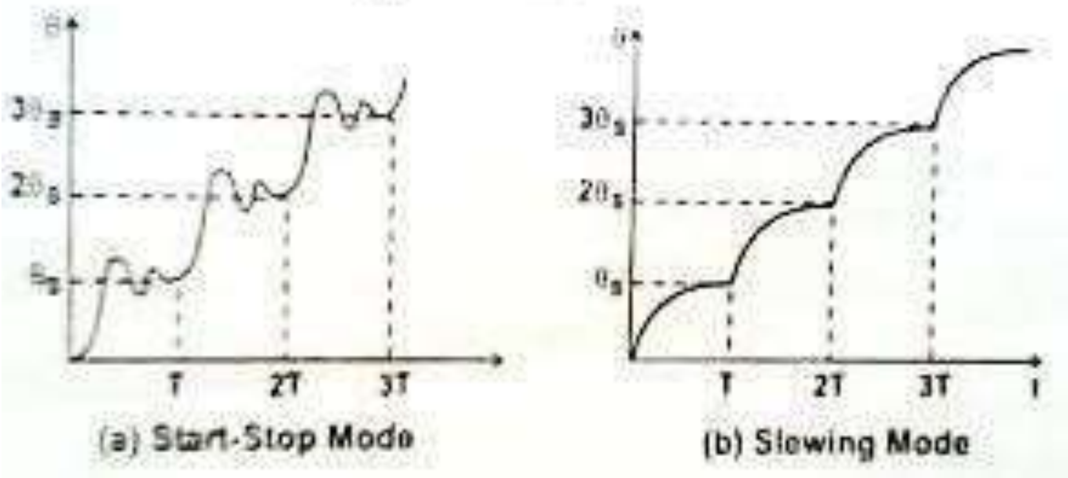


Figure 1.6.3 Dynamic Characteristics

[Source: "special electric machines" by R.Srinivasan page:2.56]

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.

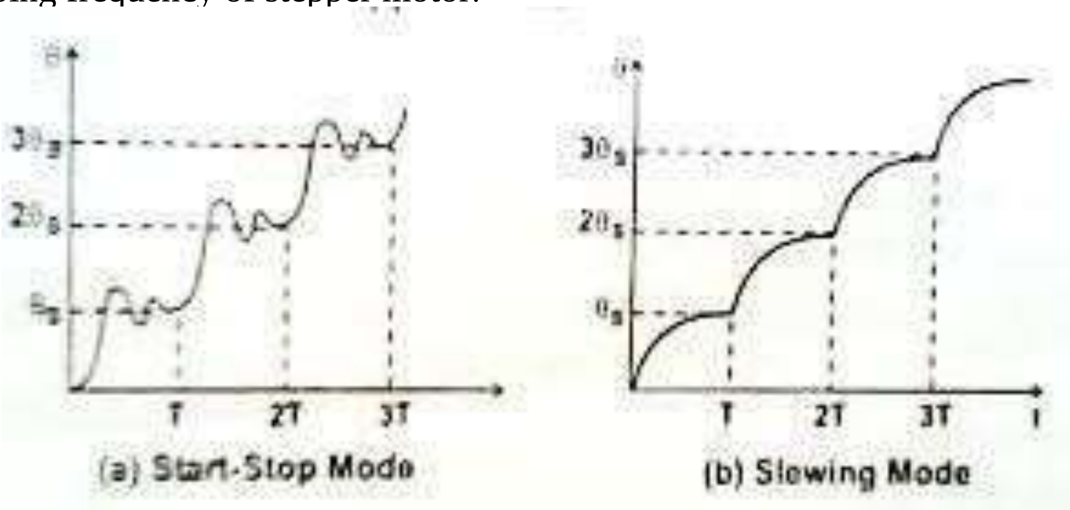


Figure 1.6.3 Dynamic Characteristics

[Source: "special electric machines" by R.Srinivasan page:2.55]

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.

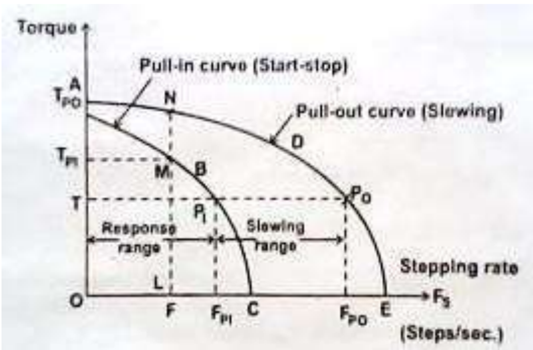


Figure 1.6.4 Dynamic Characteristics

[Source: "special electric machines" by R.Srinivasan page:2.56]

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) $K_m = T/\sqrt{\omega}$

Where T- rated motor torque

ω -rated power (w) of the motor

$K_m = \sqrt{K_t K_e / R_m}$

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.

1.1STEPPER 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:

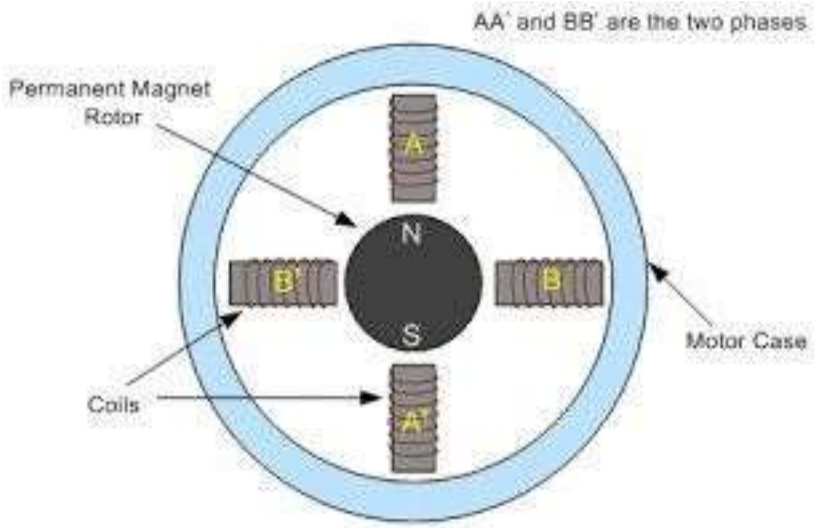


Figure 1.1.1 permanent magnet stepping motor

[Source: "special electric machines" by E.G.Janardanan page:9]

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:

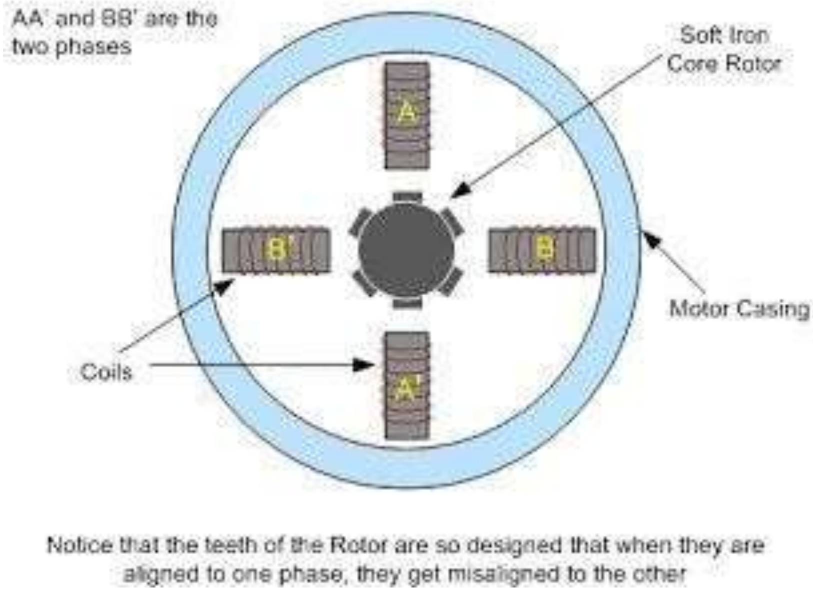


Figure 1.1.2 variable reluctance stepper motor

[Source: "special electric machines" by E.G.Janardanan page:2]

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:

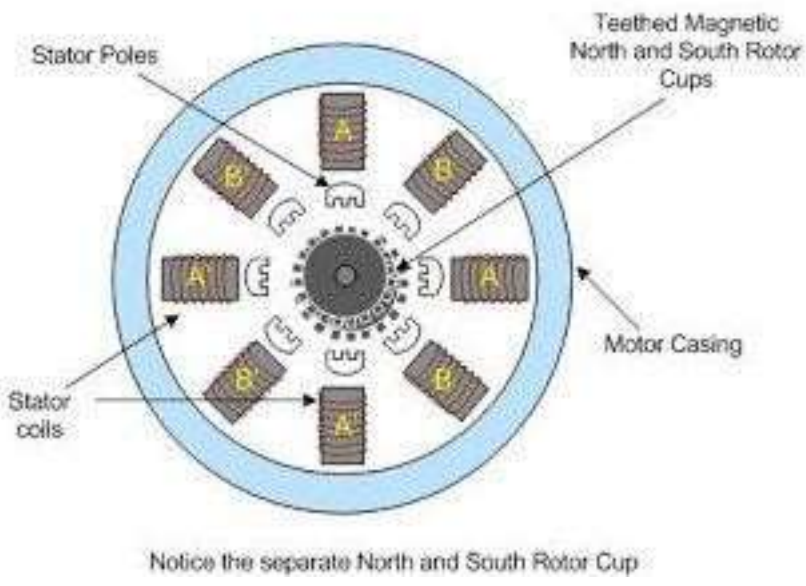


figure 1.1.3 Hybrid synchronous stepper motor

[Source: "special electric machines" by E.G.Janardanan page:12]

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

6. APPLICATIONS OF STEPPER MOTOR:

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

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.

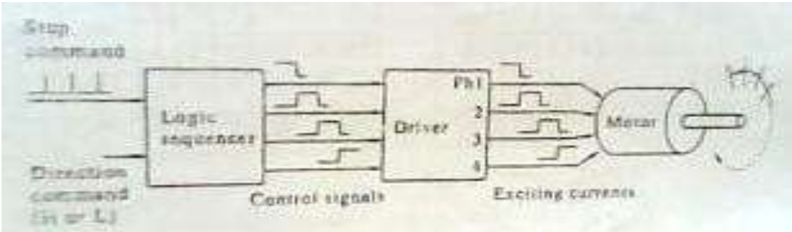


Figure 1.7.1 Block Diagram of the drive system of a stepping motor
[Source: "special electric machines" by R.Srinivasan page:2.63]

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

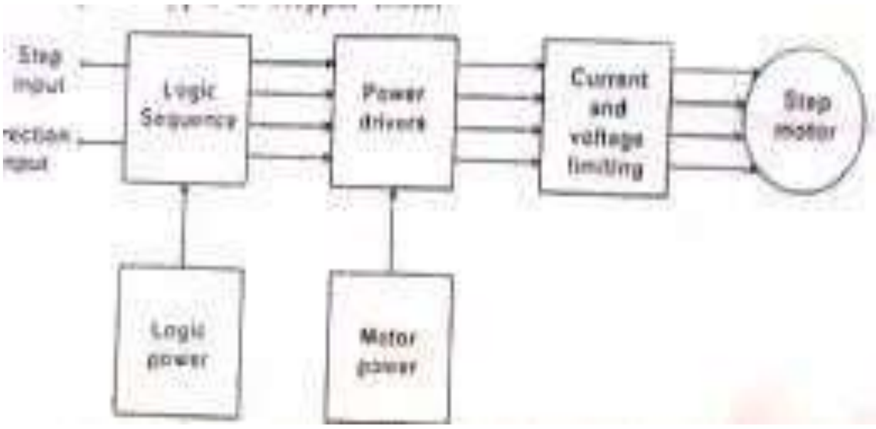


Figure 1.7.2 Block Diagram of a typical step motor control
[Source: "special electric machines" by R.Srinivasan page:2.63]

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.

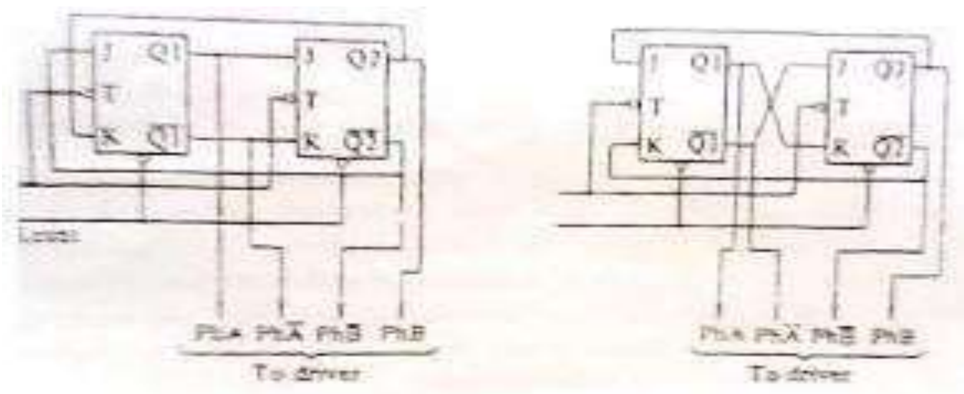


Figure 1.7.3 Logic Sequencer
[Source: "special electric machines" by R.Srinivasan page:2.64]

	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 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

Ƭ=L/R winding time constant.

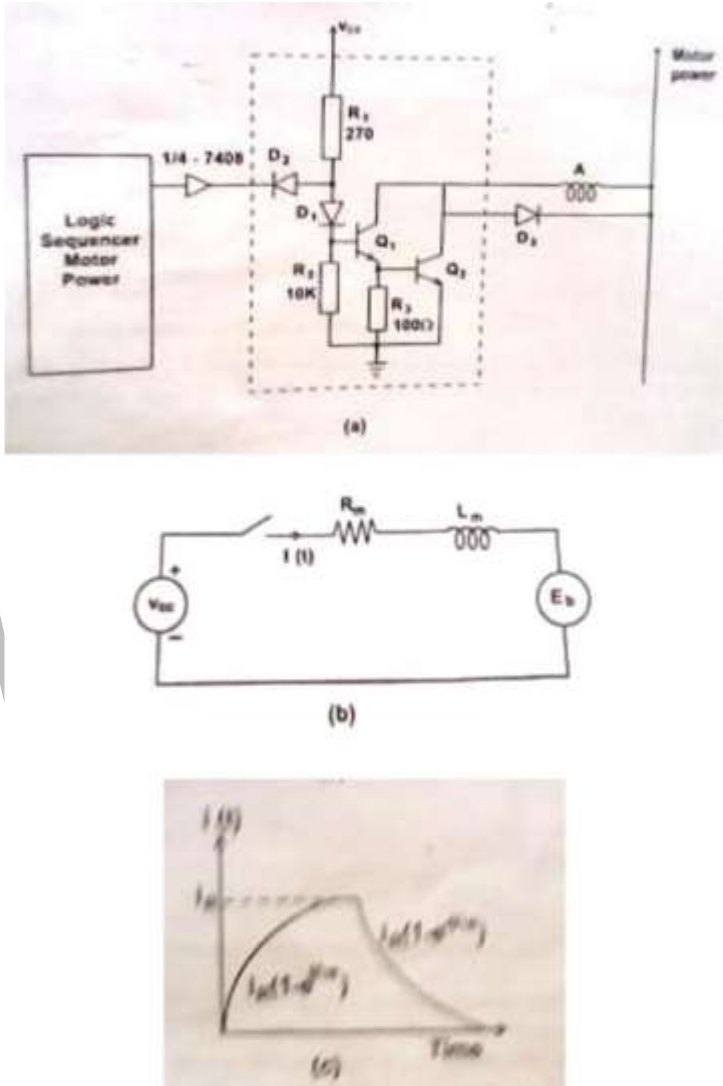


Figure 1.7.4 Power Driver Stage of Stepper Motor Controller
[Source: "special electric machines" by R.Srinivasan page:2.69]

In practice, the time constant Ƭ 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.

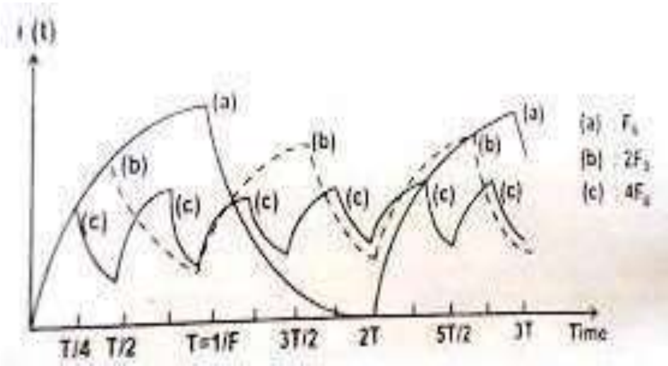


Figure 1.7.5 Effect of increasing Stepping Rate on Current Swing

[Source: "special electric machines" by R.Srinivasan page:2.70]

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

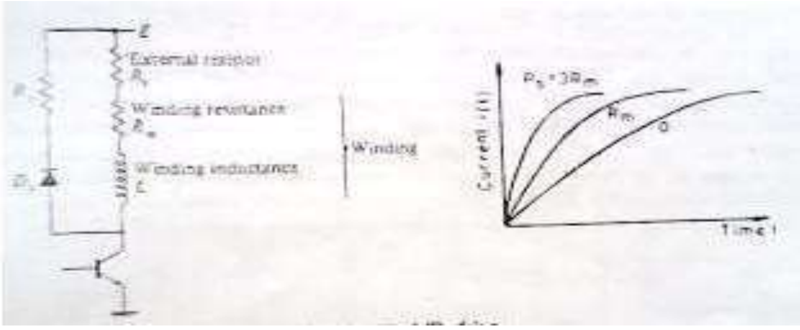


Figure 1.7.5Resistance L/R drive

[Source: "special electric machines" by R.Srinivasan page:2.71]

The circuit time constant is now reduced and the motor is able to develop normal torque even at high frequencies. The disadvantage of this method is Flow of current through external resistance causes I^2 R losses and heating. This denotes wastage of power as far as the motor is concerned. In order to reach the same steady state current I_R as before, the voltage required To be applied is much higher than before. Hence this approach is suitable for small instrument stepper motor with current ratings around 100 mA, and heating is not a major problem.

(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 both T_1 and T_2 are turned on, and the higher voltage E_H will be applied to the winding. The diode D_L is now reverse biased to isolate the lower voltage supply. The current build up quickly due to the higher voltage . The R_H 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

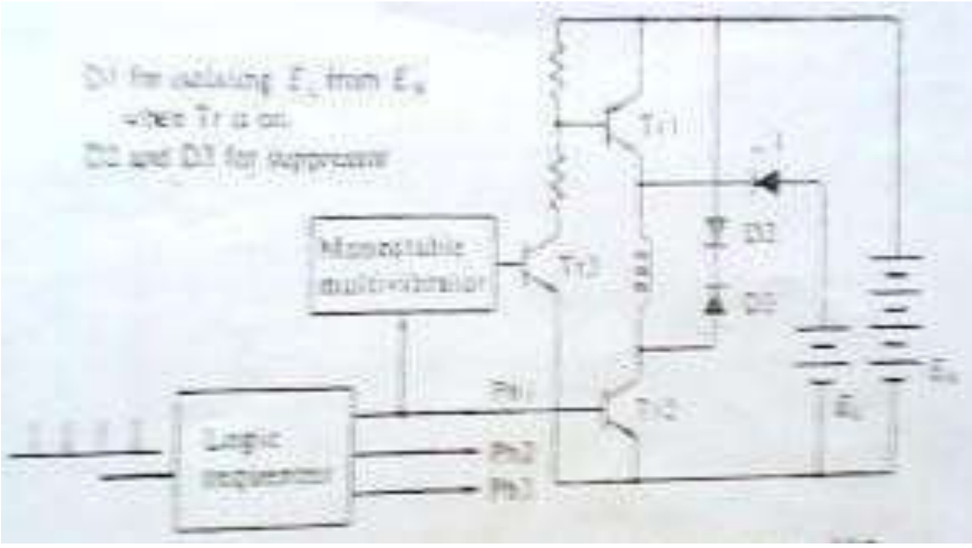


Figure 1.7.6 Dual voltage Drive

[Source: "special electric machines" by R.Srinivasan page:2.72]

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

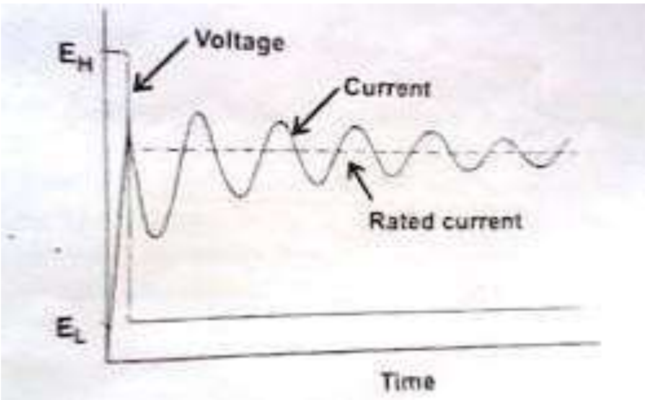


Figure 1.7.6 Voltage and current wave form in dual voltage driver

[Source: "special electric machines" by R.Srinivasan page:2.72]

When the dual voltage method is employed for the two phase on drive of a two phase hybrid motor, the circuit scheme will de such as that shown in fig.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.

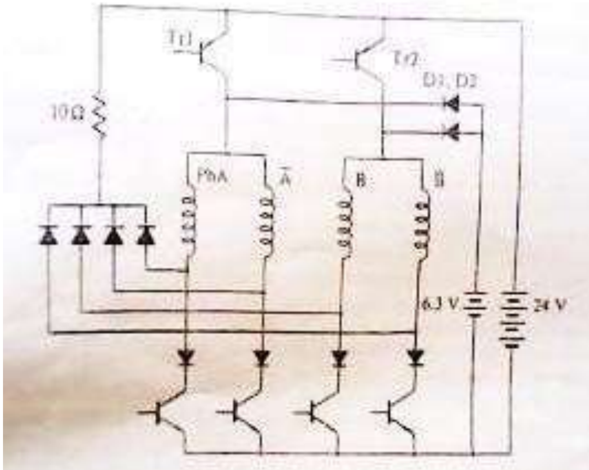


Figure 1.7.7 Dual voltage Driver circuit

[Source: "special electric machines" by R.Srinivasan page:2.72]

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.

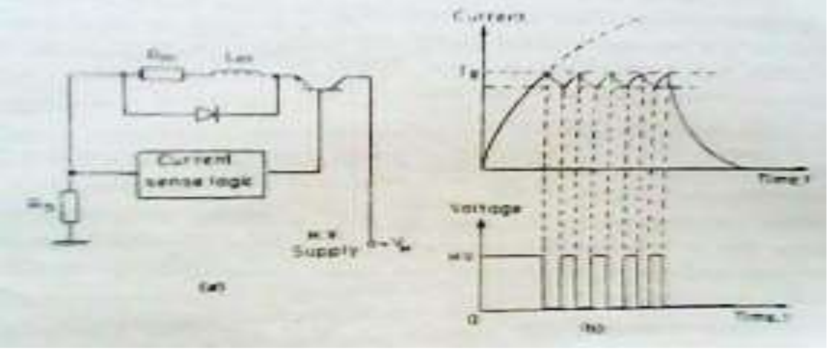


Figure 1.7.8 Oscillation of current in chopper drive

[Source: "special electric machines" by R.Srinivasan page:2.72]

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.

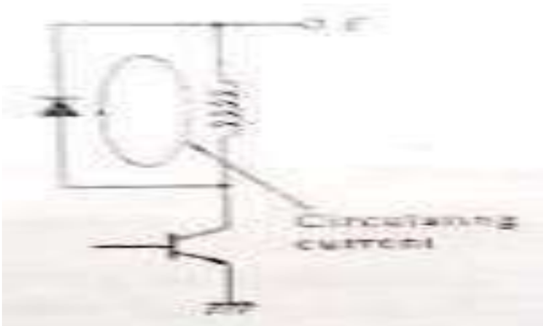


Figure 1.7.9 Diode Resistor suppressor
[Source: "special electric machines" by R.Srinivasan page:2.79]

(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

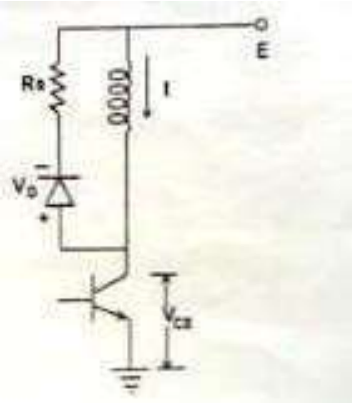


Figure 1.7.10 suppressor based on zener diode

[Source: "special electric machines" by R.Srinivasan page:2.79]

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.

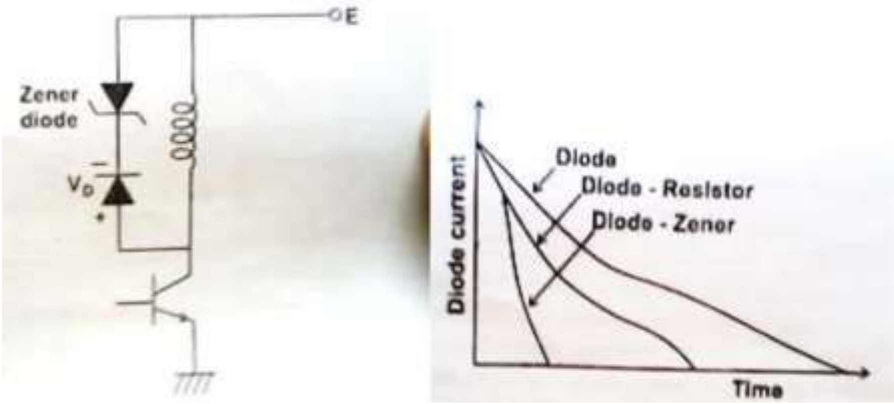


Figure 1.7.11 comparison of suppressor schemes

[Source: "special electric machines" by R.Srinivasan page:2.80]

(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:

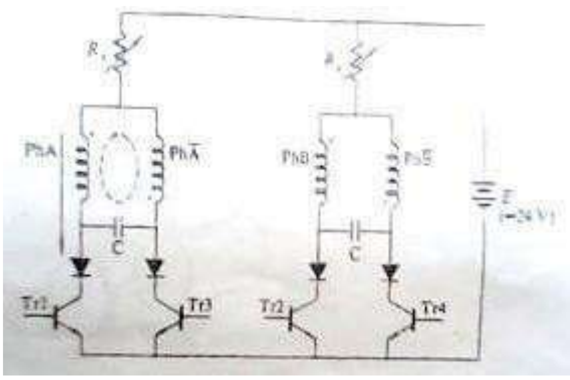


Figure 1.7.12 condenser suppressor

[Source: "special electric machines" by R.Srinivasan page:2.80]

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.

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)

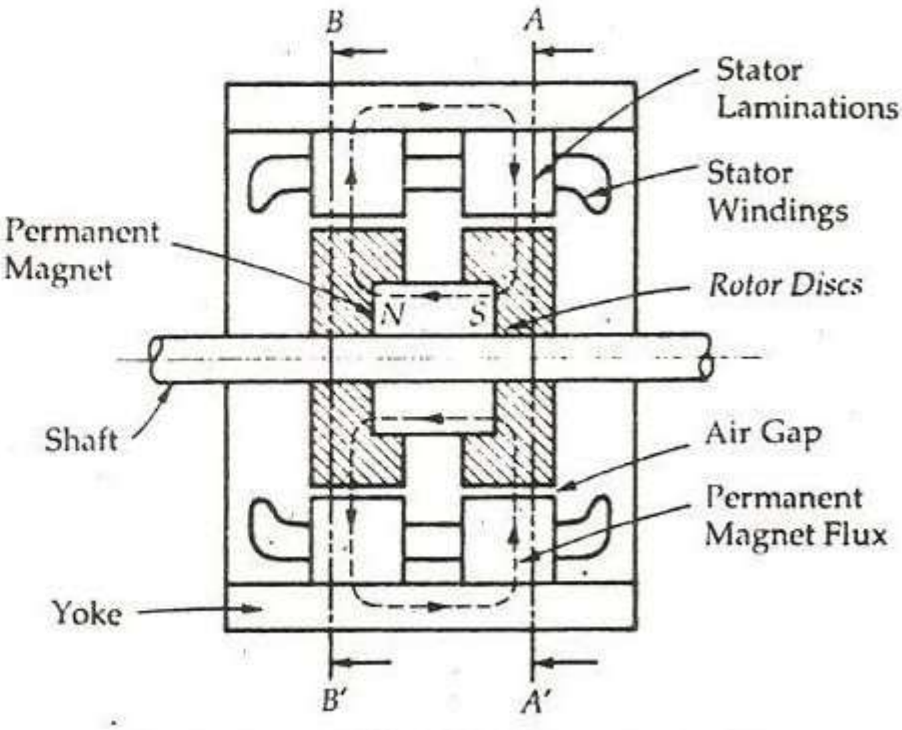


Figure 1.4.1 Hybrid stepping motor

[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.

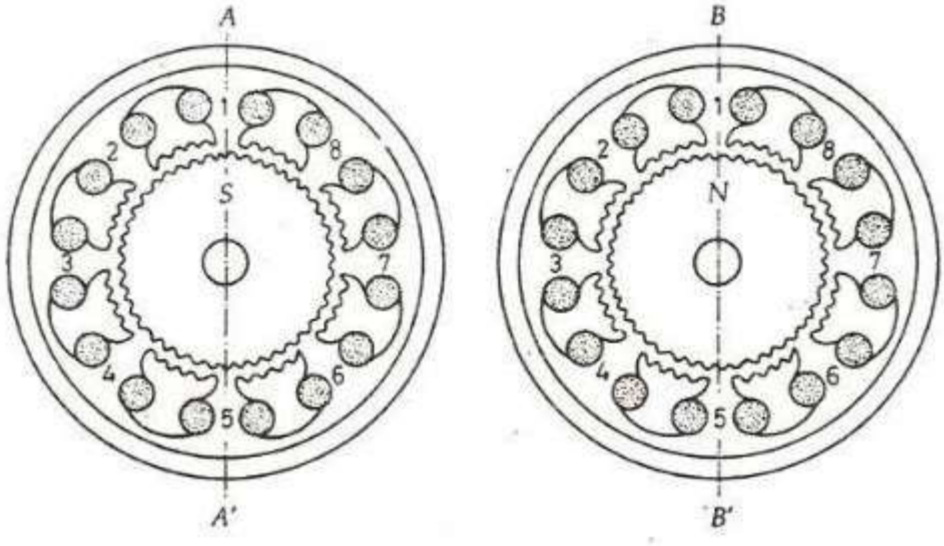


Figure 1.4.2 Hybrid stepping motor

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

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 1.8^0 in the anticlockwise direction. The phase A is now energized negatively; the rotor moves further by 1.8^0 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.

1.3 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.

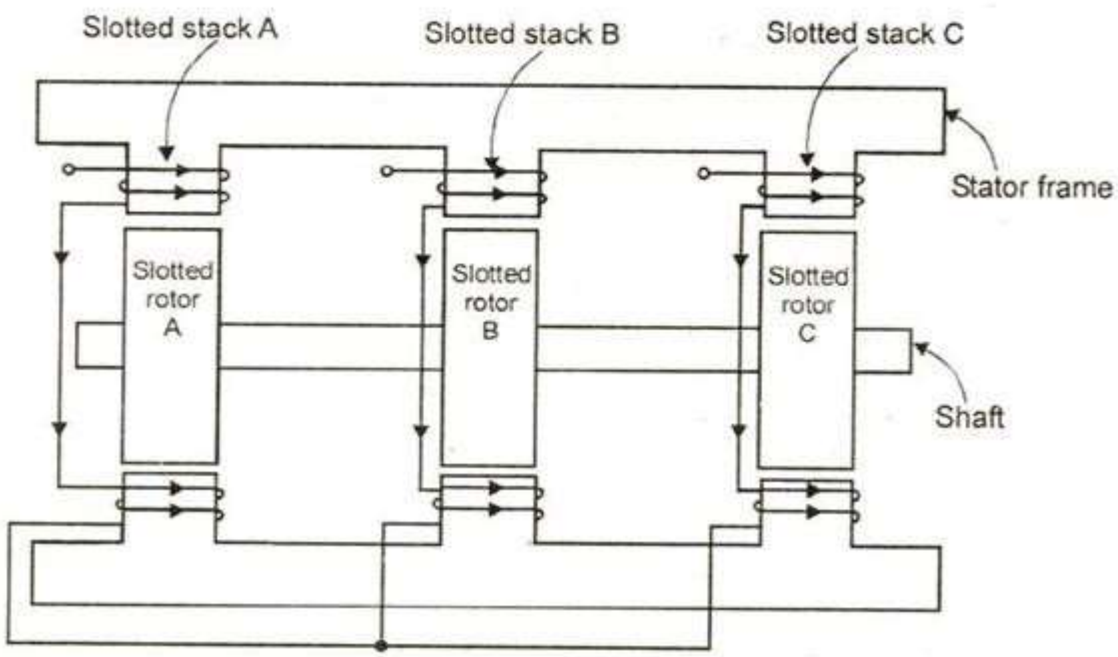


Figure 1.3.1 Multi stack variable reluctance stepping motor

[Source: "special electric machines" by E.G.Janardanan page:6]

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.

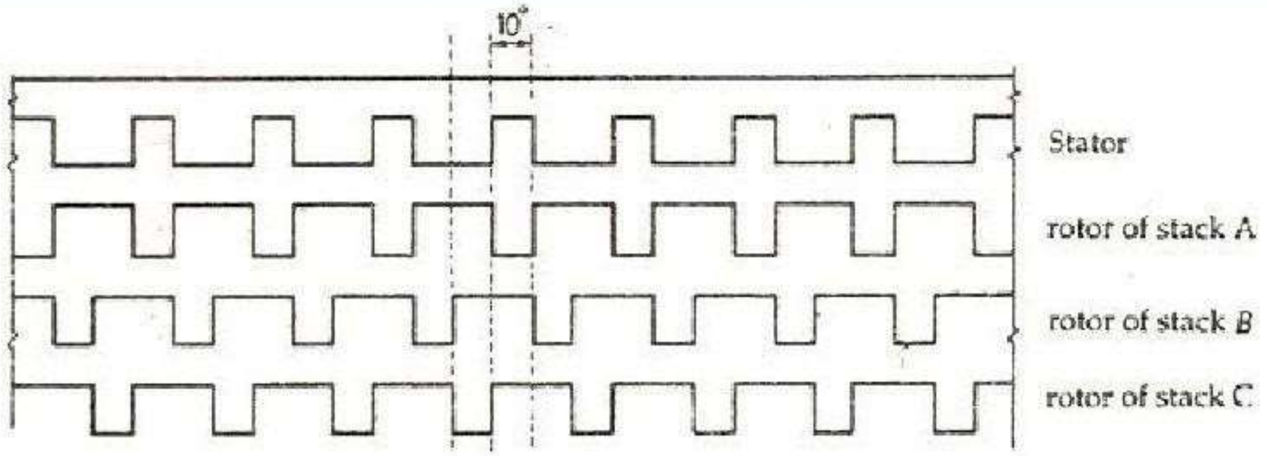


Figure 1.3.2 Relative positions of rotor and stator teeth after switching

[Source: "special electric machines" by E.G.Janardanan page:7]

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.

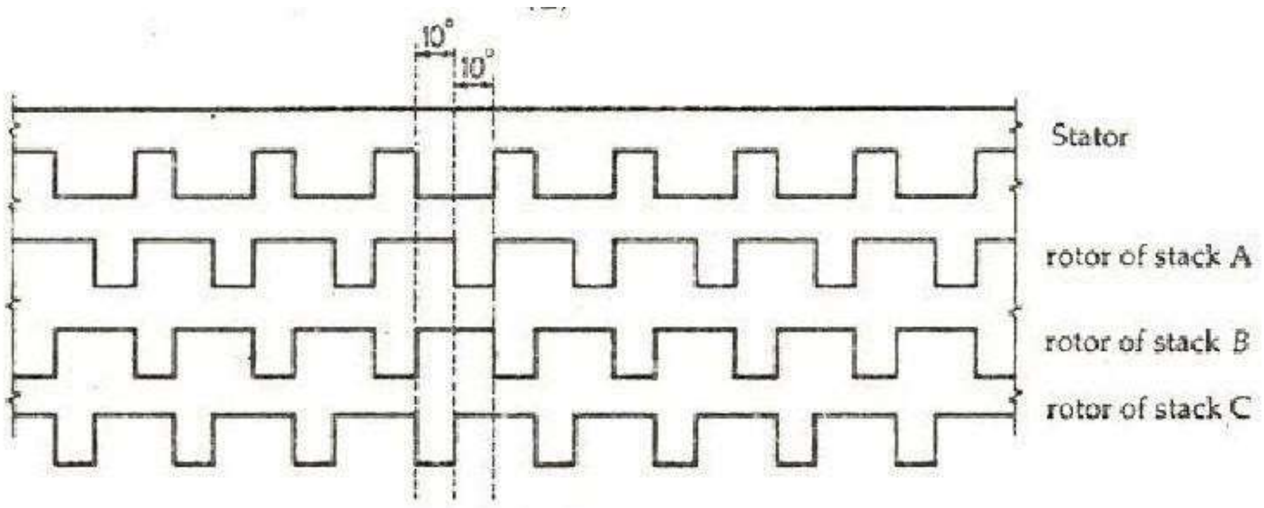


Figure 1.3.3 Relative positions of rotor and stator teeth after switching

[Source: "special electric machines" by E.G.Janardanan page:8]

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.

1.2 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

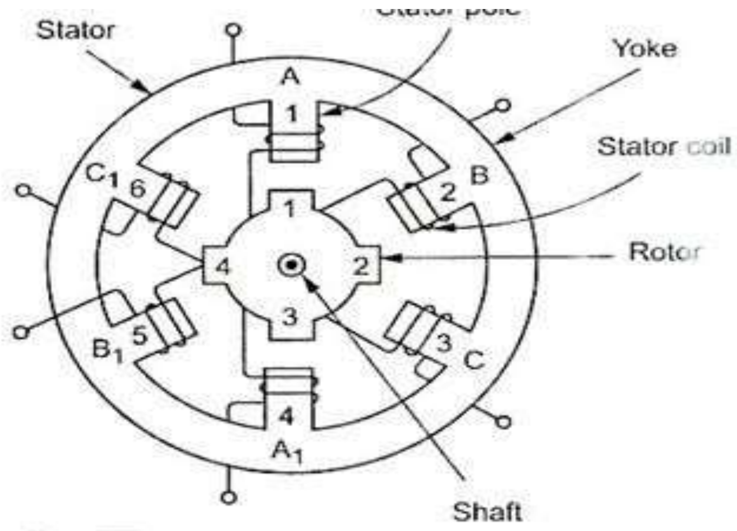


Figure 1.2.1 single stack variable reluctance stepping motor
[Source: "special electric machines" by E.G.Janardanan page:2]

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.

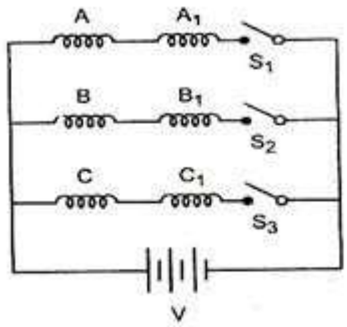


Figure 1.2.2 switching circuit

[Source: "special electric machines" by E.G.Janardanan page:2]

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.

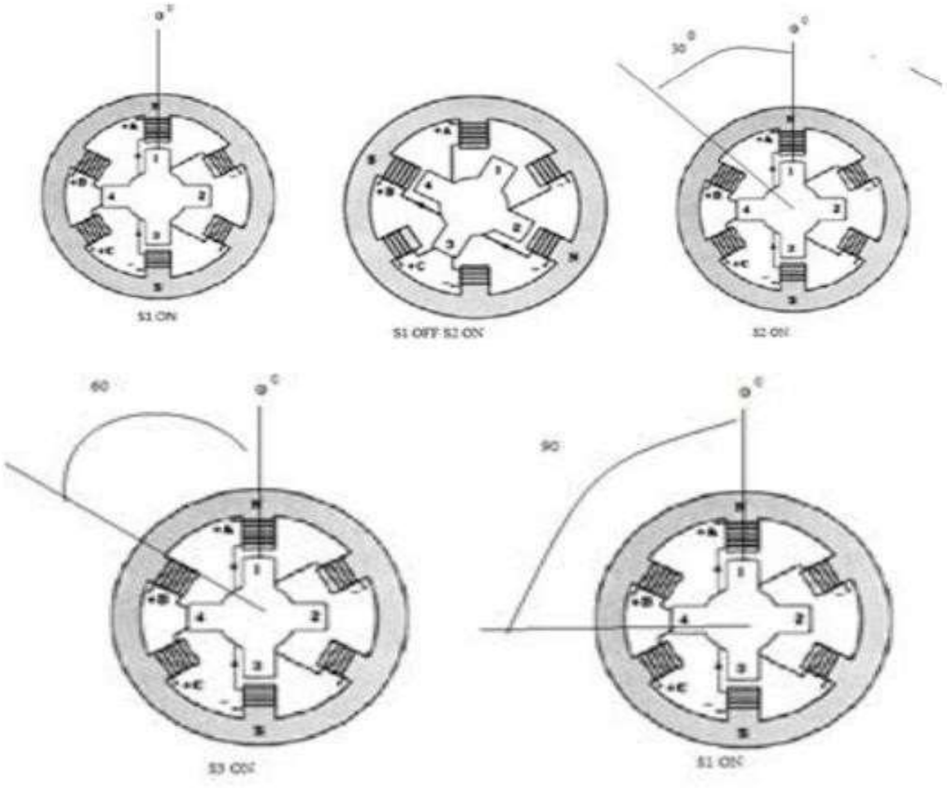


Figure 1.2.3 permanent magnet stepping motor

[Source: "special electric machines" by E.G.Janardanan page:3]

(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 a nd 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

[Source: “special electric machines” by E.G.Janardanan page:3]

(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

[Source: “special electric machines” by E.G.Janardanan page:4]

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

[Source: "special electric machines" by E.G.Janardanan page:4]

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

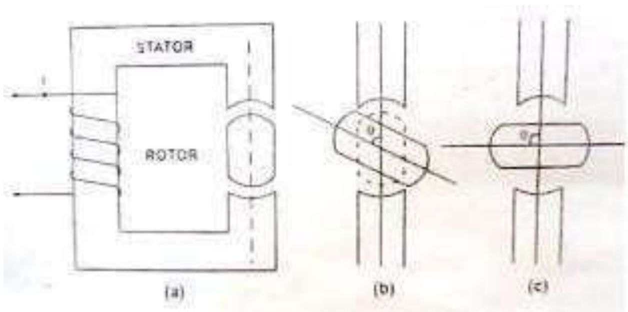


Figure 1.5.1 Magnetic circuit

[Source: "special electric machines" by Srinivasan page:2.41]

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.

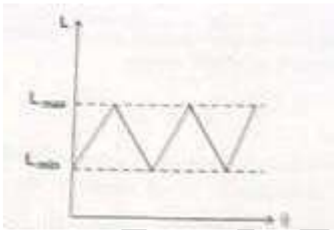


Figure 1.5.2 Magnetic circuit

[Source: "special electric machines" by Srinivasan page:2.41]

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]

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

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

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

Magnitude of e = L $_{dt}$ +ω i $_{\partial\theta}$

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.

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

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

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

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

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

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

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

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

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

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

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.