UNIT III

1. List out the advantages of switched reluctance motor.[Nov/Dec 2013 May/June 2007 April/May 2011]

1) Construction is very simple
2) Rotor carries no winding
3) No brushes and requires less maintenance
4) It is a self starting machine.

2. What is the significance of closed loop control in switched reluctance motor? [May/June 2007, Nov/Dec 2013]

1) To improve dynamic performance
2) To provide feedback linearizing control
3) To provide stability

3. List out any four applications of switched reluctance motors? [Nov /Dec 2007, April/May 2010, Nov/Dec 2011 April 2017]

1) Washing machines
2) Fans
3) Robotic control application
4) Vacuum cleaner
5) Future automobile Applications.

4. What are the types of power controllers used for switched reluctance motors? [Nov/Dec 2007]

1) Using two power semiconductors and two diodes per phase
2) Phase windings and bifilar wires
3) Dump-C converter
4) Split power supply converter

5. What is the working principle of switched reluctance motor? [April/May 2008]

The SRM develops an electromagnetic torque due to variable reluctance principle. When air gap is minimum, the reluctance will be minimum. Hence inductance will be maximum, so the rate of change of inductance is zero. When the reluctance varies, there will be a change in inductance. So when a particular stator winding of SRM is excited, the rotor pole comes in alignment with stator pole and thus the rotor rotates.

6. Why SR Machine Popular in adjustable speed drives? [Nov/Dec 2012]

1) Construction is simple and robust
2) There is no permanent magnet
3) Rotor carries no windings, no slip rings, no brushes, less maintenance
4) Power semi-conductor switching circuitry is simpler.

7. What is the significance of rotor position sensor and why it is essential for the operation of SR motors? [Nov/Dec 2012 Nov 2016]

It is necessary to use a rotor position sensor for commutation and speed feedback. The turning on and off operation of the various devices of power semiconductor switching circuits are influenced by signals obtained from rotor position sensor.

8. Mention some position sensors used in switched reluctance motor? [May/June 2013]

1) Shaft position sensor
2) Electronic position sensor.

9. Mention the applications of micro stepping VR stepper motor. [Nov/ Dec 2014]

1) Printing
2) Prototype setting.

10. List out the advantages and disadvantages of the converter circuit with two power semi- conductor devices and two diodes per phase. [Nov/Dec 2014]

Advantages:

1) Reduces switching losses of converter circuit
2) Control of each phase is completely independent of the other phases.

Disadvantages:

1) Converter circuit is expensive.

11. State the reluctance principle. [April/May 2015]

The switched reluctance principle is based on various reluctance positions of rotor with respect to 't'. When any one phase of the stator is excited, it produces its magnetic field whose axis is along the poles,the phase around which is excited. Then rotor moves in such a direction as to achieve minimum reluctance position.

12. List the characteristics of switched reluctance motor. [April/May 2015]

The switched reluctance (SR) motor is very different from the other poly phase machines because the stator and the rotor have salient poles. The motor can only be used with its specific power converter and control and consequently only overall characteristics are relevant.

13. List the disadvantages of a switched reluctance motor? [April/May 2010]

1. Stator phase winding should be capable of carrying magnetizing current.

2. For high speed operation developed torque has undesirable ripples which results in undesirable noises or acoustic noises.
3. It requires position sensors.

14. What are the two types of current control techniques?

1. Hysteresis type model
2. PWM type control.

15. Differentiate between VR stepper motor with SR motor. [Nov/Dec 2010]

(i) SR motor acts like brushless dc motor with rotor position feedback, but the stepper motor is usually fed with a square wave without rotor position feedback.

(ii) SR motor is designed for efficient power conversion of high speed comparable with those of the PM brushless dc motor. The stepper motor is usually designed as a torque motor with a limited speed range.

16. List the methods of rotor position sensing in switched reluctance motor. [May/June 2012]

1. Encoder position sensors
2. Hall effect sensors

17. What are the types of power controllers used for switched reluctance motor? (Apr/May-15,Apr/May-11,Nov/Dec-2007)

i) Using two power semiconductors and two diodes per phase

ii) (n ± 1) power switching devices and (n + 1) diodes per phase

iii) Phase windings using Bifilar wires

iv) Dump C- converter

v) Split power supply converter

18. Why rotor position sensor is essential for the operation of switched reluctance motor? (Nov/Dec-12,May/June-2006)

It is normally necessary to use a rotor position sensor for commutation and speed feedback. The turning ON and OFF operation of the various devices of power semiconductor switching circuit are influenced by signals obtained from rotor position sensor.

19. List are the disadvantages of a switched reluctance motor?

1. Stator phase winding should be capable of carrying magnetizing current.
2. For high speed operation developed torque has undesirable ripples is a est1t develops undesirable noises (or) acoustic noises.
3. For high speed current wave form has undesirable harmonics to suppress this effect large size capacitor is to be connected.
4. It requires position sensors.

20. What are the advantages of switched reluctance motor?(Nov/Dec-13,Apr/May-2009 April 2017)

1. Construction is simple and robust.
2. Rotor carries no windings, no slip rings, no brushes, less maintenance.
3. There is no permanent magnet.
4. Ventilating system is simpler as losses takes place mostly in the stator.
5. Power semi conductor switching circuitry is simpler
6. No shoot through fault likely to happen power short circuits,
7. Developed torque doesn't depends upon the polarity of current in the phaseWinding.
8. The operation of the machine can be easily change from motoring mode to generating mode by varying the region of conduction.
9. It is possible to get very high speed.
10. Depending upon the requirement T-□ characteristics can be achieved.

21. List out the advantages and disadvantages of the converter circuit with two power semiconductor devices and two diodes per phase. (Nov/Dec-14)

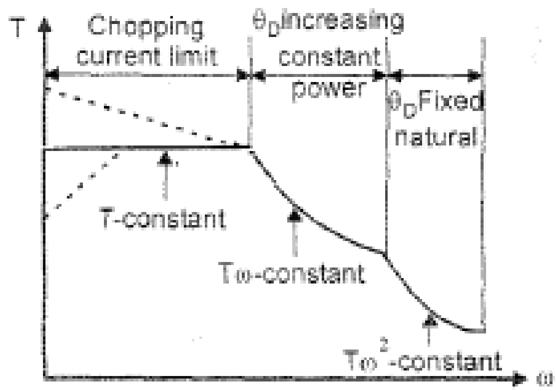
Merits:

i. Control of each phase is independent of the other phases.
ii. switching losses of the converter is low due to FD.
iii. Useful utilization of the energy.

Demerits:

i. No of switches required is high

22. Draw the general torque - speed characteristics of switched reluctance motor.[April 2017]

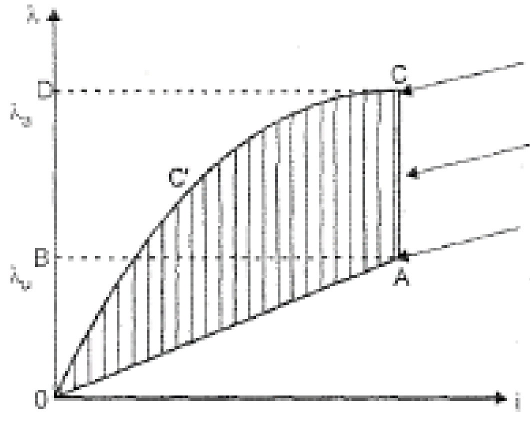


23. What are the applications of SRM. [Nov/Dec 2007 Nov2008 Nov 2016]

1. Washing machines
2. Vacuum cleaners

3. Fans
4. Future auto mobile applications
5. Robotics control applications

24. Draw the " λ-I" curve for SRM



24. What are the two types of control techniques? Apr/May-2011

1. Hysteresis type control
2. PWM type control

25. What is Switched Reluctance Motor?

The switched reluctance motor is a double salient, singly-excited motor. This means that it has salient pole on both the rotor and the stator, but only one member carrieswindings. The rotor has no windings, magnets (or) cage winding. It works on vai1é reluctance principle.

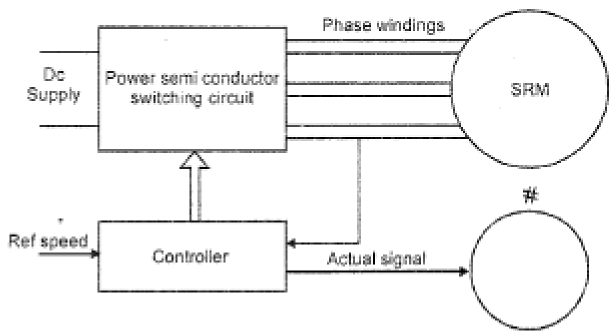
26. What is meant by energy ratio?[April 2017]

Energy ratio $= \frac{w_m}{w_m + R} = 0.45$

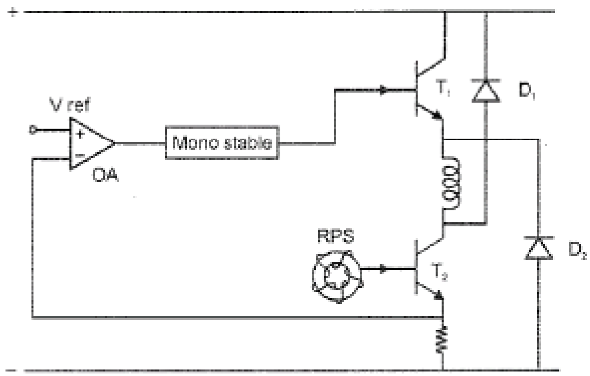
w_m = mechanical energy transformed.

This energy ratio cannot be called as efficiency. As the stored energy R is not wasted as a loss but it is feedback to the source through feed back diodes.

27. Draw the simple block diagram of SRM.



28. Draw the circuit of PWM type current control.



29. What is phase windings?

Stator poles carrying field coils. The field coils of opposite poles are connected in series such that mmf's are additive and they are called "Phase windings" of SRM.

30. What are the essential difference between SRM and Stepper Motor?

SRM	Stepper Motor
1. SRM is designed for continuous rotation.	Stepper motor is designed to rotate in step by step rotation,
2. SRM requires a rotor-position sensor.	It does not require rotor-position sensor.

31. Write down the torque equation for a switched reluctance motor drive. Apr/May-2010

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

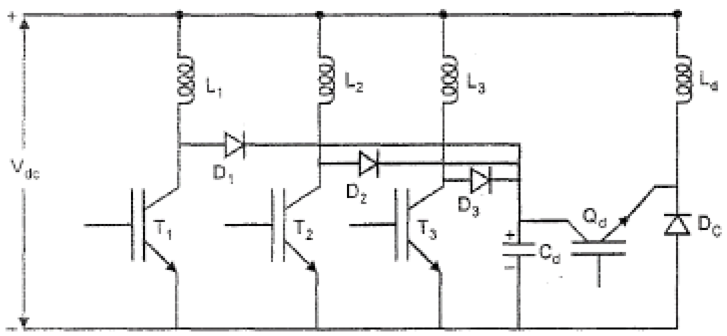
Where

T = motor torque

I = current

$\frac{\partial L}{\partial \theta}$ = change of inductance with respect to rotor angle

32. Sketch the C-dump converter circuit for switched reluctance motor.



33. What is hysteresis current control?

This type of current controller maintains a more or less constant current throughout the conduction period in each phase. This controller is called hysteresis type controller.

34. Define Chopping and single pulse mode of operation of SRM.

Chopping Mode

In this mode, also called low-speed mode, each phase winding gets excited for a Period which is sufficiently long.

Single-pulse mode

In single-pulse mode, also called high-speed mode, the current rise is within limits during the small time interval of each phase excitation.

PART – B

1. Explain the construction and working of rotary and linear switched reluctance motor. [May 2013 April 2017]

Explain the constructional features of SRM in detail. [Nov 2007] (8)

Construction and operation of SRM:

Construction of SRM:

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

The stator is made up of silicon steel stampings with inward projected poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8) All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf's are additive and they are called phase windings. Individual coil or a group of coils constitute phase windings. Each of the phase windings are connected to the terminals 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.

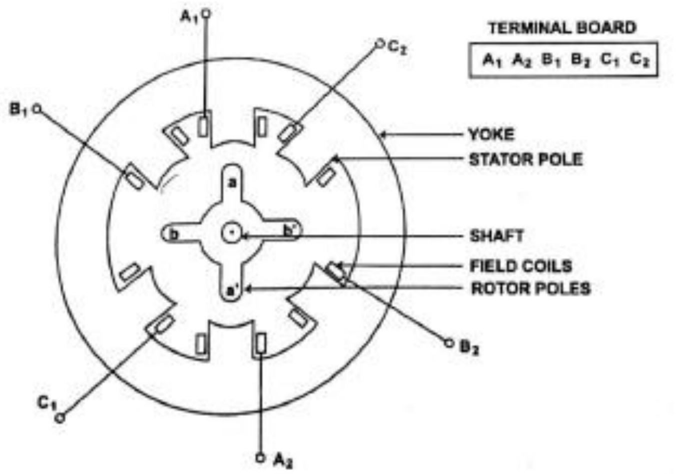


Fig. : Cross sectional view of SRM.

The rotor is also made up of silicon steel stampings with outward projected poles. Number of polesof rotor is different from the number of poles of the stator. In most of the available motors the number of poles of the rotor is 4 or 6 depending upon the number of stator poles 6 or 8.

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

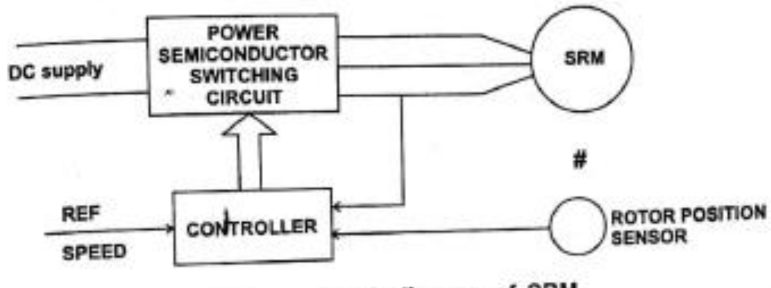


Fig. Block diagram of SRM

Block Diagram of SRM:

Fig. 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 of the switching circuit such that the desired phase winding is connected to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.

Principle of operation:

Fig. represents the physical location of the axis of 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. · They are in the minimum reluctance position so far as phase winding is concerned. Then $dLa/d\theta = 0$. At this position inductance of B winding is neither maximum nor minimum. There exists $dLb/d\theta$ and $dLc/d\theta$.

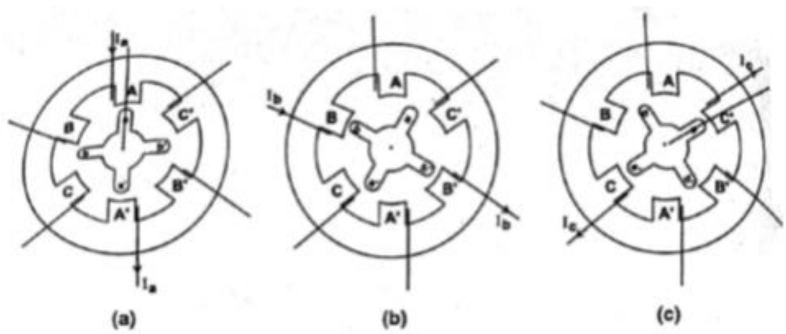


Fig. : Physical location of the axis of stator and rotor poles of 6/4 SRM.

Now if B phase is energised then the rotor develops a torque because of variable reluctance and existence of variation in inductance. The torque developed is equal $\frac{1}{2} i_B 2 \frac{dL_B}{d\theta}$. The direction of this torque 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 $dL_B/ d\theta = 0$ [vide fig. (b)]

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

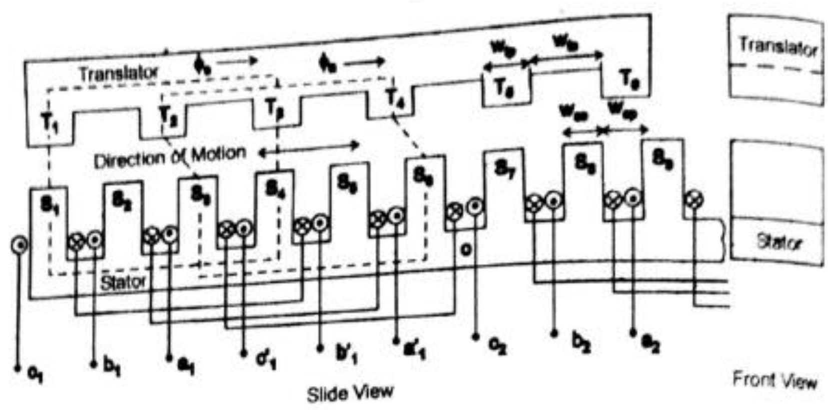
As the speed increases, the load torque requirement also changes. When the average developed torque is more than the load torque the rotor accelerates. When the torques balance the rotor attains dynamic equilibriumposition. Thus the motor attains a steady speed. At this steady state condition power drawn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

Linear Switched Reluctance Machines

Linear motor drives are being increasingly considered for machine tool drives because they reduce the need for mechanical subsystems of gears and rotary to linear motion converters, such as lead screws. Positioning accuracy is improved by the absence of gears that contribute to the backlashes in the linear motor drives, linear machine drives combined with electromagnetic levitation are strong candidates for conveyer application in semi-conductor fabrication plants and possibly in low and high speed transit applications because of their ability to produce propulsion force on the rotating part, known as the translator. without mechanical contact and friction. Linear switched reluctance machines are the counter parts of the rotating switched reluctance machines. ln fact the linear switched reluctance machine is obtained from its rotary counter part by cutting along the shat over its radius, both the stator and rotor and then rolling them out. In this section.various linear switched reluctance machine configurations are introduced. Further the ideal inductance profile is related to the stator and translator lamination dimensions. A similar relationship for the rotary switched reluctance machine that has been derived earlier is worth nothing.

Machine Topology and Elementary Operation of LSRMs

A linear SRM may have windings either on the stator or translator (the moving part). Where as in the rotary switched reluctance machine the windings are always on the stator and the rotor contains no windings. Regardless of the location of phase windings, the fixed part is called either a stator or track and the moving part is called a translator. There are two distinct configurations of linear SRM in the literature: longitudinal flux and transverse flux. These two configurations can be obtained by unrolling both the stator and rotor of a rotary SRM with a radial Magnetic flux path and axial Magnetic flux path, respectively.



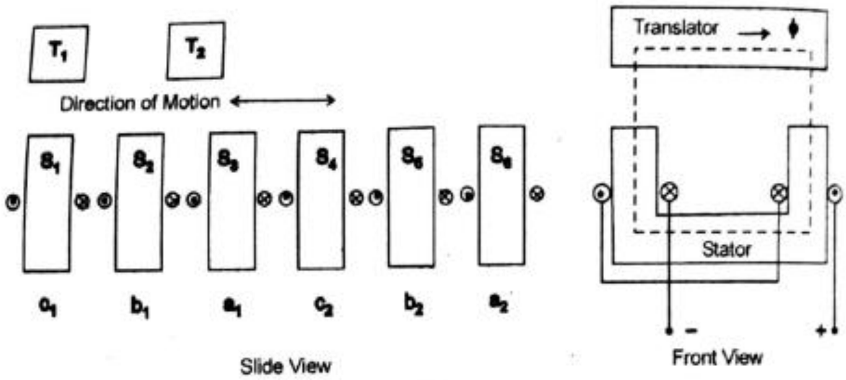
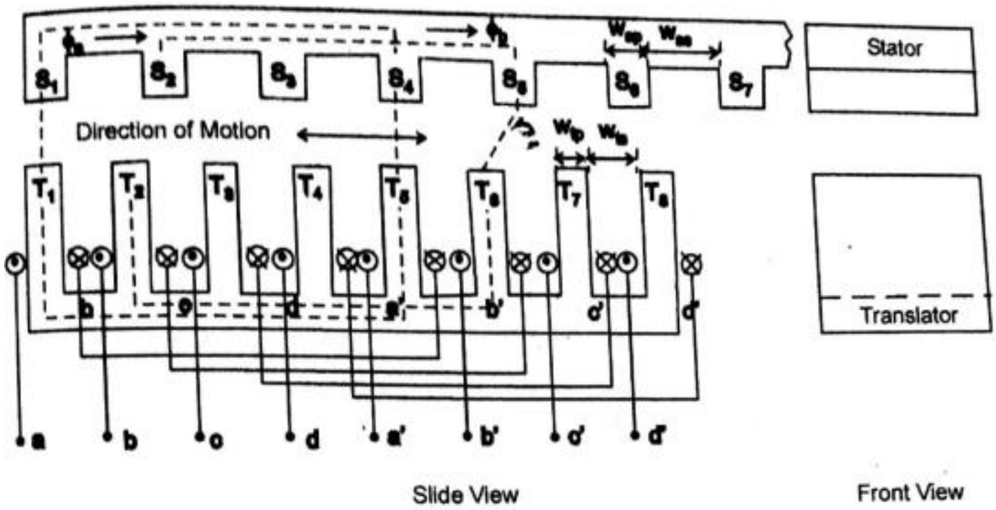


Fig. 3.22: Three-phase linear SRMs with longitudinal and transverse flux paths,

(a) Three-phase longitudinal linear SRM,(b) Three-phase transverse liner SRM

Fig. 3.22 shows the longitudinal flux and transverse flux configurations for three phase LSRM with an active (containing windings) stator and passive (with no windings) translator topology. The longitudinal magnetic flux path configuration (Fig. 3.22(a))is a linear counter part of three phase radial flux rotary SRM. The flux path in this machine is in the directionof the Vehicle Motion. This machine is simpler to manufacture, is mechanically robustand lower eddy-current losses as the flux is in the same direction as the translator motion.A transverse flux design (Fig. 3.22(b))has the flux path perpendicular to the direction of vehicle motion. If allows asimple track consisting of individually mounted transverse bars. As the flux is perpendicular to the direction of motion, an emf is induced in the core, resulting in higheddy current losses.

Longitudinal flux and transverse flux configuration for four phase LSRM with an active translator and passive stator structure are shown in Fig.



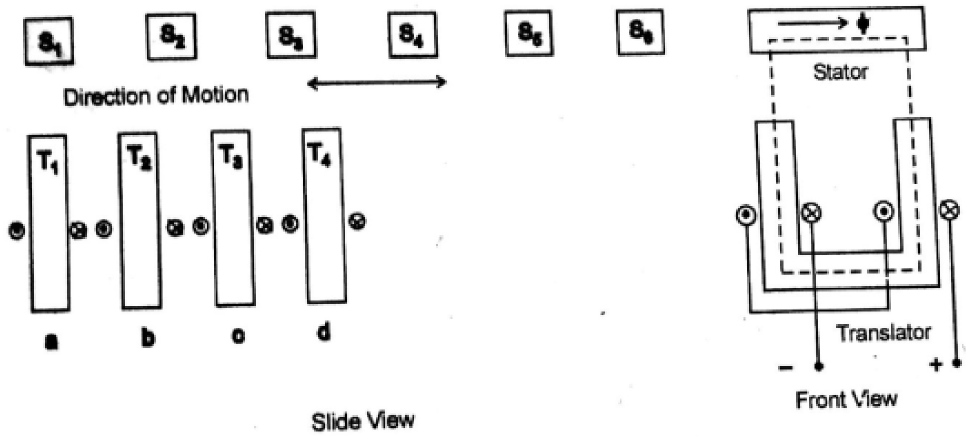


Fig. (a) Four-phase longitudinal linear SRM with active translator and passive stator, (b) Four-phase transverse linear SRM with active translator and passive stator

The active stator and passive translator SRM configuration has theadvantages of having the power supply and power converters being stationary, resulting in reduced weight of the vehicle. This design, however, requires a large number of power converter sections along the track, resulting in high costs. On the other hand, a structure with an active translator and passive stator structure requires only one section of the power converter, but the power to the converter in the translator requiring transfer by means ofcontact brushes which is not desirable for high speed applications or by inductive transfer with additional power converter circuits with consequent complexity and higher costs.

Also, the LSRM may have either two stators or two alternators or vice versa to make a double sided LSRM, as shown in. The double sided linear SRM does not have as much freedom in the air-gap tolerance as the single sided linear SRM. The single sided linear SRM provides a net levitation force that can be exploited in maglev system, but the double sided LSRM does not produce a net levitation force; it is unsuitable for such applications. Its advantages are high force density and lower inductance, as it has four air gaps in its flux path. In contrast, the single sided LSRM has two air gaps, higher inductance and lower force density compared to the double sided LSRM.

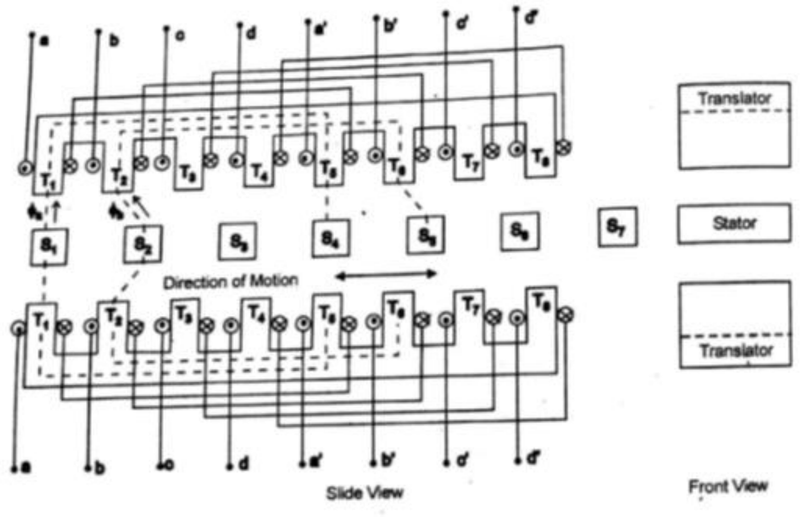


Fig. Double-sided longitudinal linear SRM

When a pair of stator windings connected in series is excited, the translator tends to move so as to align itself with the magnetic flux axis of the excited stator phase windings. This position is referred to as the fully aligned position and has the maximum phase inductance. The position corresponding to maximum reluctance value and hence minimum phase inductance is called the unaligned position and occurs when a corresponding pair of translator poles that eventually will be aligned is half a translator pole pitch away from the axis of the excited stator poles. The translator goes forward smoothly when the stator windings are switched in sequence. Depending on the converter topology and the mode of operation, the previously excited phase may be turned off before after the succeeding phase is excited. Reverse motion of the translator can be achieved by reversing the excitation sequence of the stator phases.

2. Describe the various power controller circuits applicable to switched reluctance motor and explain the operation of any one scheme with suitable circuit diagram. [May 2008Nov 2016 April 2017]

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.

Basic Requirements:

1. Each phase of SRM should be able to conduct independent of the other phases.

2. Converter should be able to demagnetize the phase before it steps into the generating region if the machine is operating as a motor and should be able to excite the phase before it steps into the generating region if operated as a generator.

3. The converter should be able to freewheel during the chopping period to reduce the switching frequency.

4. The converter should be able to utilize the demagnetization energy from the off going phase in a useful way by either feeding it back to the source or using it in the next conducting phase.

The different power semiconductor switching circuits used are

1. Two power semiconductor switching devices per phase and two diodes.

2. (n+ 1) power switching devices and (n + 1) diodes.

3. Phase winding using Bifilar wires.

4. Split-link circuit used with even-phase number.

5. C-dump circuit.

Two power semiconductor switching devices per phase and two diodes.

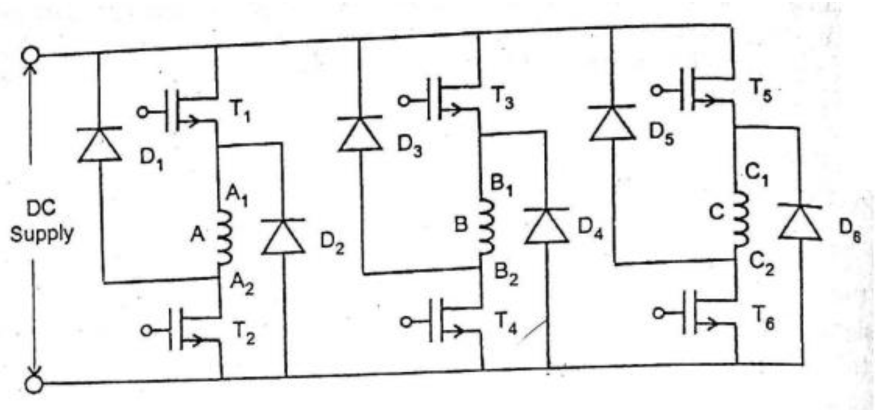


Fig. Two power semiconductor switching device and two diodes.

As shown in fig. phase winding A is connected to the dc supply through power semiconductor devices T_1 and T_2. Depending upon the rotor position, when the phase winding A is to be energized the devices T_1 and T_2 are turned ON. When the phase winding is to be disconnected from the supply (this instant is also dependent on the position of the shaft) the devices T_1 and T_2 are turned off. The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D_1 and D_2 to the supply. Thus the stored energy is fedback 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 their 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 and T_6 are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical ANDing 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 current the following methods are available.

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

Merits:

(i) Control of each phase is completely independent of the other phases.

(ii) The converter is able to free wheel during the chopping period at low speeds which helps to reduce the switching frequency and thus the switching losses of the converter.

(iii) The energy from the off going phase is feedback to the source, which results in useful utilization of the energy.

Demerits:

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

(n+1) power switching devices and (n+1) diodes.

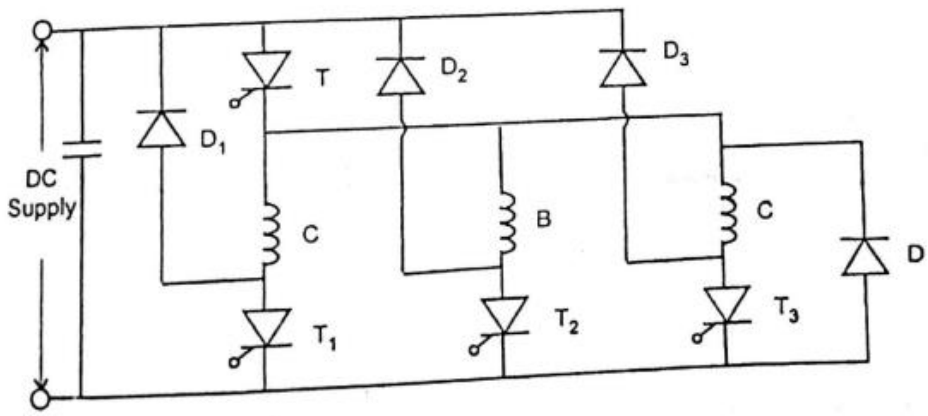


Fig. (n+1) power switching devices and (n+1) diodes.

This circuit makes use of less number of power switching devices and diodes as shown in fig. when the (SCRs) switching devices T and T_1 are turned on phase winding A is energised from the dc supply. When these devices are turned off the stored energy in the phase winding is fed back to the mains through diodes D and D_1. When devices T and T_2 are turned on the phase winding B is energised. When they are turned off, the stored energy in B phase winding is fed to mains thro' D and D_2. Similarly 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:

(i) The converter uses low number of switching devices, which reduces the cost of the converter.

(ii) The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses. · ,

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

(iv) 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:

(i) Disability to magnetize a phase while the off going phase is still demagnetising which results in higher torque ripple during commutation.

(ii) At higher speeds, of the off going phase cannot be de-energized fast enough because the common switch 'T' keeps turning on intermediately, disabling forced demagnetization.

(iii) The common switch conducts for all the phases and thus has highest switching stress .

Phase winding using bifilar wires:

. Each phase winding has two exactly similar phase windings as shown in fig. For this bifilar wires are used. Eachphase 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.

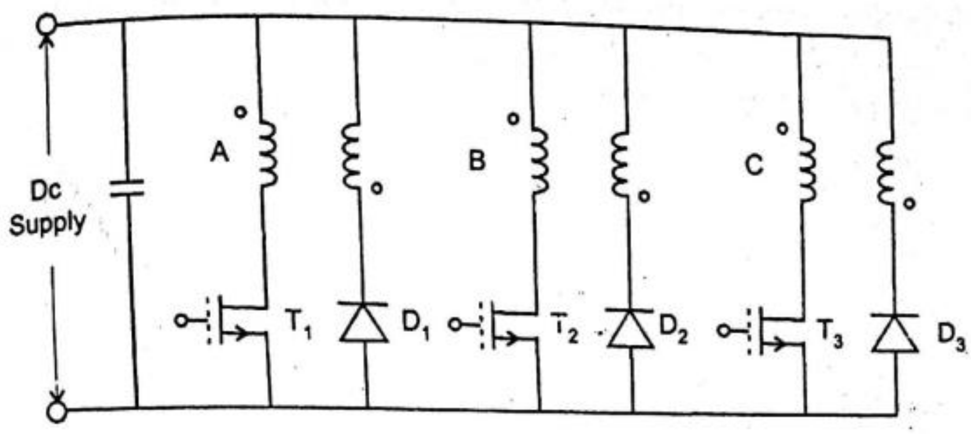


Fig. : Phase winding using bifilar wires.

When T_1 is turned on the de current passes through the phase winding A. When the device T_1 is turned off the stored energy in the magnetic field is fed back to the de source through the winding A' and D_1 to the supply.

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

Merits:

(i) The converter uses lower number of switching devices thus reducing the cost on the converter.

(ii) The converter allows fast demagnetization of phases during commutation.

Demerits:

(i) Bifilar winding suffers from double number of connections.

(ii) A poor utilization of copper.

(iii) Free wheeling is not possible during chopping as the phases have $-V_{dc}$.This causes of higher ripples in current and torque during chopping.

(iv) The imperfection in the coupling between the two winding causes voltage spikes during turn-off. .

(v) The copper loss associated with the auxiliary winding are unacceptable high for many applications.

Split - link circuit used with even phase number:

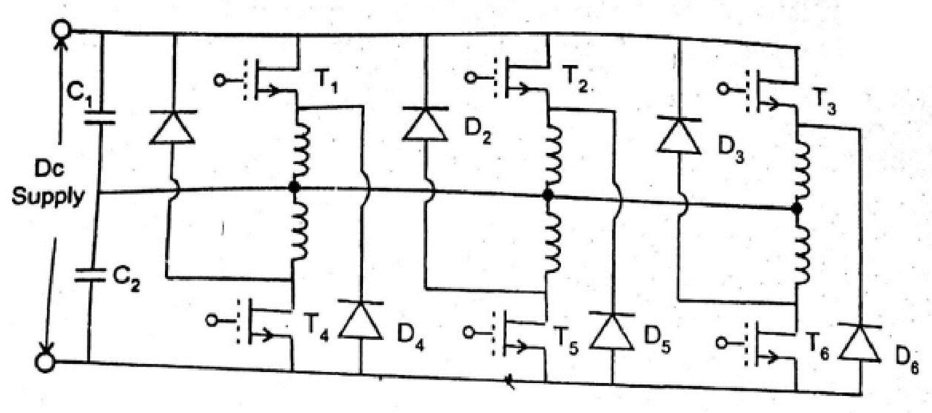


Fig. : Split link circuit used with even phase number.

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

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 T_1 is turned on, phase winding 1 is energized by capacitor C_1. When switch T_1 is turned off, the stored energy in the phase winding 1 is fed back to the capacitor C_2 through diode D_4.

When T_4 is turned on by capacitor C_2 and phase winding 4 is energised. When switch T_4 is turned off, stored energy in the winding 4 is feedback to the capacitor C_1 through diode D_1. The similar operation takes place in the remaining winding also.

Merits:

(i) It requires lower number of switching devices.

(ii) Faster demagnetization of phases during commutation.

Demerits:

(i) During chopping, free wheeling is not possible as the phaser have the voltage Vdc/2. This causes higher switching frequency and more losses.

(ii) This is not feasible for low voltage application.

(iii) The converter is less fault tolerant as fault in any phase will unbalance the other phase that is connected to it.

3. Draw a schematic diagram and explain the operation of a 'C' dump converter used for the control of SRM. [May 2017]

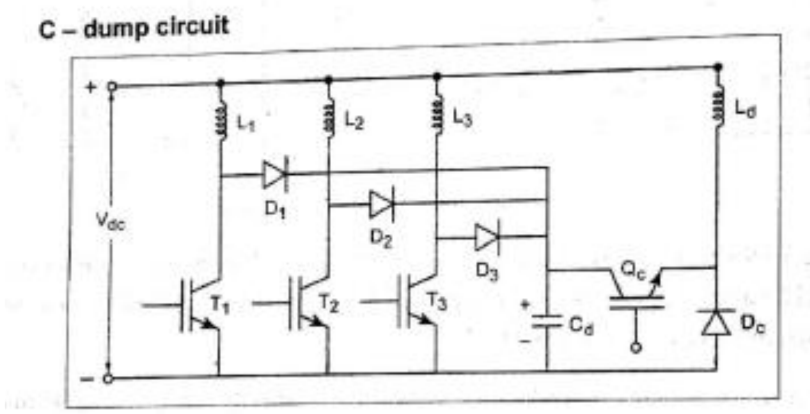


Fig. Basic 'c' dump converter circuit

The C-dump circuit shown in Fig.3. 19 makes use of (n+1) diodes to feedback the energy from the dump capacitor to the supply via the step-down chopper circuit.

The power semiconductor device T_l is turned on to initiate the conduction process. Note that the phase winding A is in series with the device T_l. Thus the phase winding A. is energized. During the commutation [turn-off] period, the diode 'D_1' is forward, biased and the energy from the machine phase [(i.e.,) phase winding] is transferred to the dump capacitor 'C_d'. Note that phases are demagnetized by turning off the respective phase switches.

The excess energy from the dump capacitor 'C_d' is transferred into the source through the diode 'D' by turning on the power switch

‘T’. The mean capacitor voltage is maintained well above the supply voltage to have rapid defluxing after commutation.

If any failure occurs in control circuit, that will lead to rapid raise of charge across the capacitor ‘C_d’ and if protective measures were not taken, the controller circuit could fail due to over voltage.

Advantages .

(i) The circuit uses lower number of switching devices.

(ii) The presence of diodes ensures faster demagnetization of phases.

Disadvantages

(i) The requirement of maintaining voltage across the dump capacitor well above the supply voltage and the control of the switch ‘T’ makes this converter a complicated circuit.

(ii) The use of capacitor and inductor in the dump circuit.

4. Derive the torque equation of SRM.[Nov 2012 Nov 2014 Nov 2016]

Theory of Torque Prediction:

(i) Flux linkages,

$$\lambda = N\phi \qquad e = N\frac{d\phi}{dt}$$

$$\lambda = Li \qquad e = L\frac{di}{dt}$$

(ii) Flux, $\phi = \frac{MMF}{Reluctance} = \frac{Ni}{s}$

Flux linkage, $\lambda = N\phi = \frac{N^2 i}{s}$

Inductance, $L = \frac{Flux\ linkage}{current} = \frac{\lambda}{i}$

$$= \frac{N^2 i}{si}$$

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

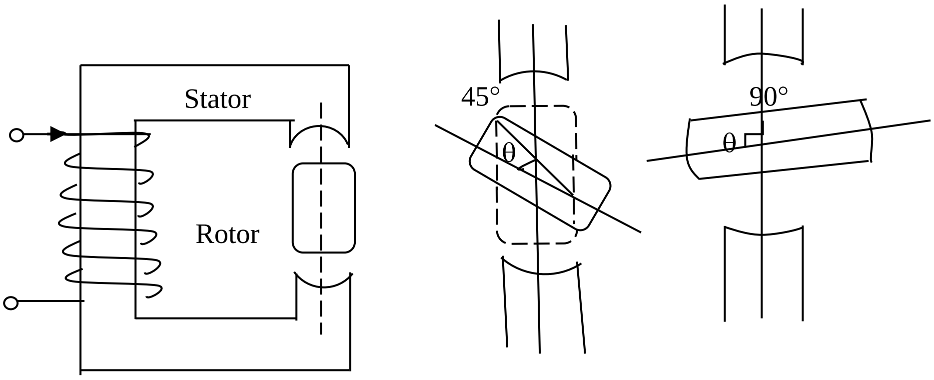
Flux linkages can be varied by,

(i) Varying flux (ϕ)

(ii) Varying the current “I”

(iii) Varying reluctance “s”

Consider a magnetic circuit as shown,



(a) (b) (c)

The stator consists of magnetic core with two pole arrangement stator core carries a coil rotor is also made up of ferrous material. The rotor core is similar to a two salient pole machine.

Let the angle between the axis of stator pole and rotor pole be 0.

Case I: Angular displacement θ = 0°

The airgap between stator and rotor is very small. Therefore, the reluctance of the magnetic path is least.

$$s = \frac{l}{\mu A} \qquad \text{if } l \text{ is} \downarrow \Rightarrow s \text{ is} \downarrow \Rightarrow L \text{ is} \uparrow$$

Due to minimum reluctance, the inductance is maximum (L_{max})

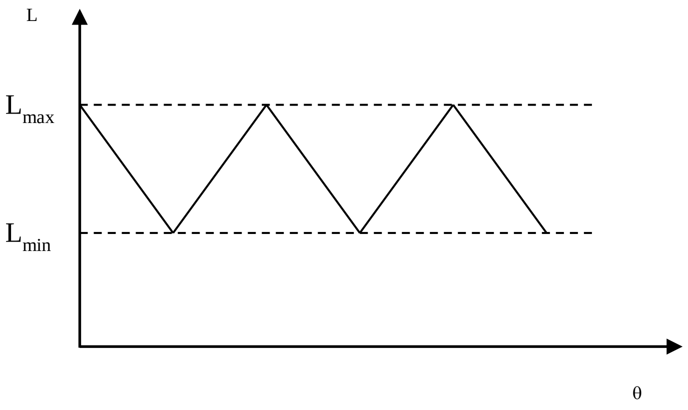
Case II: θ = 45°

In figure (b), in this only a portion of rotor poles cover the stator poles. ∴ Reluctance of the magnetic path is more than case I. Due to which the inductance becomes less than L_{max}

Case II: θ = 90°

Theairgap between the stator and rotor has maximum values. ∴ Reluctance has maximum value yielding minimum inductance (L_{min})

Variation in inductance with respect to the angle between the stator and rotor poles is



Variation in inductance w.r.t to 0

Derivation of reluctance torque:

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

$$e = \frac{-d\lambda}{dt} \text{ where } \lambda = N\phi(\text{or})Li$$

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

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

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

Magnitude of $e = L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial \theta} \qquad \rightarrow (1)$

Stored magnetic field energy,

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

The rate of change of energy transfer due to variation is stored energy (or) power.

$$\frac{d\omega_e}{dt} = \frac{1}{2}L \cdot 2i\frac{\partial i}{\partial t} + \frac{1}{2}i^2\frac{\partial L}{\partial t} \qquad \rightarrow (2)$$

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

$\rightarrow$ (a)

Power received from the electrical source = ei from (1)

$$\therefore \qquad ei = iL\frac{\partial i}{\partial t} + \omega i^2 \frac{\partial L}{\partial \theta} \qquad \rightarrow (3)$$

Substitute (2) & (3) in (a)

Mechanical power developed

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

$$P_m = \frac{1}{2}\omega i^2 \frac{\partial L}{\partial \theta} \qquad \rightarrow (4)$$

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

$$\therefore \qquad T = \frac{P_m}{\omega} \qquad \rightarrow (5)$$

Sub (4) in (5),

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

Note:

(i) Torque $\Rightarrow$ Motoring when $\frac{\partial L}{\partial \theta}$ is +ve

(ii) Torque $\Rightarrow$ Generating when $\frac{\partial L}{\partial \theta}$ is -ve

(iii) Torque is αi^2.

5. Draw and explain the general torque-speed characteristics of SRM. [Nov 2007 Nov 2012 Nov 2016]

Torque - Speed Characteristics:

Torque developed (i.e.) average torque developed by SRM depends upon the current waveform 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 waveform gets changed and the average torque developed gets reduced.

Fig. (a) represents the speed torque characteristics ' of SRM forconstant e 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 to the same duty cycle is shown in fig. (b).

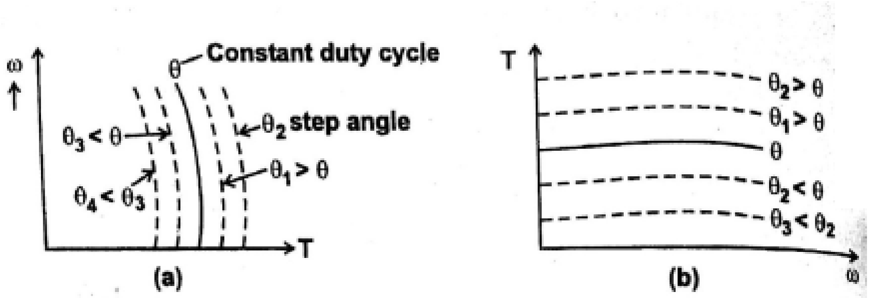


Fig. Torque speed characteristics at constant conduction angle e and duty cycle:

Torque speed characteristics for fixed θ and for various duty cycles are shown in fig. θand 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 conduction angle the torque can be varied by varying the duty cycle of the chopper. However the maximum torque developed is restricted to a definite value based on mechanical consideration.

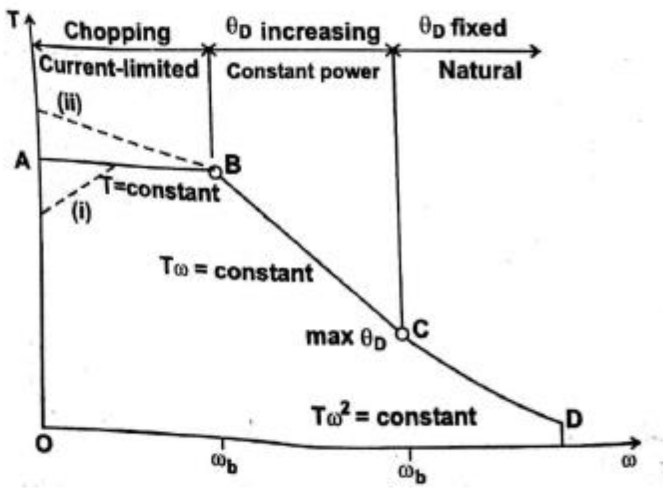


Fig. General torque speed characteristics of switched reluctance motor.

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

At very low speeds, the torque/speed capability curve may deviate from the flat-torque characteristics. If the chopping frequency is limited or if the band width of the current regulator is limited, it is difficult to limit the currentwithout the help of self emf of the motor and the current reference may have to be reduced. This is shown by curve (i). in fig.

If very low windage and core loss permit the copper losses to be increased, so that with higher current a higher torque is obtained as shown in curve (ii) in fig.

Under intermittent conditions, of course very much higher torque can be obtained in any part of the speed range uptoω_b.

The motor current limits the torque below base speed. The 'corner point' or base speed 'ω_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.) θ_{on} is decreased, there is a considerable speed range over which maximum current can still be forced into the motor. This maintains the torque at a higher level to maintain constant-power characteristics. 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 θ_D to its maximum value θ_{Dmax}. θ_D is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power, maximum permissible conduction angle $\theta_{Dmax}$and duty cycle of the chopper is unity.

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

6. Describe the hysteresis type and PWM type current regulator for one phase of a SRM [May 2010 Nov 2014]

Control Circuits For SRM

For motoring mode operation of switched reluctance machine, the pulses of the phase current should accurately coincide with increasing inductance. The timing and dwell (i.e.,) period of conductance of the current pulse determine the torque, efficiency and other parameters.

For high currents, the torque-current relationship is more or less linear. For higher power levels, more complex controls are employed. Where wide range of speed is required at constant power, microprocessor based controllers are employed. At high speeds, the peak current is limited by self emf.

The control methods available for SRM are two types, namely,

1. Hysteresis type current regulator
2. Voltage - PWM control or duty cycle control

Hysteresis type current regulator

The schematic arrangement for this type of control circuit is shown in followingfigure.

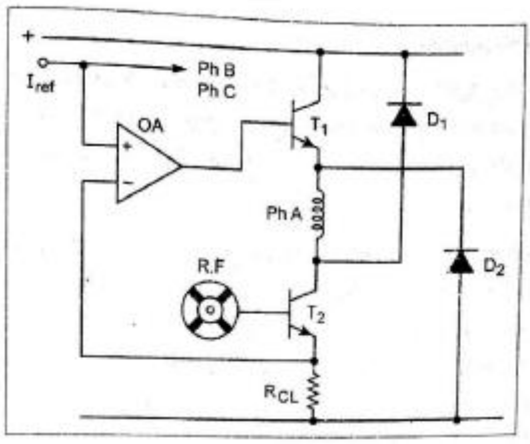


Fig. Hysteresis type current regulator

OA→ Operational amplifier

R_{CL}→ Current limiting resistor

RF→ Rotor feed back

T_1,T_2→ Switching transistors

D_1, D_2→Diodes

The fig. shows the current waveform controlled by the hysteresis type currentregulator

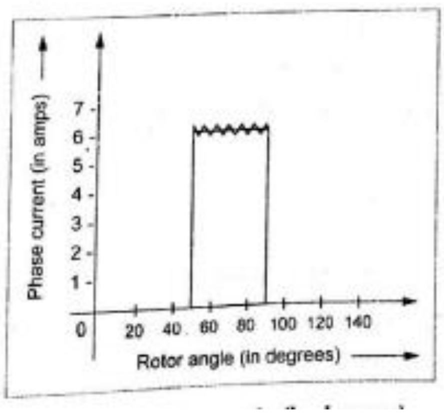


Fig. Rotor angle (in degree)

The above current waveform is controlled by a hysteresis type current regulator and it maintains almost constant current over the entire speed range.

Operating Principle

In the circuit of Fig., a transducer [Usually a tacho generator for this circuit] is connected from the rotor and then the output signal from the transducer is given as a feedback signal to the transistor T_2. This signal in tum is fed at the input of the operational amplifier.

The operational amplifier compares this signal with the reference current and then the amplified signal is given to the transistor T_1. This signal in combination with collector current will flow from the emitter of the transistor T_1 through the Phase winding A of the machine. Thus the current through the phase winding A can be controlled depending on the requirement. The current limiting resistor (R_{CL}) limits the current according to the design requirement.

When the reference current increases, the torque developed also increases. At low currents, torque is proportional to the square of the current and its relationship becomes more linear at higher values of current. But very high values of current reduces the torque/amperedue to saturation.

With loads whose torque varies monotonically with speed [From example fans and blowers], the speed adjustment is possible even without feedback. But to have accurate speed control, speed feedback is needed. To obtain the speed feedback signals shaft position sensor, optical encoders are used.

The 'hysteresis type' current regulator requires current transducer of widebandwidth, but the switched reluctance drive has the advantage that they can be grounded at one end with the other end is connected to the negative terminal of the lower phase leg switch. The sensors used are shunts or hall-effect sensors with built in current sensing.

This type of control produces a constant – torque type of characteristics.

Voltage PWM type current regulation

The following Fig. shows the regulator using fixed-frequency PWM of the voltage with variable duty-cycle.

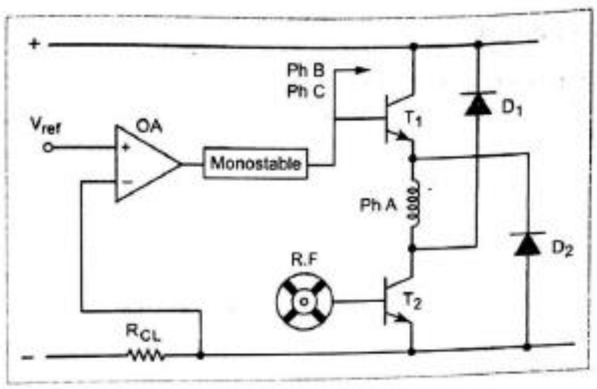


Fig. Voltage PWM type current regulator

OA $\rightarrow$ Operational amplifier

$R_{CL} \rightarrow$ Current limiting resistor

RF → Rotor feed back

T_1,T_2→ Switching transistors

D_1, D_2→ Diodes

The mechanical signal (speed of the motor) is converted into electrical signal (current), through the transducer (tachogenerator), which is fed to the transistor T_2. The resultant current from the emitter of the transistor T_2 flow through the current limiting resistor ((CLR) to the negative of the supply.

The voltage at phase A changes, because of the feedback signal. This feedback voltage is given as an input to the operational amplifier, which compares this input signal with reference voltage. The difference of these two signals is amplified and fed to the monostable circuit.

This circuit modulates the pulsewidth of the incoming signal based on the requirement and the modulated signal is given at the base of T_1. This signal combines with collector current of T_1 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.

7. Discuss the microprocessor based control of SRM. [May 2008 May 2010 Nov 2012 Nov 2014 Nov 2016]

Explain the role of computers in the control of SRM. [Nov 2007 April 2017]

Microprocessor or Computer based Control ofSRM drive:

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

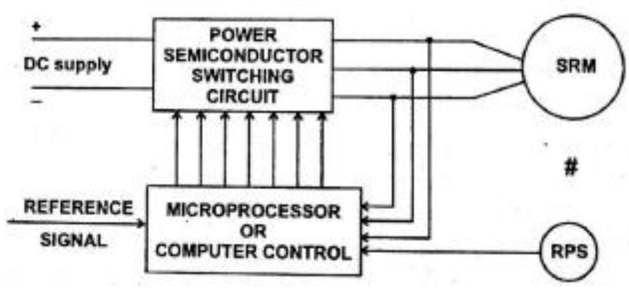


Fig. : Microprocessor or computer based control of SRM

Fig. shows the block diagram of microprocessor based control system 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 type of power semiconductor switching circuits are used for different application. Normally the circuits are invertor circuit configuration.

The power semiconductor devices are turned on and off by controller circuit. Here the controller circuit is microprocessor or computer based control system.

In the SRM drive shown in fig. 3.34, 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 receive the status of current, flow through the phase winding and reference signal.

The microprocessor or computer compare 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) Estimation of feedback signals.

(f) General sequencing control.

(g) Protection and fault overriding control.

(h) Data acquisition.

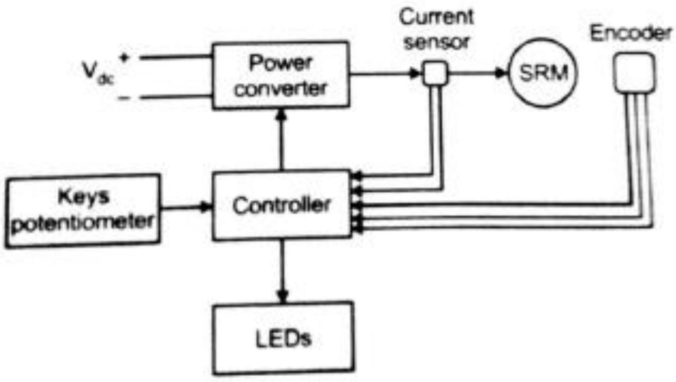
The superiority of microprocessor or computer controlover the conventional hardware based control can be easily recognized for complex drive control system. The simplification of hardware saves control electronics cost and improves the system reliability. Thedigital control has inherently improves the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

The software control algorithm can easily be altered or improved without changing the hardware. Another important feature is that the structure and parameters of the control system can be altered in real time making the controller adaptive to the plant characteristics.

8. Explain the closed loop control analysis of SRM.[May 2007 Nov 2013]

Closed Loop Control of SRM Drive

Switched reluctance motor for variable speed applications is a robust, reliable and almost maintenance free electric drive suitable for industrial, transport and domestic sector. The SRM is always operated with closed loop control. Figure shows the general closed loop block diagram of SRM.



General block diagram of the SRM drive

This block diagram consists of power converter, SRM. controller, current sensor and encoder. Here, the encoder senses the rotor position and sends it to the controller block. The current sensor also senses the motor current and sends it to controller. Here, we can set reference signal by using potentiometer. This signal is also fed to the controller block.

This controller block processes the all the signals and generates the control PWMsignals. These signals are fed to the power semiconductor switching circuit. Depending upon theenergization of phase winding, the SRM rotates according to desired speed.

In the controller block, we can incorporate different control techniques.

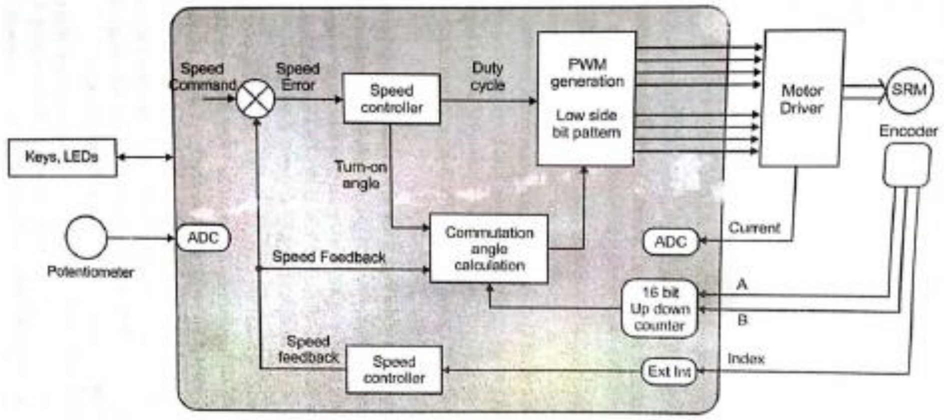
- Voltage SRM control with speed closed loop.
- Motor starts from any position with rotoralignment.
- Two directions ofrotation.
- Motoringmode.
- Minimum speed (set by user).
- Maximum speed (set by user).
- Encoder position referenee for commutation.

Detailed closed loop control of SRM drive

Figure shows the system configurations and the peripherals of the microcontroller device used for the SR motor control.

The microcontroller runs the main control algorithm. Itgenerates 4-phase PWM output signals for the SR motor power stage according to the user interface input and feedback signals. The required speed is set by a potentiometer, furthermore a start/stop and right/left switch is provided. When the start command is given the start-up sequence with the rotoralignment is performed and the motor is started in the desired direction.

The rotor position is evaluated using the external encoder and the commutation angle is calculated. When the actual position of the motor isequal to the reference position, the commutation ofthe phases in the desired direction of rotation is done; the actual phase is turned off and the following phase is turned on. For the speed calculation no additionalvelocity sensor is needed. motor speed is derived from the position information.



The reference speed is calculated from user defined potentiometer value. The speed error between reference speed and actual speed is used in the speed controller to manipulate the voltage applied to each phase winding and the firing angles. As mentioned earlier PWM voltage regulation is used in low and mid-speed regions, whereas advancing the turn-on angle in the single-pulse control comes active in the high speed area.

The control algorithm is build up in such a matter, when the PWM regulation reaches its limits the single-pulse regulation takes over. Then during the PWM cycle, the actual phase current is compared with the absolute maximum value for the rated current. As soon as the actual current exceeds this value the PWM duty cycle is restricted. The procedure is repeated for each commutation cycle of the motor.

9. Explain the steady state performance analysis of SRM.

Variation of inductance of a coil / phase with respect to θ:

As shown in fig. (a) and (b)

Let β_S be the pole arc in radians of stator poles.

Let β_r, be the pole arc in radians of rotor poles.

Let $\beta_r > \beta_S$

Case I: When θ=0.

The axis of the rotor pole is in alignment with that of stator pole as shown in fig. Then the inductance of the coil is La, because the stator reference axis and rotor reference axis are in alignment. At this position flux linkage of phase winding of stator has maximum value and hence inductance of the phase winding has maximum value for given current.

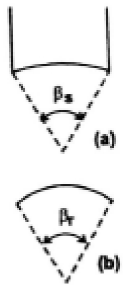


Fig Pole arc of stator and rotor poles.

So L = La.

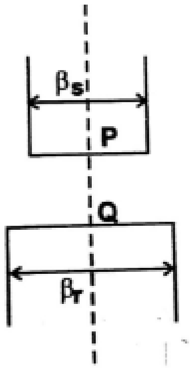


Fig.Axis of rotor pole in alignment with stator pole.

Case II: When $\theta = \frac{\beta_r - \beta_S}{2}$,

The rotor reference axis makes angular displacement of $\frac{\beta_r - \beta_S}{2}$ with stator reference axis as shown in fig. One edge of the rotor pole is along the edge of stator pole. At this position reluctance is minimum. Then inductance of the coil continues to be La. When θvaries from 0 to $\frac{\beta_r - \beta_S}{2}$, L = La.

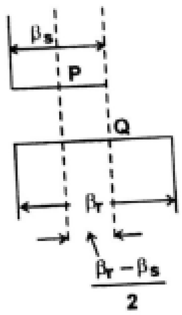


Fig. Axis of rotor displaced through /2 from stator reference axis.

Case III: When $\theta = \frac{\beta_r + \beta_S}{2}$,

Pole pitch of the rotor $= \frac{2\pi}{Nr}$

half the pole pitch of the rotor $= \frac{\pi}{Nr}$

Assume $\theta = \frac{\beta_r + \beta_S}{2} < \frac{\pi}{Nr}$

In this position shown in fig. flux pattern is such that flux linkages per unit current of the stator is less than the previous case but not minimum

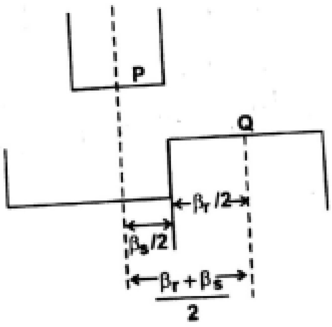


Fig. Rotor reference axis displaced through $\frac{\beta_r + \beta_S}{2}$ from stator reference axis.

$\therefore$ L < La; L = Lu; Lu < L < La

at $\frac{\beta_r - \beta_S}{2} < \theta < \frac{\beta_r + \beta_S}{2}$

Case IV: When $\theta = \frac{\pi}{Nr}$

For $\frac{\beta_r + \beta_S}{2} \le \theta \le \frac{\pi}{Nr}$

Inductance L = Lu.

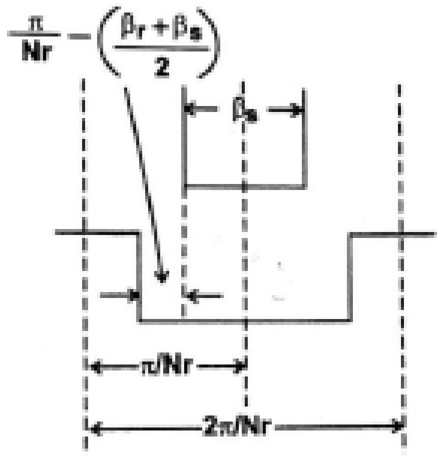


Fig.: Rotor reference axis displaced through :/Nr from stator reference axis

Case V: $\theta = \frac{\beta_r + \beta_S}{2}$ after $\frac{\pi}{Nr}$ (or)

$\theta = \frac{2\pi}{Nr} - \left(\frac{\beta_r + \beta_S}{2}\right)$ as far as rotor pole 2 is considered.

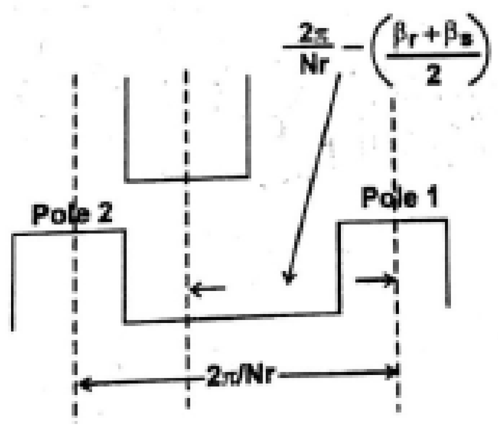


Fig. Rotor reference axis displaced through $\frac{2\pi}{Nr} - \left(\frac{\beta_r + \beta_S}{2}\right)$ **from stator reference axis.**

After which the stator pole comes under the influence of rotor pole 2. Now the inductance variation is from Lu to La as the rotor pole moves towards so as to cover the stator pole.

Variation of inductance of a phase winding with respect to θ in an shown in fig.

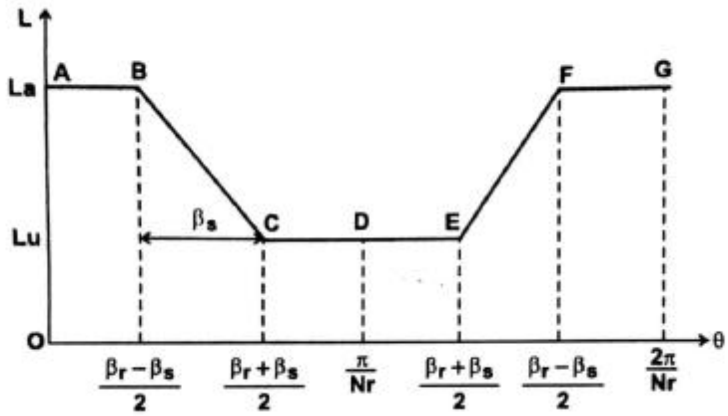
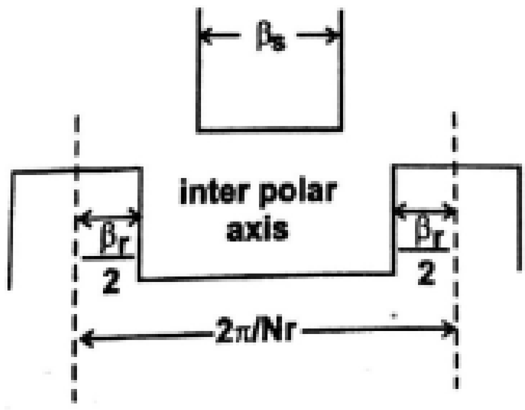


Fig. Variation of inductance of phase winding with respect to θ.

The interpolar arc is greater than stator polar arc in which the pole arcs are determined by the essential torque production mechanics. It is the tendency of the poles to align to largest variation in the phase inductance ofthe stator with respect to rotor position as shown in fig. 3.16.

$$\therefore \frac{2\pi}{Nr} - \beta_r > \beta_S$$



Fig, unaligned position oi stator and rotor pole axis.

This ensures that there will be no overlap between the stator pole andthe rotor pole is unaligned relative to the stator pole axis, thus very low inductance is achieved.

From the fig. the following observations are made.

From point A to B

θvaries from 0 to $\frac{\beta_r - \beta_S}{2}$; $L = La$

when $\frac{\partial L}{\partial \theta} = 0$

From point B to C

$$BC = \frac{\beta_r + \beta_S}{2} - \left(\frac{\beta_r - \beta_S}{2}\right)$$

$$BC = \beta_S$$

As θ varies from $\frac{\beta_r - \beta_S}{2}$ to $\frac{\beta_r + \beta_S}{2}$,

$\frac{\partial L}{\partial \theta}$ exist and is **negative**

From point C to D

$$CD = \frac{\pi}{Nr} - \left(\frac{\beta_r + \beta_S}{2}\right)$$

At this point θ varies from $\frac{\beta_r + \beta_S}{2}$ to $\frac{\pi}{Nr}$

$$L = Lu; \frac{\partial L}{\partial \theta} = 0$$

From D to E

$$DE = \frac{2\pi}{Nr} - \left[\frac{\pi}{Nr} + \left(\frac{\beta_r + \beta_S}{2}\right)\right]$$

θvaries from $\frac{\pi}{Nr}$ to $\frac{\beta_r + \beta_S}{2}$

$$L = Lu; \frac{\partial L}{\partial \theta} = 0$$

From E to F

$$EF = \frac{\beta_r - \beta_S}{2} - \frac{\beta_r + \beta_S}{2} = -\beta_S$$

θvaries from $\frac{\beta_r + \beta_S}{2}$ to $\frac{\beta_r - \beta_S}{2}$

$\frac{\partial L}{\partial \theta}$ exist, it is **positive**

From F to G

$$FG = \frac{2\pi}{Nr} - \frac{\beta_r - \beta_S}{2}$$

$$L = La; \frac{\partial L}{\partial \theta} = 0$$

10. Explain the construction and working principle of switched reluctance motor.[May 2007 May 2008 Dec 2013 May 2015]

Construction and operation of SRM:

Construction of SRM:

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

The stator is made up of silicon steel stampings with inward projected poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8) All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf's are additive and they are called phase windings. Individual coil or a group of coils constitute phase windings. Each of the phase windings are connected to the terminals 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.

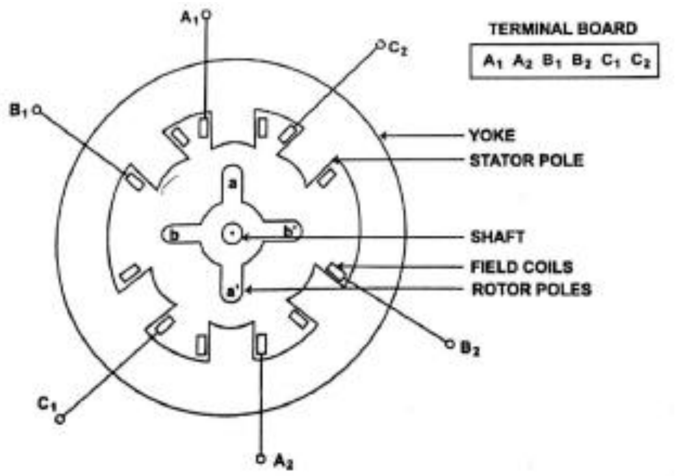


Fig. : Cross sectional view of SRM.

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 stator poles 6 or 8.

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

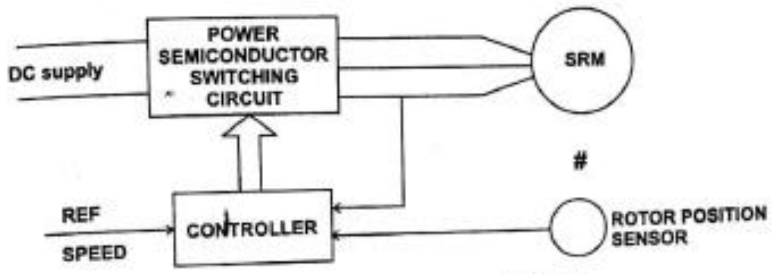


Fig. Block diagram of SRM

Block Diagram of SRM:

Fig. 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 of the switching circuit such that the desired phase winding is connected to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.

Principle of operation:

Fig. represents the physical location of the axis of 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. · They are in the minimum reluctance position so far as phase winding is concerned. Then $dLa/d\theta = 0$. At this position inductance of B winding is neither maximum nor minimum. There exists $dLb/d\theta$ and $dLc/d\theta$.

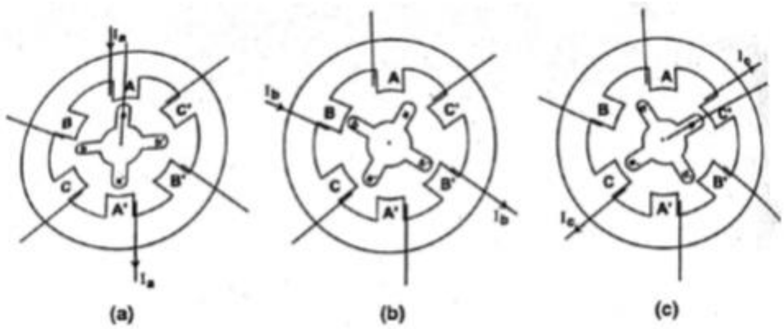


Fig. : Physical location of the axis of stator and rotor poles of 6/4 SRM.

Now if B phase is energised then the rotor develops a torque because of variable reluctance and existence of variation in inductance. The torque developed is equal $\frac{1}{2} i_B 2 \frac{dL_B}{d\theta}$. The direction of this torque 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 $dL_B/ d\theta = 0$ [vide fig. (b)]

Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as $\frac{dL_C}{d\theta}$ exists. The motor continues to rotate. When the rotor rotates further 30°, the torque developed due to winding C is zero [vide fig. (c)] Then the phase winding C is switched off and phase winding A is energised. Then rotor experiences a torque and rotates further step of 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.

11 .Discuss the need of rotor position sensor in SRM and Voltage, torque equations of SRM. [Nov 2012May 2015]

Explain the shaft positioning sensing of SR motor. [Nov 2007](8)

Discuss the method of Rotor position sensing of switched reluctance motor. [May 2013]

Shaft Position Sensing:

- Commutation requirement of the SR motor is very similar to that of a PM brushless motor.
- The shaft position sensor and decoding logic are very similar and in some cases it is theoretically possible to use the same shaft position sensor and the same integrated circuit to decode the position signals and control PWM as well.
- The shaft position sensors have the disadvantage of the associated cost, space requirement and possible extra source of failure. Reliable methods are well established. In position sensors or speed sensors, resolvers or optical encoders may be used to perform all the functions of providing commutation signals, speed feedback and positionfeedback.
- Operation without position sensor is possible. But to have good starting and running performance with a wide range of load torque and inertias, sensor is necessary.
- When the SR motor is operated in the 'open-loop' mode like a stepper motor in the slewing range, the speed is fixed by the reference frequency in the controller as long as the motor maintains 'step integrity'. (i.e.) stay in synchronism. Therefore like an ac synchronous motor, the switched reluctance motor has a truly constant speed characteristics.

This open-loop control suffers from two disadvantages.

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

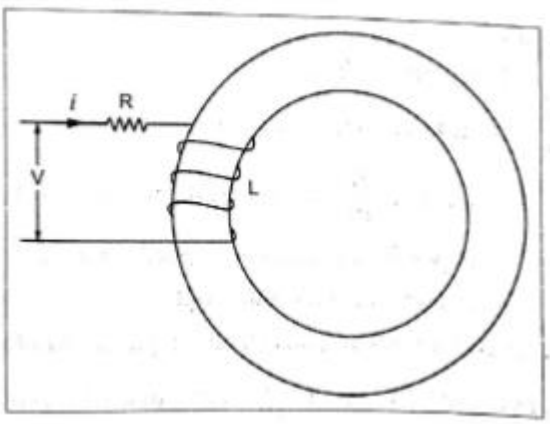
(b) To ensure reliable starting.

- Because of the large step angle and a lower torque / inertia ratio, the SR motor usually does not have reliable 'starting rate' of the stepper motor.
- Also some form of inductance sensing or controlled current modulation(i.e.) such as sinewave modulation may be necessary in the control at low speeds.

Voltage and Torque Equations of SRM

Basic voltage equation of SRM

Consider the RL circuit of switched reluctance motor shown in following Fig



Fig, Basic R—L circuit of SRM

From the above Fig.

$$V = iR + \frac{d\lambda}{dt} \qquad ...1$$

Where, $\lambda \rightarrow$ is a function of θ and L

$iR \rightarrow$ is the ohmic drop

$$\frac{d\lambda}{dt} = \frac{d\theta}{dt}(i) + \theta\frac{di}{dt} \qquad ...2$$

$$V = (i)(R) + \frac{d(Li)}{dt} \qquad ...3$$

$$= iR + L\frac{di}{dt} + i\frac{dL}{dt} \qquad ...4$$

$$V = iR + L\frac{di}{dt} + (i)(\omega)\frac{dL}{d\theta} \qquad ...5$$

$L\frac{di}{dt} \rightarrow$Emf due to incremental inductance

$(i)(\omega)\frac{dL}{d\theta} \rightarrow$self inducedemf that can be denoted as “e”.

So the equation 5 can be written as,

$$V = iR + L\frac{di}{dt} + e \qquad ...6$$

In the above equation,

iR is the ohmic drop

dr . . .

$L\frac{di}{dt}$ isemf due to incremental inductance

$e = (i)(\omega)\frac{dL}{dt}$ is the self inducedemf or self emf which depends on current, speed and the rate of change of inductance with rotor angle.

Thus equivalent circuit of SRM consists of a phase winding, a resistance and incremental inductance and self-emf $L\frac{di}{dt}$ emf due to incremental inductance is zero.

During the flat-top period, emf ‘e’ is constant. At some instant, the inductance is constant, ‘e’ will be zero and $L\frac{di}{dt}$ will be a constant. Thus the term $L\frac{di}{dt}$ absorbs all the applied voltage.

Equation for mechanical energy transferred in SRM

Multiply the equation 5 by "i" on both sides,

$$Vi = i^2R + L_i \frac{di}{dt} + i^2(\omega)\frac{dL}{d\theta} \qquad ...7$$

We know that the energy stored in the magnetic field

$$W_{mag} = \frac{1}{2}Li^2$$

Rate of change of energy stored in the magnetic circuit,

$$\frac{dW_{mag}}{dt} = dt\left[\frac{1}{2}Li^2\right] \qquad ...8$$

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

$$= Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{dt}$$

$$\frac{dW_{mag}}{dt} = Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{d\theta} \times \frac{d\theta}{dt}$$

$$\Rightarrow \frac{dW_{mag}}{dt} = Li\frac{di}{dt} + \frac{1}{2}i^2(\omega)\frac{dL}{d\theta} \qquad ...9$$

$$\left.\begin{matrix}\text{Mechanical energy}\\ \text{transferred}\end{matrix}\right\} = \left\{\begin{matrix}\text{Electrical}\\ \text{energy}\\ \text{input}\end{matrix}\right\} - \left(i^2R\right) - \left\{\begin{matrix}\text{Rate of change of}\\ \text{energy stored in}\\ \text{the magnetic circuit}\end{matrix}\right\}$$

$$= (Vi) - \left(i^2R\right) - \frac{dW_{mag}}{dt}$$

$$= \left(i^2R\right) + L_i\frac{di}{dt} + i^2(\omega)\frac{dL}{d\theta} - \left(i^2R\right) - L_i\frac{di}{dt} + -\frac{1}{2}i^2(\omega)\frac{dL}{d\theta}$$

Thus, the mechanical energy transferred.

$$P_m = i^2(\omega)\frac{dL}{d\theta} - \frac{1}{2}\left(i^2\right)(\omega)\frac{dL}{d\theta}$$

$$\Rightarrow \boxed{P_m = \frac{1}{2}\left(i^2\right)(\omega)\frac{dL}{d\theta}} \qquad ...10$$

Deviation of reluctance torque:

As per Faraday's law of electromagnetic induction, an emf is induced in an electric circuit when there exists a change in flux linkage.

$$e = -\frac{d\lambda}{dt} \qquad \text{where} \lambda = N\phi \text{ (or) } Li$$

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

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

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

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

Magnitude of $e = L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial \theta} \rightarrow (1)$

Stored Magnetic field energy,

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

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

$$\frac{d\omega e}{dt} = \frac{1}{2}L \cdot 2i\frac{\partial i}{\partial t} + \frac{1}{2}\frac{\partial L}{\partial t} \rightarrow (2)$$

Mechanical power developed/ consumed = power received from the electrical source – power due to change in stored energy in the inductor. →(a)

Power received from the electrical source = ei

From (1),

$$\therefore \quad ei = iL\frac{\partial i}{\partial t} + \omega i^2\frac{\partial L}{\partial \theta} \rightarrow (3)$$

Substitute (2) & (3) in (a),

Mechanical power developed

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

$$P_m = \frac{1}{2}\omega i^2\frac{\partial L}{\partial \theta} \rightarrow (4)$$

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

$$\therefore \quad T = \frac{P_m}{\omega} \rightarrow (5)$$

Sub (4) in (5),

$$\left.\begin{array}{l}\text{Reluctance}\\ \text{Torque}\end{array}\right\} T = \frac{1}{2}i^2\frac{\partial L}{\partial \theta}$$

Note:

(i) Torque ⇒ Monitoring when $\frac{\partial L}{\partial \theta}$ is "+ve"

(ii) Torque ⇒ Generating when $\frac{\partial L}{\partial \theta}$ is "-ve"

(iii) Torque is αi^2.

10. Compare SR motor with VR stepper motor [May 2007 Nov 2013] (6m)

SI. No.	Switched reluctance motor (SRM)	Variable reluctance stepper motor
1	The SRM is normally operated with shaft position feedback to synchronize with the rotor position thereby controlling conduction angle and commutation of the phase currents.	The stepper motor is usually fed by a square wave of phase current without rotor position feedback.
2	The SRM motor is designed forefficient power conversion uptoatleast 300KW.	Normally designed to maintain step integrity rather than to achieve efficient power conversion.
3	The SRM usually operates at high speeds	The stepper motor is usually designed as a torque motor with a limited speed range.
4	It is meant for continuous rotation.	It rotates in steps.
5	Closed loop control is essential for its optimal working.	It works in open loop operation.
6	No half step operation and microstepping are possible.	It is capable of half step operation and micro stepping.
7	It has power ratings upto 75 KW(100 HP)	It has comparatively lower power rating.
8	It has higher overall efficiency. The SRM is naturally designed to operate efficiently for wide range of speed.	It has lower efficiency. Efficiency is not an important factor for stepper motor.
9	SRM requires a rotor position sensor.	It does not require rotor positionsensor.
10	Mainly used in domestic applications like vacuum cleaners, washing machines and general purpose industrial drives.	Mainly applied in computer controlled systems and robotics.

13. Discuss the sensorless operation of Switched Reluctance Motor. [May 2013]

Sensorless Control of Switched Reluctance Motor Drive

Switched Reluctance Motors have gained momentum in the highly competitive marker of adjustable speed motor drives. Simple structure and low cost are the most important reasons for this popularity. SRM drives have made a successful entrance into various sectors of industry such as aerospace, automotive, and home appliances. Its Simple construction, due to the absence of magnets, rotor conductors.brushes improve system efficiency over a wide speed range and makes the SRM drive an interesting alternative to other commercially available drives.

The accurate knowledge of the rotor position is required for good performance of the switched reluctance motor drive. The entrance of SRMs in the sensitive applications industries has proved the need for highly reliable and fault tolerant rotor position sensing methods. The need for the rotor angle information in SRM has been traditionally satisfied by the use of some form of rotor position sensor.

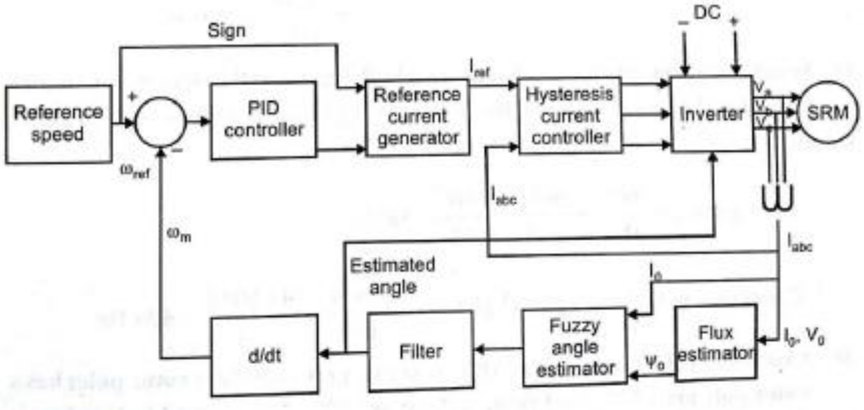
Rotor position sensing is an integral part of SRM control because of the nature of reluctance torque production. In fact, excitations of the SRM phases need to be properly synchronized with the rotor position for effective control of speed, torque and torque pulsation. But it needs a mechanism to detect rotor position for correct operation. An encoder, resolver, or Hall shaft position sensors are usually employed to determine the rotor position. However, these discrete position sensors not only add complexity and to the system but also tend to reduce the reliability of the drive system.

However, in recent years, there have been extensive research activities to eliminate direct rotor position sensors, simply by indirectly determining the rotor position. To avoid additional cost size and unreliability associated with external position sensorsdeveloping a reliable, precise, and low-cost position sensorless control seem necessary

Principle of Operation of the SRM Sensorless Scheme

The fundamental principle of operation of a SRM is based on the variation in flux linkage with the change in the angular position of the rotor. The sensorless scheme relies on the fuzzy based rotor position estimator model of the SRM drive. The dynamics of the SRM drive can be represented by a set of non-linear first-order differential equations. The block diagram of the sensorless scheme is shown in figure 3.48. It consists of various sub-systems necessary for PID speed controlled SRM drive with fuzzy logic used as a rotor position estimator. The flux estimator produces flux linkage by using phase voltage and current as inputs.

The experimental data of flux linkage and phase current are used as inputs to fuzzy estimator and map them in fuzzy rule base for estimating the angle as an output. The suitable type of low pass filter has been used to produce refined estimated angle for inverter operation and simultaneously used to obtain estimated speed for comparison.



Sensorless control of SRM