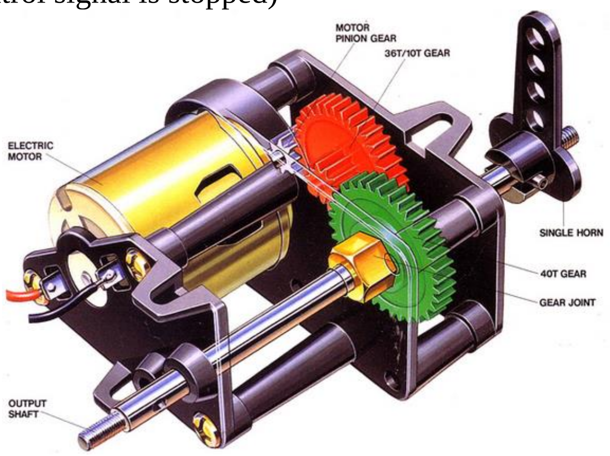
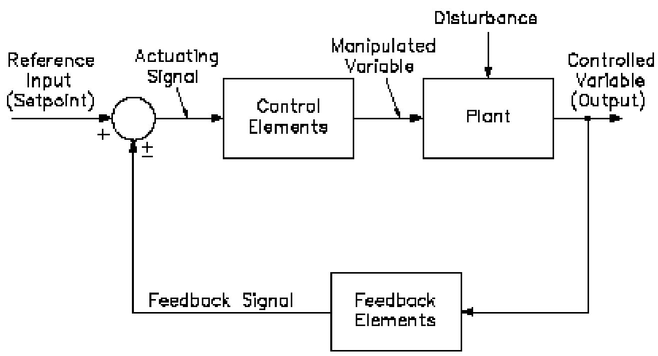
MODULE I

Servomotor

- Motor to rotate a certain angle for a given electrical input (signal) – **Servomotor**
- **Servomechanism** – A feedback control system which is used to control the position of the object (Closed loop control)
- controlling shaft position
- controlling angular speed of the shaft
- Motor driven by control signal based on the error information supplied to the controller
- Motors and can drive the load directly; usually coupled by gear train
- It should have linear torque-speed characteristics
- Output torque at any speed should be proportional to the applied control signal
- Quickly reversible
- Operation should be stable without any oscillations or overshoots
- Response should be very fast with respect to error signal
- Inertia of rotor should be as small (servomotor must stop running without any time delay when control signal is stopped)



Servomotor – Feedback Control



Servomotor Types

- A DC motor with servomechanism is referred as **DC servo motor**.
- A AC motor with servomechanism is referred as **AC servo motor**.
- AC servo-motors are generally preferred for low power use.
- For high-power use DC servomotors are preferred because they operate more efficiently in high-power than AC servo-motors.

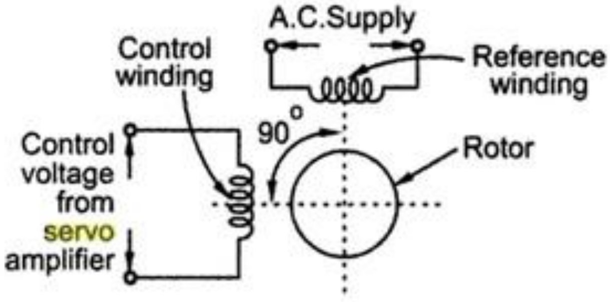
- There are various types of DC servomotors which are

Armature and field controlled DC Servomotor

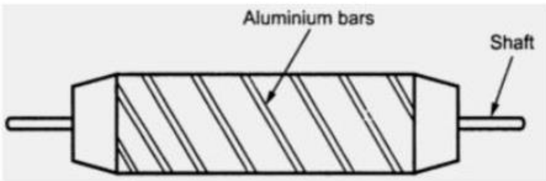
Series motors; Split series motors; Shunt control motor; Permanent magnet shunt motor.

AC Servomotor

- Basically two phase induction motor
- Output power – fraction of watts to few hundred of watts
- Operating frequency is 50 Hz to 400 Hz

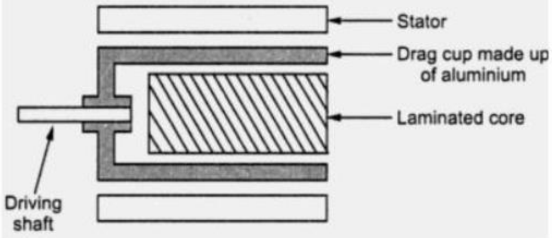


- AC servomotor – Stator & Rotor
- Stator – 2 windings; displaced by 90^0
- Main/fixed/reference winding – constant voltage supply
- Control winding – variable voltage from servo amplifier – 90^0 out of phase with main winding voltage – rotating magnetic field
- Reduce loading on amplifier – control winding input impedance is increased – tuning capacitor in parallel to control winding
- Rotor
- Squirrel cage rotor



- The usual squirrel cage rotor has aluminium bars which are shorted at the ends with the help of the end rings.
- The overall construction looks like a cage. The construction is similar to the squirrel cage rotor used for the three phase induction motors

- Drag cup rotor



- To reduce the inertia further, a drag cup type of rotor construction is used. There are two air gaps in this construction.
- The drag cup is made up of nonmagnetic material like copper, aluminium or an alloy. The slotted rotor laminations used in this construction.

- These are wound for as many number of poles as possible so that operating speed of motor is very low. Such a construction is used in very low power applications.

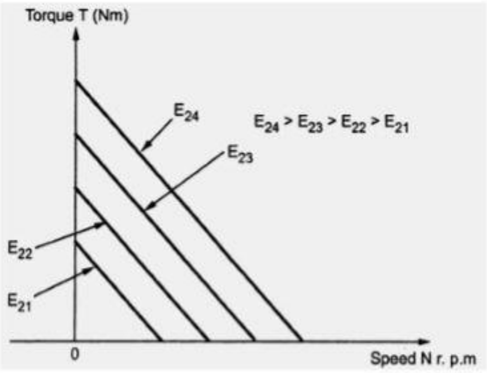
Operating Principle

- The operating principle of two phase a.c. servomotor is same as that of normal three phase induction motor.
- The control voltage applied to the control winding and the voltage applied to the reference winding are 90degree out of phase.
- Hence the flux produces by current through control winding is also 90o out of phase with respect to the flux produced by the current through the reference winding.
- The resultant flux in the air gap is hence rotating flux sweeps over the rotor, the e.m.f. gets induced in the rotor.
- In the two phase a.c. servomotors, the polarity of the control voltage determines the direction of rotation.
- A change in the sign of the control voltage reverses the direction of rotation of the motor. Since the reference voltage is constant, the torque and the angular speed are the functions of the control voltage.

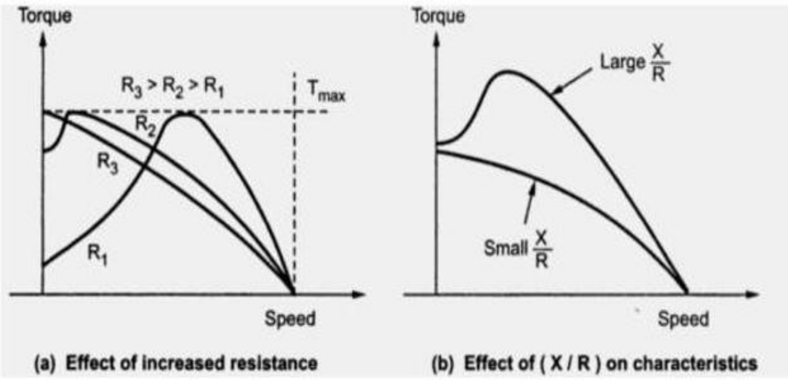
Torque-Speed Characteristics

A servomotor must have

- Linear torque-speed characteristics
- Slope of the torque-speed characteristics must be negative.
- The characteristics must be parallel to one another for various values of the control voltage applies.



Torque-speed characteristics of a.c servomotor

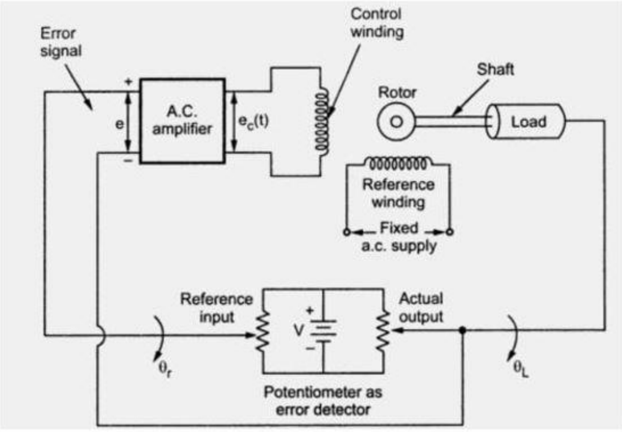


Features (Adv.) of A.C. Servomotor

- Light in weight for quick response.
- Robust in construction.
- It is reliable and its operation is stable in nature.

- Smooth and noise free operation.
- Large torque to weight ratio.
- Large resistance to reactance ratio.
- No brushes or slip rings are required. Hence maintenance free.
- Driving circuits are simple to design.
- The negative slope of the torque-slip characteristics adds more friction improving the damping. This improves the stability of the motor. This features is called **internal electric damping** of two phase AC servomotor.

AC Servomotor Application



Application of a.c. servomotor : A.C. position control system

The other applications of a.c. servomotors.

- Instrument servos
- Process controllers
- Robotics
- Self-balancing recorders
- Machine tools

- The DC servomotors is more or less same as normal DC motor. There is some minor constructional difference between the two. All DC servomotors are essentially separately excited type. This ensures the linear nature of torque-speed characteristics.

Basic Working Principle

- The DC servomotor is basically a torque transducer which converts electrical energy into the mechanical energy. The torque developed on the motor shaft is directly proportional to the field flux and the armature current.

$$T_m=K_m\Phi I_a \quad ....(1)$$

where T_m = Motor Torque

K_m = Proportionality torque constant

Φ = Field flux and I_a = Armature current

In addition to the torque developed, when armature conductors rotate in the field flux, they cut the flux and e.m.f. gets induced in the armature. This e.m.f. is called as back e.m.f. in case of DC motors. It is directly proportional to the shaft velocity ω_m rad/sec.

$$E_m=K_b\Phi\omega_m \quad .....(2)$$

where E_b = Back e.m.f. and K_b = Back e.m.f. constant

ω_m = Motor angular speed in rad/sec

As back e.m.f. opposes the supply voltage, the voltage equation of the DC motor is given by

$$V=E_b+I_aR_a \quad ....(3)$$

where V = Supply voltage

R_a = Armature resistance

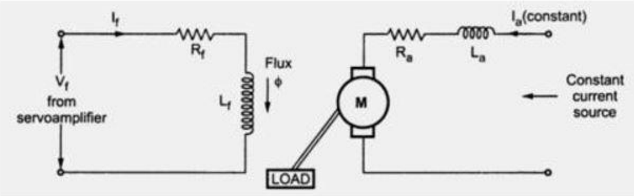
The equations (1), (2) and (3) form the basis of DC servomotor operation.

Basic Classification DC Servomotor

The DC servomotors are classified as

1. Variable magnetic flux motors i.e., Field controlled motors.
2. Constant magnetic flux motors i.e., Armature controlled motors.

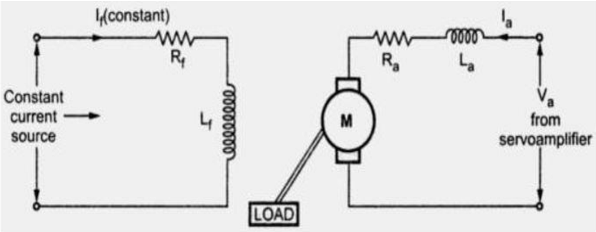
Field controlled DC Servomotor



Features of Field Controlled DC Servomotor

It is preferred for small rated motors. It has large field inductance to resistance ratio. The ratio of inductance to resistances determines the time constant and hence the time constant of field controlled DC servomotor is large. The overall operation is an open loop system. The control circuit is simple to design.

Armature controlled DC Servomotor

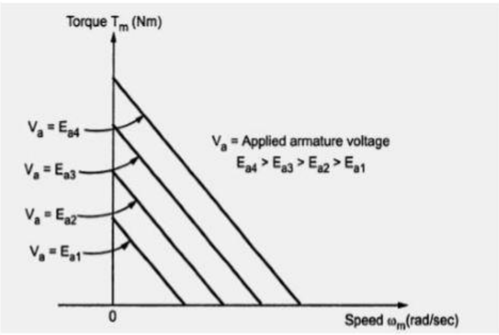


Armature controlled d.c. motor

Features of Armature Controlled D.C. Motor

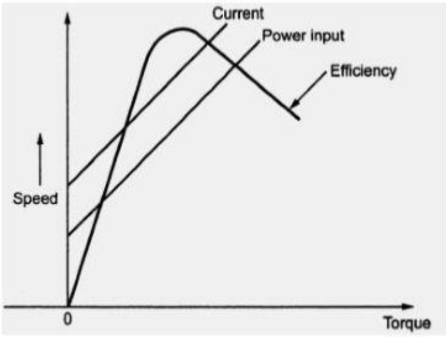
It is suitable for large rated motors. The value of armature inductance is small. Hence its time constant is small. Hence motor can give quick response to the changes in the control signal. The overall operation is a closed loop system. The back e.m.f. provides internal damping which makes the motor operation more stable. The efficiency and overall performance is better than field controlled motor.

Characteristics of a DC Servomotor



Torque-speed characteristics of d.c. servomotor

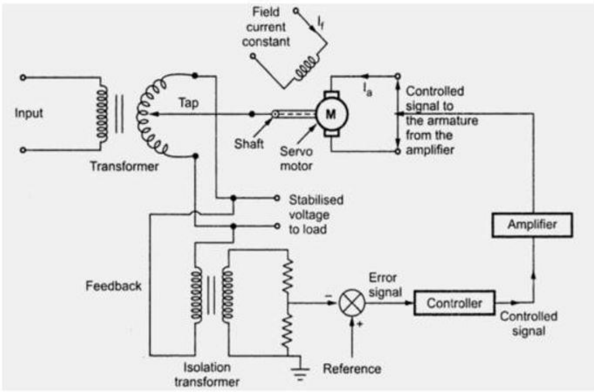
Other Performance Characteristics



Performance characteristics of a typical d.c. servomotor

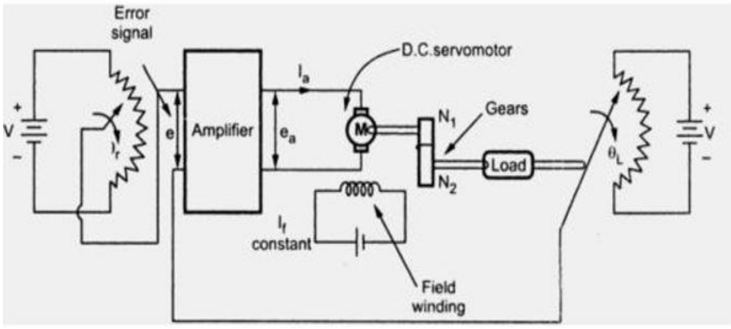
Applications of dc servomotor

Servo-stabilizer



Application of d.c. servomotor : Servostabilizer

Position Control System



Application of d.c. servomotor : D.C. position control system

The other applications of DC servomotors are:

- Air craft control systems
- Electromechanical actuators
- Process controllers
- Robotics
- Machine Tools

Comparison between AC servomotor and DC servomotor

A.C Servomotor	D.C. Servomotor
1) Low power output of about 0.5 W to 100 W.	1) Deliver high power output
2) Efficiency is less about 5 to 20 %.	2) High Efficiency.
3) Due to absence of commutator maintenance is less.	3) Frequent maintenance required due to commutator.
4) Stability problems are less.	4) More problems of stability.
5) No radio frequency noise.	5) Brushes produce radio frequency noise.
6) Relatively stable and smooth operation.	6) Noisy operation.
7) A.C. amplifier used have no drift.	7) Amplifiers used have a drift.

Comparison between Armature Controlled and Field Controlled Servomotors

Field Controlled	Armature Controlled
1) Due to low power requirement amplifiers are simple to design.	1) High power amplifiers are required to design
2) Control voltage is applied to the field.	2) Control voltage is applied to the armature.
3) Time constant is large.	3) Time constant is small.
4) This is open loop system.	4) This is closed loop system.
5) Armature current is kept constant.	5) Field current is kept constant.
6) Poor efficiency.	6) Better efficiency.
7) Suitable for small rated motors.	7) Suitable for large rated motors.
8) Costly as field coils are must.	8) Permanent magnet can be used instead of field coils which makes the motor less expensive.

MODULE 2

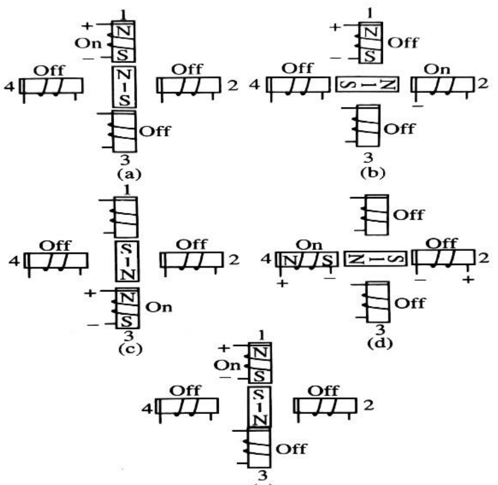
STEPPER MOTOR

- Stepper motor are also called stepping motors or step motors.
- A stepper motor is a special electrical machine which rotates in discrete angular steps in response to a programmed sequence of input electrical pulses.
- The stepper motor works on the principle that a magnetic interaction takes place between the rotor and the stator , which makes the rotor move.
- Step Angle $\beta = (360^0$ / No. of stator phases x No. of rotor teeth

$$\beta = (360^0 / m N_r)$$

PRINCIPLE OF OPERATION

- When Stepper motor receives a step, it will rotate through some precise angle which depends upon the type of stepper motor and the stop until the next pulse is received.
- The total angle of displacement of shaft is equal to step angle multiplied by the number of pulses.
- Consider a rotor with two permanent poles and four(1,2,3,4) stationary electro magnets surrounding the rotating rotor, the four electro magnets are called as stator.
- When Magnet 1 is activated by applying a voltage pulse, the rotor will get aligned to Magnet 1.
- When Magnet 1 is de-activated and Electro magnet 2 is activated, this will cause rotor to move 90^0 in clockwise direction towards right electro magnet, aligning itself with the active magnet.
- This process will be repeated in the same manner when magnet 3 ,4 and 1 gets activated until the rotor reaches the starting position
- It requires 4 steps to complete one revolution.



Principle of Operation of Stepper Motor

Types of Stepper Motors

- Variable reluctance (VR) stepper motor

    1) Single stack VR stepper motor

    2) Multi stack VR stepper motor

- Permanent magnet stepper motor
- Hybrid stepper motor

Variable Reluctance (VR) Stepper Motor

- VR stepper motor works on the principle that a magnetic material placed in a magnetic field experiences a force to align it in a path of minimum reluctance.
- A stator with salient poles that have concentric windings which form different phases. The stator phases are excited by current pulses to establish a magnetic field.
- Rotor has salient structure with projecting teeth and has no windings or permanent magnet.
- Classified as

    1) Single stack VR stepper motor

    2) Multi stack VR stepper motor

Single stack VR stepper motor
<u>CONSTRUCTION</u>

STATOR

- ➢ Stator is made up of silicon steel stampings.
- ➢ Projecting poles.
- ➢ Poles carry concentric windings.
- ➢ There are four independent stator circuits or phases A,B C and D ,each one can be energized by a direct current pulse from the drive circuit.
- ➢ Eight stator coils are connected in 2 coil groups form has four separate circuits called phases.
- ➢ Each phase has its own independent switch
- ➢ Diametrically opposite pairs of stator coils are connected in series such that when one tooth becomes a N- pole , the other one becomes a S-pole.

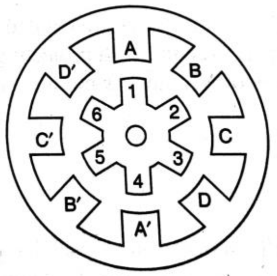
ROTOR

- ➢ Made up of laminated silicon steel.
- ➢ Projecting teeth on its outer periphery.
- ➢ Permanent magnets.

- No. of rotor teeth and the stator poles should not be equal. This is to make the motor self starting and also have a bidirectional rotation of rotor.

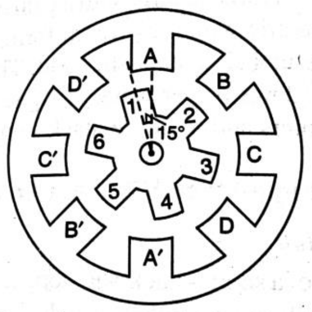
WORKING

- Rotor teeth can assume any position until the stator winding is energized.
- All switches S_1 to S_4 in OFF position initially.
- Turn ON S_1 , so that phase A is energized. This will make stator poles A and A' as north and south magnetic poles.
- The stator poles attract rotor teeth moves to occupy a position of minimum reluctance. Thus rotor teeth 1 and 4 take the rest positions as shown below



Rotor position when phase A is excited

- Next switch S_2 is turned ON and S_1 is turned OFF.
- This operation de energizes phase A and excites phase B.
- The rotor will move in such a direction to occupy the minimum reluctance path by travelling minimum angular distance. This is achieved by the movement of the rotor in counterclockwise direction by 15^0 . The rotor takes its equilibrium position.



Rotor position when phase B is energised

- The angle through which the rotor moves for a switching operation is called step angle by
- β = (360^0 / No. of stator phases x No. of rotor teeth
- β = (360 / (4x6)) = 15^0
- With S_2 OFF and S_3 ON , the rotor moves again by 15^0 in the CCW direction and comes to rest in the as shown below figure.

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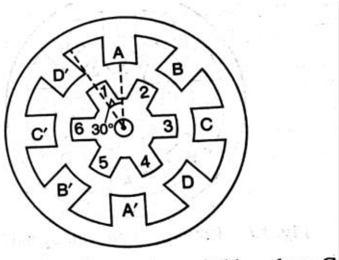
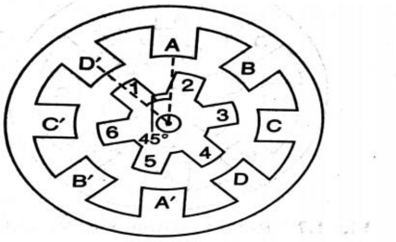


Position of rotor after switching phase C

- By switching S_4 ON and S_3 OFF, the rotor rotates by 15^0 in CCW direction and takes the root position shown in figure below. By continuing this switching operation in the sequences S_1 , S_2 , S_3 , S_4 , S_1 , …….. Rotor moves in CCW direction with step angle of 15^0 .



Rotor position after switching phase D

Table 1.1 Truth table

S_1	S_2	S_3	S_4	θ
1	0	0	0	0
0	1	0	0	15°
0	0	1	0	30°
0	0	0	1	45°
1	0	0	0	60°

1 – ON; 0 – OFF

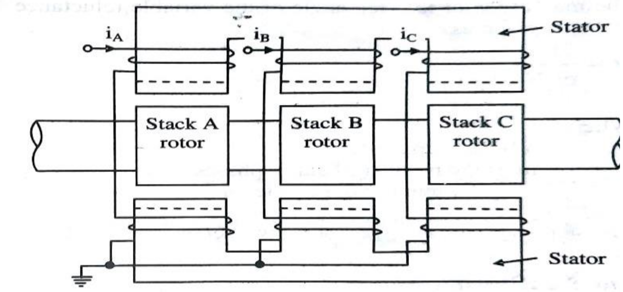
Multi stack VR stepper motor

➢ A multi stack (or m-stack) variable reluctance stepper motor can be considered to be made up of 'm' identical single stack variable reluctance motors with their rotors mounted on a single shaft.

➢ The stators and rotors have the same number of poles (or teeth).

➢ All the stator pole windings in a given stack are exited simultaneously and, therefore the stator winding of each stack forms one phase.

➢ Motor has the same number of phases as number of stacks.



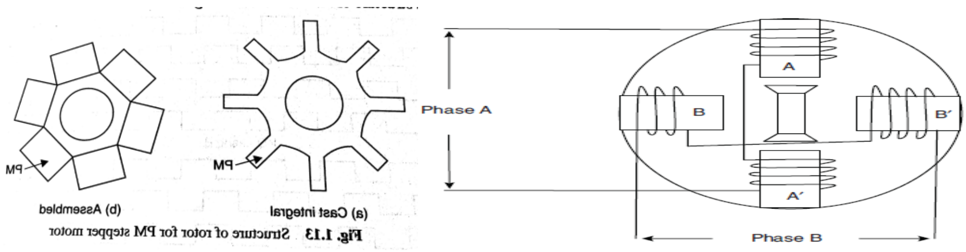
➢ In each stack, stator and rotors have 12 poles (teeth. The stator teeth in each stack are aligned. When the phase winding A is excited rotor teeth of stack A are aligned with the stator teeth.

➢ When phase A is de-energized and phase B is excited the rotor teeth of stack B are aligned with stator teeth. The new alignment is made by the rotor movement of 10° in the anticlockwise direction. Thus the motor moves one step due to change of excitation from stack A to stack B

- Step angle : (360/ (3 X 12)) → 10°
- Next phase B is de-energized and phase C is excited. The new alignment is made by the rotor movement of 10° in the anticlockwise direction.
- Another change of excitation from stack C to stack A will once more align the stator and rotor teeth in stack A.
- During this process (A → B → C → A) the rotor has moved one rotor tooth pitch.

Permanent Magnet Stepper Motor

- In a permanent magnet stepper motor, the rotor is made up of permanent magnet and the stator is same as that of variable reluctance stepper motor. It operates on the reaction between a permanent magnet rotor and the electromagnetic field.
- Similar to that of a VR stepper motor.
- Stator consists of salient poles wound with concentric coils. The coils are grouped and connected in series to form different phases.
- The rotor carries no windings but has permanent magnets. The rotor can be made in the form a PM spider cast integral or an assembled structure.



WORKING

- Consider two phase motor, it has four stator poles and two rotor poles.
- When a phase is energized, it sets up a magnetic flux and rotor will position to lock its N pole and S pole to stator S pole and N pole respectively.
- Different modes of operation

1) Single phase ON mode

2) Two phase ON mode

3) Alternate one - phase and two - phase mode

1) Single phase ON mode

- When phase A is energized , the N pole of the rotor S pole formed by stator phase A get interlocked and further movement of the rotor is arrested. Then phase B is energized and de energizes the phase A , thus the rotor is moves by 90^0 in clockwise direction and takes the position.

- This sequence of switch operations is repeated so that for each operation the rotor moves in clockwise direction with step angle 90^0 .

· Permanent magnet stepper motor when one phase is energised at a time

Phase A	Phase B	θ
ON	OFF	0
OFF	ON	90
ON	OFF	180
OFF	On	270
ON	OFF	360=0

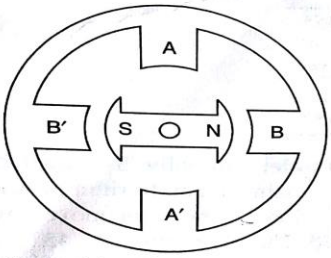


Fig. 1.15 Position of rotor when B is energised

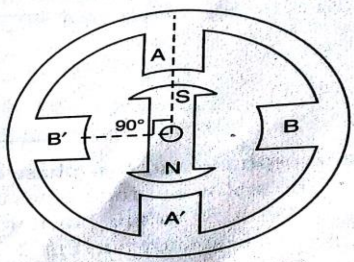
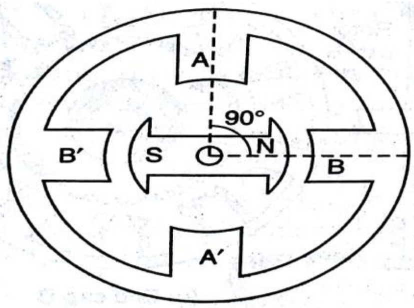
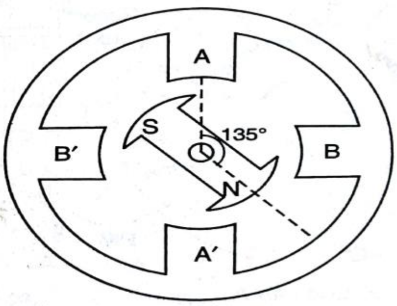


Fig. 1.16 Position of rotor when A is energised

2) Alternate one - phase and two - phase mode / half step mode

- Initially phase A is energized , the stator and rotor poles attract but the rotor remains in equilibrium position.
- Then the phase B is also energized, the rotor moves by 45^0 in clockwise direction and occupies the position.
- De-energizes the phase A ,thus the rotor moves by 45^0 in clockwise direction and occupies the equilibrium position.
- This sequence of switch operations is repeated so that for each operation the rotor moves in clockwise direction with step angle 45^0 .





Permanent magnet stepper motor when one and two phases are energised in sequence

Phase A	Phase B	θ
ON	OFF	0
ON	ON	45
OFF	ON	90
ON	ON	135
ON	OFF	180
ON	ON	255
OFF	OF	270
ON	ON	315
ON	OFF	0

Hybrid Stepper Motor

- The system incorporates the advantages of both permanent magnet and variable reluctance types and utilizes a special arrangement of permanent magnet poles over the entire concentric multi-toothed rotor/shaft assembly.
- Stator is made up of soft iron stampings.
- Stator poles are provided with windings. Windings on diametrically pole pair are connected in series to form a phase.
- Phases are energized by a DC source.
- At the centre of the rotor , an axially magnetized cylindrical permanent magnet is mounted on the shaft. This PM produces unipolar magnetic field.
- The stator magnetic field produced by external excitation.
- Two end caps made of laminated silicon sheet steel cover the poles of the PM.

<u>WORKING</u>

- Consider a four pole two – phase HSM with 15 rotor teeth on each rotor section.
- Coils wound on poles A and A' are connected in series to form phase A and on pole B and B' form phase B.
- Step angle = $(360/N_r \text{ X } m)$

  $= (360/\ 30 \text{ X } 2) = 6^0$
- PM is assumed to be mounted on the shaft in such a way that teeth of rotor1 are magnetized south and those of rotor2 are magnetized north.
- Switching circuit for exciting the phases as shown below

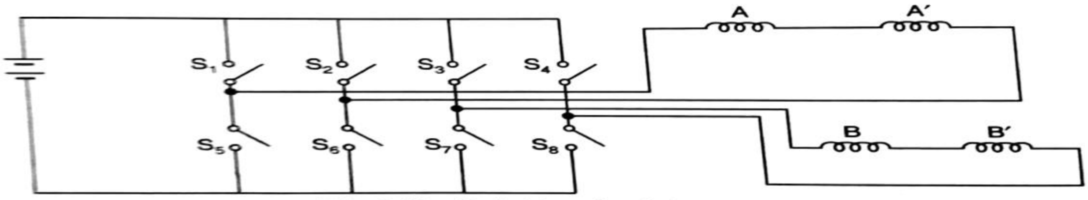


Fig. 1.24 Switching circuit for HSM

- When S_1 and S_6 is in ON position, the phase A is excited.

- This will make pole A magnetized as north and A’ as south.
- This will cause attraction of some teeth of rotor 1 towards pole A and few teeth of rotor 2 towards pole A’.
- The rotor moves by 6^0 in clockwise direction and occupies the position.

➢ When S_1 and S_6 are switched off and S_3 and S_8 are switched ON.

- It magnetize pole B and B’ as north and south respectively.
- Rotor teeth again move by 6^0 in clockwise position and stay in position.

➢ When S_3 and S_8 are switched OFF and S_2 and S_5 are switched ON.

- It magnetize pole A and A’ as north and south respectively.
- Rotor teeth again move by 6^0 in clockwise position and stay in position.

➢ When S_2 and S_5 are switched off and S_4 and S_7 are switched ON.

- It magnetize pole B and B’ as north and south respectively.
- Rotor teeth again move by 6^0 in clockwise position and stay in position.

(a) One-phase mode

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1	0	0	0	0	1	0	0
0	0	1	0	0	0	0	1
0	1	0	0	1	0	0	0
0	0	0	1	0	0	1	0
1	0	0	1	0	1	1	0

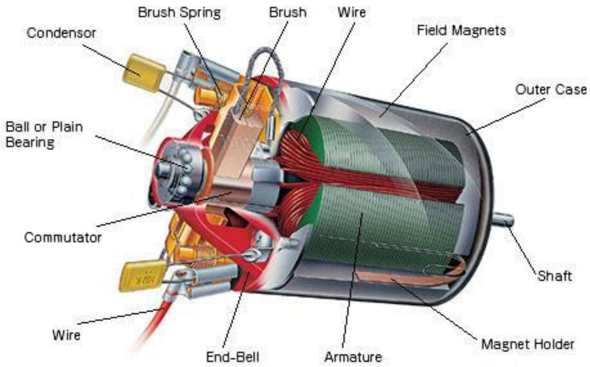
COMPARSION BETWEEN DIFFERENT STEPPER MOTORS

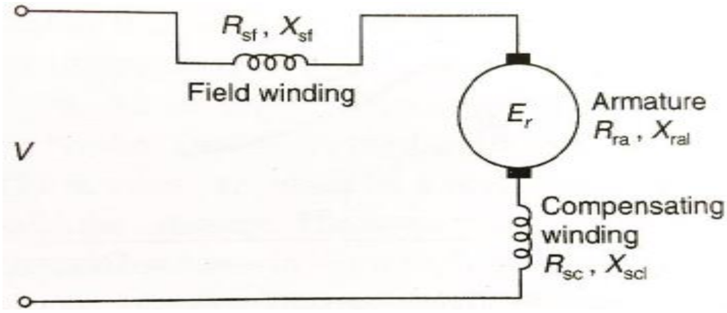
Motor type	Advantages	Disadvantages
Variable Reluctance Motor	1. Robust –No magnet 2. Smooth movement due to no cogging torque. 3. High stepping rate and speed slewing capability.	1. Vibrations 2. Complex circuit for control 3. No smaller step angle 4. No detent torque.
Permanent Magnet Stepper Motor	1. Detent torque 2. Higher holding torque 3. Better damping	1. Bigger step angle 2. Fixed rated torque. 3. Limited power output and size
Hybrid Stepper Motor	1. Detent torque 2. No cumulative position error 3. Smaller step angle 4. Operate in open loop	1. Resonance 2. Vibration

MODULE III

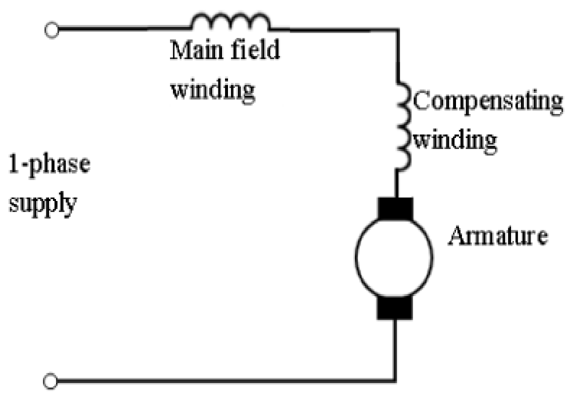
AC Series Motors

- Stator is made up of laminations and has salient poles. Usually two or four poles are employed
- Machine wound field coils are provided on the stator poles
- Rotor is also laminated with slots to accommodate armature winding
- Rotor windings are connected to commutator segments mounted on the shaft.
- Stator winding and rotor windings are connected in series with the aid of high resistance brushes (placed on the commutator)
- Armature reaction causes reduction in air gap flux and for compensating the same, compensating windings are connected in series with the stator winding.

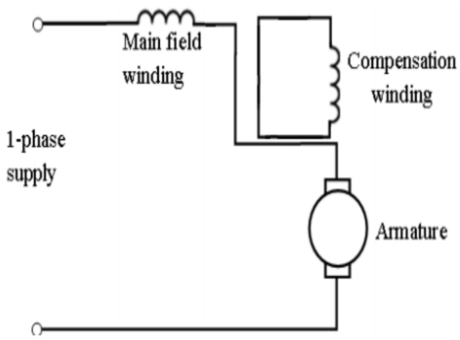




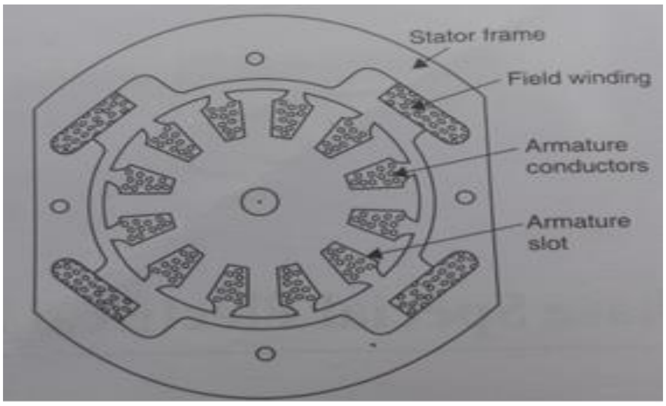
Conductively compensated winding



Inductively compensated winding



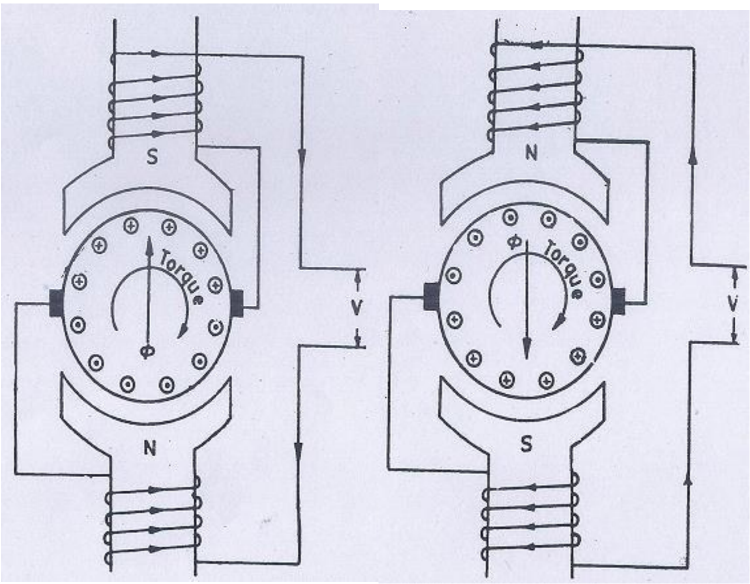
AC Series Motor Construction

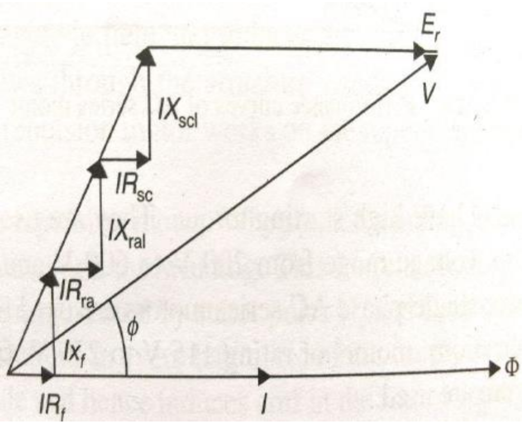


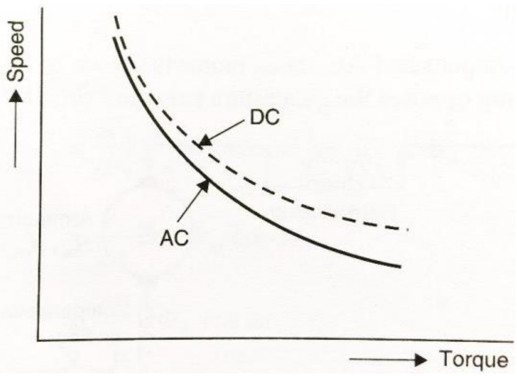
Operation of AC Series Motor

- The working principle of an A.C. series motor is the same as that of the D.C. series motor.
- The armature and field are wound and interconnected in the same manner as the D.C. series motor.
- During positive cycle, assume that the top field pole in figure below is SOUTH. The direction of current is “into to this surface”. When applying Fleming’s Right-hand rule, we can see that the direction of torque (force) is in clock wise direction.
- When an alternating EMF is applied to the terminals, since field and armature windings are connected in series, the field flux and armature current reverse simultaneously every half cycle, but the direction of the torque remains unchanged.
- The torque is pulsating, but its average value is equal to that which a D.C. motor will develop if it had the same RMS. value of flux and current.
- Motor connections, direction of torque, etc. for two successive half cycles are shown in Figure. In each half cycle, the magnetic polarity as well as armature current direction reverses.

Operation of AC Series Motor







Phasor Diagram Torque Speed Characteristics

Applications

- Grinding mills
- Mixers
- Electric drillers
- Electric traction

Universal motor

Can run on both single-phase AC and DC supply hence the name universal. It is also highly modified so that it can run on both types of current. Whether the universal motor is connected to AC or DC supply, it will still work as a DC series motor due to its design and modifications. It has low speed at full load and high speed at low load.

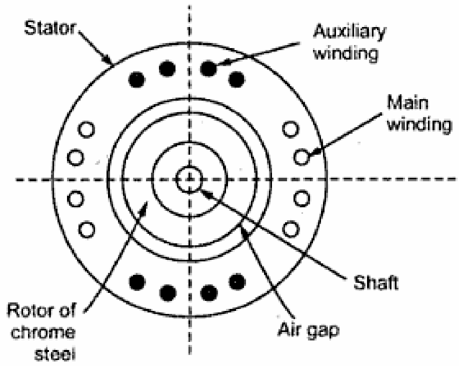
Hysteresis Motor

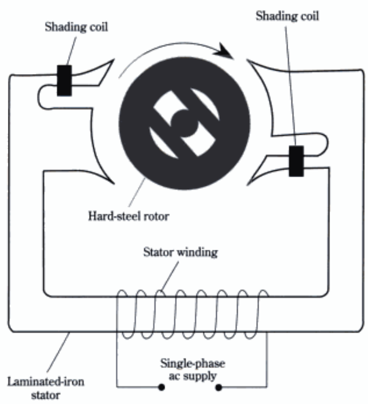
A hysteresis motor is a synchronous motor without salient (or projected) poles and without dc excitation which starts by virtue of the hysteresis losses induced in its hardened steel secondary member by the revolving filed of the primary and operates normally at synchronous speed and runs on hysteresis torque because of the retentivity of the secondary core.

Hysteresis Motor-Construction

Stator:

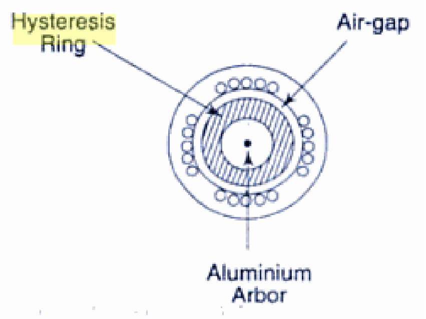
- A stator designed to produce a synchronously-revolving field from a single-phase supply.
- The stator carries main and auxiliary windings (which is called split phase hysteresis motor) so as to produce rotating magnetic field





Rotor:

- The rotor of hysteresis motors are made with magnetic material of high hysteresis losses. i.e. whose hysteresis loop area is very large

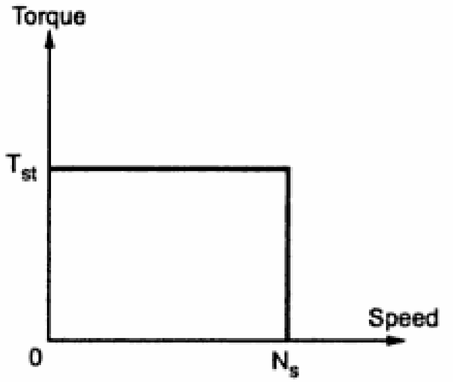


Hysteresis Working Principle

- When stator is energized, it produces rotating magnetic field.
- The rotor, initially, starts to rotate due to eddy-current torque and hysteresis torque developed on the rotor. Once the speed is near about the synchronous, the stator pulls rotor into synchronism.
- As relative motion between stator field and rotor field vanishes, so the torque due to eddy currents vanishes.
- Due to the hysteresis effect, rotor pole axis lags behind the axis of rotating magnetic field. Due to this, rotor poles get attracted towards the moving stator poles.
- Thus, rotor gets subjected to torque called hysteresis torque. This torque is constant at all speeds.

Torque-Speed Characteristics

- The starting and running torque is almost equal in this type of motor.
- As stator carries mainly the two-windings its direction can be reversed interchanging the terminals of either main winding or auxiliary winding.



Advantages of Hysteresis Motor

- As rotor has no teeth, no winding, there are no mechanical vibrations.
- Due to absence of vibrations, the operation is quiet and noiseless.
- Suitability to accelerate inertia loads.
- Possibility of multispeed operation by employing gear train.

Disadvantages of Hysteresis Motor

- The output is about one-quarter that of an induction motor of the same dimension.
- Low efficiency
- Low power factor
- Low torque
- Available in very small sizes

Applications of Hysteresis Motor

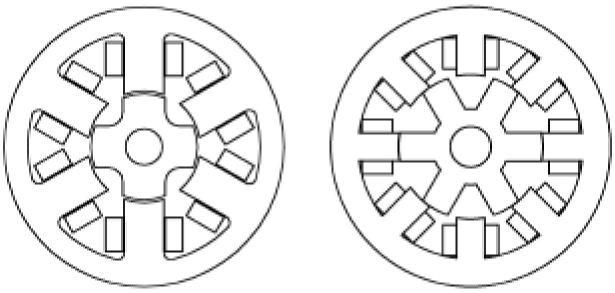
- Due to noiseless operation it is used in sound recording instruments, sound producing equipments, high
- quality record players, electric clocks, tele printers, timing devices etc

MODULE IV

Switched Reluctance Motor

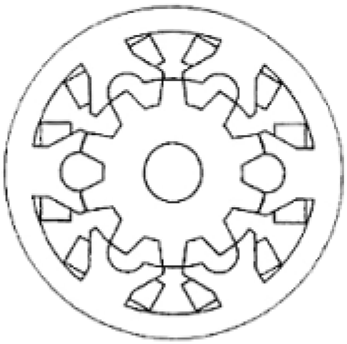
SRM Principle

Reluctance torque into mechanical power both the stator and rotor - salient-pole; high O/p torque. No windings or permanent magnets or commutator, brush on the rotor. Torque is produced by the alignment tendency of poles. Rotor will shift to a position where reluctance is to be minimized and thus the inductance of the excited winding is maximized.



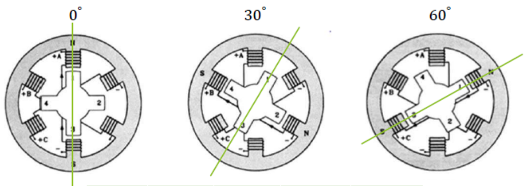
6/4 Pole 8/6 Pole

(a)



(b)

SRM Working



Cycle	Phase A	Phase B	Phase C	Position
1	ON	OFF	OFF	0
	OFF	ON	OFF	30
	OFF	OFF	ON	60
2	ON	OFF	OFF	90
	OFF	ON	OFF	120
	OFF	OFF	ON	150
3	ON	OFF	OFF	180

Characteristic features of SRM

- Low cost (no permanent magnet)
- Torque-inertia ratio: High
- Simple construction & Robust
- High tolerance
- High efficiency
- Max operating speed

- Similar to Variable reluctance stepper motor – closed loop; rotor position feedback

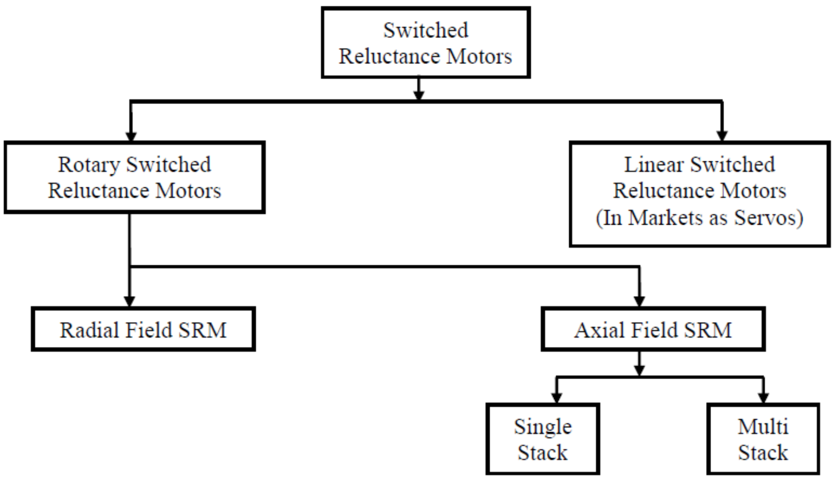
SRM Disadvantages

- Rotor position sensors required
- Torque ripples are high
- Acoustic noise is present

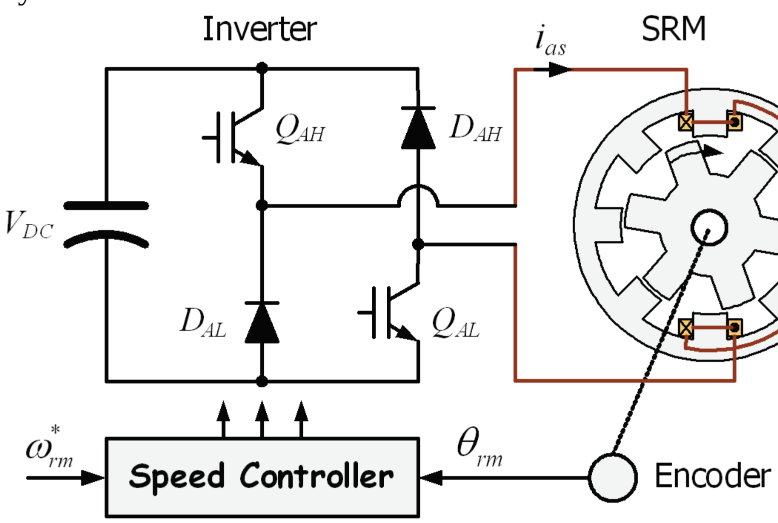
SRM Applications

- General purpose industrial drives;
- Application-specific drives: compressors, fans, pumps, centrifuges;
- Domestic drives: food processors, washing machines, vacuum cleaners;
- Electric vehicle application;
- Aircraft applications;
- Servo-drive.

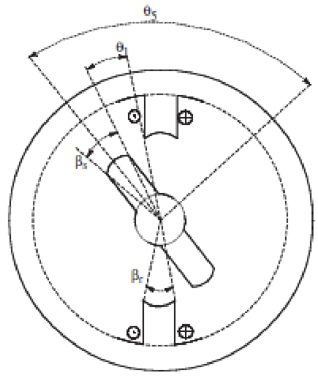
SRM Types



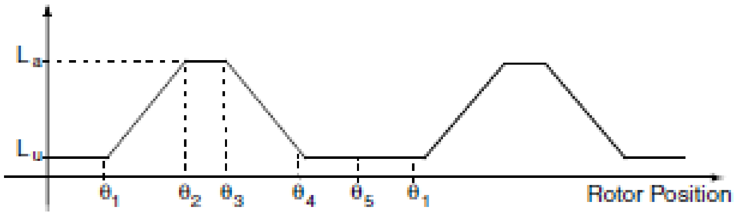
SRM Driving System



Magnetic circuit of SRM
Rotor position of two pole SRM



where βs *and βr are stator and rotor pole arcs, respectively*
Pr is the number of rotor poles
Inductance Profile



$$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{P_r} - (\beta_s + \beta_r)\right]$$

$$\theta_2 = \theta_1 + \beta_s$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s)$$

$$\theta_4 = \theta_3 + \beta_s$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r}$$

- Four Regions:
- 0 − θ1 and θ4 − θ5:

stator and rotor poles are not overlapping
flux is determined by the air path
inductance minimum; unaligned inductance, *Lu*
NO torque production

- θ1 − θ2:

stator and rotor poles are overlapping
flux pass through stator-rotor laminations
increasing inductance, positive slope
current impressed in the winding; positive torque

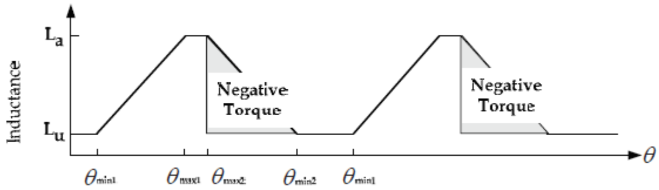
This region comes to an end when the overlap of poles is complete

- $\theta 2 - \theta 3$:

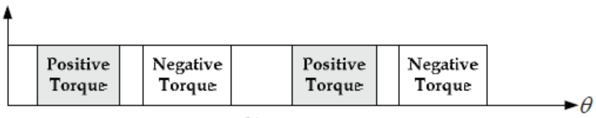
Movement of rotor; but stator and rotor overlap
flux passes through stator and rotor poles
inductance maximum, aligned inductance, *La*
Maximum torque

- $\theta 3 - \theta 4$:

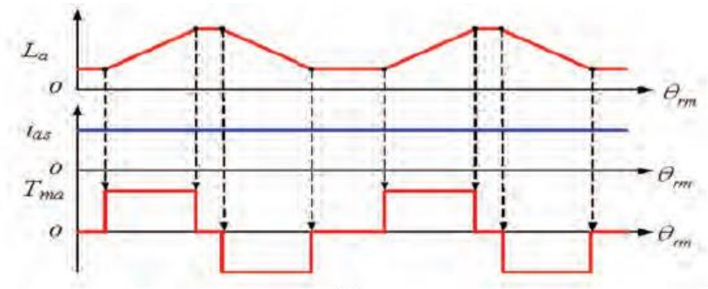
rotor pole is moving away from overlapping the stator pole
flux is determined by the air path, similar to $\theta 1 - \theta 2$ region
Decreasing inductance, negative slope
negative torque production
Inductance and Torque



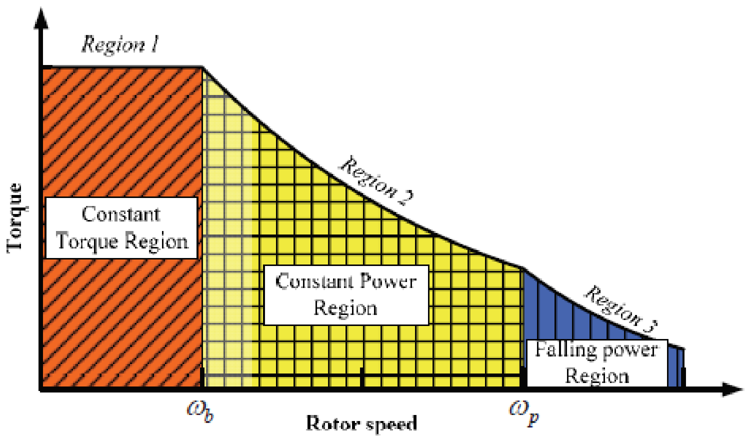
(a) Inductance profile



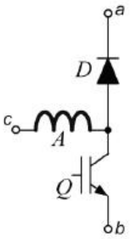
(b) Torque zone



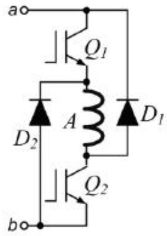
Torque-Speed Characteristics



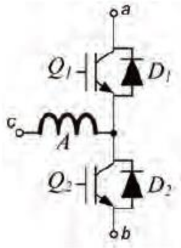
Power Converters



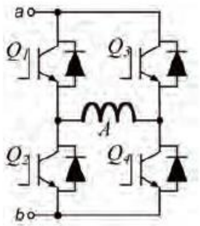
(a) One switch



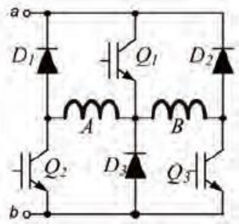
(b) Asymmetric



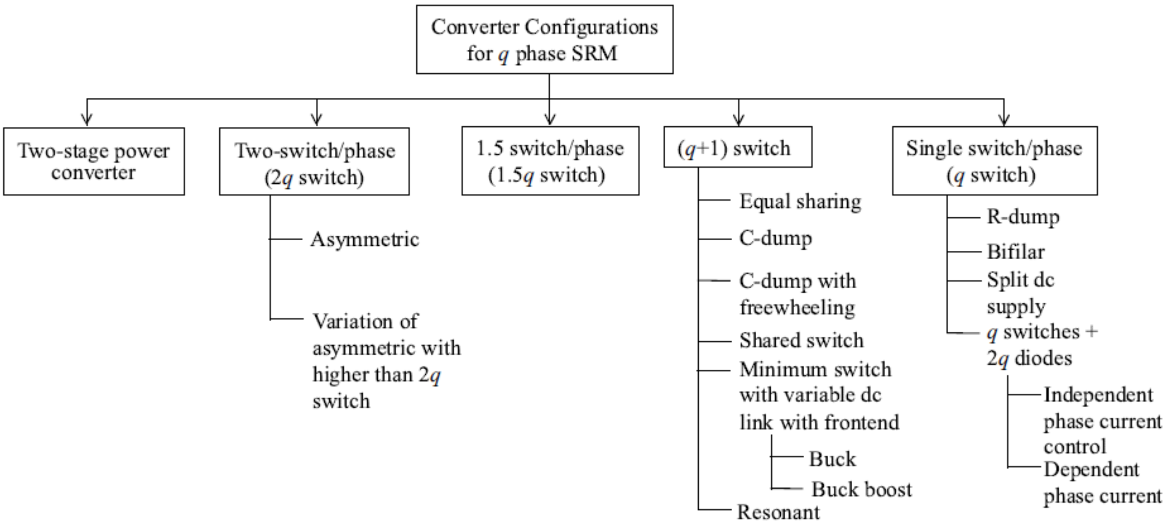
(c) Bidirectional



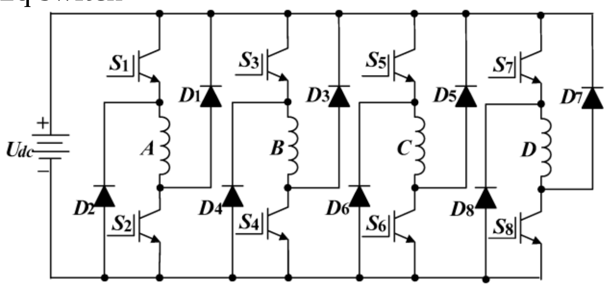
(d) Full bridge



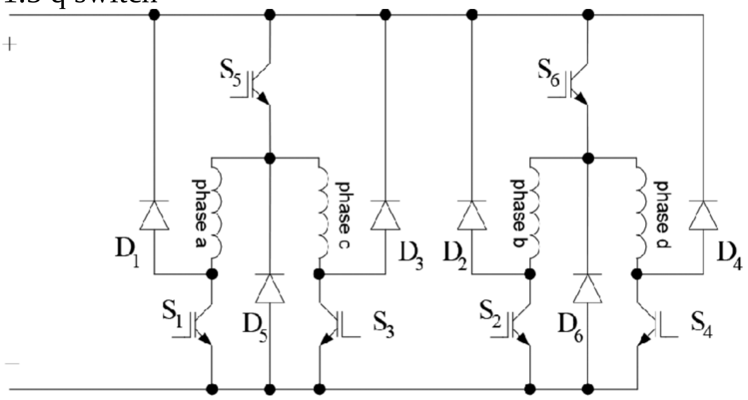
(e) Shared switch

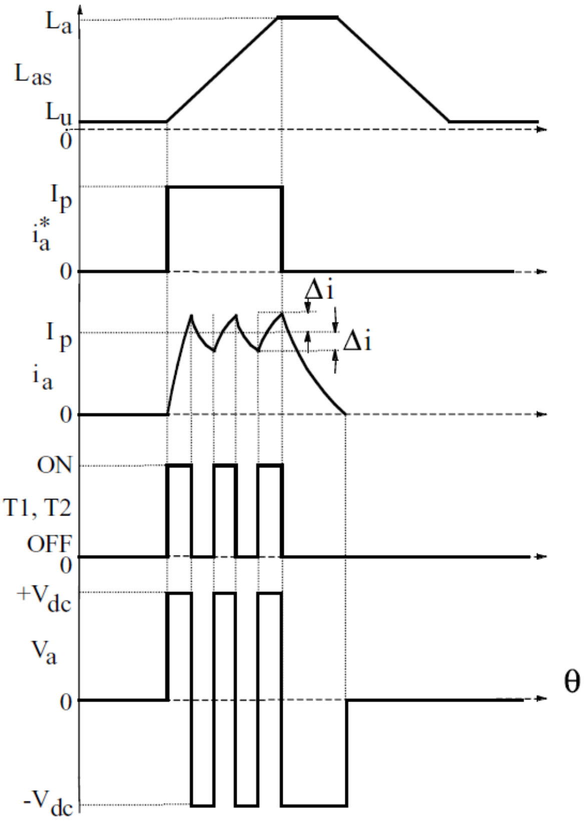


Asymmetric bridge
2q switch

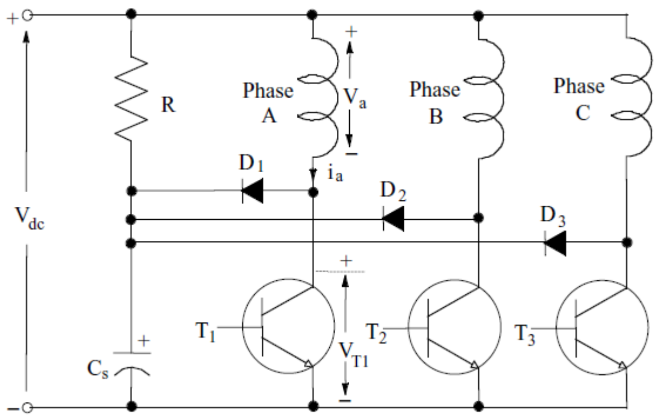


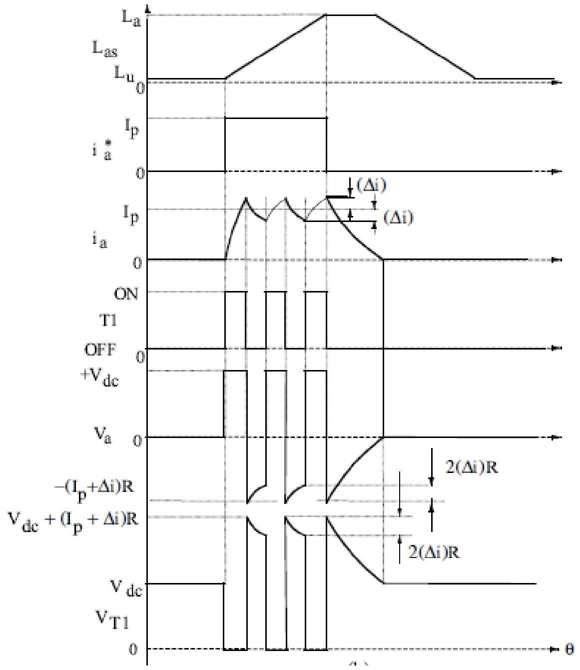
1.5 q switch



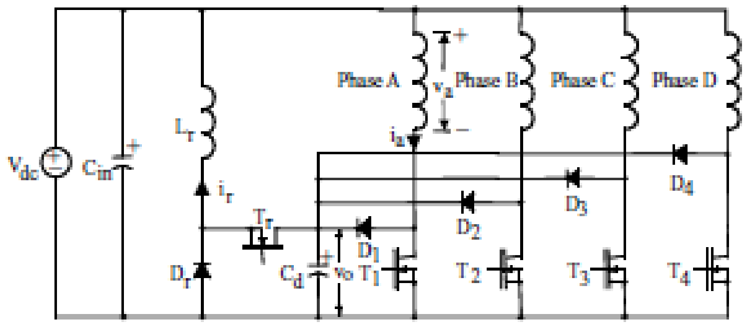


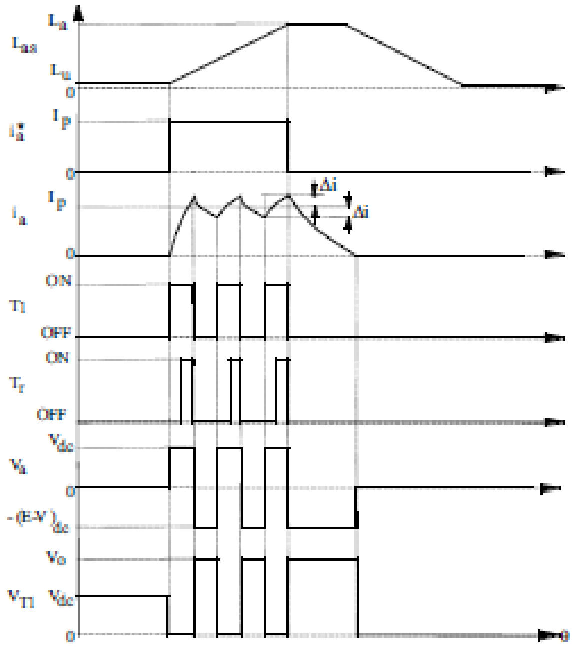
R-dump (q switch)



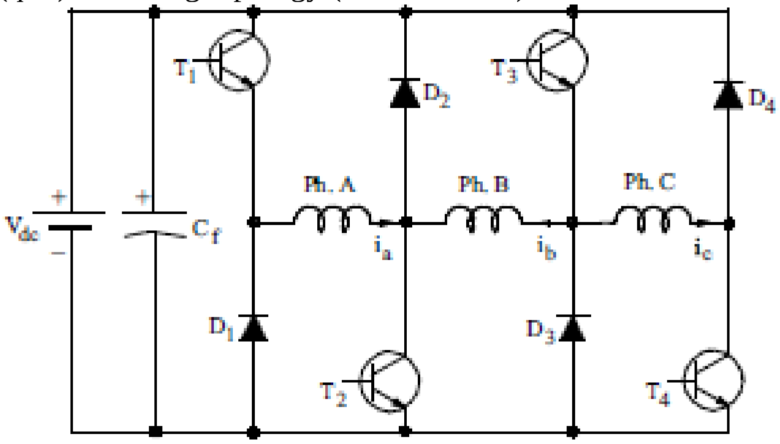


C-dump converter (q+1 switch)

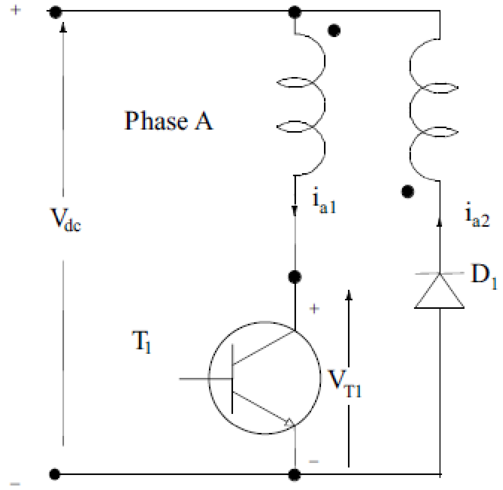


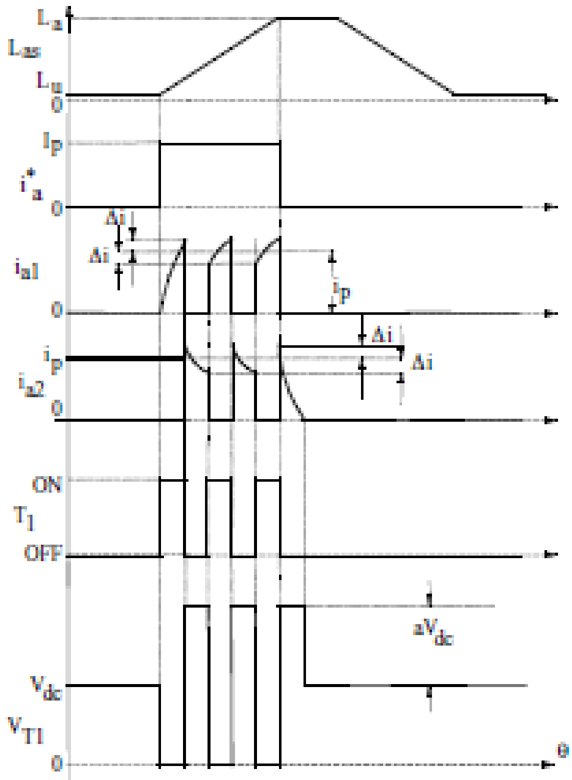


(q+1) switching topology (shared switch)



Bifilar type (q switch)





Voltage and Torque Equation

By Faraday's Law of Electromagnetic Induction, the EMF induced is given by

$$e=-\frac{d\psi(\mathrm{i},\theta)}{dt}$$

Where $\psi(\mathrm{i},\theta)$ is the flux linkage which is a function of current and rotor angle;

$$\frac{d\psi(\mathrm{i},\theta)}{dt}=L\frac{di}{dt}+i\frac{dL}{dt}$$

$$\frac{d\psi(\mathrm{i},\theta)}{dt}=L\frac{di}{dt}+i\frac{dL}{d\theta}\cdot\frac{d\theta}{dt}$$

$$\frac{d\psi(\mathrm{i},\theta)}{dt}=L\frac{di}{dt}+\omega i\frac{dL}{d\theta}$$ Since, angular velocity $\omega=\frac{d\theta}{dt}$

Hence, magnitude of emf is given by

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

Hence, power developed is given by

$$ei=Li\frac{di}{dt}+\omega i^2\frac{dL}{d\theta}$$

The energy stored in a magnetic field is given by;

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

Power due to variation in this magnetic field is;

$$\frac{dW_e}{dt}=\frac{1}{2}L\cdot 2i\frac{di}{dt}+\frac{1}{2}i^2\frac{dL}{dt}$$

$$\frac{dW_e}{dt}=\frac{1}{2}L\cdot 2i\frac{di}{dt}+\frac{1}{2}i^2\frac{dL}{d\theta}\cdot\frac{d\theta}{dt}$$

$$\frac{dW_e}{dt}=Li\frac{di}{dt}+\frac{1}{2}\omega i^2\frac{dL}{d\theta}$$

Hence, Mechanical power developed is given by

P_m = Power developed from supply – power variation in magnetic field

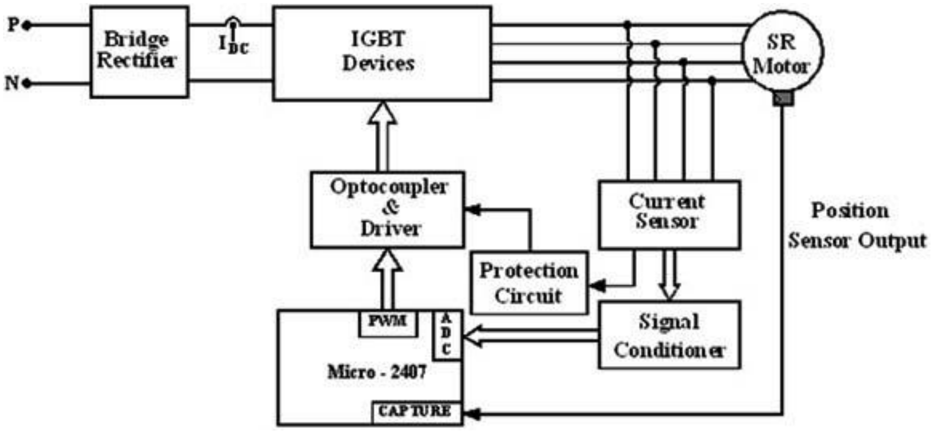
$$P_m=\left(Li\frac{di}{dt}+\omega i^2\frac{dL}{d\theta}\right)-\left(Li\frac{di}{dt}+\frac{1}{2}\omega i^2\frac{dL}{d\theta}\right)$$

$$P_m=\frac{1}{2}\omega i^2\frac{dL}{d\theta}$$

Hence, torque developed is given by;

$$T=\frac{P_m}{\omega}=\frac{1}{2}i^2\frac{dL}{d\theta}$$

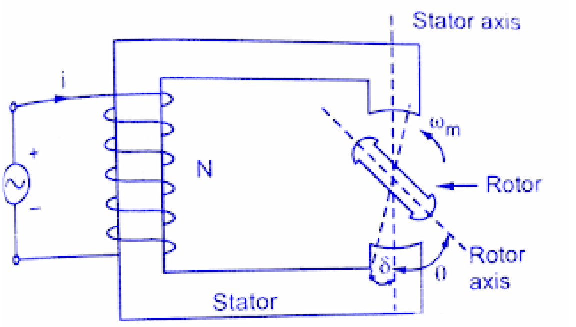
Microprocessor based control of SRM



Reluctance Motor

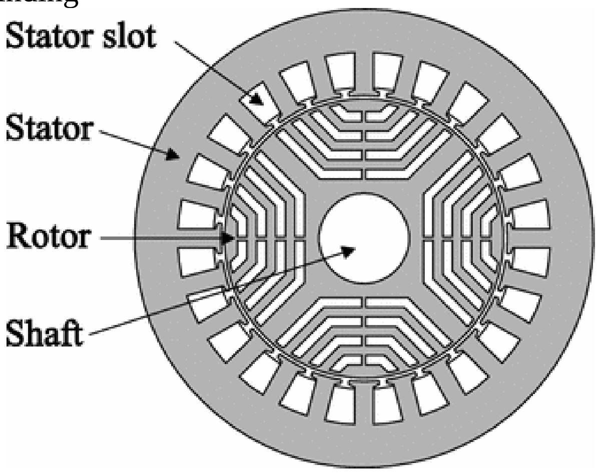
Single-phase or Three-phase rotor turns in synchronism with the rotating magnetic flux induction motor with a modified squirrel-cage rotor and salient poles.

Single phase Reluctance motor



Stator:

- Main Winding
- Auxiliary winding

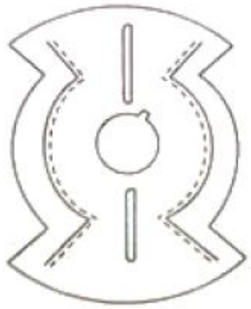


- Main winding: no rotating magnetic field
- Auxiliary winding: with series capacitor – produce rotating magnetic field
- Split phase technique of production of the rotating magnetic field
- Speed of magnetic field is the synchronous speed which is decided by the number of poles

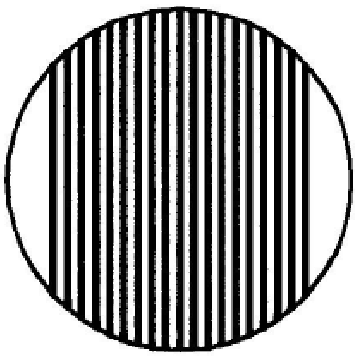
Rotor:

- Rotor of a reluctance motor is made up with **soft magnetic material** -some **rotor teeth are removed** at appropriate places to produce **salient poles**

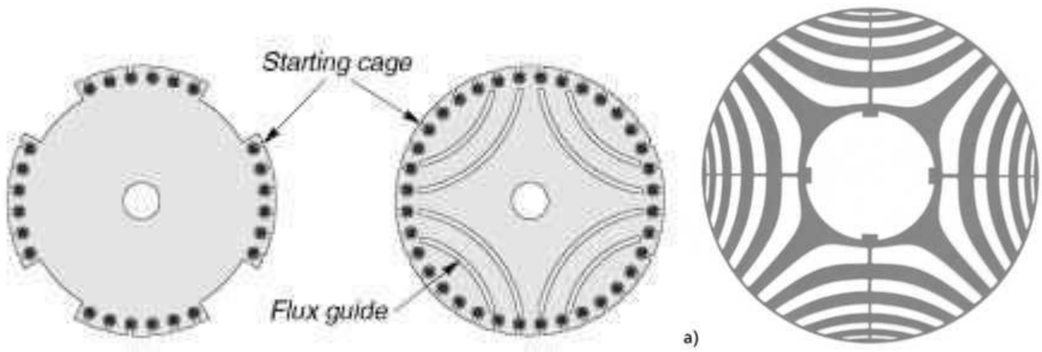
Radial Lamination

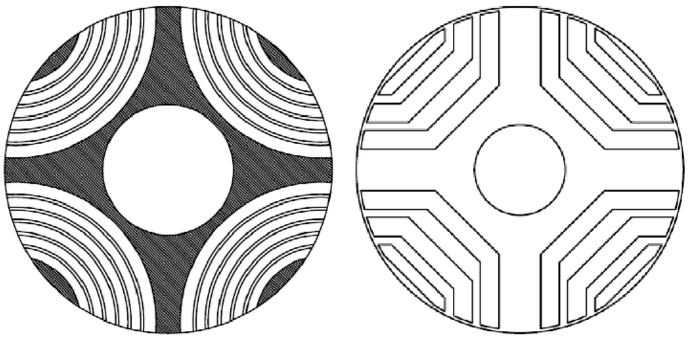


Axial Lamination



Rotor





(a) Axially laminated rotor (b) Transversally laminated rotor

- rotor carries the **short-circuited copper or aluminium bars** and it acts as a **squirrel-cage rotor**. **iron piece** is placed **in a magnetic field**, it **aligns** itself in a **minimum reluctance position** and gets locked magnetically**reluctance motor**, rotor tries to align itself with the axis of rotating magnetic field in a minimum reluctance position-synchronous speed

- **reluctance motor** runs as a synchronous motor

Advantages

- No D.C supply is necessary for the rotor.
- Constant speed characteristics.
- Rbust construction.
- Less maintenance.

Disadvantages

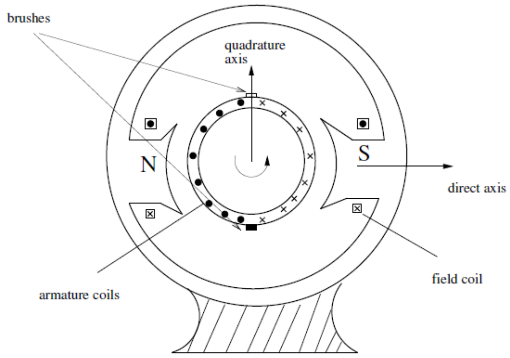
- Less efficiency
- Poor power factor
- Need of very low inertia rotor
- Less capacity to drive the loads

Applications

- Signalling Devices
- Control Apparatus
- Automatic regulators
- Recording Instruments
- Clocks
- All timing devices
- Teleprinters
- Gramophones

MODULE V

DC Motor

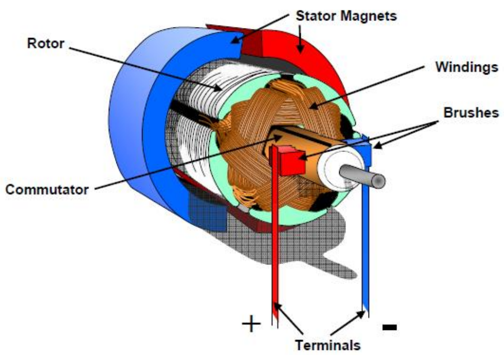


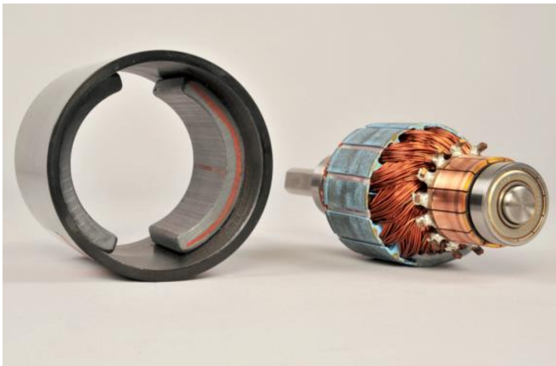
- Stator
  - Shunt
  - Series
  - Compound

Types

- Permanent Magnet Brushed DC Motor
- Permanent Magnet Brushless DC Motor

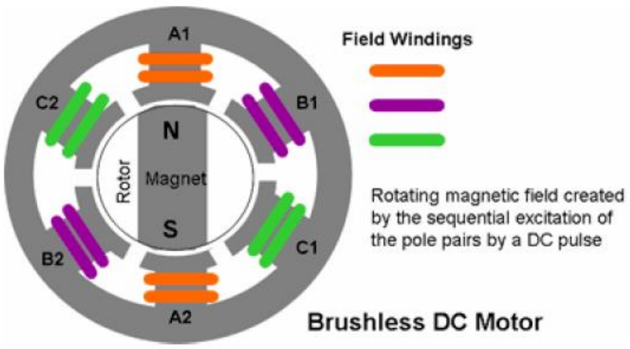
PM Brushed DC Motor-PMDC



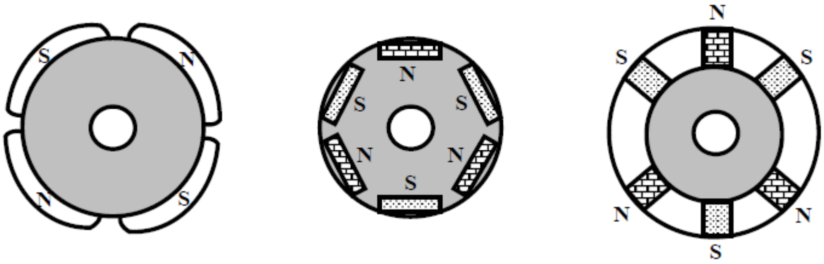


PM Brushless DC Motor

- Stator & Rotor



- Different rotor cores



Advantages of BLDC

- Better speed versus torque characteristics
- Faster dynamic response
- High efficiency
- Long operating life; less maintenance
- Noiseless operation
- Higher speed ranges

Disadvantages:

- up to about 5 kW
- Magnets more expensive for >5 kW
- Magnets are vulnerable to demagnetisation due to high fields and high temperatures-high power applications
- Inverter switching losses are significant at higher power levels

Applications

Low rating motors

- Automotive
- Robotics
- small arm movements

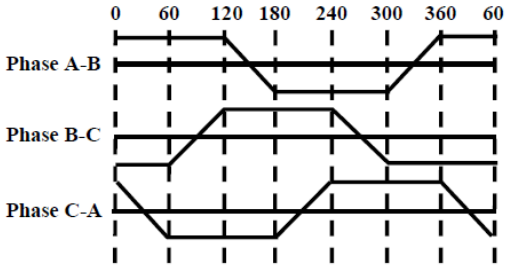
High rating motors

- Appliances (fans, laser printers, wheel chairs and photocopiers)
- Automation (car, electric bikes)
- industrial applications

Stator

- stacked steel laminations with windings placed in the slots
- stator resembles that of an induction motor
- windings are distributed in a different manner
- single-phase, 2-phase and 3-phase configurations
- three stator windings connected in star (High torque at Low speed) /delta (Low torque at Low speed)
- windings are distributed over the stator periphery to form an even numbers of poles
- the trapezoidal motor gives a back trapezoidal EMF
- the sinusoidal motor gives a back EMF in sinusoidal waveform
- the phase current also has trapezoidal and sinusoidal variations in the respective types of motor
- torque output by a sinusoidal motor smoother than that of a trapezoidal motor

Phase voltage waveform of 3 phase BLDC



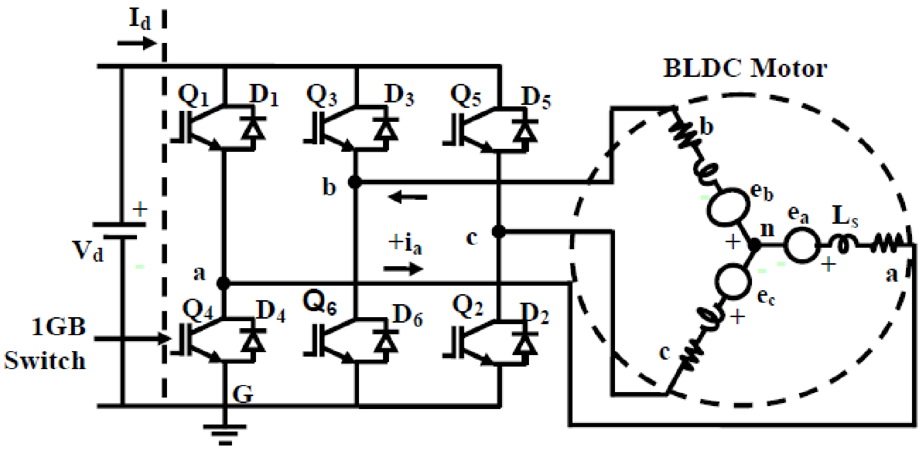
Rotor

- made of permanent magnet
- two to eight pole pairs with alternate North (N) and South (S) poles
- Ferrite magnets)/ alloy magnets (Neodymium (Nd), Samarium Cobalt (SmCo), Neodymium Ferrite Boron (NdFeB))
- ferrite magnets: less expensive, low flux density
- alloy magnets: high magnetic density, smaller rotor and stator for the same torque

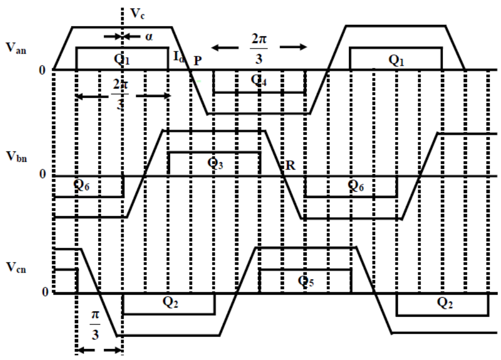
Hall Sensor

- commutation of a BLDC motor is controlled electronically
- stator windings should be energized in a sequence
- know the rotor position: Hall sensor
- Hall sensors embedded into the stator on the non-driving end
- rotor magnetic poles (N/S) pass near the Hall sensors, they give a high or low signal
- combination of these three Hall sensor signals: sequence of commutation

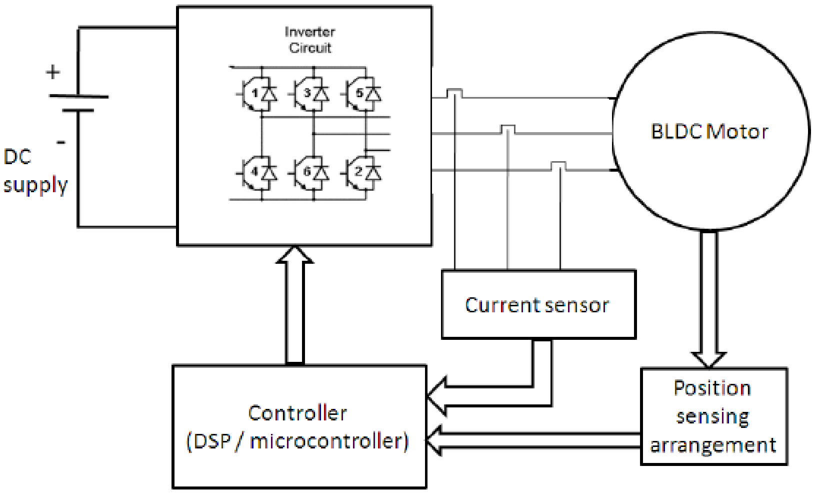
3 phase circuit of BLDC



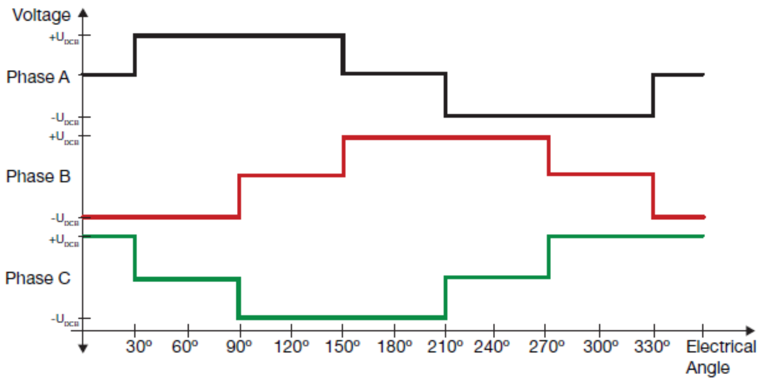
3 phase switching sequence



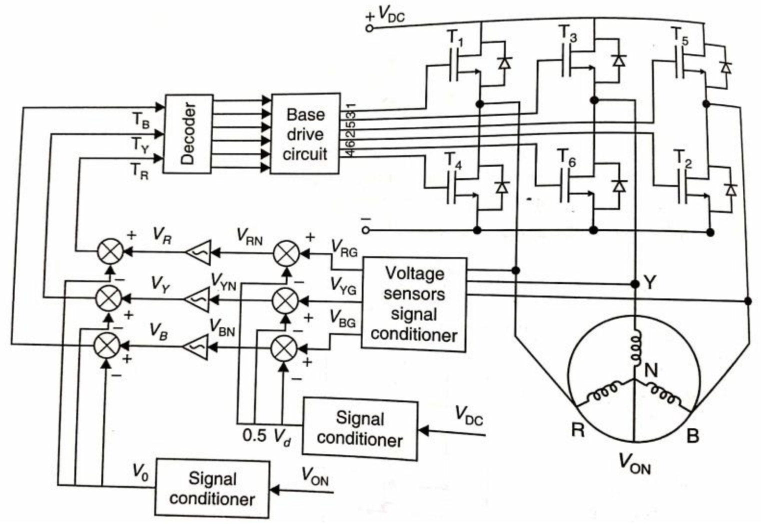
PM BLDC Motor-Control



6 step commutation



Sensorless control

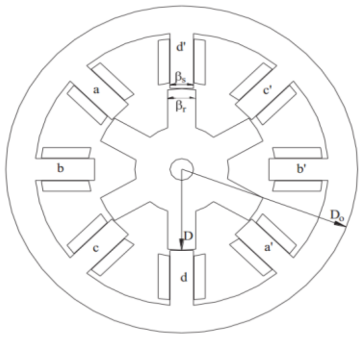


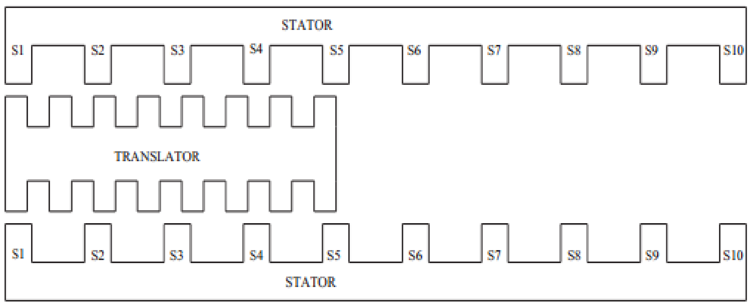
$+V_{DC}$
T_1
T_3
T_5
T_4
T_6
T_2
T_B
T_Y
T_R
Decoder
Base drive circuit
462531
V_R
V_{RN}
V_{RG}
V_Y
V_{YN}
V_{YG}
V_B
V_{BN}
V_{BG}
Voltage sensors signal conditioner
Y
N
R
B
V_{ON}
0.5 V_d
Signal conditioner
V_{DC}
V_0
Signal conditioner
V_{ON}

MODULE VI

Linear SRM

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





LSRM configurations

There are two distinct configurations of the LSRM

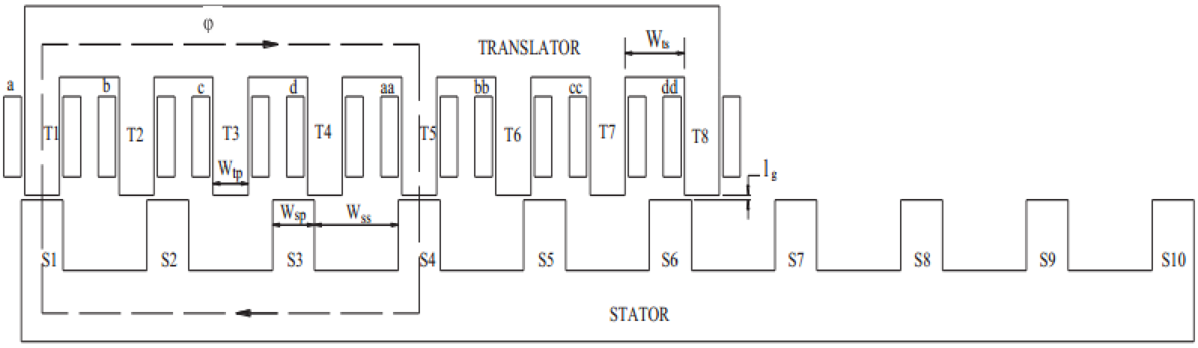
- Longitudinal flux LSRM
- Transverse flux LSRM

Both configurations can be obtained by unrolling the stator and rotor of the rotary switched reluctance motor (RSRM) with the radial magnetic flux path and the axial magnetic flux path respectively. The flux path in the longitudinal machine is in the direction of the translator motion. This machine is simpler to manufacture, mechanically robust and has lower eddy current losses, as the flux is in the same direction as the translator movement. The transverse flux design has the flux path perpendicular to the direction of the translator motion. It allows a simple track consisting of individually mounted transverse bars. As the flux is perpendicular to the direction of motion, an electro motive force (EMF) is induced in the core resulting in high eddy current losses.

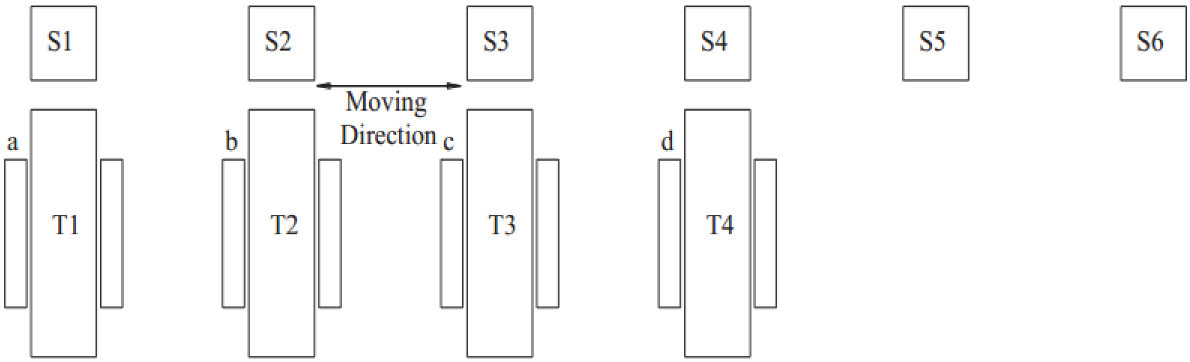
LSRM

- Two topologies of LSRM are
  - Active stator (with windings)
  - Passive stator (without windings)
- The active stator and passive translator LSRM configurations have the advantage in having the power supply and power converters being stationary, resulting in a reduced weight of translator.
- But, that necessitates a large number of power converter sections along the track resulting in high cost.

- On the other hand, the 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 requires transfer by means of contact brushes, which is not desirable for high speed applications.

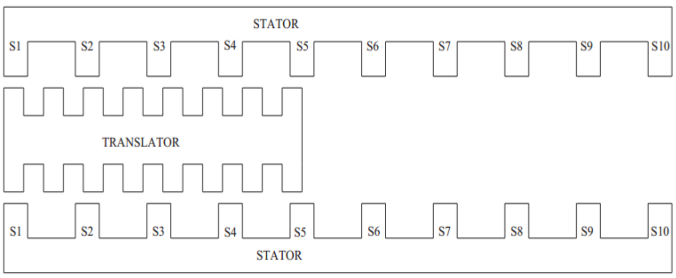


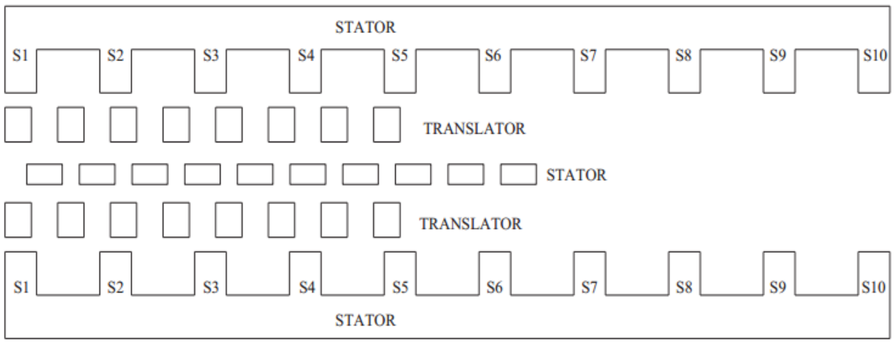
(a) Longitudinal magnetic flux path configuration

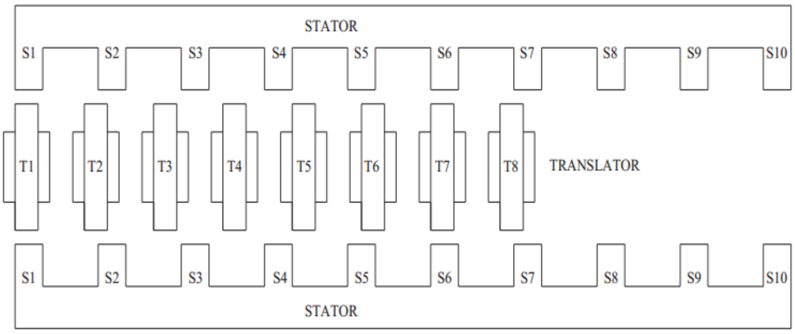


(b) Transverse magnetic flux path configuration

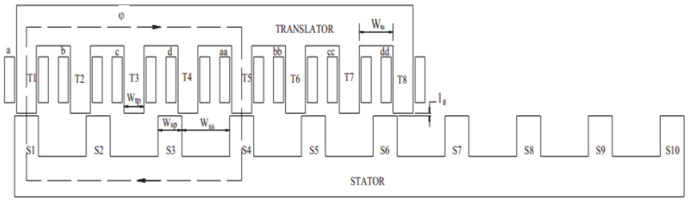
- The LSRM may have either two stators or two translators or vice versa to make a double-sided LSRM,







Working



(a) Longitudinal magnetic flux path configuration

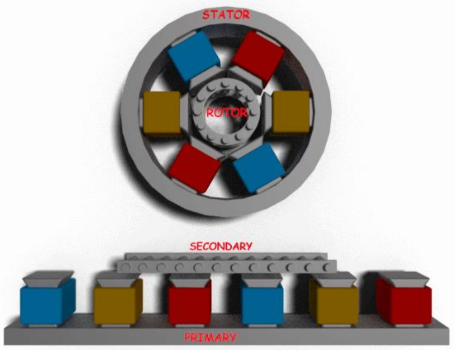
- A phase constitutes a pair of opposite poles that will have its windings excited at the same time. With an 8/6 design, there are four phases.
- In Figure (a), poles T1 and T5 represent the first phase (phase ‘a’), poles T2 and T6 the second phase (phase ‘b’), poles T3 and T7 the third phase (phase ‘c’), and poles T4 and T8 the fourth phase (phase‘d’). By having a phase switched on, the generated fluxes become additive and form a complete flux loop.
- When a phase is said to be in an aligned position, the translator poles of that phase are perfectly aligned with the stator poles.
- The translator poles of phase ‘a’ (T1 and T5) are fully aligned with the stator poles S1 and S4.
- In the aligned position, the inductance is at its maximum because the magnetic reluctance of the flux is at its lowest. On the other hand, the minimum inductance position is known as unaligned position. In Figure (a), phase ‘c’ is at unaligned position.
- If the windings of phase ‘c’ were to be excited at the current state, the translator will develop the tendency to move towards the right until its poles reach an aligned state. That is, T3 and T7 become aligned with S3 and S6, respectively.
- For the translator to be in continual motion, the windings of each phase must be switched on and off at the correct intervals.
- Assuming the translator is currently situated as shown in Figure (a) and moving to the right, the correct order of phase excitation is phases c, d, a, b and repeat.
- Once phase ‘c’ becomes fully aligned, its windings get switched off, and phase ‘d’ gets switched on. Phase ‘d’ will then move towards the right to achieve maximum inductance and then get switched off, which prompts phase ‘a’ to switch on.
- The whole switching mechanism gets repeated until the translator is at its desired position.

Linear Induction Motor

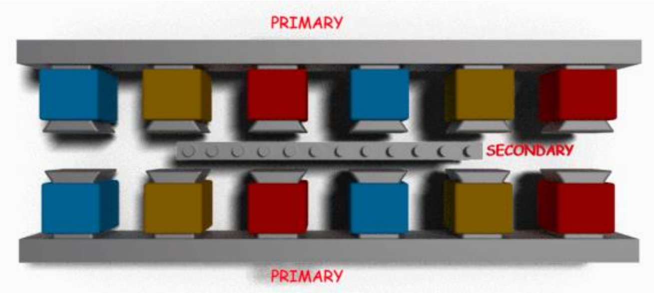
- Linear Induction Motor abbreviated as **LIM** is a special purpose system that we use to achieve rectilinear motion rather than rotational motion as in the case of conventional motors.

- LIM is quite an engineering marvel, to convert a general motor for a special purpose with more or less similar working principle, thus enhancing its versatility of operation.
- A linear induction motor (**LIM**) is an alternating current (AC), asynchronous linear motor that works by the same general principles as other induction motors but is typically designed to directly produce motion in a straight line. Characteristically, linear induction motors have a finite primary or secondary length, which generates end-effects, whereas a conventional induction motor is arranged in an endless loop.

Construction



- The basic construction of a linear induction motor is similar to a three phase induction motor but it does not look alike a conventional induction motor.
- If we cut the stator of a polyphase induction motor and lay on a flat surface, it forms the primary of the linear induction motor system.
- Similarly, after cutting the rotor of the induction motor and making it flat, we get the secondary of the system.
- There is another variant of LIM also being used for increasing efficiency known as the **Double Sided Linear Induction Motor** or **DLIM**, as shown in the figure below. It has primary on either side of the secondary, for more effective utilization of the flux from both sides.



Working

- When the primary of a LIM gets excited by a balanced three-phase power supply, a flux starts traveling along the entire length of the primary.
- This linearly traveling magnetic field is equivalent to the rotating magnetic field in the stator of a three phase induction motor or a synchronous motor.
- Electric current gets induced in the conductors of the secondary due to the relative motion between the traveling flux and the conductors.
- Then the induced current interacts with the traveling flux wave to produce linear force or thrust.

- If the primary is fixed and the secondary is free to move, the force will pull the secondary in the direction of the force and will result in the required rectilinear motion.
- When we give supply to the system the developed field will result in a linear traveling field, the velocity of which is given by the equation,

$$V_s = 2tf_s \ m/sec$$

- where f_s is the supply frequency in Hz, V_s is the velocity of the linear traveling field in meter per second, and t is the linear pole pitch i.e. pole to pole linear distance in meter.
- For the same reason as in the case of an induction motor, the secondary or runner cannot catch the speed of the magnetic field. Hence there will be a slip. For a slip of s, the speed of the linear induction motor will be

$$V = (1 - s)V_s$$

Applications

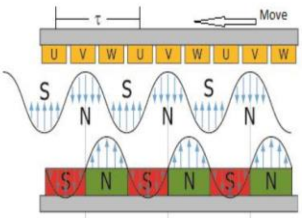
- A **linear induction motor** is not that widespread compared to a conventional motor, taking its economic aspects and versatility of usage into consideration. But there are quite a few instances where the LIM is indeed necessary for some specialized operations.
  Few of such applications are listed below.
  - Automatic sliding doors in electric trains.
  - Mechanical handling equipment, such as propulsion of a train of tubs along a certain route.
  - Metallic conveyor belts.
  - Pumping of liquid metal, material handling in cranes, etc.

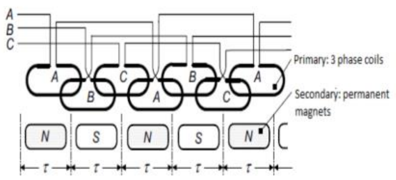
Linear Synchronous Motor

A linear synchronous motor is basically a RSM unrolled flat. The stationary part is called the primary and is equivalent to the RSM stator; the moving part called the secondary and is equivalent to the rotor. The working principle is the same as that of the RSM. The equations used to analyze the RSM are also valid in the analysis of the LSM with the following changes: the rotating magnetic field is changed to a travelling magnetic field, torque becomes thrust, rotational synchronous speed.

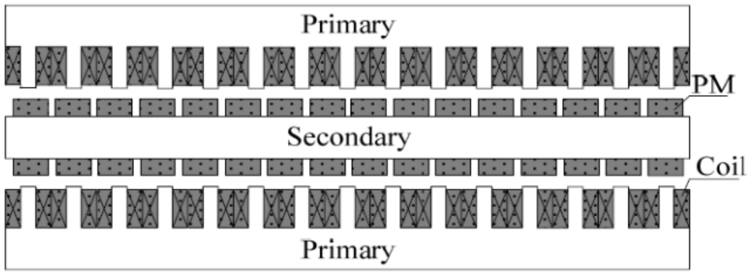
Types

- A LSM can be double sided or single sided, slotted or slot-less, iron-cored or air-cored.
- The secondary part is generally an array of permanent magnets (PM) arranged in an alternating way and usually attached to the load.
- The primary is generally poly-phase electromagnet, linearly arranged such that a travelling magnetic field is produced in the air gap.
- It is usually stationary and attached along a track.





Slotted single sided with travelling Magnetic field Slot-less single sided air cored



Slotted double sided