EE 8005 - Special Electrical Machines.

UNIT - I :- Sttepper Motor.

Constructional features - Principle of operation - Types - Torque Prediction - Linear Analysis - Characteristics - Drive circuits - closed loop control - Concept of lead angle - Application.

UNIT - II : Switched Reluctance Motors

Constructional features - Principle of operation - Torque Prediction - characteristics steady state Performance Prediction - Analytical Method.

UNIT - III : Permanent Magnet Brushless D.C Motor

Fundamentals of Permanent Magnets - Types. Principle of operation - Magnetic Circuit analysis EMF and Torque Equations - Power converter circuits and their controllers - characteristics and control - Applications.

UNIT-IV : Permanent Magnet Synchronous Motors.

Constructional features - Principle of operation - Sine wave motor with EMF & Torque equation - Phasor diagram - Power Practical windings - Performance characteristics - Digital controllers - Performance controllers - Applications.

UNIT-V : Other Special Machines.

Constructional features - Principle of operation and characteristics of Hysterisis motor - Linear Induction Synchronous Reluctance Motor - Repulsion Motor - Applications.

UNIT-1

STEPPER MOTOR.

Introduction:-

A stepper motor is a brushless DC motor whose rotor rotates through a fixed angular step when its stator windings are energized in a programmed manner. Rotation occurs because of the magnetic interaction between rotor poles (N & S) and the poles of the sequentially energized stator winding.

Stepper motors are electromagnetic incremental devices that convert electric pulse to shaft motion (rotation). These motors rotates a specific number of degrees as a respond to each input electric pulse.

Typical types of stepper motor can rotate 2°, 2.5°, 5°, 7.5° and 15° per input electrical pulse. Rotor position sensors (or) sensorless feedback based techniques can be used to regulate the output response according to input reference command.

Features of Stepper Motor:-

* Available resolutions ranging from Severa steps up to 400 steps per revolution.
* several horsepower ratings
* Ability to track signals as fast as 1200 per seconds.

Applications:-

1) Printers
2) Disk drives
3) Machine Tools
4) Robotics
5) Tape Drives.

stepper motor consist of two parts,

Stator ⇒ has phase windings

Rotor ⇒ has no electrical windings.

Step angle:-(β)

Step angle is defined as the angle through which the stepper motor shaft rotates for each command pulse.

$$\text{Step angle } \beta = \frac{360^\circ}{mN_r}$$

$$\beta = \frac{(N_s - N_r)}{N_s N_r}$$

where,

m is number of phases and

N_r is the number of rotor poles

N_s is the number of stator poles.

Resolution:-

Resolution is defined as the number of steps needed to complete one revolution of rotor shaft.

$$\text{Resolution} = \frac{\text{no. of steps}}{\text{Revolution}}$$

$$= \frac{360^\circ}{\beta}$$

Stepping Rate:-

Number of steps per second is called stepping rate. If the stepping rate is increased by too quickly, the stepper motor comes out of synchronism and stops.

At high speeds (called slewing mode), the motor emits an audiable while having a fundamental frequency equal to stepping rate.

Torque Constant :-

It is defined as the initial slop of the torque - current curve of the stepper motor. It is also called as torque Sensitivity.

Pull - in torque :-

It is the maximum torque the Stepper motor can develop in start-stop mode at a given stepping rate, without losing synchronism.

Pull - out Torque :-

It is the maximum torque the Stepper motor can develop at a given stepping rate, without losing synchronosim.

Principle and working of stepper motor :-

Application of stepper Motor :-

i) Robotics
ii) IC fabrications
iii) X-Y Plotters
iv) Disk - drivers
v) Wiper movement
vi) Space Vechicles
vii) X - Ray Machine.

Types of stepper motor :-

i) Variable Reluctance stepper motor

ii) Permanent magnet stepper motor.

iii) Hybrid stepper motor.

VARIABLE RELUCTANCE STEEPER MOTOR.

Construction :

Stator :-

* The Stator is made up of stack of steel lamination

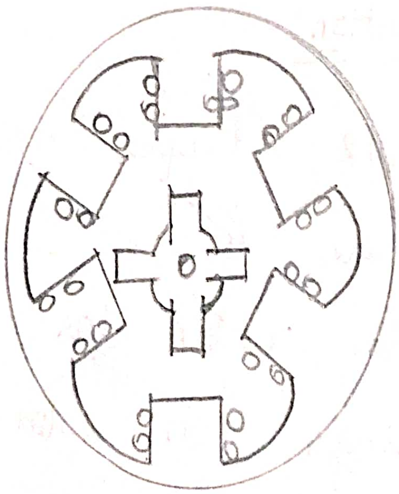
* It has inward projected Poles each wound with and exciting coil.

Rotor :-

* The rotor is also made up of steel laminations.

* The number of rotor poles should be different from that of stator.

* The rotor does not carry any winding.



Here.

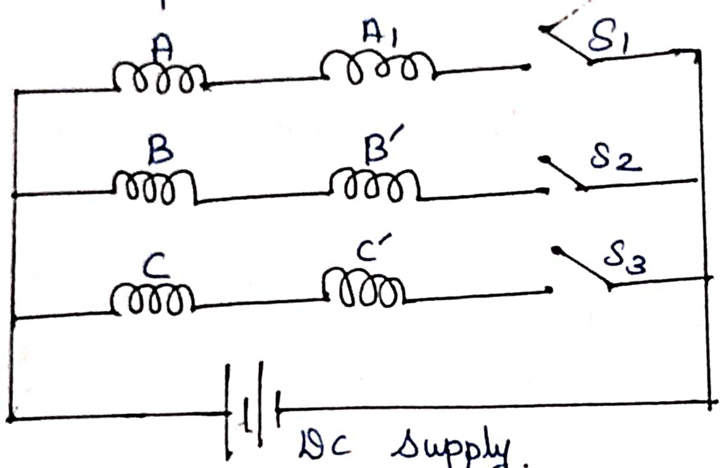
$N_s = 6, \quad N_r = 4.$

step angle. $\beta = \frac{6-4}{6 \times 4} \times 360^\circ$

$\beta = 30^\circ$

* Diametrically opposite pairs of stator coils are connected in series such that one tooth becomes a N-pole, the other one becomes S-pole.

* The switching of phase currents is done with the help of solid-state switches.



[Electrical connection of VR stepper motor]

Principle Of Operation:-

The VR stepper motor consist of stator and motor. There is no permanent magnet either on the rotor (or) the stator. There is no windings on rotor. It is a single stack motor.

The stator is made of soft iron stampings. It has six equally-spaced projected poles (or) teeth. The stator windings are wound on stator poles. The rotor is also made of soft iron stampings. It is a 4 pole salient type of the same width as the stator pole or teeth.

Here, the stator windings consist of three phases A, B and C.

The six stator windings are connected in 2-coil groups to form three seperate circuits. It is called phases. Phase A consist of terminals A_1 and A_2. Similarly phase B has B_1 and B_2. and phase C has C_1 and C_2. Each phase has it own independent switch. The current flow through winding can be controll by mechanical swith of by using solid-state control. The opposite pairs of stator coils are connected in series such that when one pole (or) teeth becomes a north (N)-pole and other one becomes a South poles (S).

When there is no current in stator current in stator windings, the rotor rotates forward (or) backward to a position that forms a path of maximum reluctance with the magnetized stator pole (or) teeth. The given VR stepper motor is 3 phase, four pole rotor motor. The step angle of this motor is β.

$$\beta = \frac{360^\circ}{m N_r} = \frac{360^\circ}{3 \times 4}$$

$$\boxed{\beta = 30^\circ}$$

Operation -

The VR stepper Motor has following mode of operation.

1) 1-phase - ON (or) Full-step operation.

2) 2-phase - ON mode

3) Alternate 1-phase on 2-phase - on - mode (Half-step operation)

4) Micro stepping Operation.

operation :-

Mode 1 : 1-phase ON (Full Step operation)

→ Only one phase is Energized at any time.

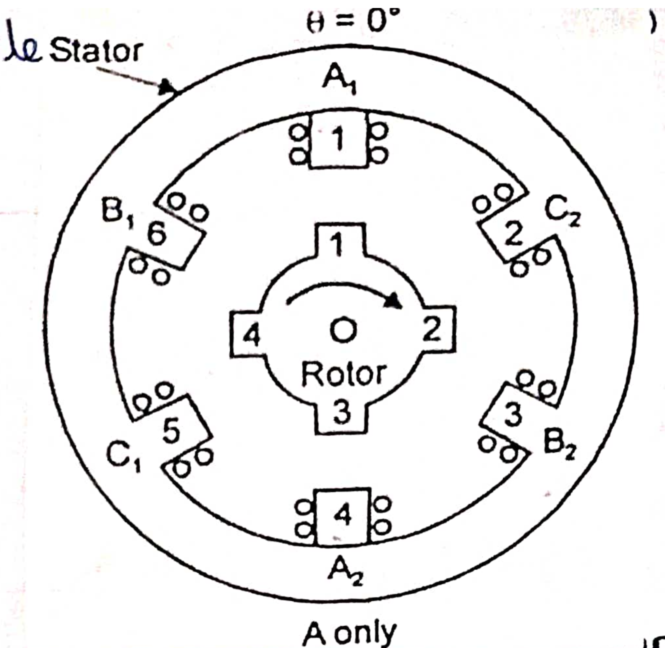
when Switch S_1 is closed :

✓ Stator poles AA_1 get Magnetized.

✓ The rotor, therefore attracted to the minimum reluctance position.

i.e) rotor pole

Poles 1 & 4.

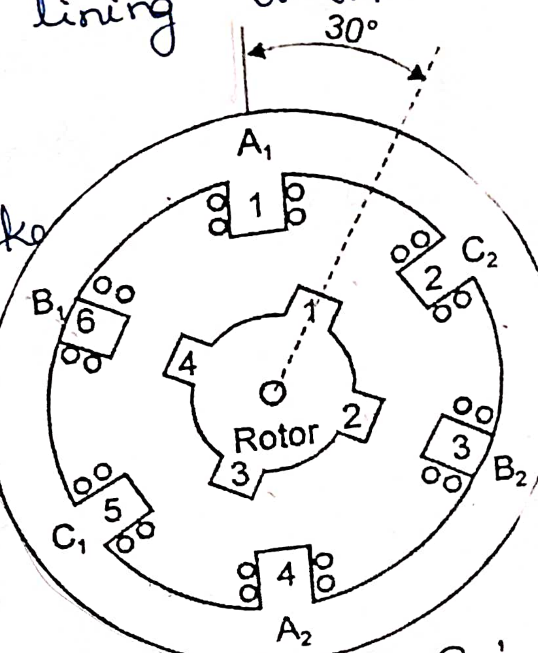


→ when switch S2 is closed after opening S1 :-

✓ Stator poles BB1 get magnetized.

✓ The rotor poles 2 & 4 lining with Stator Poles 2 & 5.

✓ As a result rotor make displacement of 30°.



when switch S3 is closed after opening S2 :-

✓ Stator poles CC1 get magnetized.

✓ The rotor poles 1 & 3 line up with Stator poles 3 and 6.

✓ The rotor rotates an additional angle 30° (CCW).

when switch S_3 is open and switch S_1 are closed again :-

Rotor teeth 2 & 4 will align with stator poles 1 & 4. ie) rotor run further angle of 30°.

The direction of rotation depends on the sequence in which the phase windings are energized.

i.e) $S_1 \to S_2 \to S_3 \Rightarrow$ CCW, $S_1 \to S_3 \to S_2 \Rightarrow$ CW

Counter Clock wise

S_1	S_2	S_3	θ
✓	–	–	0°
–	✓	–	30°
–	–	✓	60°
✓	–	–	90°
–	✓	–	120°
–	–	✓	150°

Clock wise

S_1	S_2	S_3	θ
✓	–	–	0°
–	–	✓	3
–	✓	–	60
✓	–	–	90
–	–	✓	12
–	✓	–	1

Mode 2: 2-Phase ON (Full step operation) (4).

→ In this mode of operation 2 stator Phases are excited simultaneously.

→ When two phases like AB, BC, CA, again AB... are energized, the rotor experiences torque from both phases and comes to rest at a mind-way between the two adjacent full step positions.

When the phase 'A' and Phase 'B' are energized

→ The rotor rotates in counter clockwise direction by an angle of $\theta = 15^\circ$.

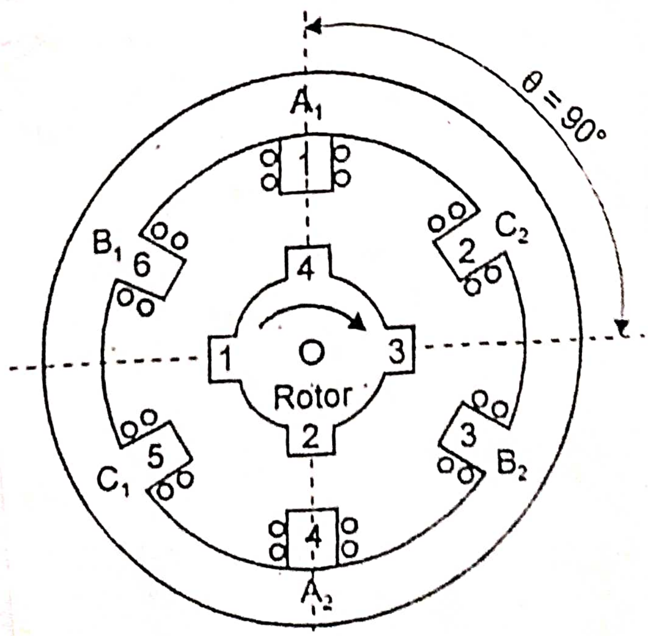
When the phase B and C are energized:

→ The rotor rotates another 30° in Counter clock wise direction.

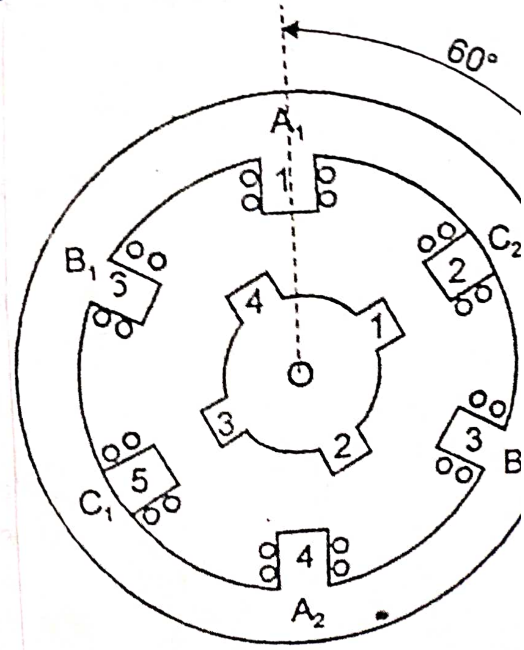
When the phase C & A are energized:-

further 30° in

cloc



A only



C only

If the phase A & B are again energized,:-
the rotor rotates further 30°.

To reverse the direction of rotation, switching sequence is changed.

ie) AC, CB, BA, AC....

Truth Table.

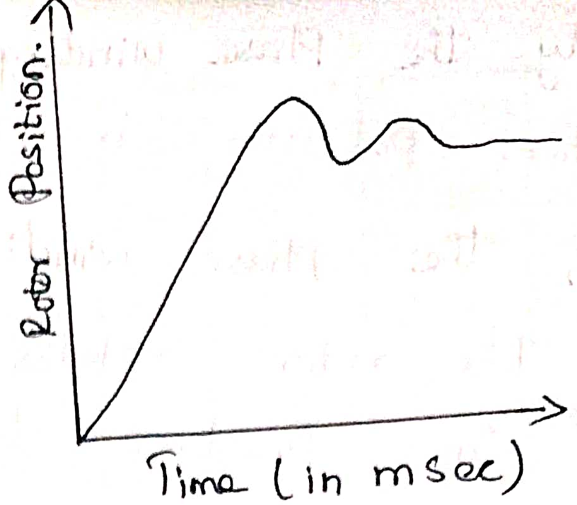
Counter Clock wise

	S_1	S_2	S_3	θ
AB	✓	✓	–	15°
BC	–	✓	✓	45°
CA	✓	–	✓	75°
AB	✓	✓	–	105°
BC	–	✓	✓	135°
CA	✓	–	✓	165°
AB	✓	✓	–	195°

Clock wise.

	S_1	S_2	S_3	θ
AC	✓	–	✓	15°
CB	–	✓	✓	45°
BA	✓	✓	–	75°
AC	✓	–	✓	105°
CB	–	✓	✓	135°
BA	✓	✓	–	165°
AC	✓	–	✓	195°

(1-φ-ON-Mode-Response)



(Two φ. ON-mode-Response)

Advantages of 2-Phase ON-mode over 1-φ ON-mode of operation:-

✓ Two Phase ON mode Provides greater holding torque than 1-φ ON mode operation.

✓ Good Transient Response the oscillation damps more quickly in the two-phase ON-mode than in the case of single Phase ON-mode

Mode 3: Half step operation:-

✓ The Half Step operation can be obtained by exiting the three phase in the sequence. A, AB, B, BC, C.

✓ This is nothing but alternate one-phase ON and two-phase-ON mode of operation.

✓ In this mode, the rotor can rotate each Step angle 15° ie) half of full step angle

Only the Phase winding A ... with rotor position is θ = 0°.

Then the phase winding 'A & B' are energized for an angle of 15° in the rotor rotates Counter clockwise direction.

Next the Phase winding 'B' is energized and 'A' is de-energized :

The rotor rotates further 15° in Counter clock wise direction.

next the Phase winding 'B & C' are energized :-

The rotor rotates further 15°.

Truth Table :-

	S_1	S_2	S_3	θ
A	✓	–	–	0°
AB	✓	✓	–	15°
B	–	✓	–	30°
BC	–	✓	✓	45°
C	–	–	✓	60°
CA	✓	–	✓	75°
A	✓	–	–	90°

(Counter-clockwise)

	S_1	S_2	S_3	θ
A	✓	–	–	0°
AC	✓	–	✓	15°
C	–	–	✓	30°
CB	–	✓	✓	45°
B	–	✓	✓	60°
BA	✓	✓	–	75°
A	✓	–	–	90°

(Clockwise)

Mode 4 - micro stepping :-

In this step of operation, the step angle is very small.

It utilizes two phases simultaneously but with the two currents deliberately made un-equal.

ie) The current in phase A is held constant and the current flow through 'b' phase winding is increased in very small increments untill maximum current is reached. Then current in phase 'A' is reduced to zero using very small decrements.

In this way very ... The
(even $\beta = 0.018°$) can be obtained. rotor

PERMANENT MAGNET STEPPER MOTOR

Construction:-

It consist of two main parts, one is stator and other one rotor.

Stator:-

The stator is made up of a stack of steel laminations. It has projecting poles. the stator has 4 poles. The stator windings (or) phase windings are wound in the stator poles. Here, the 2 stator poles are energized by one winding. Now the motor has 2 windings (or) phases. It is marked as 'A' & 'B'. The phase 'A' consist of two terminals A_1 & A_2. Similarly, phase B winding consists of two terminals, B_1 and B_2.

Rotor:-

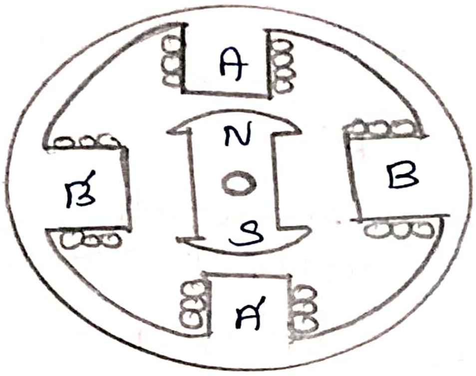
The Rotor is permanent magnet. It is made up of magnetically 'hard' ferrite.

The rotor is cylindrical one. Here, the rotor consist of 2 poles. (17)

$$\text{step angle } \beta = \frac{360^\circ}{m N_r}$$

$$m = 2, \quad N_r = 2$$

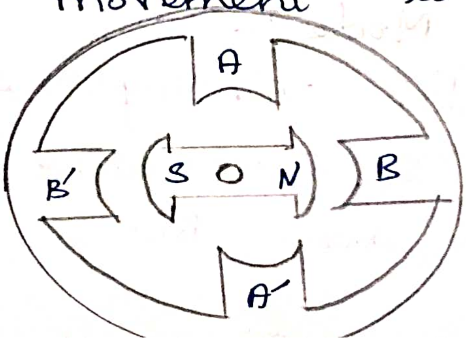
$$\beta = \frac{360^\circ}{2 \times 2} = 90^\circ.$$



Operation:- (Single Phase ON-Mode):

When phase B is energized. The stator Poles BB' get magnetized.

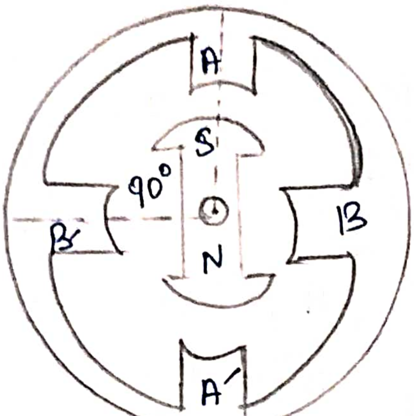
Now, the rotor moves such that, N-Pole of the rotor and S-Pole of the Pole formed by stator Phase B get interlocked and further movement is arrested.



Next, phase A is energi[...] de-energized.

✓ Now stator poles BB' get magnetized. [...]

✓ The rotor rotates by 90° and takes the Position as shown in fig...



This sequence of energizing the Phase is repeated. So, that rotor rotates with step angle 90° clockwise direction.

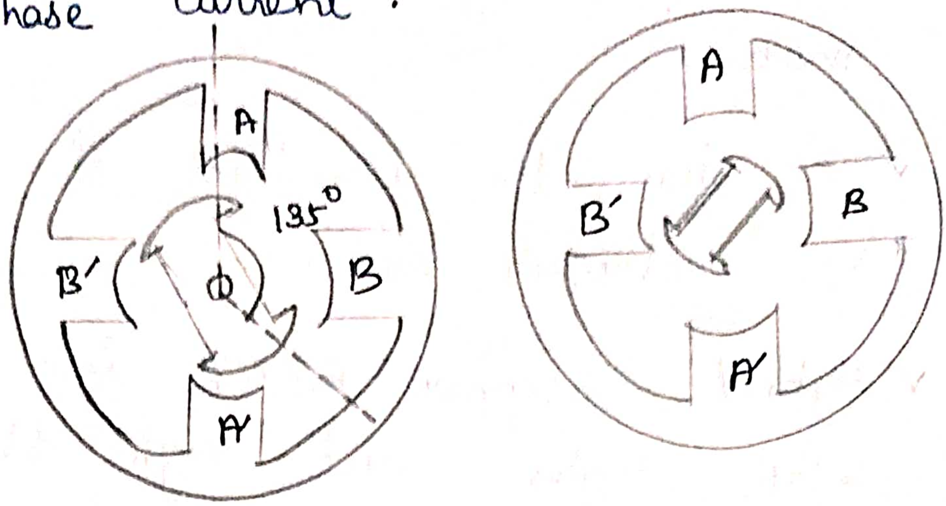
Truth Table :-

	S_1	S_2	θ
A	✓	-	0°
B	-	✓	90°
A	✓	-	180°
B	-	✓	270°.

Two-Phase ON-Mode :-

✓ The stator winding A & B are energized Simultaneously. The resulting rotor position is mid-way between two adjacent full-step Positions.

The direction of rotation depends on the polarity of Phase Current.

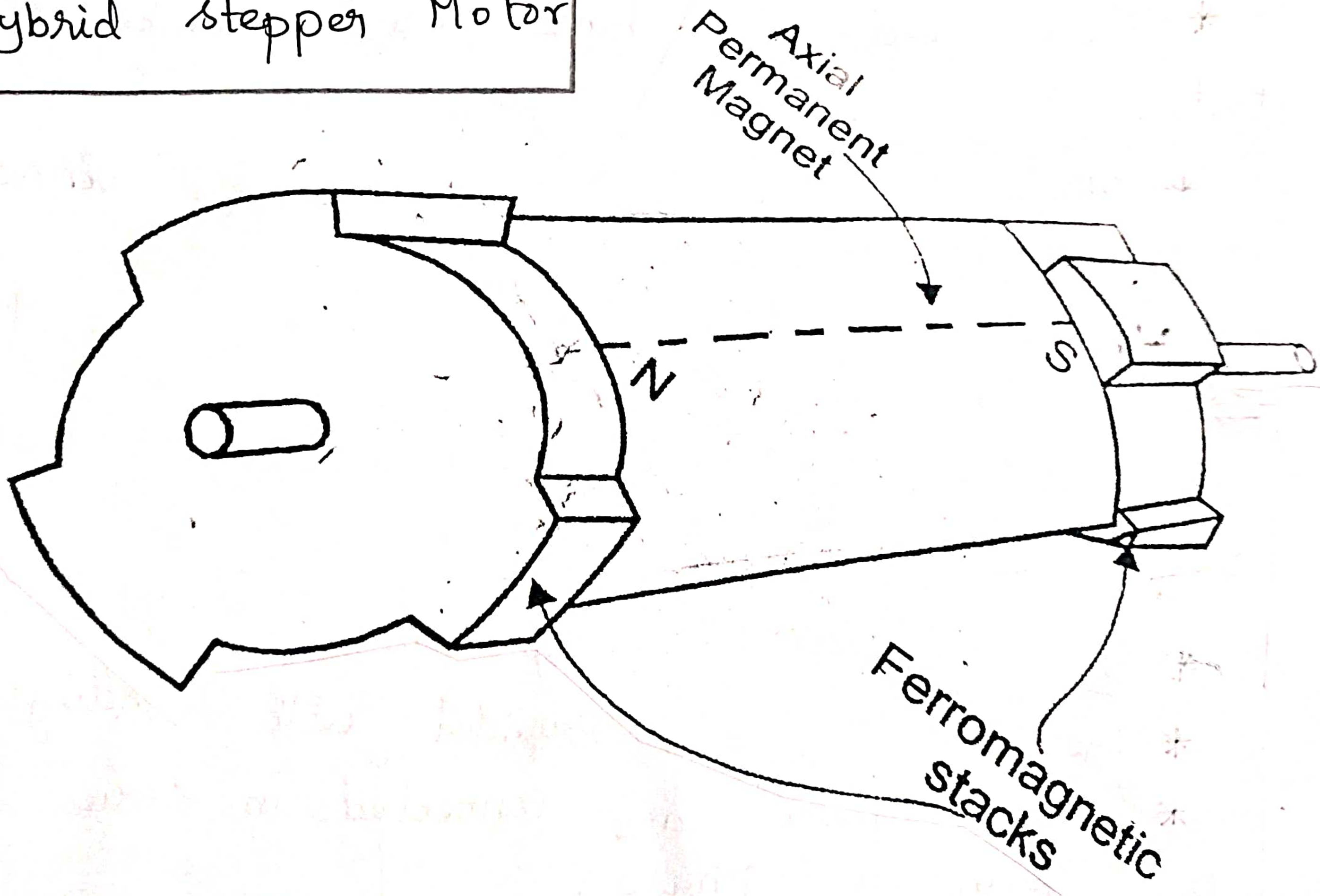


Truth Table :-

A	B	θ
+	+	45°
−	+	135°
−	−	225°
+	−	315°
+	+	45°.

[The + & − simpyle denotes direction of current.]

Hybrid stepper Motor



✓ Hybrid stepper motor ... among the various types of stepper motor.

✓ It has the advantages of both PM and VR stepper motor.

✓ Hybrid stepper motor is used where small step angles and high starting torque are essential.

Construction:

<u>Rotor:-</u>

* The rotor consist of permanent magnet. Two end-caps are fitted on both ends of this axial magnet.

* These end-caps have equal number of teeth.

* The tooth of the one end cap coincides with slot of the other.

<u>Stator:-</u>

* The stator is made up of soft iron stampings.

* The stator has subteeth.

* The poles are provided with windings.

* opposite poles are connected in series to form a Phase.

Working :-

$$\text{step angle} = \frac{360^\circ}{(12\times 2\times 15)}$$

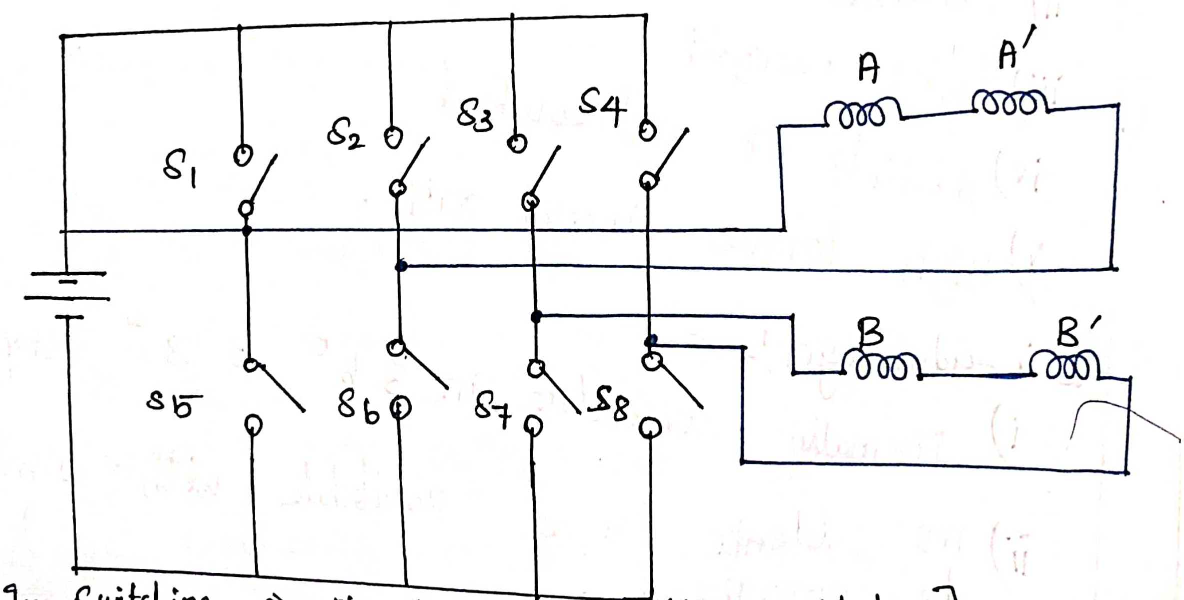
$$\boxed{\beta = 6^\circ}$$

✓ The stator poles will get magnetized with North & South pole depend upon the current direction.

✓ when pole A magnetized north and A' south. This will cause some teeth of rotor 1 towards pole 'A' and few teeth of rotor 2 towards pole A'.

✓ when pole B magnetised north and B' south: Rotor teeth again move in 6° in clockwise direction.

Repeating this sequence of operation, we can get the rotation of rotor with steps of 6° in clockwise direction.



[fig- Switching circuit for Hybrid Stepper Motor.]

Multi - Stack Variable Reluctance ... Motor

In figure 2.9 (a) is shown stack A with stator teeth (or) Poles 1, 2, 3, 4 .... stack B is shown in fig (2.9-b) with stator Poles 1, 2, 3, 4 ... displaced from stack A by 10° CCW. Further in figure 2.9 (C), the stack C as shown in with its stator poles 1, 2, 3, 4 ... offset from stack B by an angular displacement of 10° CCW.

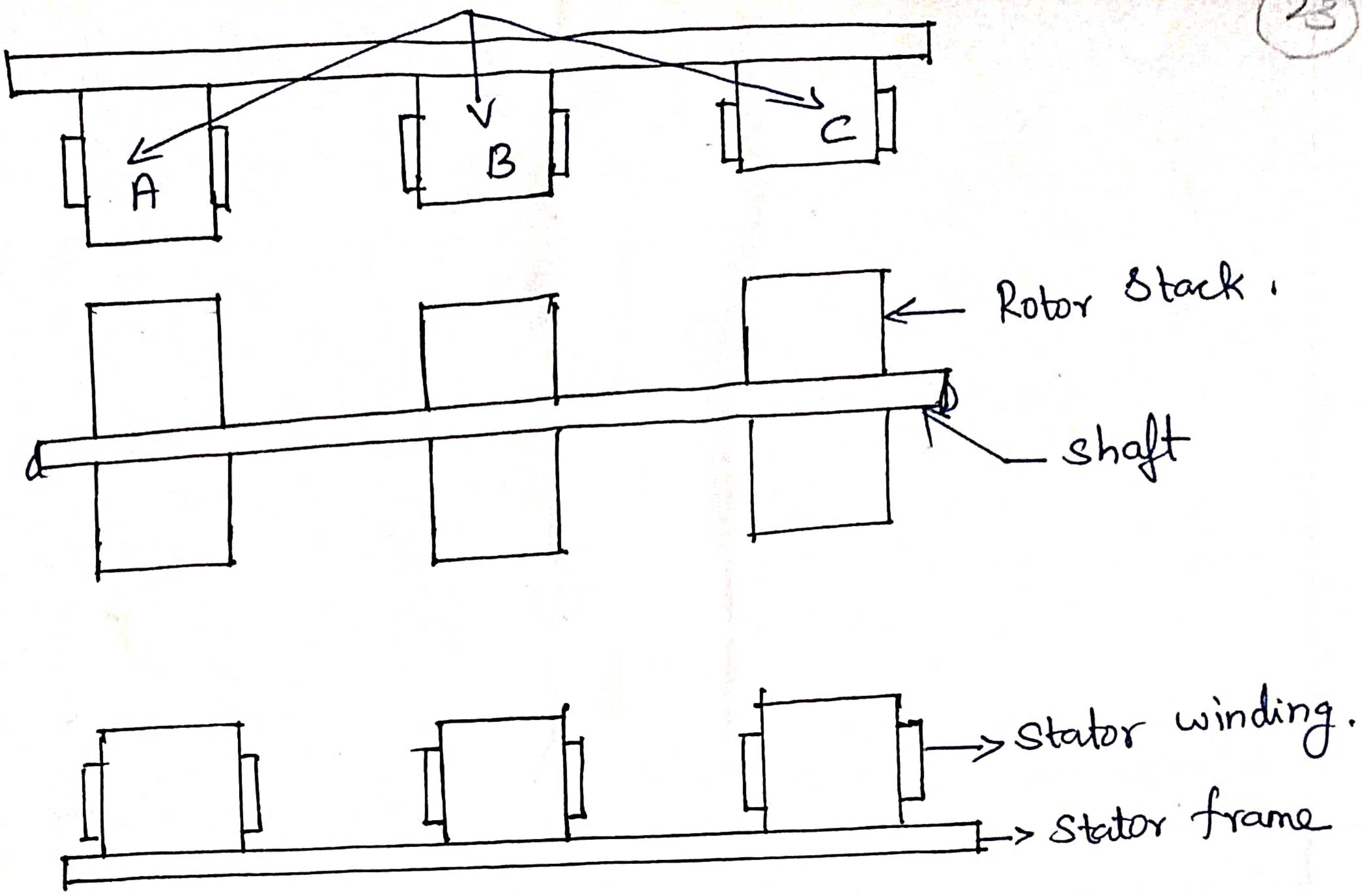
Note that rotor teeth on the three Stacks do not have any angular displacement from each other as the ~~rotor~~ stator Poles, have, the rotor teeths are aligned.

Advantages :-

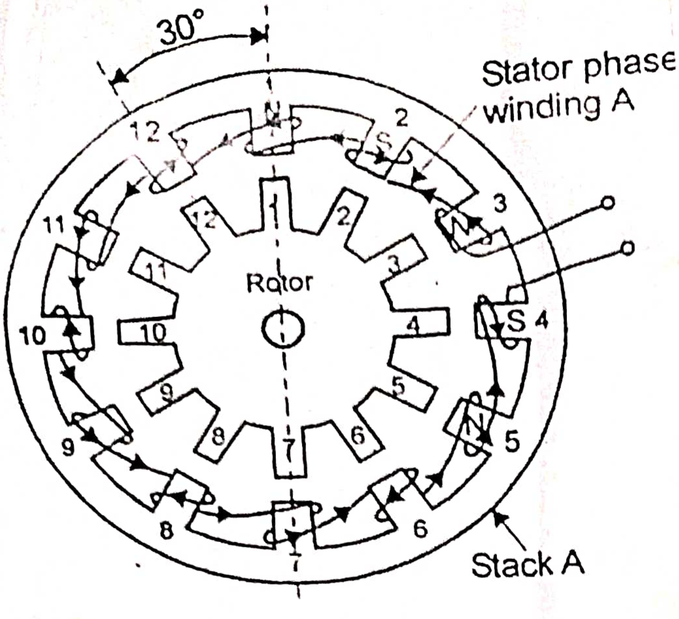
i) Low rotor inertia
ii) Capable of High stepping rate
iii) Light weight
iv) Ability to freewheel
v) High torque inertia ratio.

Dis-advantages :-

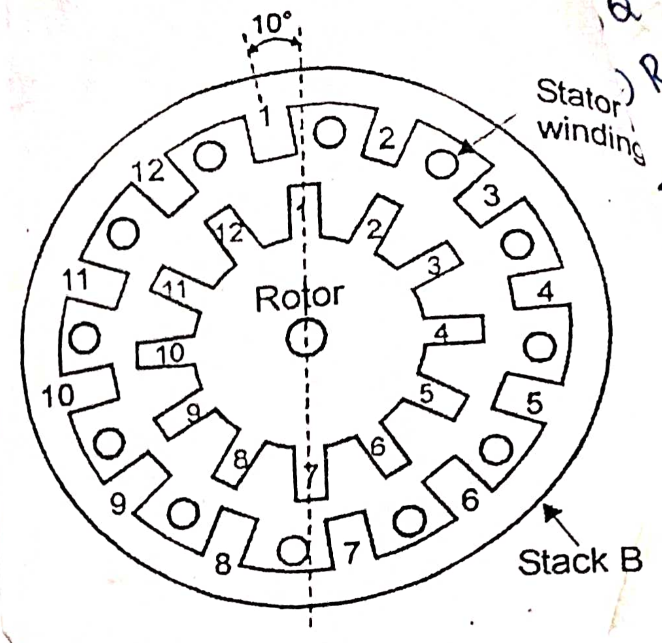
i) Normally available in 3.6° to 30° step angle.
ii) No detente torque available with windings de-energized.



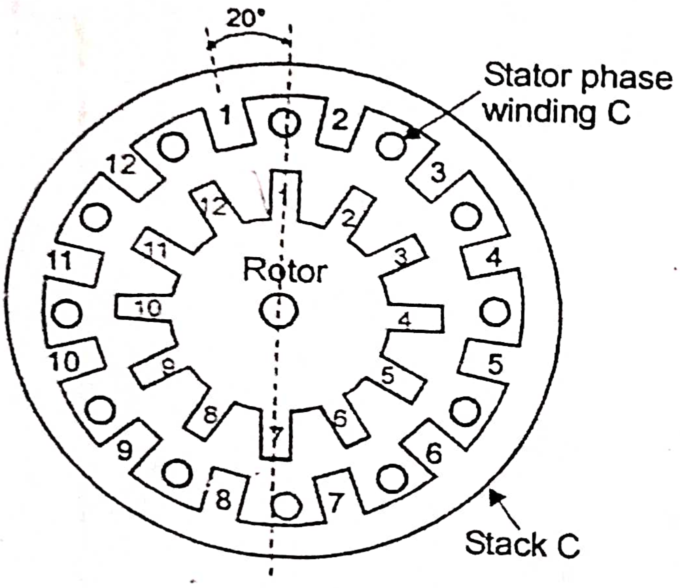
- The multi stack variable reluctance stepper motor are used to obtain smaller step angle (range of 2 to 15°).
- In this type, each phase has seperate stator and rotor sections called stacks.
- The 3 - stator stack consist of windings that corresponds to three phases.
- The rotor stacks are unwound and have projecting teeth. The rotor teeth of stack 'A' is displaced by 15° from stack B and 30° from stack C
- The rotor teeth of phase B and C also have 15° mechanical off set.



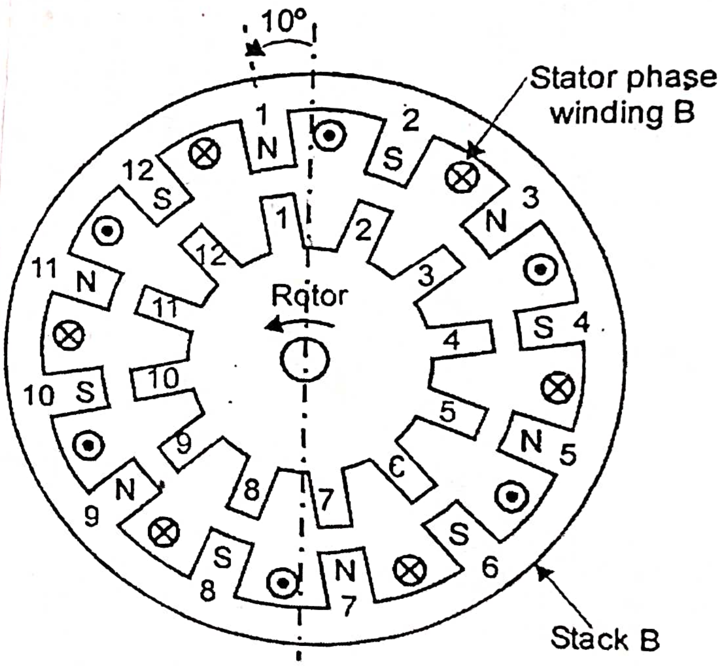
(a)



(b)



(c)



(d)

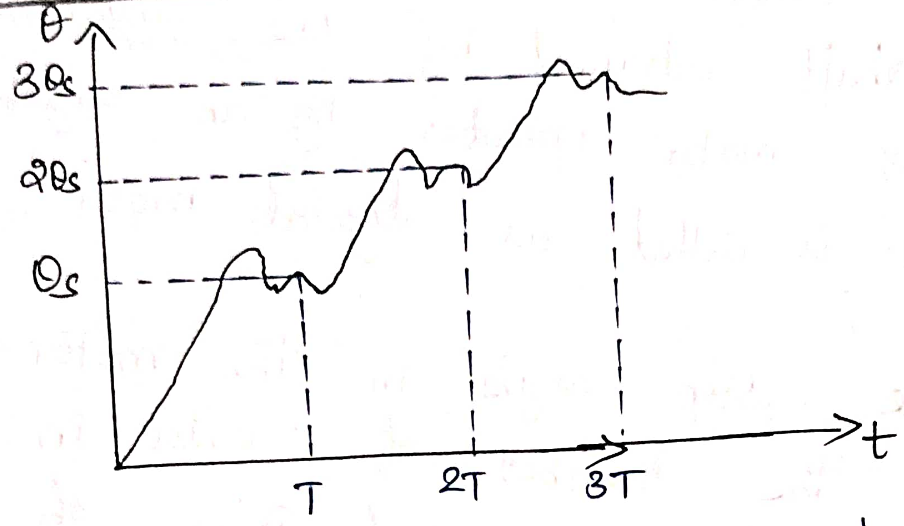
The stator laminations are also offset in angular displacement by one-third of a stator pole pitch. For a 12-pole stator, the pole pitch is 30° and therefore the three stator stacks must be offset from each other in angular displacement of 10°.

Q → Pull in torque at stepping rate A.
R → Pull out torque at stepping rate A.

There are 2 operating modes.

1) Start - stop mode &
2) Slewing mode.

i) Start - Stop mode :-



Second pulse is given to the motor before the motor has attained steady position due to first pulse.

Pull-in rate :- It is the maximum stepping rate at which the motor will start & stops without missing steps, against load torque.

Pull-out rate : It is the maximum stepping rate at which the motor will slew without missing steps against load torque.

~~MICROCONTRO~~

MICROPROCESSOR - BASED CONTROL OF STEPPER MOTOR

The stepper motors are mainly used in computer peripherals, plotters, robots and machine tools for precise incremental rotation. In stepper motor, the stator windings are exited by electrical pulses and for each pulse the motor shaft advanced by one angular step. The stepper motor operates by an digital pulse. There fore it is called as digital motor.

The step angle in the motor is determined the number of poles in the rotor and the number of pairs of stator windings (one pair of stator winding is called one phase). The stator windings are called 'control windings'.

The stepper motor is controlled by switching ON/OFF the stator windings. Generally the stepper motor has four stator winding and require four switching sequence. It is shown in the figure.

CHARACTERISTICS OF STEPPER MOTOR.

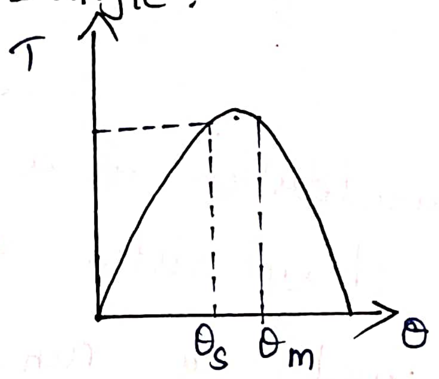
Characteristics of stepper Motor.

- Static characteristics
- Dynamic characteristics.

Static characteristics :-

1. Torque - angle
2. Torque - current

1. Torque - angle :-



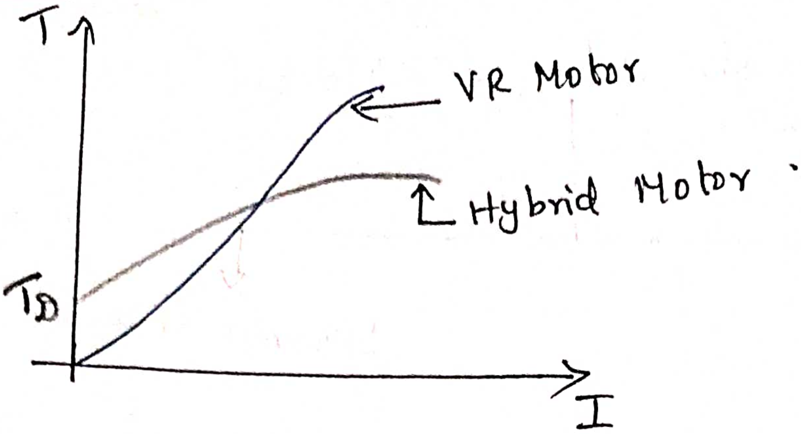
Torque Vs stepangle characteristics of stepper motor is shown in fig.

when rotor is in equilibrium position, external torque is applied. Now the rotor is moved. The angular displacement is measured.

vary the load - torque and find the corresponding displacement.

The variation of displacement is plotted against the torque.

2. Torque - Current

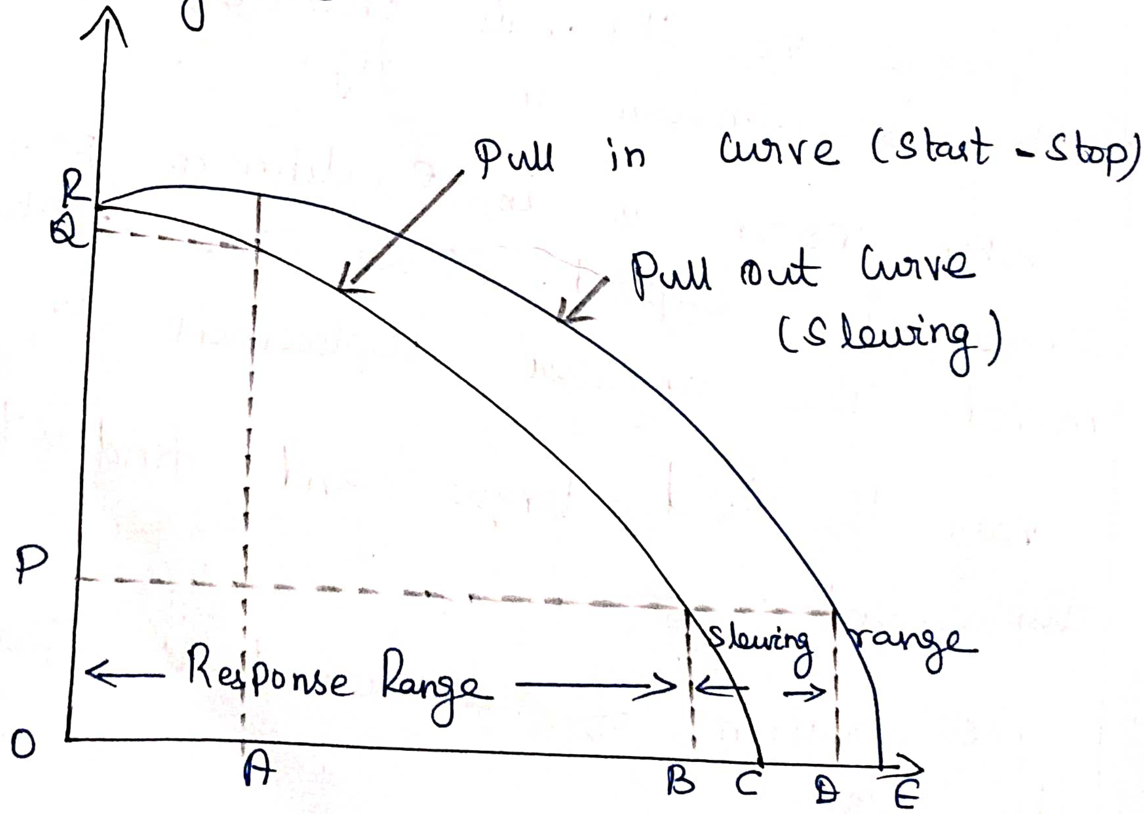


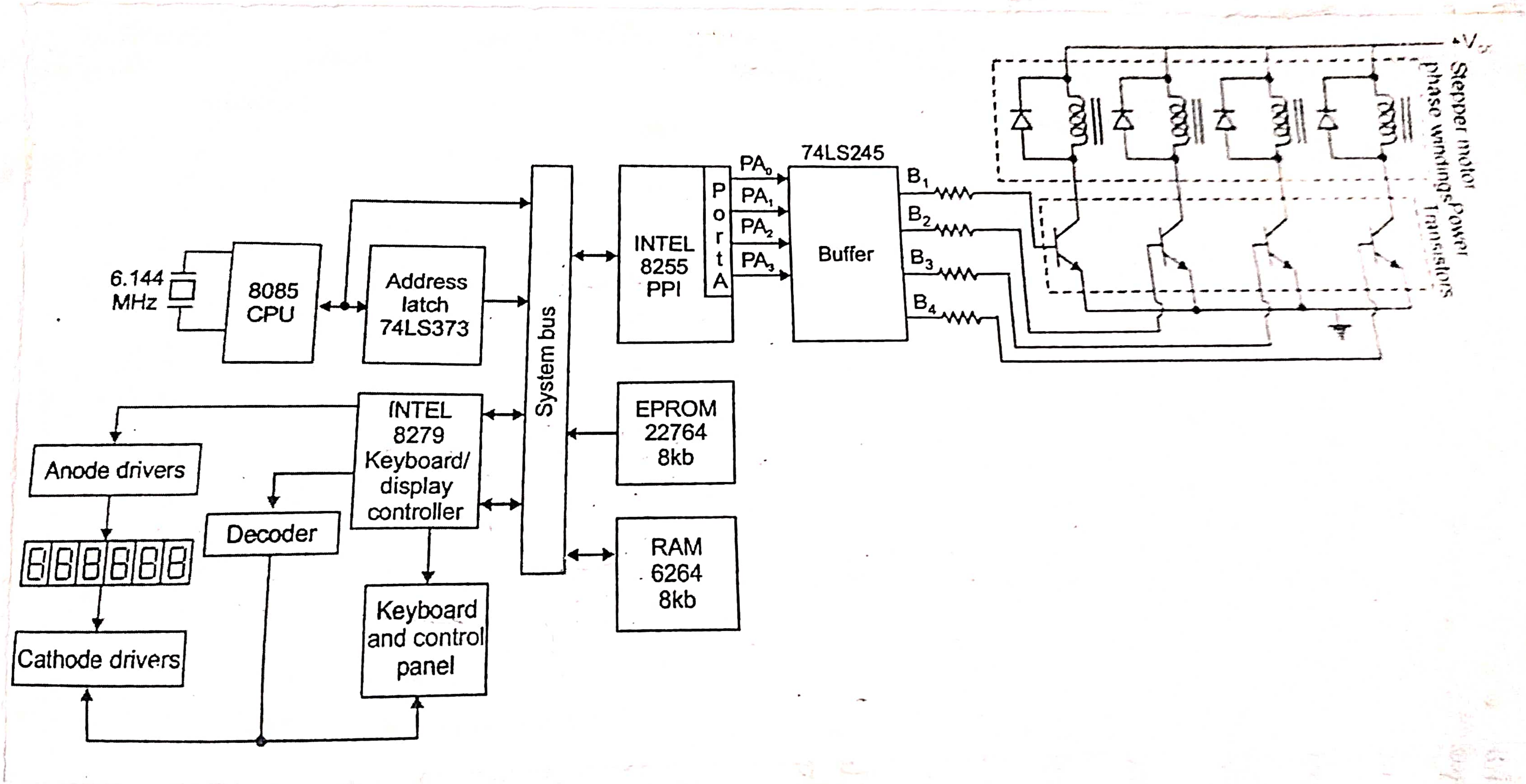
Detent torque :-

It is the maximum torque that can be applied to an unexcited motor without slipping the rotor from the equilibrium position.

Dynamic Characteristics :-

The dynamic characteristics of a stepper motor represent the characteristics when it is running (or) about to run.





6.144 MHz
8085 CPU
Address latch 74LS373
System bus
INTEL 8255 PPI
Port A
PA0
PA1
PA2
PA3
74LS245
Buffer
B1
B2
B3
B4
Stepper motor phase windings
Power Transistors
EPROM 22764 8kb
RAM 6264 8kb
INTEL 8279 Keyboard/ display controller
Anode drivers
Decoder
Cathode drivers
Keyboard and control panel

Switching Sequence	Clockwise rotation				Anticlockwise rotation			
	PA_3	PA_2	PA_1	PA_0	PA_3	PA_2	PA_1	PA_0
Sequence - 1	1	1	0	0	0	0	1	1
Sequence - 2	0	1	1	0	0	1	1	0
Sequence - 3	0	0	1	1	1	1	0	0
Sequence - 4	1	0	0	1	1	0	0	1

[Switching Sequence for Full-Step Operation]

Clockwise rotation				Anticlockwise rotation			
PA_3	PA_2	PA_1	PA_0	PA_3	PA_2	PA_1	PA_0
1	1	0	0	0	0	1	1
0	1	0	0	0	0	1	0
0	1	1	0	0	1	1	0
0	0	1	0	0	1	0	0
0	0	1	1	1	1	0	0
0	0	0	1	1	0	0	0
				1	0	0	1
1	0	0	1	0	0	0	1
1	0	0	0				

[Switching Sequence for Half-step Operation].

figure 1.8 shows microprocessor based stepper motor control. Here, the stepper motor consist of 4 phase windings. A freewheeling diode is connected across the phase winding. The stepper motor winding can be energized by turning on the power transistor in the Power Circuit.

The system consist of microprocessor (8085, 8086 etc...) EPROM and RAM memory for Program and data storage and for stack using INTEL 8279, a keyboard and six number of 7- Segment LED Display have been interfaced in the system. By using the keyboard, the operator can issue commands to control the system. The LED display have been provided to display messages to the operator.

LINEAR ANALYSIS OF STEPPER MOTOR.

The Linear analysis of the stepper motor with respect to torque performance Produced by the torque.

Let,

T_m → Motor Torque Produced by the rotor in N-M

J → Inertia of the rotor and Load combination in kgm^2.

ω - Angular velocity of the rotor.

D - Damping co-efficient (or) Viscous frictional

T_f - Frictional load Torque independent of the

θ_s - Step angle in radians.

f - Stepping rate in steps/sec (or) pps.

Frictional Load Torque,

$$T_f = k\theta$$

According to the rotor dynamics,

$$T_m = J\frac{d\omega}{dt} + D\omega + T_f \quad \text{—— (1)}$$

Also $\theta_s = \omega t$ = step angle.

$$\omega = \theta_s/t = 1/t\ \theta_s = f\theta_s \quad \text{—— (2)}$$

where $f = 1/t$

Equation (2) sub in eqn (1),

$$T_m = J\,d/dt\,(f\theta_s) + D(f\theta_s) + T_f \quad \text{—— (3)}$$

Step angle $\theta_s = \frac{360^\circ}{mN_r}$ is fixed for particular type of motor. Due to this, θ_s can be considered as constant.

$$\therefore T_m = J\theta_s \cdot \frac{d}{dt}(f) + D\theta_s(f) + T_f$$

In the above equation, the viscous friction constant is neglected because the equation is Linear One.

Linear And

Linear Analysis:

If the damping Co-efficient is neglected, $D = 0$

Now, the torque equation becomes.

$$T_m = J\frac{d\omega}{dt} + T_f \qquad \text{——— (5)}$$

$$T_m - T_f = J\frac{d\omega}{dt}$$

$$\frac{T_m - T_J}{J} = \frac{d\omega}{dt}$$

$$d\omega = \left[\frac{T_m - T_f}{J}\right] dt \qquad \text{——— (6)}$$

Integrating the above equation, we can get -

$$\omega = \left[\frac{T_m - T_f}{J}\right] t + \omega_1 \qquad \text{——— (7)}$$

where,

ω_1 = Integration Constant

$\omega = \theta_s f$

$\omega_1 = \theta_s f_1$

Now, Substituting ω and ω_1 in equation (7),

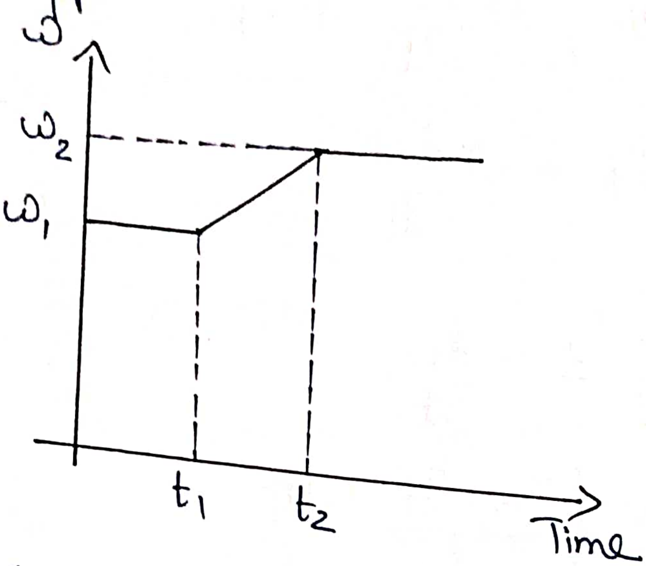
$$(\theta_s f) = \left[\frac{T_m - T_f}{J}\right] t + \theta_s f_1 \qquad \text{——— (8)}.$$

The above equation is divided by θ_s,

$$\frac{\theta_s f}{\theta_s} = \left[\frac{T_m - T_f}{J\theta_s}\right] t + \frac{\theta_s f_1}{\theta_s}.$$

$$f = \left[\frac{T_m - T_f}{J\theta_s}\right] t + f_1 \quad \text{———} (9).$$

The above equation is the stepping rate of the stepper motor.



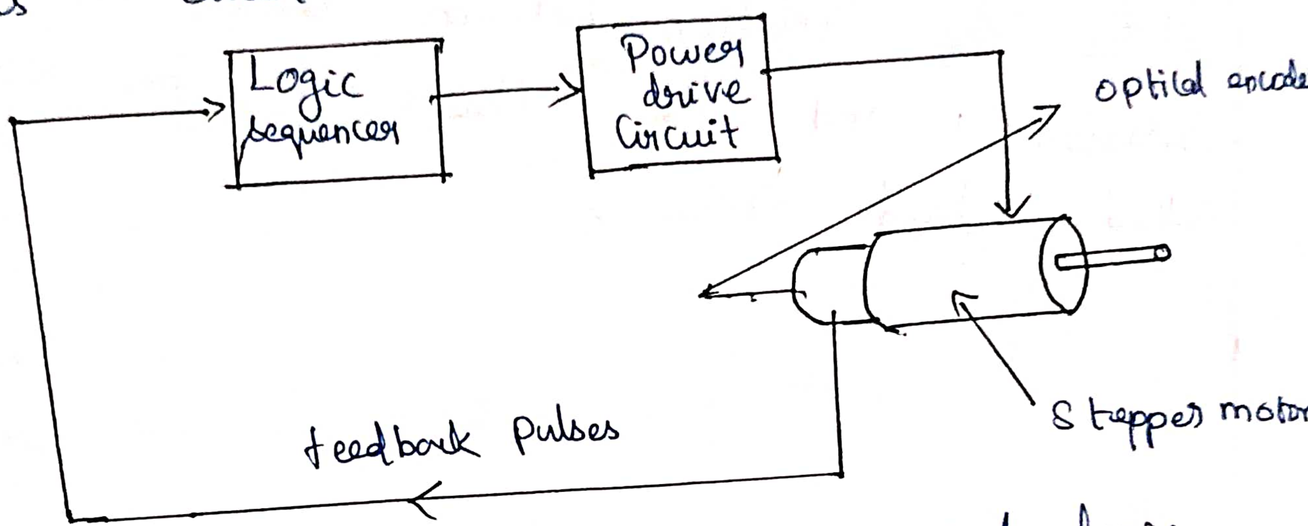
above figure shows the linear acceleration from ω_1 to ω_2.

CLOSED CONTROL LOOP OF STEPPER MOTOR :-

In this drive systems explained the closed loop control of stepper Motor. The step command pulses were given from an external Source.

The open-Loop drive is attractive and widely accepted in applications of speed and Position Control. However, the Performance of Stepper motor driven in open-Loop mode may fail to follow a Pulse Command when the frequency of the Pulse train is too high the Inertial Load is too heavy.

The performance of stepper motor can be increased to a great extent by employing Position feedback.. (or) speed feed back to determine the Proper phase windings to be switched at Proper timings. This type of control is called as "Closed-Loop drive".



The above block diagram consist of logic sequencer, power drive circuit, optical encoder and stepper motor. In a closed-Loop control, a Position sensor is needed for detecting the rotor Position. For this purpose we can use optical encoder. This optical encoder is coupled with motor shaft. In addition to we can use mechanical sensor for detecting the rotor position.

The pulses from the optical encoder ... the position. This digital information of the logic sequencer SWIT... Pulses are fed to the logic sequencer determines the ... Now, The logic sequencer determines the ... Phase windings of the stepper motor through Con... Power drive circuit. Now, the stepper motor Posi... rotates. The relation between the rotor's present Position and the Phases to be excited is called lead angle.

UNIT-II.

SWITCHED RELUCTANCE MOTOR.

Constructional features - Rotary and linear SRM - Principle of operation - Torque production - Steady state performance prediction - Analytical method - Power converters and their controllers - Methods of Rotor Position sensing - Sensorless operation - characteristics and closed Loop control - Application.

Introduction :-

Single excited machine - only stator has windings.

Doubly salient Machine - both stator and rotor has salient Poles.

Principle - similar to single stack variable reluctance Stepper motor. The structure of the motor is simple with concentrated coils

Since, the movement of rotor and hence the torque involves a switching of currents into the stator windings when there is a variation of reluctance, this motor is called "Switched Reluctance Motor".

SRM requires,

⇒ Power Controller

⇒ Rotor Position Sensors.

Advantages :-

* High efficiency.
* maximum operating speed.
* Good performance of the motor in terms of torque / inertia ratio together with four quadrant operation, making it an attractive Solution for variable speed applications.

✓ Construction is simple and robust.

✓ There is no permanent magnet.

✓ Rotor carries no windings, no slip rings, no brushes & Less maintenance.

✓ Power semiconductor switching circuitry is simpler.

✓ It is the self starting machine.

✓ It is possible to get very high speed.

Dis- advantages:-

* Stator Phase winding should be capable of carrying magnetizing current.

* For High speed operation, the developed Torque has undesirable ripples which results in undesirable noises (or) acoustic noises.

* It requires position sensors.

construction and operation of SRM:-

Stator is made up of silicon steel stampings with inward Projected Poles. The field coils are connected to the output terminals of a Power Semiconductor Switching Circuitry.

Rotor is made up of silicon steel stampings, with outward projected Poles. Number of Poles of rotor is different from the number of poles of stator. The rotor shaft Carries a Position Sensor.

Dc supply is given to the Power Semiconductor switching circuitry which is connected to Various phase windings of SRM. Rotor Position sensor Provides information about the Position of rotor.

Based on the rotor position information the devices are switched ON & OFF such that the desired winding is excited.

Consider that the rotor poles r_1 & r_1' and stator poles c & c_1' are aligned. When a current is applied to phase a with the current direction as shown in fig.

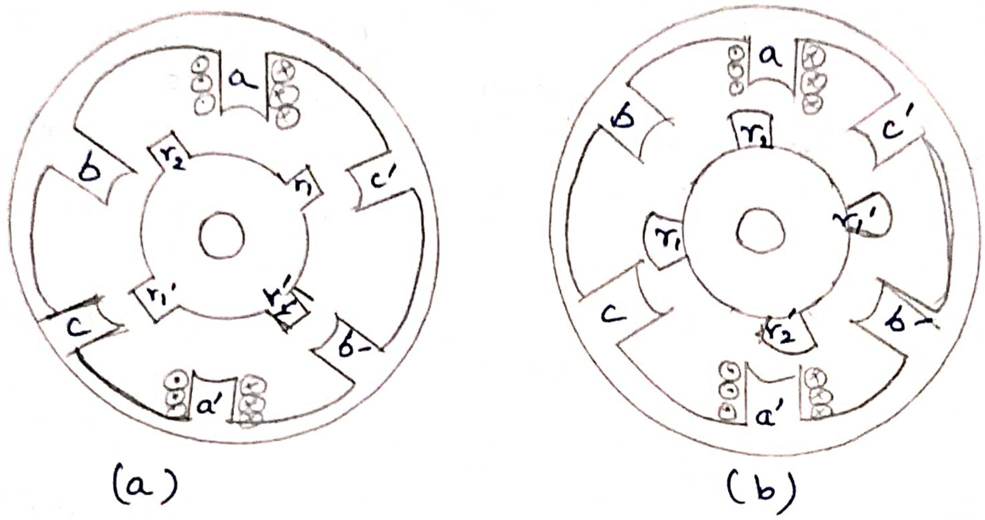


fig. 2.1 Operation of Switched Reluctance Motor.

A flux is established through stator poles a and a' and rotor poles r_2 and r_2' which tends to pull the rotor poles r_2 and r_2' towards the stator poles a and a' respectively. When they are aligned, the stator current of phase a is turned off.

Now, the stator winding b is excited pulling r_1 and r_1' toward b and b' respectively in a clockwise direction. Likewise energization of the c phase winding results in the alignment of r_2 and r_2' with c and c' respectively. Hence it takes three phase energization in sequence to move the rotor by 90°, and one revolution of rotor movement is affected by switching currents in each phase as many times as there are number of rotor poles. The switching of currents in the sequence acb results in the reversal of rotor rotation.

Power controllers used for SRM :-

1> classic converter - using two power semiconductors and two diodes per phase.

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

3> Phase windings using bifilar wires.

4> Dump - C - converters.

5> split power supply converter.

(1) Classic Converter :-

Power semiconductor switching circuits for SRM :

Two power semiconductor switching devices per phase and two diodes.

when T_1 and T_2 are ON, current flows from A_1 to A_2.

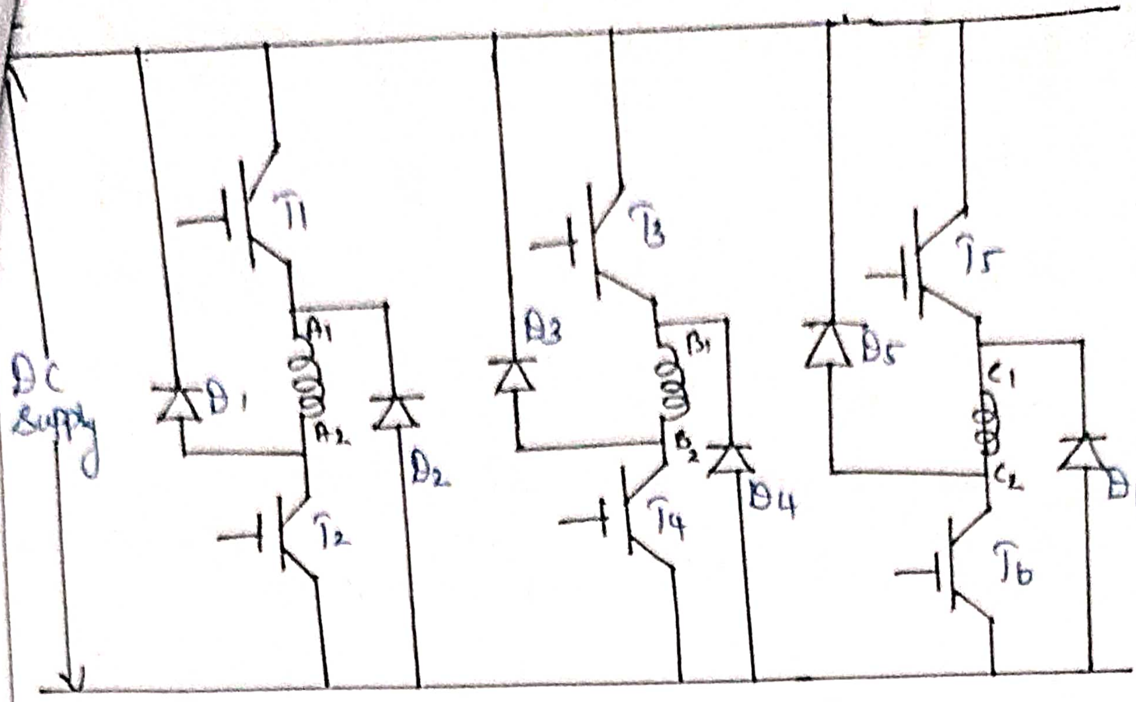
when T_1 & T_2 are OFF, current flows through D_2, A_1, A_2, D_1, to mains. Thus stored energy is fed back to mains.

Upper devices T_1, T_3 and T_5 are turned ON and OFF by the signals obtained from position sensor.

Lower devices T_2, T_4 and T_6 are controlled by signals obtained by chopping frequency signals. By this way, effective phase current is varied from a very low value to a high value.

control of each phase is completed independent of other phases.

converter is able to freewheel which helps to reduce f_s and switching losses.

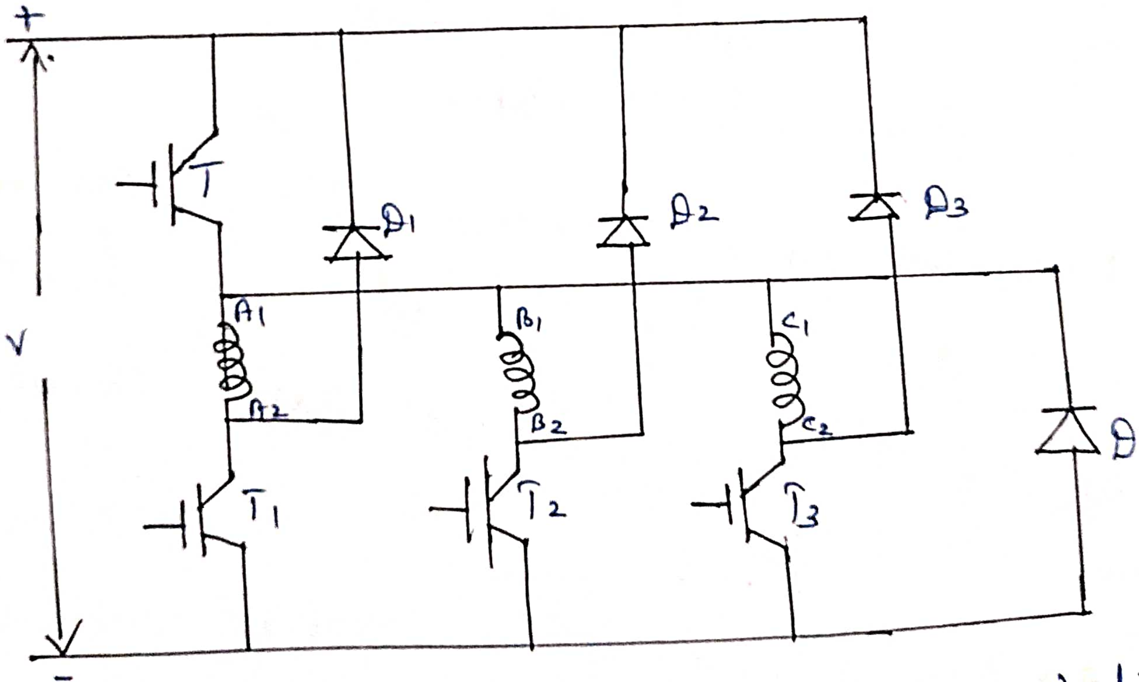


[fig 2.2 classic Converter.]

Drawback:

1> More Numbe of switches are required in each Phase.

2) (n+1) power switching devices and (n+1) diodes:-



[fig 2.3 (n+1) Power switching devices and (n+1) diodes converter].

It requires less number of switching devices and diodes.

To excite phase A, T and T_1 are ON when T and T_1 are OFF, stored energy is fed back through diode D and D_1 to mains. To excite phase B, T and T_2 are ON.

Limitation:-

* At high speeds, phase cannot be de-energized fast through the diodes because control thyristor keeps switching ON with a long duty cycle.

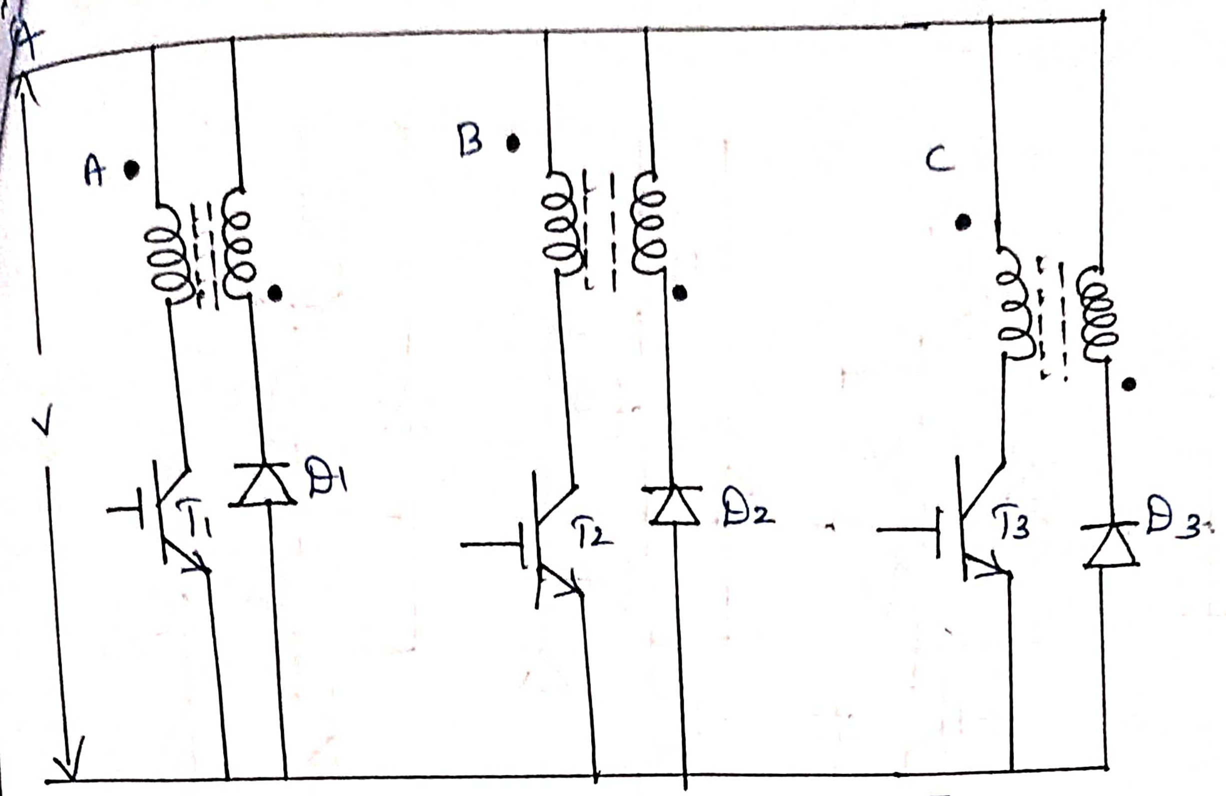
(3) Phase winding with Bifilar wires:-

1> Each phase consist of two identical windings and are magnetically coupled when one of them are excited.

2> Enable bipolar excitation with a reduced number of switching elements.

3> when T_1 is ON, current passes through winding A.

4> when T_1 is OFF, stored energy is fed back to mains through A' and A.



[fig 2.3 Bifilar wire Converter].

Limitations:-

* Bifilar windings require double number of Connections.
* Poor utilization of copper.
* Voltage spikes due to imperfect coupling between the bifilar winding.

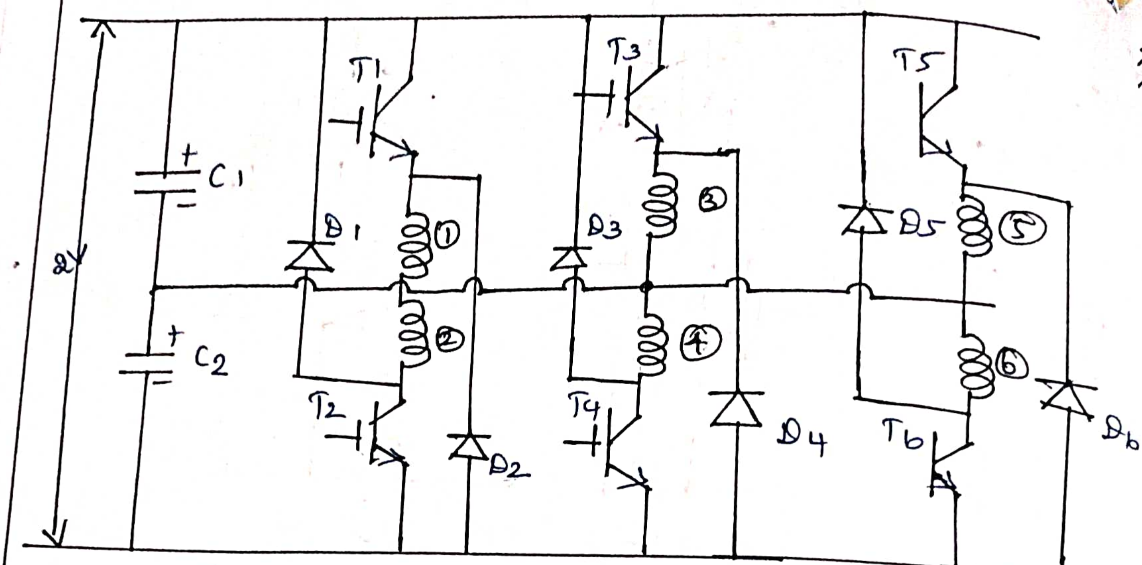
(4) Split Link circuit :

Lower number of switching devices.

main supply is split into two halves using split capacitor.

Converter is less faulty tolerant as fault in any phase will unbalance the other Phase that is connected to it.

Not feasible for low voltage application



[fig 2.4 → split link converter circuit]

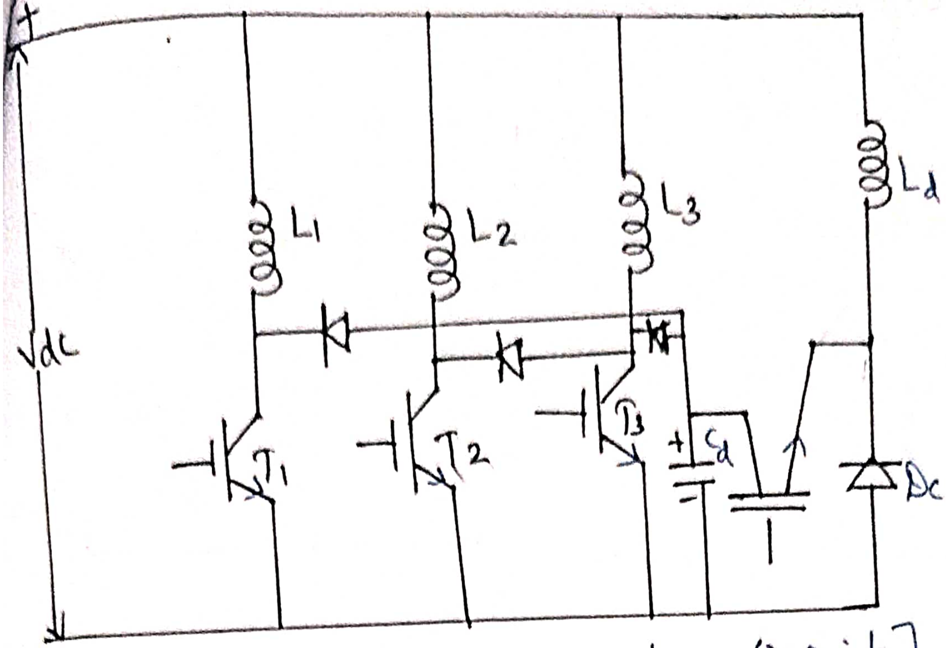
(5) Dump-C Converter :-

* Consist of three phase winding, 3 IGBT's three feedback diodes and a step down chopper.

* The device count is reduced to n+1

* The maximum power switches allow independent phase current controllable performance of the converter is good.

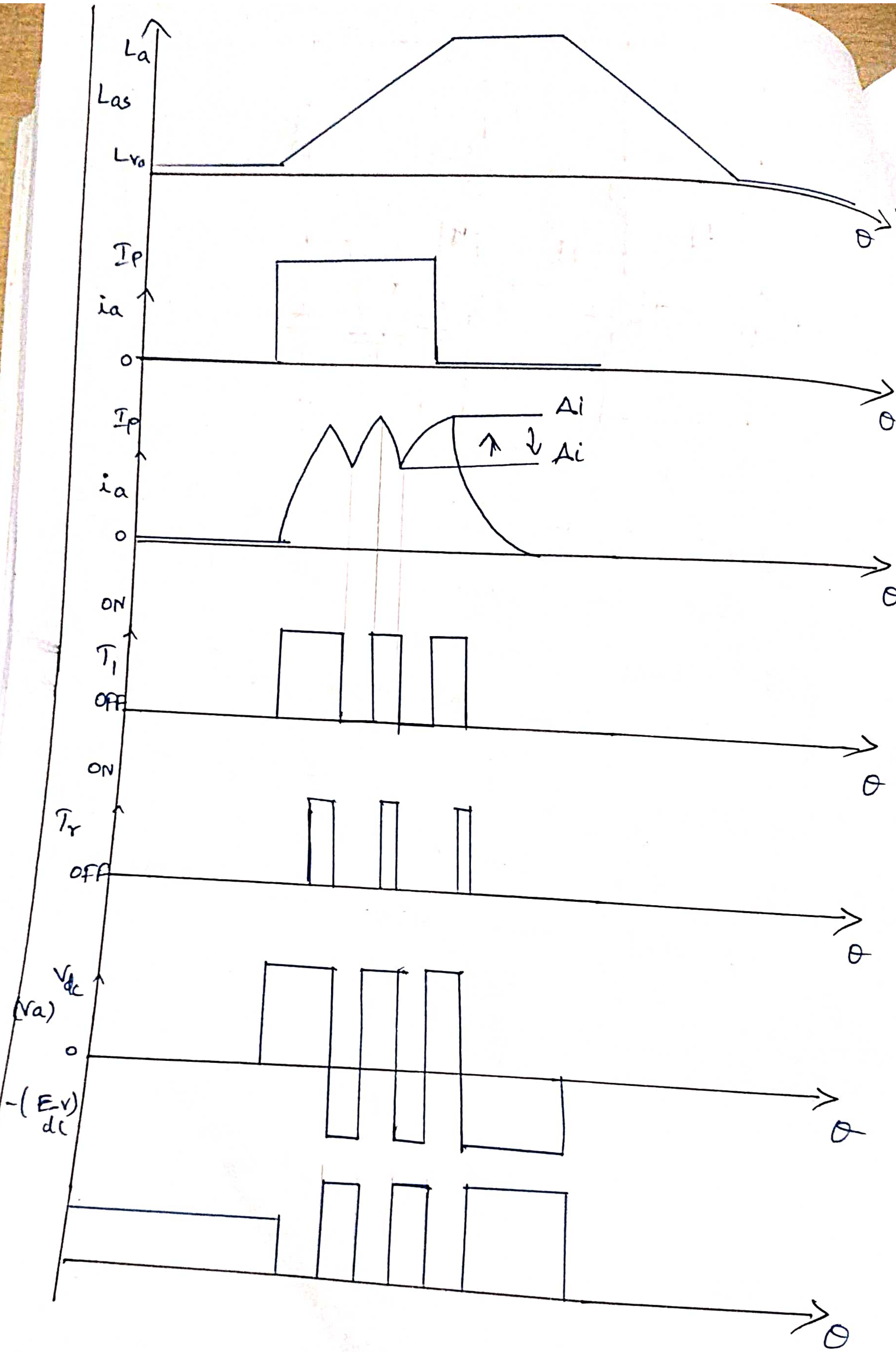
* Converter efficiency is good.



[fig 2.5 Dump C converter circuit]

Dump capacitor voltage is maintained at 2 vdc to allow fast damagnetization. But capacitor and Inductor in dump circuit and also voltage rating of other devices is twice the bus voltage

Monitoring of dump capacitor voltage & control of dump switch makes the converter very complicated and also the converter does not allow free-wheeling.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TORQUE PRODUCTION.

1) Write the torque equation of switched Reluctance motor. (2 marks : may / June - 2013)

2) Explain the Principle of operation of SRM and derive the torque equation (8 mark Nov/Dec - 2012)

3) Derive the expression for static torque in SRM. (6 mark . Nov/Dec - 2016).

Torque Equation

Mechanical Power developed = Electrical Energy i/p − Rate of change of stored energy in the magnetic circuit.

As per Faraday's law of electromagnetic Induction, emf is

$$e = -\frac{\partial \lambda}{\partial t} \quad \text{——— (1)}$$

$$\boxed{\text{flux linkage } \lambda = Li} \quad \text{——— (2)}$$

Sub (2) in (1),

$$e = -\frac{\partial (Li)}{dt}$$

differentiating above eqn,

$$e = -\left[L \cdot \frac{\partial i}{\partial t} + i \frac{\partial L}{\partial t}\right]$$

Multiply and divide by ∂θ,

$$e = -\left[L.\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial t} \times \frac{\partial \theta}{\partial \theta}\right]$$

$$= -\left[L.\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial \theta} \times \frac{\partial \theta}{\partial t}\right] \quad \text{——(3)}$$

$$\boxed{\omega = \frac{\partial \theta}{\partial t}} \quad \text{——— (4)}$$

Sub (4) in (3)

$$e = -\left[L.\frac{\partial i}{\partial t} + i\omega.\frac{\partial L}{\partial \theta}\right]$$

Considering magnitude value and neglecting negative sign.

$$e = L.\frac{\partial i}{\partial t} + i\omega.\frac{\partial L}{\partial \theta} \quad \text{——(5)}.$$

Power $= e \times i$

(5) ⇒ $$\boxed{\text{Power i/p} = Li.\frac{\partial i}{\partial t} + i^2\omega.\frac{\partial L}{\partial \theta}} \quad \text{——(6)}$$

Energy stored in the magnetic field,

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

Rate of change of stored energy, $= \frac{dW_e}{dt}$

$$\Rightarrow \frac{d}{dt}\left[\frac{1}{2}Li^2\right]$$

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

$$W_e = L\, i\, \partial i/\partial t + \frac{i^2}{2} \frac{\partial L}{\partial t} \quad \text{—— (7)}$$

Multiply and divide by $\partial\theta$ (7),

eqn (7) becomes,

$$\frac{dW_e}{dt} = L i \cdot \partial i/\partial t + i^2/2 \cdot \partial L/\partial t \times \partial\theta/\partial\theta$$

$$= L i \cdot \frac{\partial i}{\partial t} + \frac{i^2}{2} \cdot \frac{\partial L}{\partial \theta} \cdot \partial\theta/\partial t$$

$$\boxed{\frac{dW_e}{dt} = L i \cdot \frac{\partial i}{\partial t} + \frac{i^2 \omega}{2} \cdot \frac{\partial L}{\partial \theta}} \quad \text{—— (8)}.$$

sub (6) & (8) in (A),

Mechanical Power developed $(P_m) = L i \cdot \frac{\partial i}{\partial t} + i^2\omega \cdot \frac{\partial L}{\partial \theta} - L i \cdot \frac{\partial i}{\partial t} - \frac{i^2 \omega}{2} \cdot \partial L/\partial\theta$

$$P_m = \frac{i^2 \omega}{2}\, \partial L/\partial\theta \quad \text{—— (9)}.$$

In General,

$$P = T\omega$$

$$\Rightarrow T = P/\omega \quad \text{—— (10)}$$

Sub (9) in (10),

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

As $T \propto i^2$, it is independent of the direction of current.

Operation Modes of SRM :-

- Based on the nature of current, there are 2 operation modes.
  - * Single pulse mode - high speed mode
  - * PWM mode - low speed mode.

Single Pulse Mode :-

Current raise is within the limits during small time internal of each phase excitation. This build up of current limit is due to the winding inductance and counter emf generated in stator winding.

The switch is closed when Inductance begins to raise and the current at once reaches a constant value. If current pulse is constant and Positive, $L(\theta)$ is raising the Positive torque is developed.

θ_0 -> switch on angle

θ_2 -> Switch off angle

$(\theta_1 - \theta_0)$ -> angle of advance

$(\theta_2 - \theta_3)$ -> conduction angle transistor

$(\theta_3 - \theta_2)$ -> diode conduction angle of inverter.

$(\theta_2 - \theta_0) \rightarrow$ Source delivers energy to motor.

$(\theta_3 - \theta_0) \rightarrow$ energy is fed back to source.

This source voltage is applied to the winding when the inductance begins to rise. Because low inductance allows current build up to be faster. when the current begins to fall, negative voltage is applied to the phase winding.

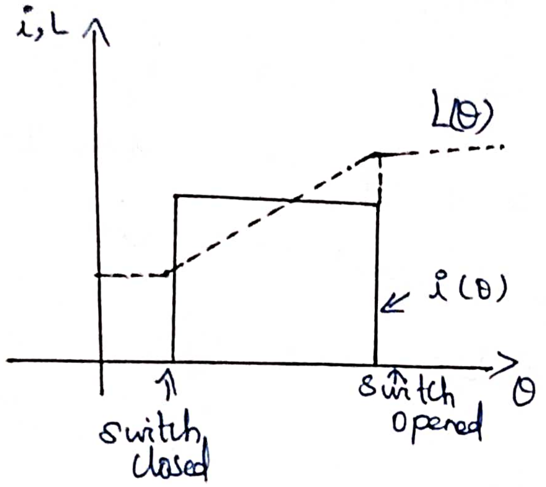
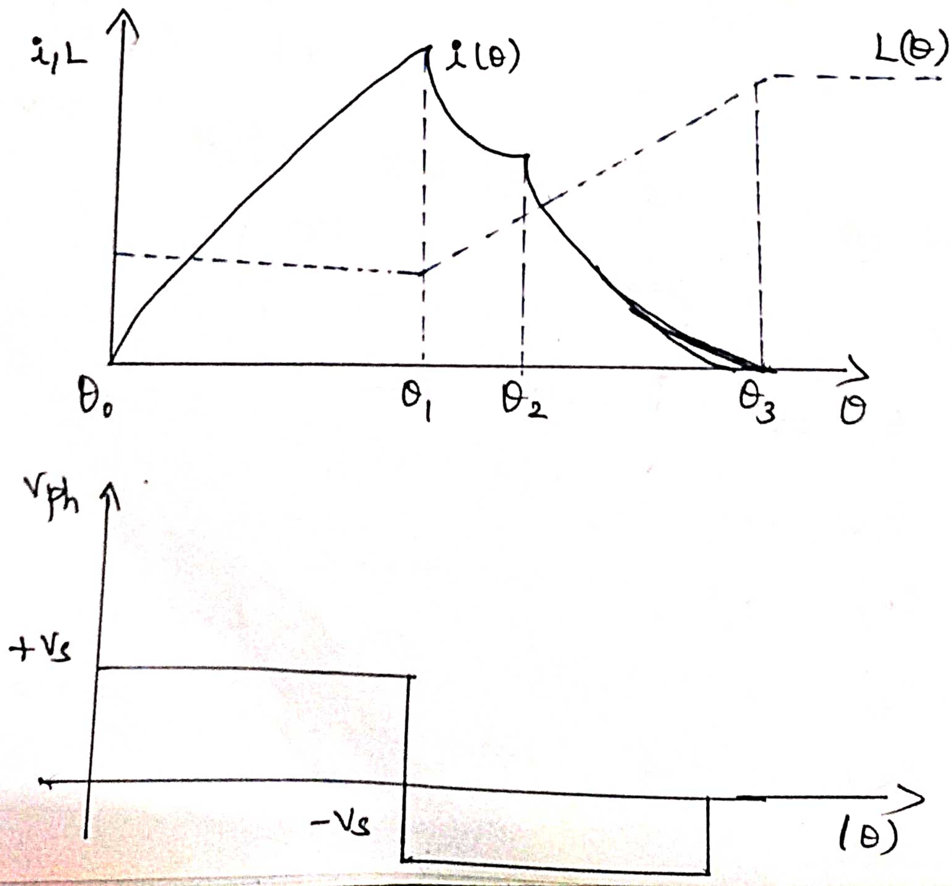


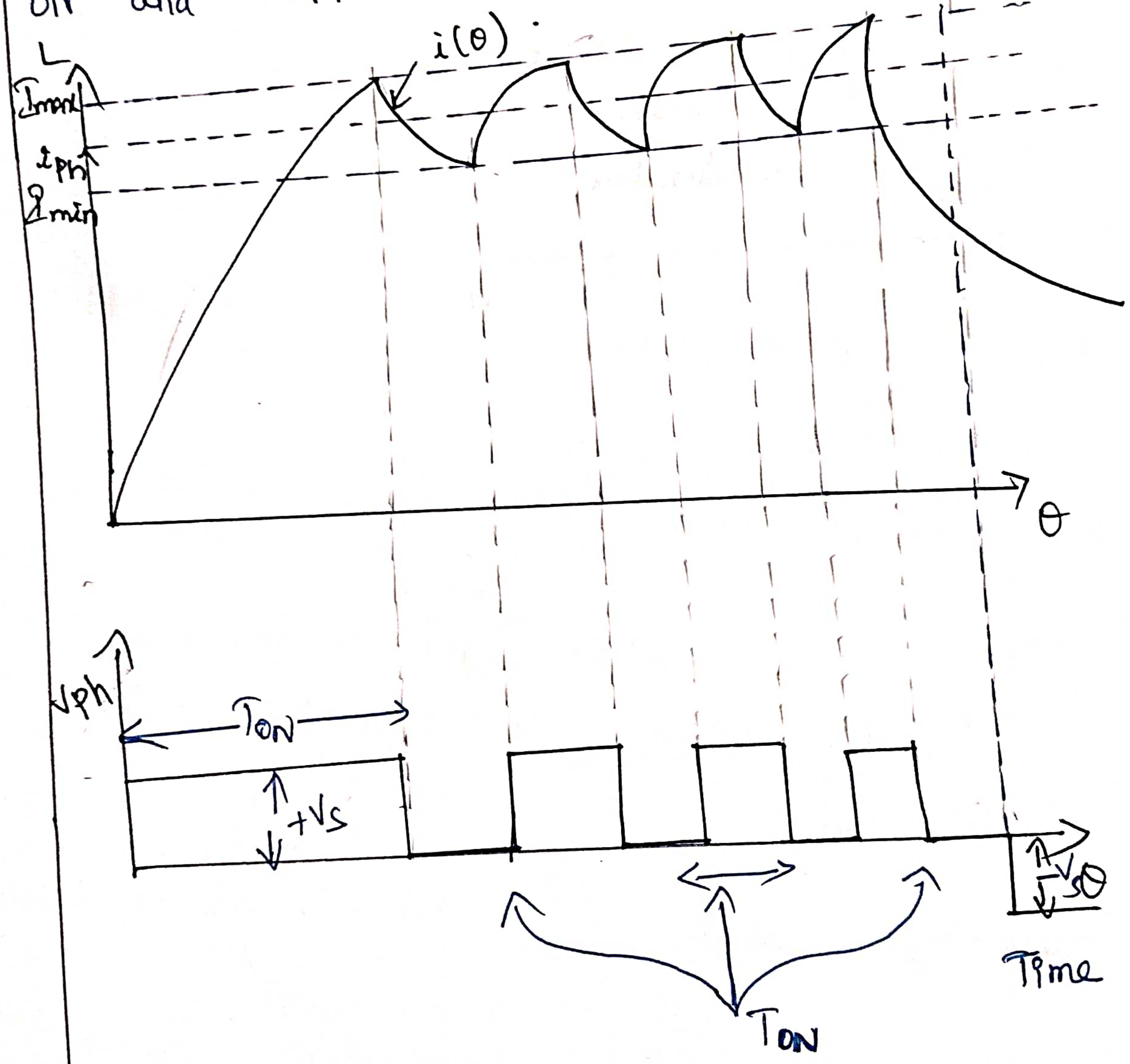
fig 2.6 → current waveform at high speed Mode.



PWM mode :-

* each phase winding is excited for a longer period and hence current build up is also high.

To limit the current rise, a current limiting device is incorporated in the drive system. The current is controlled to be within the prescribed limits by switching ON and OFF the devices.



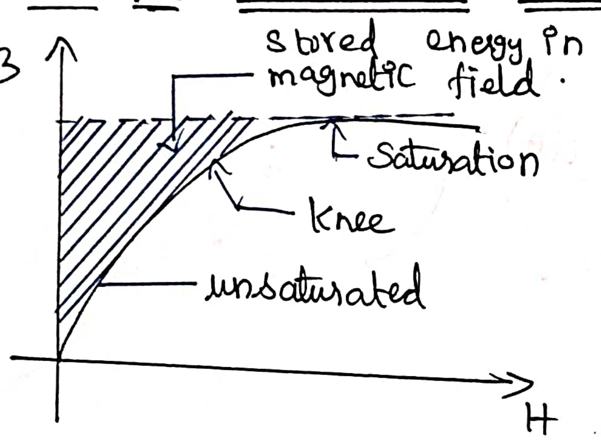
Commutation Overlap:-

Conduction Period on each Phase Should not exceed the step angle and a Small amount of overlap is desirable to acheive less ripples in torque.

(maximum and minimum O/P of torque)

Higher value of overlap leads to Positive impulses of torque at Positive Commutation angles.

B-H curve of a Performance Material:



(fig 2.7 → B-H curve)

Flux density $B = \phi / A$

magnetic field strength $= \frac{Ni}{L}$

$\lambda - i$ curve of electromagnetic is increased gradually, stored energy in magnetic field is also increased.

During unsaturated condition, stored energy

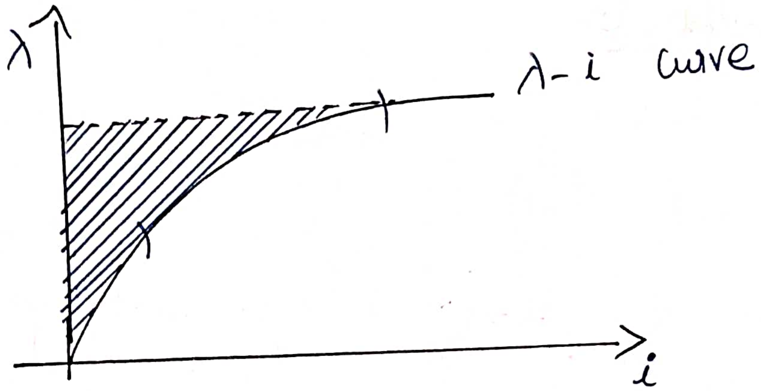
$$= \frac{Li^2}{2}$$

λ = flux linkage.

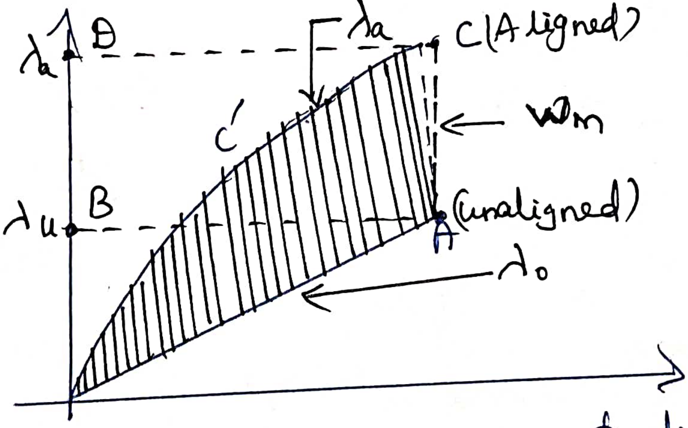
where, L is Constant and has a high value

During Saturated Condition, there is a limit on the stored energy. And any increase current further does not cause an increase in stored energy appreciably.

At knee Portion, increase in stored energy per ampere gradually gets reduced.



[fig 2.8 -> λ-I curve of SRM.]



[fig 2.9 -> λ-i curve for different rotor position.]

ROTOR POSITION SENSORS

Commonly used position sensors are,

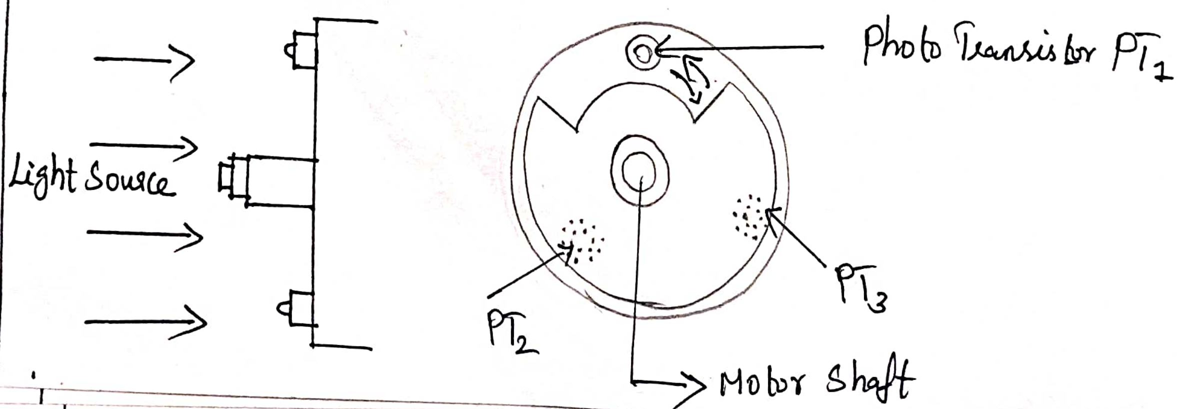
* 1> Photo Transistors
* 2> Photo diodes
* 3> Hall elements
* 4> Magnetic sensors
* 5> Pulse encoders &
* 6> variable differential transformers.

Photo transistors:-

Based on photo electric principle, Photo transistors are fixed on the stator. Number of Photo Transistors is equal to Number of stator phases.

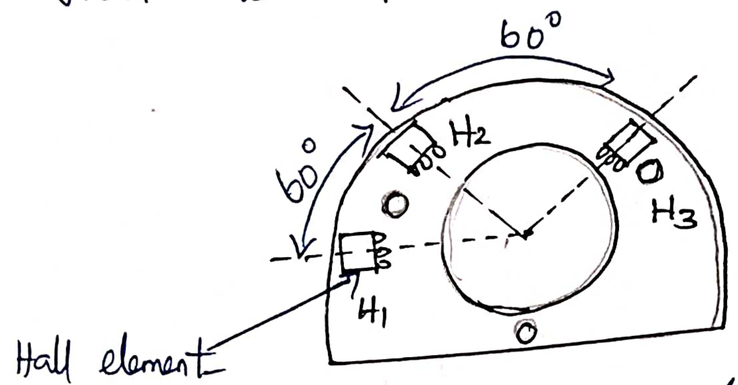
A revolving shutter is installed on the rotor shaft.

when the gap is aligned with PT_1, PT_1 will generate a current due to light falling on it while PT_2 and PT_3 carry only a small leakage current because the light is blocked by revolving shutter.



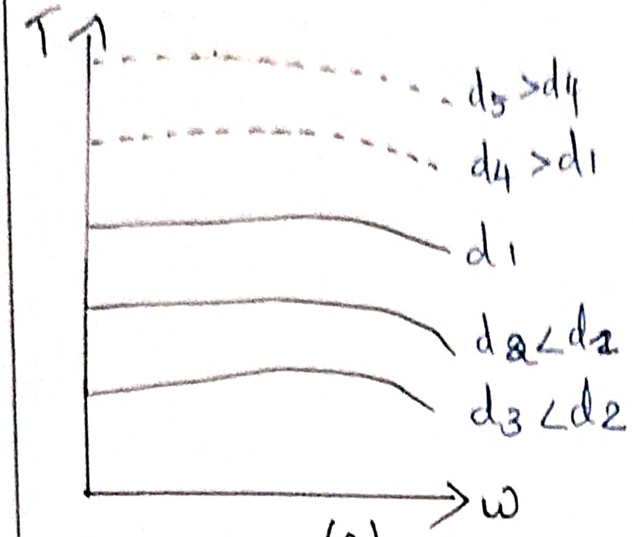
Position Sensors:

The function of a Hall sensor is based on the physical principle of the Hall effect named after its discover E. H Hall (Edwin Harbert Hall).
It means that a voltage is generated transversely to the current flow direction in an electric conductor (the Hall voltage), if a magnetic field is applied perpendicularly to the conductor.

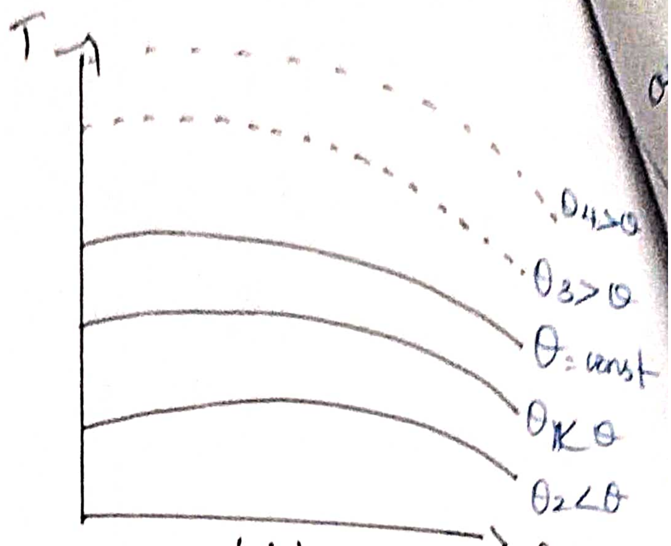


A typical structure of Hall position sensor for three phase SRM motor is illustrated in above figure. It is made up of three Hall components and rotating plate with permanent magnet fixed on the rotor shaft. Similar to the gap of the photo-transistor sensors, the permanent magnet on the rotating plate is installed suitably so that the output of the Hall components can indicate the phase current proper rotor position for the control.

Torque - speed characteristics:



(a)



(b)

Torque developed by SRM depends upon the current waveforms of each phase winding. Current waveform depends upon the conduction period and chopping period and speed.

consider a case conduction angle θ is constant and chopper duty cycle is one. i.e.) it conducts continuously. For low speed operating condition current is assumed to be almost flat shape Thus developed torque is constant. High speed operating condition the current waveform gets changed, and the torque developed is reduced.

The above plot shows speed - Torque characteristics of SRM for constant θ and duty cycle. It is constant at low speeds and slightly drops as speed increases.

Torque - speed capability Curve:

Maximum Torque developed in a motor and maximum Power it can be transffered or usually restricted by mechanical sub-system design parameters.

For a given conduction angle, torque can be varied by varying the duty cycle of the chopper. However, the maximum developed torque is restricted to definite value based on mechanical considerations points. A, B in the figure represents constant maximum torque region of operation. At operating point 'B' conduction angle is 'θ'. It is a constant value.

That is point at which the speed is maximum with constant torque. The Power transfferred at point 'B' is Tω.

The curve 'BC' in the fig. represents a maximum permissible torque at each speed without exceeding the maximum permissible power transferred.

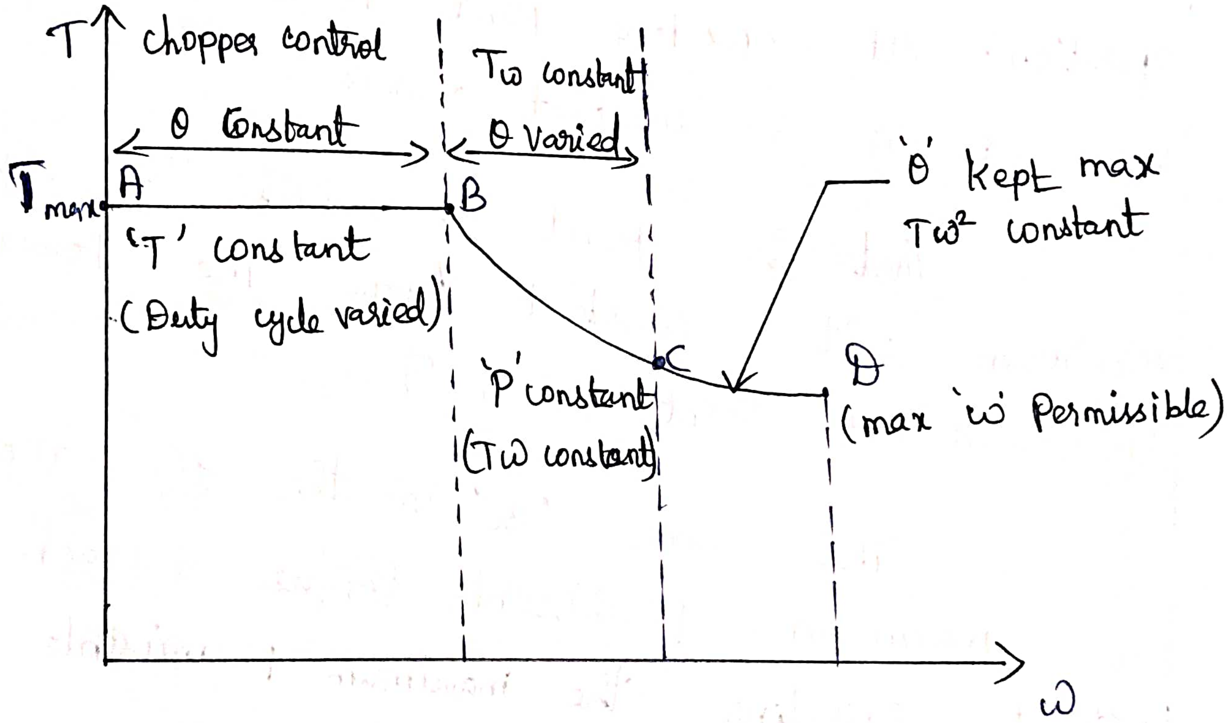
This region is obtained by varying θ, the permissible maximum value θ_{max} and keeping the Power "Tω" to the maximum

At any point in this region can be obtained by varying 'θ' and by chopper.

Point 'C' corresponds to maximum permissible power, maximum permissible conduction angle and duty cycle of chopper is unity.

Curve "C D" represents "$T\omega^2$" constant, the conduction angle is ~~kq~~ kept maximum and duty cycle is maximum and $T\omega^2$ is maintain constant.

'D' corresponds to maximum 'ω' permissible. The region between the curve ABCD and 'x' axis is the permissible region of operation of SRM.



...Demerits and Application of SRM:-

Merits:

1> Construction is simple and robust.

2> Rotor carries no windings, no sliprings, no brushes, less maintenance.

3> There is no permanent magnets.

4> Ventilating system is simpler as losses takes place mostly in the stator.

5> Power semiconductor switching circuitry is simpler.

6> It is the self-starting machine.

De-merits:

1> Stator phase winding should be capable of carrying magnetising current also.

2> Size of the motor is comparable with induction motor size variable speed drive.

3> It requires a rotor position sensor (RPS)

Applications:-

1> Wachine machines.

2> Vacume cleaners

3> Fans

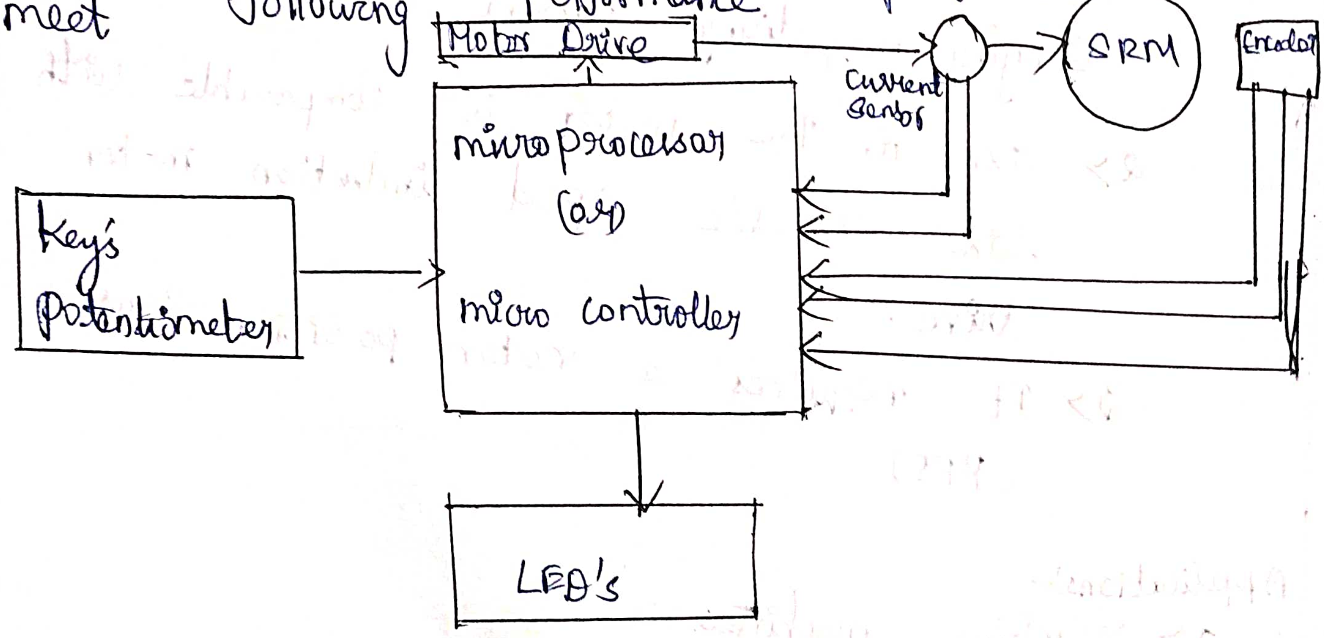
4> Future automobile applications.

Microprocessor (or) computer Based control of SRM :-

A general purpose microprocessor controlled closed-Loop switched Reluctance motor (SRM) drive system is designed to drive a four phase SRM with minimum number of switches, while achieving maximum flexibility.

The main objective of this microprocessor based control of SRM is to develop software controlling of various modes of operation.

This System can be designed to drive a SR motor. The application ~~which~~ should meet following performance specification.



of speed control of SR motor with encoder

position Sensor.

→ variable line voltage up to rated 42 V DC.

→ Control techniques incorporates.

→ Motor starts from any position with rotor alignment.

→ Two directions of rotation.

→ Motoring Mode.

→ minimal speed 600 rpm (can be set by user).

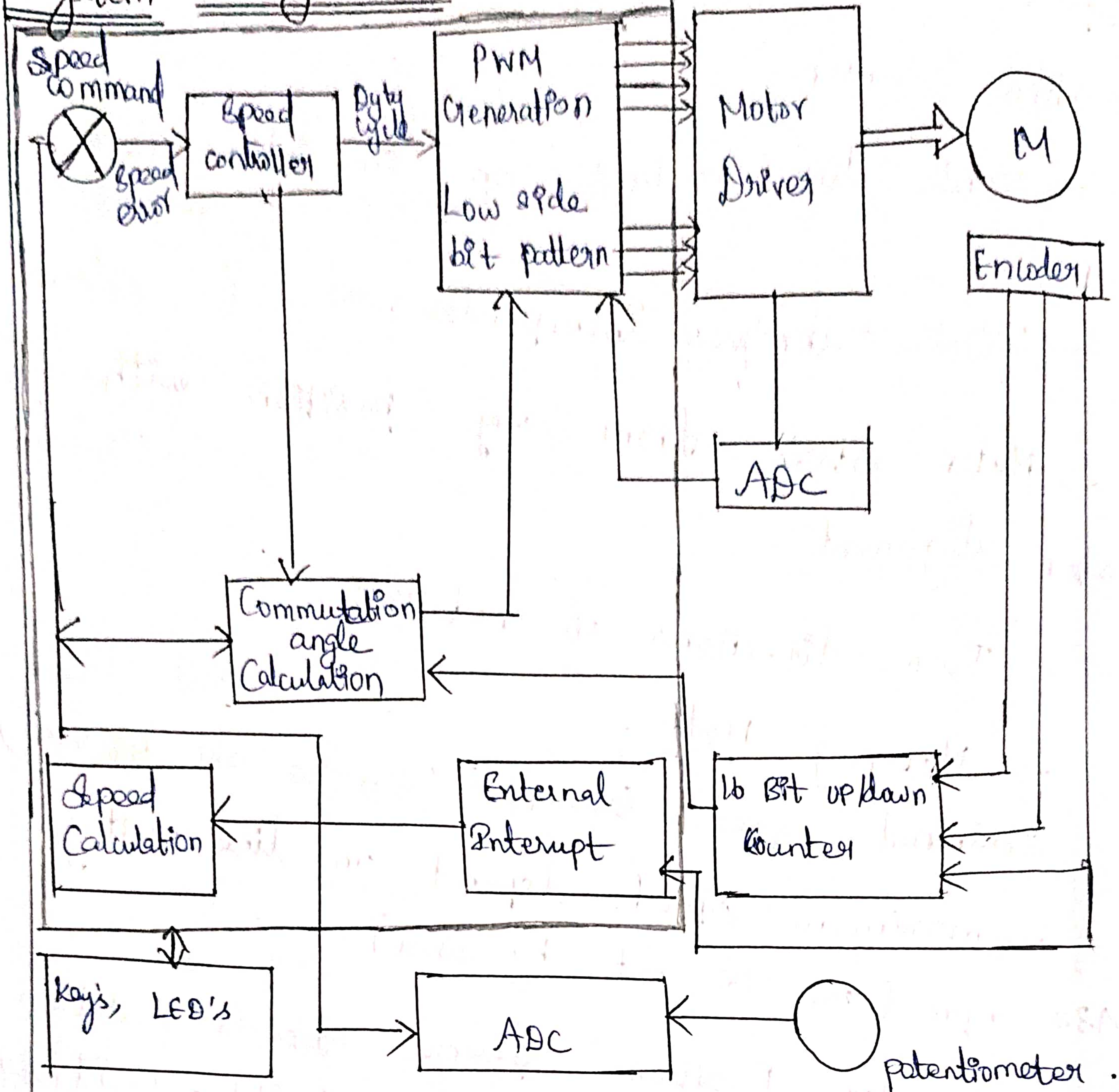
→ maximum speed depend on line voltage 4320 rpm (can be set by user).

→ encoder Position reference for commutation.

→ user Interface [start/stop switch, right/left switch; Potentiometer for speed adjustment, LED, Indicators].

→ DC-Bus over current protection.

System configuration :-



The microprocessor runs the main control algorithm. It generates 4-Phase PWM output signals for the SR motor power angle 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.

in the speed calculation no additional velocity sensor is needed. motor speed is derived from the position information. The reference speed is calculated from user defined potentiometer value. 67

The speed error between commanded speed and actual speed is used in the speed controller to manipulate the voltage applied to each phase winding and firing angles.

PWM voltage regulation is used and mid-speed regions. where as 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 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 ~~dg~~ duty cycle is restricted. The procedure is repeated for each commutation.

is opposite to that of a conventional Dc motor.

Stator - armature winding connected to Dc supply through a solid state inverter.

⇒ Rotor - permanent magnet,

⇒ Numbers of poles of rotor is equal to no. of poles of stator.

⇒ mechanical commutator.

⇒ made up of copper.

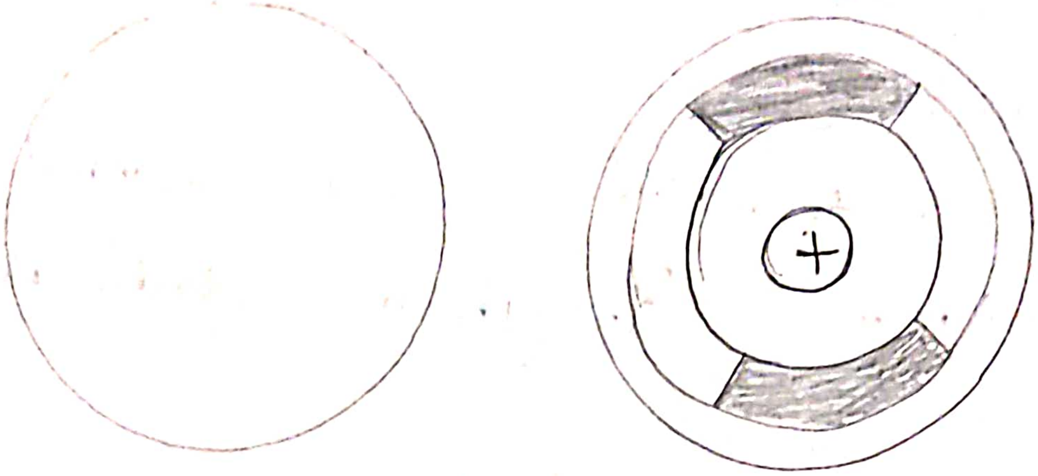
⇒ commutator segments are insulated from each other by a thin layer of mica.

⇒ Function of commutator is to convert the alternating emf into unidirectional emf.

⇒ The Dc current passing through brushes sets up an mmf which is in quadrature with the main field. mmf irrespective of the speed of the motor.

⇒ This current has two parallel paths in armature winding.

⇒ concentrated winding - winding around one teeth.



Construction :-

A brushless DC motor is a polyphase synchronous motor with a permanent magnet rotor.

This motor requires electronic commutator for its operation, requires rotor position sensor.

Inverter uses transistors, MOSFET's for low power devices and thyristors for high power devices. hence, the motor position sensor gives the rotor position, information and sends the control signals for turning on the controlled switches.

Stator:-

A brushless D.C motor is called as inside-out DC motor because the construction

The magnitude of the electro motive force V_H, which is called the Hall voltage, is given by,

$$V_H = \frac{1}{d} B I_c R_H$$

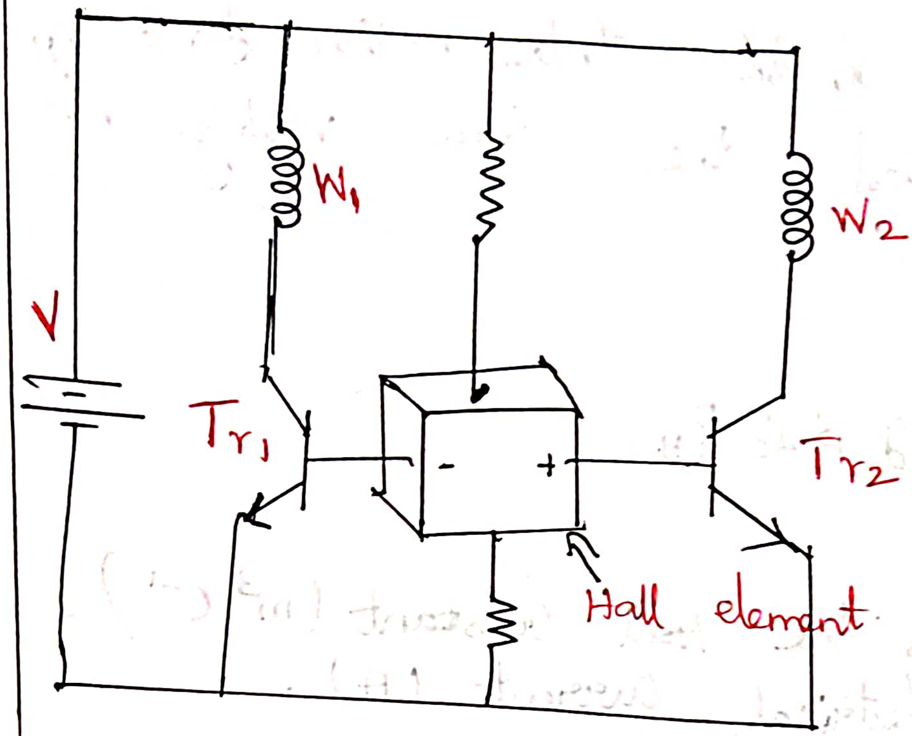
where,

$R_H \rightarrow$ is the Hall constant ($m^3 C^{-1}$).
$I_c \rightarrow$ electrical current (A).
$B \rightarrow$ flux density.
$d \rightarrow$ thickness of the semiconductor pallet.

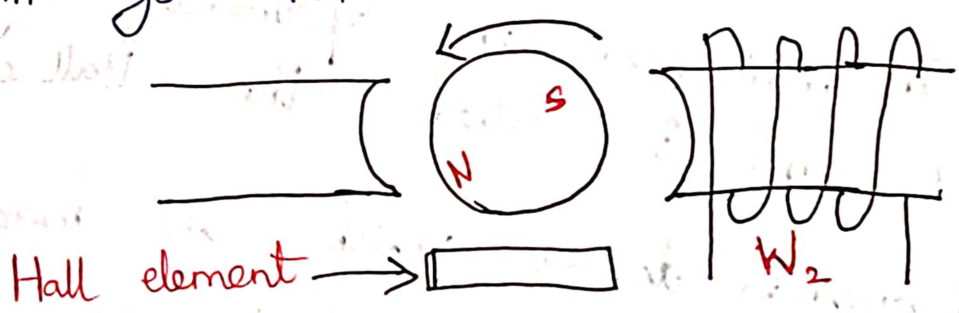
This Phenomenon was discovered by E.H Hall in 1878 from an experiment using a metal segment and is called the "Hall effect". Semiconductor devices which are made for use in detecting magnetic fields are called "Hall elements (or) Hall generators".

Basic Principle of the Brushless DC motor using a Hall element.

The below figure shows the brushless DC motor using a Hall element.



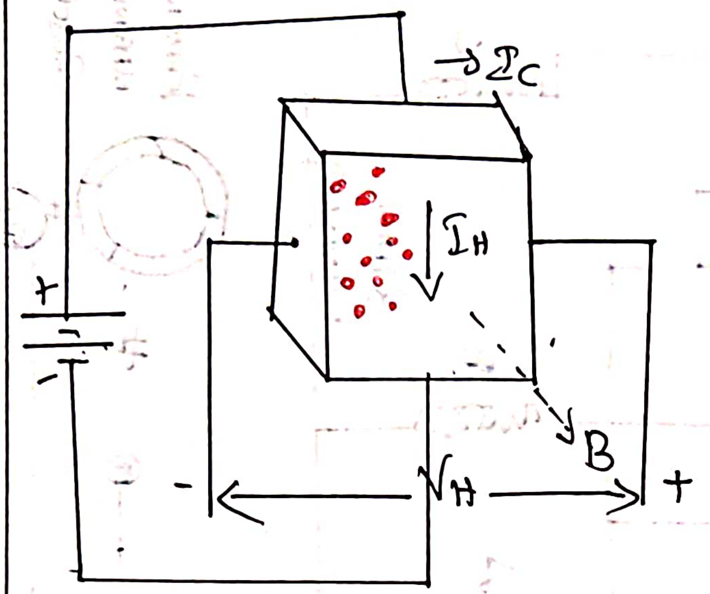
Output signals from the Hall element operate two transistors Tr_1 and Tr_2 to control the electrical currents in stator windings 'W_1' & 'W_2'.



The Hall element detects the north pole of the rotor magnet and winding 'W_2' is energized to produce the south pole which drives the rotor in the "CCW" directions.

Since no magnetic field is applied to the hall element in this positional relation, both transistors are in the off state, and no currents flows in (W_1) (or) W_2.

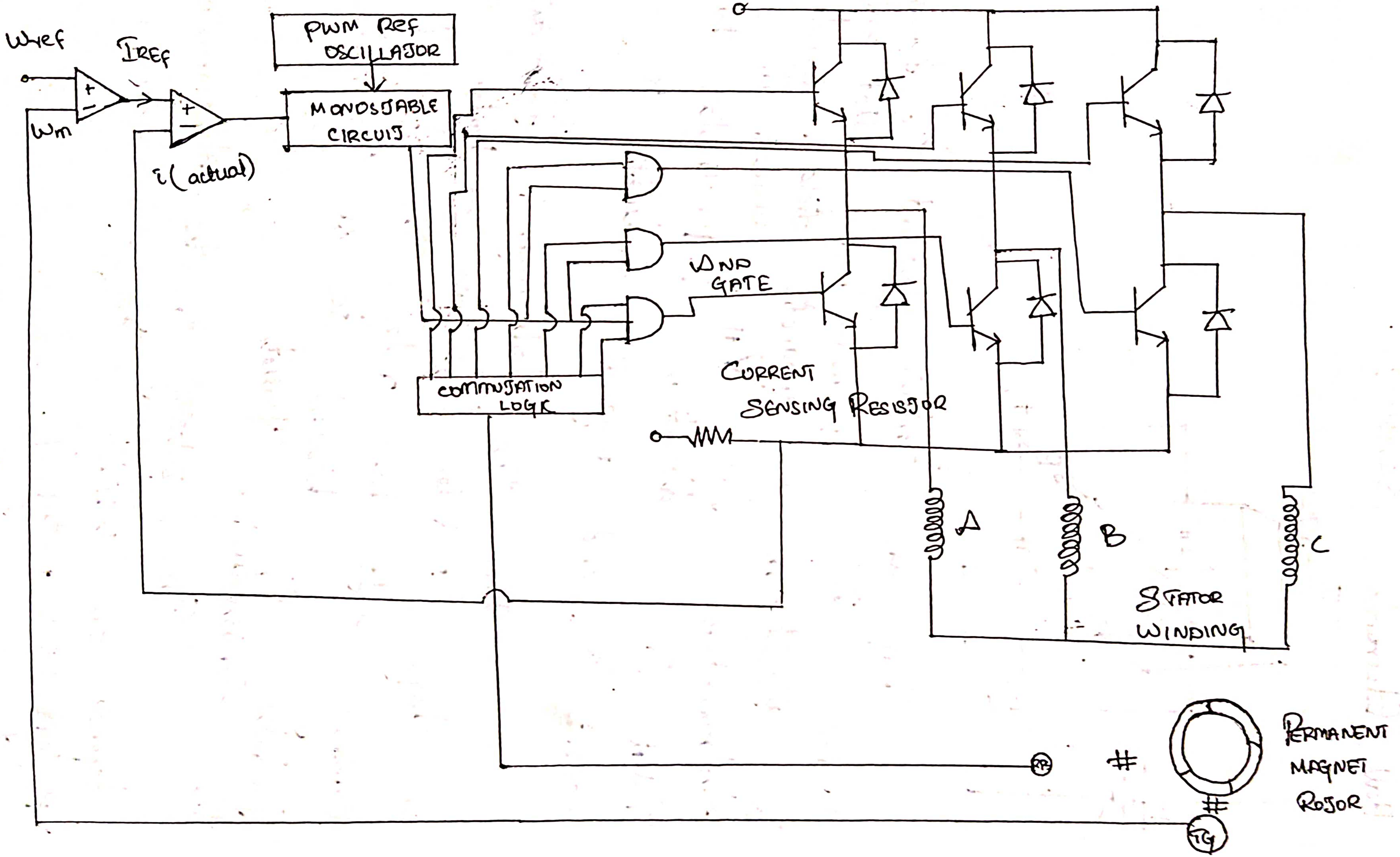
Hall Elements sensor:-



When an electric current 'I_C' flows downwards in a semiconductor pallet which is placed in a magnetic field. And the electromotive force 'V_H' is created in the pallet in a direction perpendicular to both current 'I_C' and magnetic induction 'B'.

Since, the electromagnetic force acts on chargeed particles (electrons (or) holes) according fleming's left hand rule, the charged particles are biased to the left side of the semiconductor pallet.

[The polarity of the electromotive force depends on whether the semiconductor dist p-type (or) n-type].



Wref
Iref
Wm
i(actual)
PWM Ref OSCILLATOR
MONOSTABLE CIRCUIT
AND GATE
COMMUTATION LOGIC
CURRENT SENSING RESISTOR
A
B
C
STATOR WINDING
PERMANENT MAGNET ROTOR
TG

of transistor.

→ AND gates are used to drive the lower leg devices.

Speed comparator:-

→ The speed comparator compares the reference speed (ω_{ref}) with the actual motor speed (ω_m). The speed error signal is given as current reference (I_{ref}) to the current comparator.

Current comparator:-

The current comparator compares the reference current (I_{ref}) with the actual current (I_{actual}). The resulting error signal is fed to the monostable circuit.

Rotor Position Sensor:-

→ Rotor position sensor converts the information of rotor shaft position.

→ The signal from the rotor Position sensor is fed to commutation Logic.

$$= e_{ph} \times I$$

$$P = 4 B_g r l T_{ph} \omega_m I \quad \text{——— (2)}$$

Sub (2) in (1)

$$T = \frac{4 B_g r l T_{ph} \omega_m I}{\omega_m}$$

$$\boxed{T = 4 r l B_g T_{ph} I \quad N\text{-}m}$$

Power Converter Circuits and their Controllers.

Power Converter :-

→ An inverter is used. It controls the commutation.

→ PWM technique is used to control the current through the stator winding.

Commutation Logic Circuit :-

→ It Provides 6 output signals, that are used for driving base

Resultant torque = $T_{ea} + T_{eb} + T_{ec}$

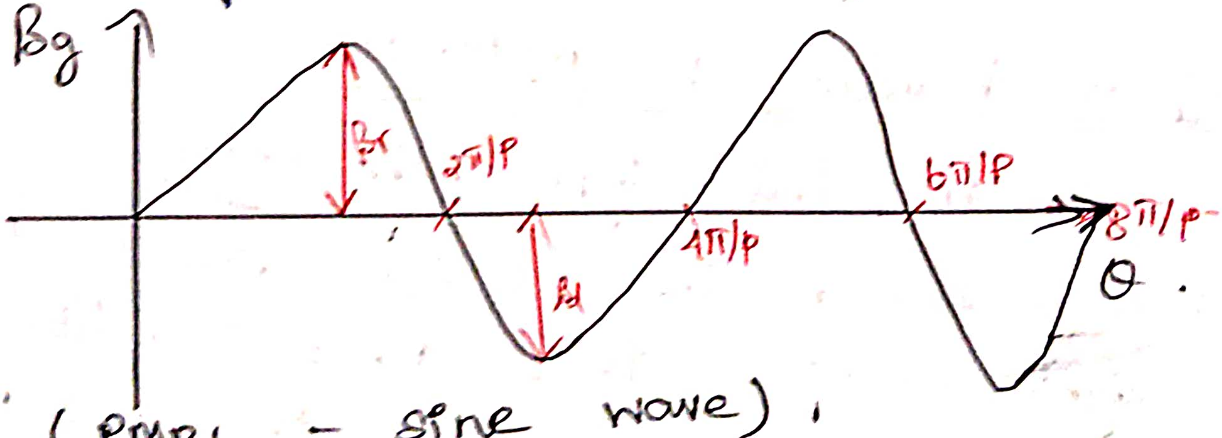
$= (3/2) \, k I_m$.

Shaft torque is independent of rotor position.

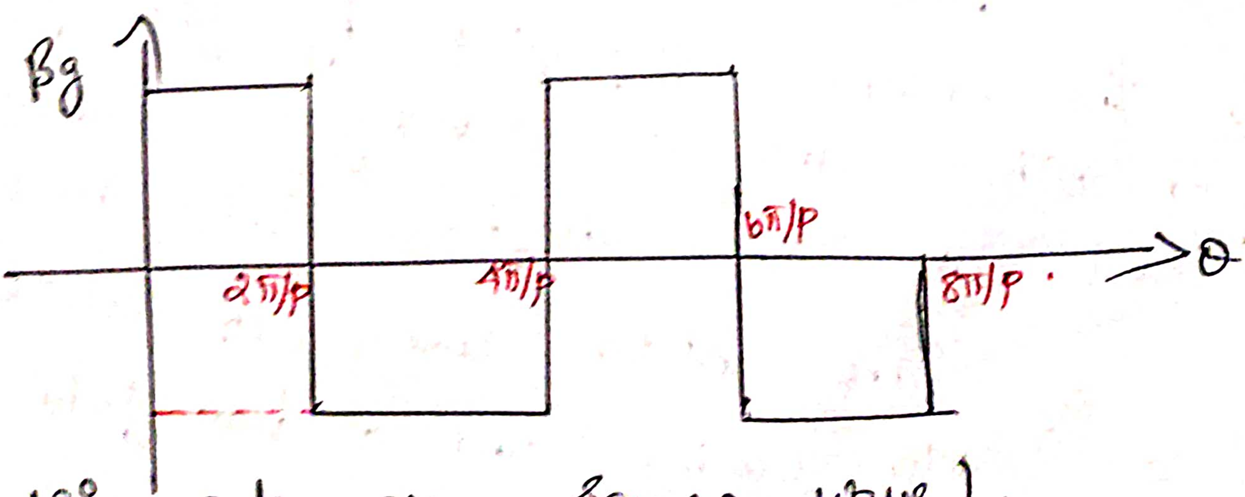
Classification of PMBLDC Motor:-

1) PMBL square wave motor.
   a) 180° pole arc motor.
   b) 120° pole arc motor.

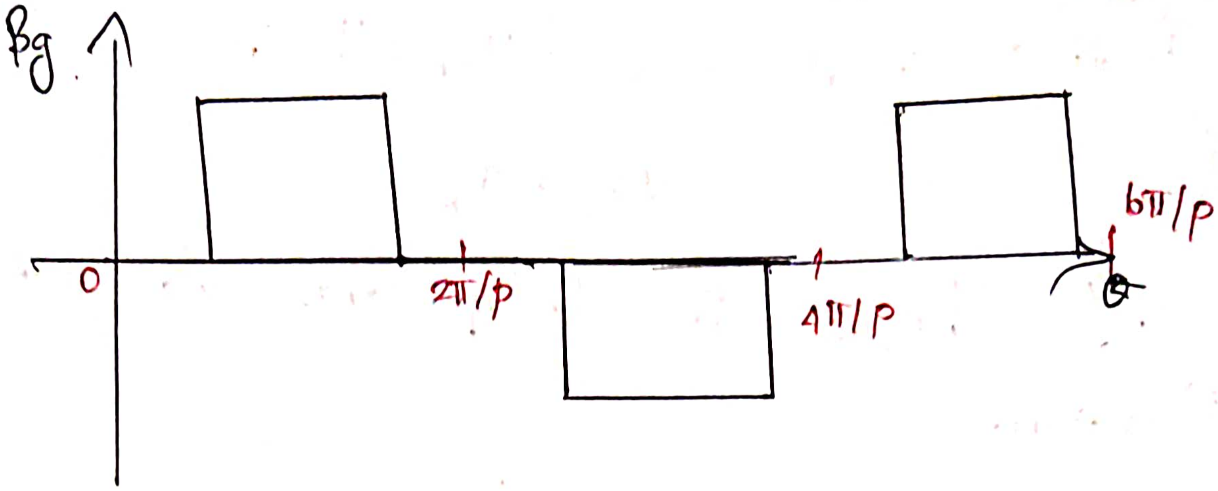
2) PMBL sine wave motor - Airgap flux density distribution sinusoidal.



(PMBL - sine wave).



(180° pole arc square wave).



Types of BLDC Motor:

There are 2 types of Brushless DC motor available in Practice. They are,

* Unipolar brushless DC motor.
* Bipolar brushless DC motor.

Unipolar brushless DC motor :-

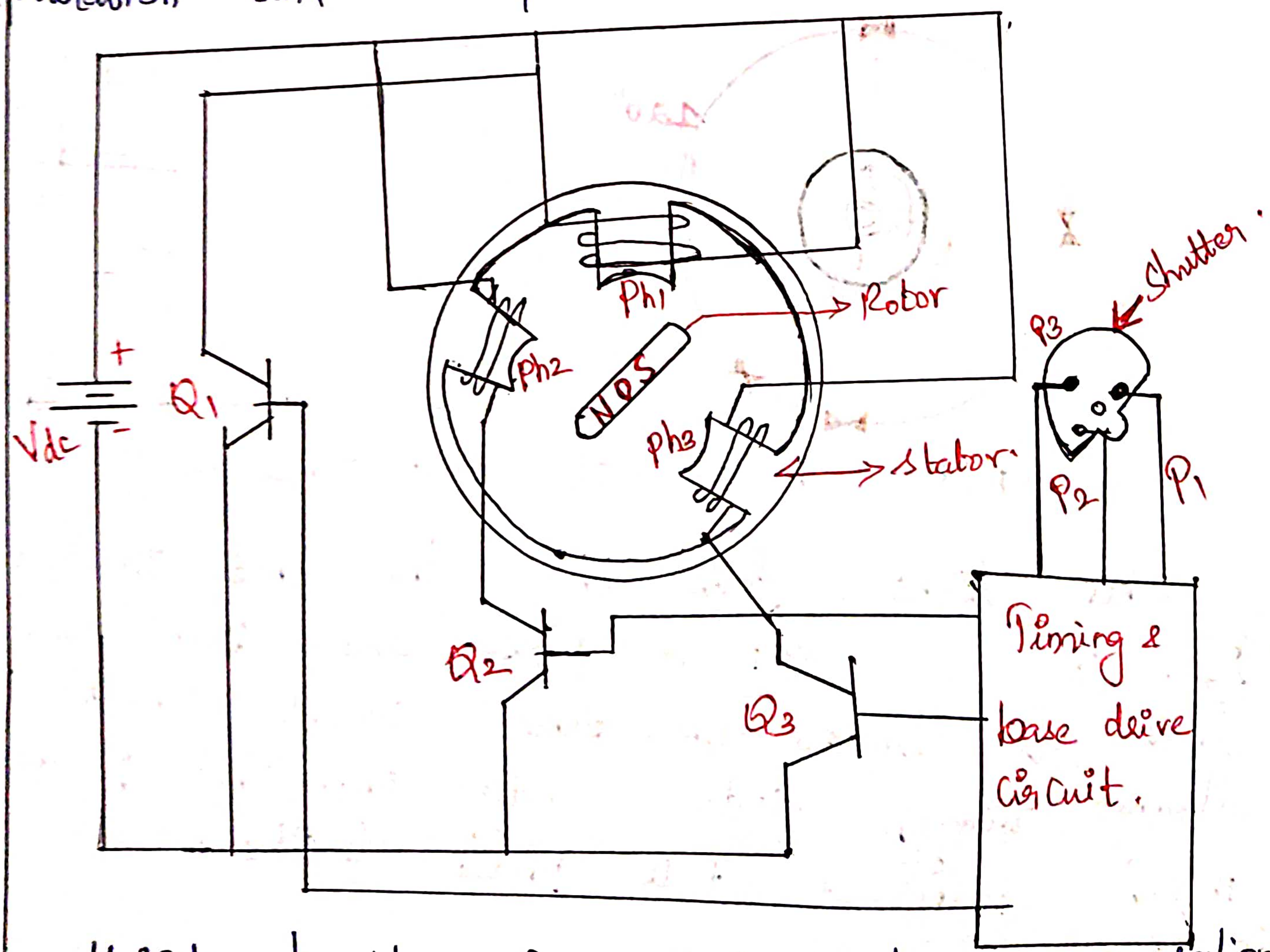
In this type the rotor consist of optical sensor. The optical sensor has a light source, three photo transistors P_1, P_2 & P_3, mounted on the end Plate of the motor, seperated by 120° from each other and a revolving shutter coupled to the shaft of the motor.

The stator consist of a three Pole stator winding and a two pole rotor;

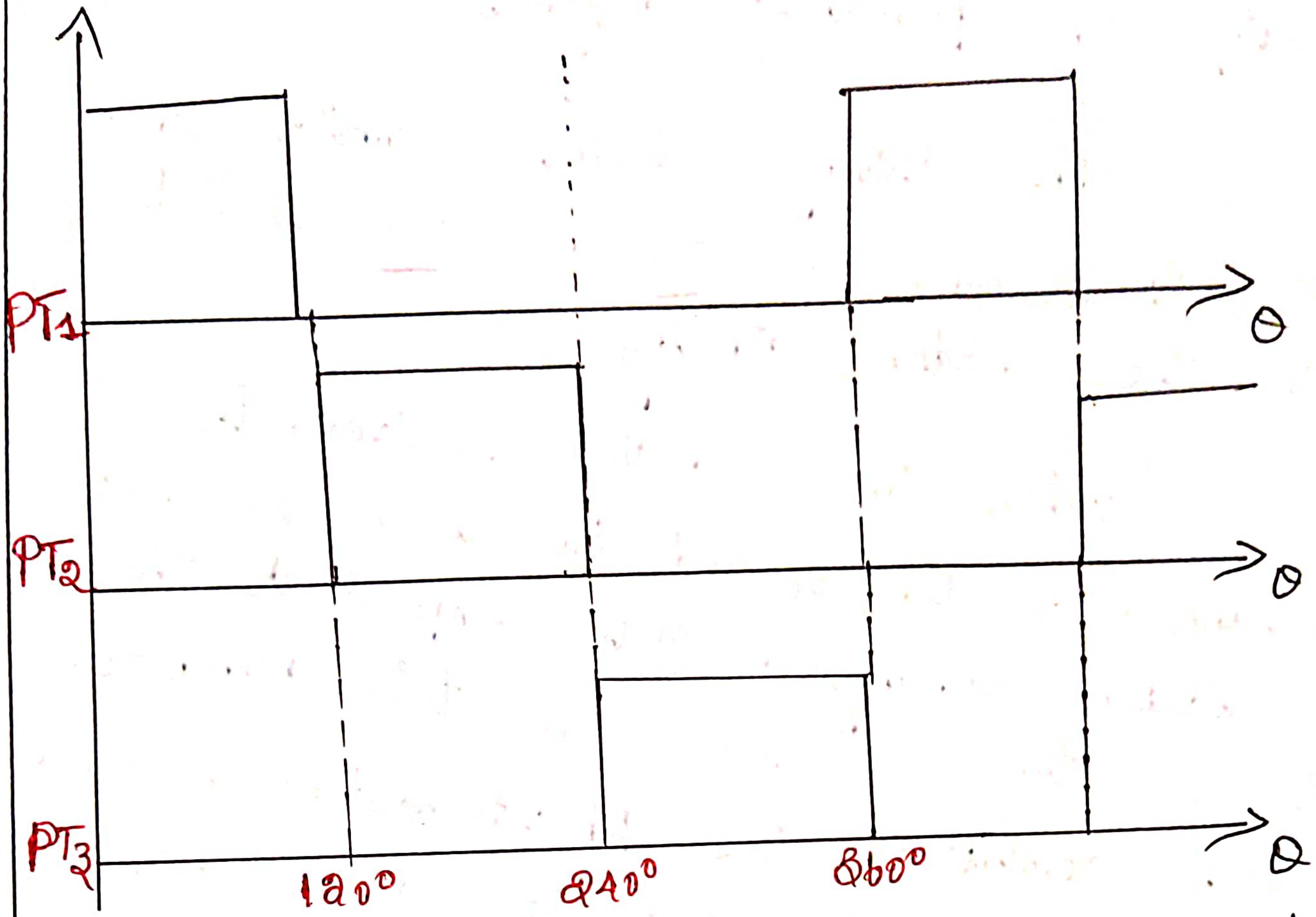
consisting of permanent magnets.

The driving circuit consists of three transistors Q_1, Q_2 and Q_3 used to excite the stator windings.

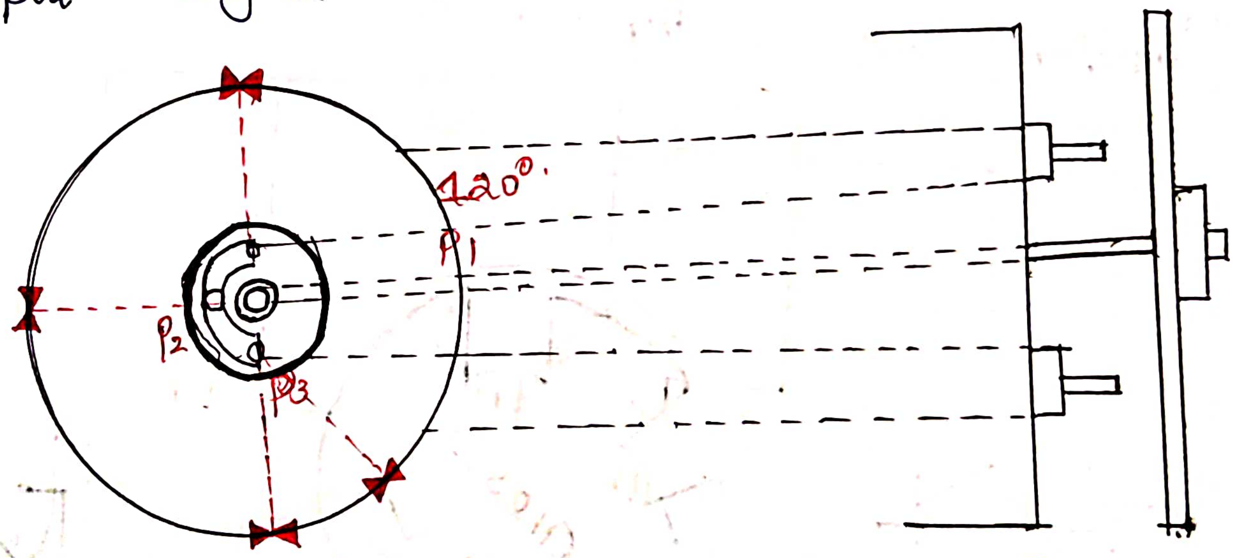
When the shutter revolves, the Phototransistors Q_1, Q_2 and Q_3 used to excite the stator windings, gets exposed to the light in the sequence of their numbers. In each revolution, the phototransistors generate the pulses P_{11}, P_{12} and P_{L3} which have duration and displacement of 120°.



Unipolar brushless DC motor's construction & operation



[Input signal for unipolar BLDC motor]

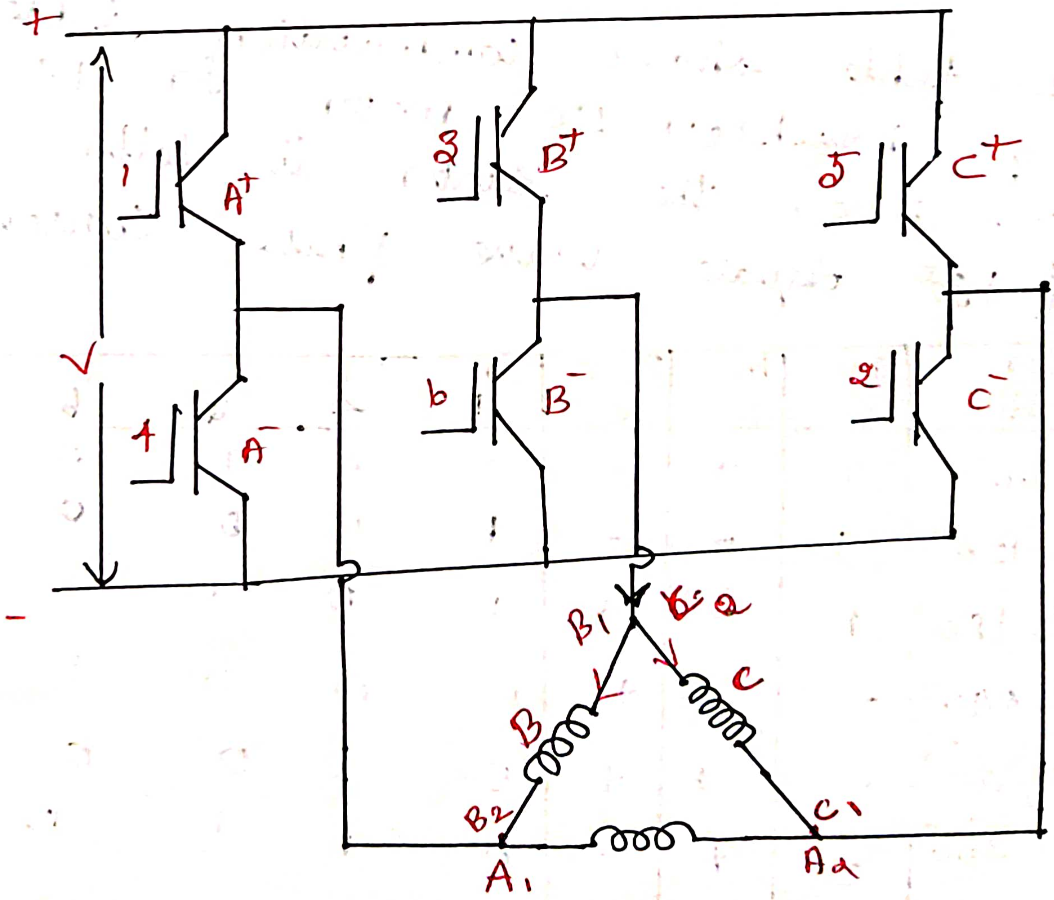


[PMBLDC motor with Phototransistors]

when light falls on the Photo transistors P_1, it generate a pulse and transistors Q_1, gets turned ON. Hence Current Starts flowing through stator winding Ph_1. This Produces North Pole at Pole Phase of Ph_1.

BLDC motor with 120° magnet arcs and 180° square wave phase currents :-

The ideal brushless machine with 120° magnet arc and 180° square wave phase currents. Here rotor pole magnet arc is 120°. Here, the phase current waveform is 180°. Assume, the motor phase windings are delta connected.



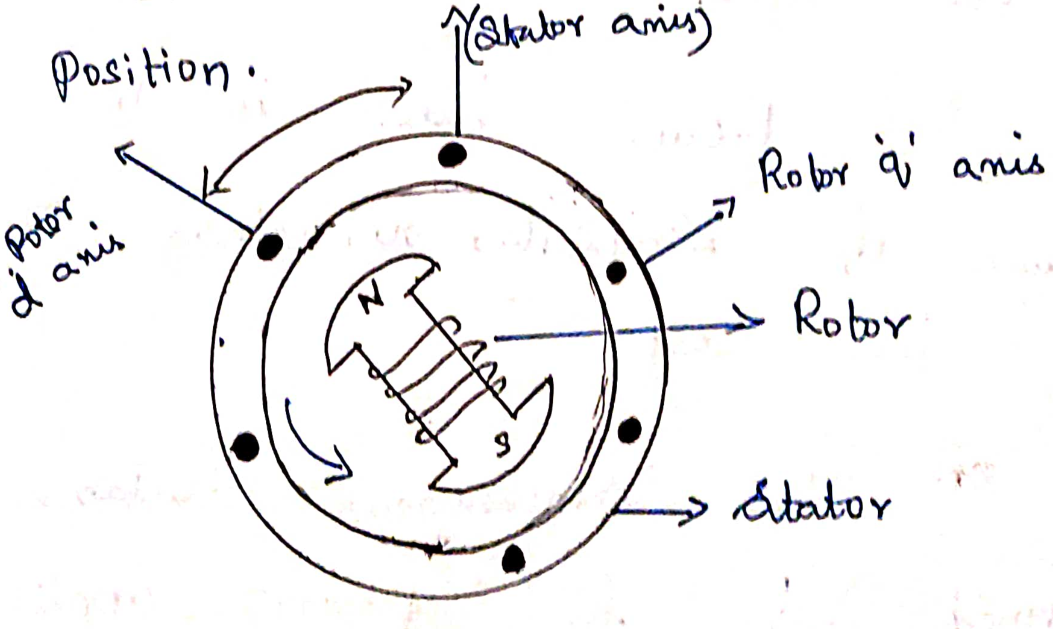
From this figure, the rotor magnet poles are shaded to distinguish north and South. Here, each rotor position, two devices are conducting. The phase belts are as complete 60° of the stator bore.

The table shows commutation tables for 3-φ brushless DC motor for 120° magnet arcs. Here, the stator is delta winding and 180° square wave phase currents.

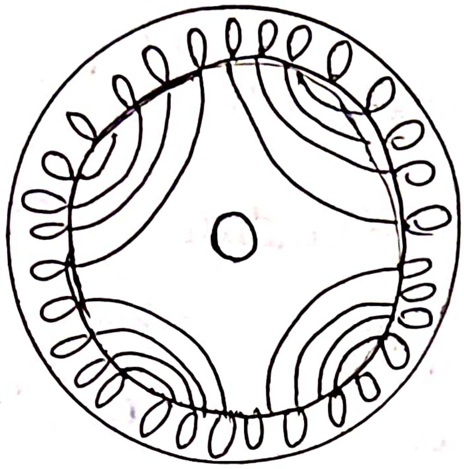
Rotor Position	Phase A	Phase B	Phase C	ab 1	ab 4	bc 3	bc 6	ca 5	ca 2
0° – 60°	+	+	−	0	0	1	0	0	1
60° – 120°	+	−	−	1	0	0	0	0	1
120° – 180°	+	−	+	1	0	0	1	0	0
180° – 240°	−	−	+	0	0	0	1	1	0
240° – 300°	−	+	+	0	1	0	0	1	0
300° – 360°	−	+	−	0	1	1	0	0	0

Construction and Working Principle of Synchronous reluctance Motor :-

The structure of reluctance motor is same as that of salient Pole synchronous machine as shown in fig. The rotor does not have any field winding. The stator has three phase symmetrical winding, which creates sinusoidal rotating magnetic field in the air gap, and the reluctance torque is developed because the induced magnetic field in the rotor has tendency to cause the rotor to align with the stator field at a minimum reluctance Position.



Cross Section of Synchronous reluctance Motor:-



The rotor of the modern reluctance Machine is designed with iron laminations in the axial directions seperated by non-magnetic material. The performance of synchr-onous reluctance motor motor may approach that of induction machine. The P.f will be 0.8 The efficiency of the reluctance Machine may be higher than an induction motor.

Because there is no copper loss.

Because of simplicity, robustness of construction and low cost.

The Synchronous reluctance motor is designed for high power applications.

The stator consists of multiple Projecting (Salient) electromagnet poles, similar to a wound field brushed DC motor. The rotor consist of soft magnetic material, such as laminated silicon steel, which has multiple projections acting as a salient magnetic poles through magnetic reluctance.

The number of rotor poles is typically less than the number of stator poles, which minimize the torque ripple and prevents the poles from all aligning simultaneously - a position which cannot generate torque.

When a rotor pole is equidistant from the two adjacent stator poles, the rotor pole is said to be in the "fully un-aligned" position. This is the position of maximum magnetic reluctance for the rotor pole.

when a stator pole is energized, the rotor torque is in the direction that will reduce reluctance. Most modern designs are of the switched reluctance type. because electronic commutation gives significant control advantages for motor starting, speed control, and smooth operation (low torque ripple).

Rotor design :-

Salient rotor :-

The Synchronous reluctance motor has no Starting torque. and runs up from Stand - Still by induction action. There is an auxillary Starting winding. This has increased the pull out torque, the power factor and the efficieny.

The Synchronous reluctance Motor is broadly classified into 2 type,

i) Axially laminated and

ii) Radially Laminated.

Reluctance Motor can deliver very high power desity at low cost, making them ideal for many applications.

Dis-advantages are high "torque-ripple" (the difference b/w maximum & minimum torque during one revolution), when operated at low speed, and noise caused by torque ripple.

The complexity in designing and controlling the motor is done by using low-cost embedded systems for control-typically based on microprocessor using control according to the rotor positions and current (or) voltage feedback.

Radially laminated:-

EMF Equation of PMSM :-

The flux density in the airgap of PMSM can be represented as a sinewave as shown in figure,

$$B = B_{max} \sin P\theta .$$

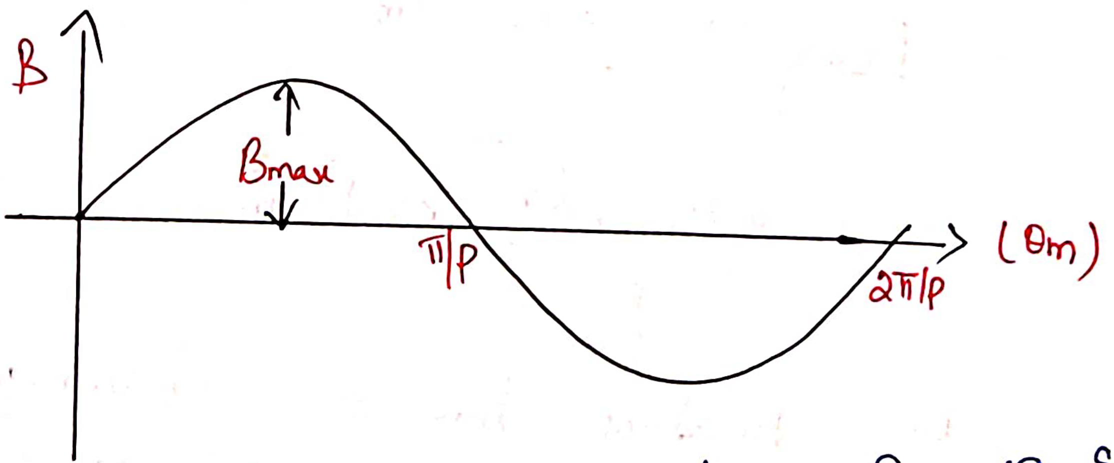
where,

B = flux density (Tesla)

B_{max} = maximum flux density (Tesla).

P = Number of Poles.

θ_m = mechanical rotor position.



flux density in the strip $B_m = B_m \sin P\theta$.

Incremental flux in strip. $d\phi = B_{max}\, l\, r \sin P\theta\, d\theta$.

where l is the length of armature (m).

'r' is the radius of armature.

Flux enclosed by the coil in the position shown is,

$$\varphi = \int_{\omega_m t}^{\omega_m (t+\pi/p)} d\varphi .$$

where ω_m is the mechanical rotor velocity, (rad/sec)

$$\varphi = \int_{\omega_m t}^{\omega_m (t+\pi/p)} B_{max}\, lr \sin p\theta \, d\theta .$$

$$= \frac{B_{max}\, lr}{p} \left[-\cos p\theta \right]_{\omega_m t}^{\omega_m (t+\pi/p)}$$

$$= \frac{B_{max}\, lr}{p} \left[-\cos\left(\omega_m t + \pi/p\right) - \cos p(\omega_m t) \right]$$

$$= \frac{2 B_{max}\, lr}{p} \cos p\omega_m t$$

According to Faradays law of electromagnetic Induction, the emf induced in single turn coil is,

$$e_{turn} = \frac{-d\varphi}{dt}$$

$$= -\frac{d}{dt}\left[\frac{2B_{max}\, l r}{P}\cos P\omega_m t\right].$$

$$= 2B_{max}\, l r\, \omega_m \sin P\omega_m t.$$

The emf induced per phase is,

$$e_{ph} = T_{ph} \times e_{turn}$$

where T_{ph} is turns per phase;

$$e_{ph} = 2B_{max}\, l r\, \omega_m T_{ph} \sin p\omega_m t$$

$$e_{ph} = \hat{E}_{ph} \sin P\omega_m t$$

$$= \hat{E}_{ph} \sin \omega_m t$$

where,

$$P\omega_m = \omega_e.$$

'ω_e' is the electrical angular velocity, E_{ph} is the rms value of phase emf,

$$E_{ph} = \frac{\hat{E}_{ph}}{\sqrt{2}}$$

$$\therefore E_{ph} = \sqrt{2}\,\hat{B}\, r l\, T_{ph}\, \omega_m, \ (\hat{B} = B_{max})$$

$$\omega_m = \omega_e / p.$$

Flux per pole $\varphi = B_{av} \times \frac{2\pi r}{2P} \cdot l$.

$B_{av} = 2/\pi \, B_{max}$.

$\therefore \varphi = 2/\pi \, B_{max} \cdot \frac{2\pi r}{2P} \cdot l$

$= \frac{2 B_{max} \cdot r l}{P}$

$B_{max} \cdot r l = \frac{P\varphi}{2}$

Substitude the above eqn in E_{ph} value,

$E_{ph} = \frac{\sqrt{2}(P\varphi)}{2} \omega_m T_{ph}$

$= \frac{\sqrt{2}(P\varphi)}{2} \frac{\omega_e}{P} T_{ph}$

$= \frac{\sqrt{2}(P\varphi)}{2} \frac{2\pi f}{P} T_{ph}$.

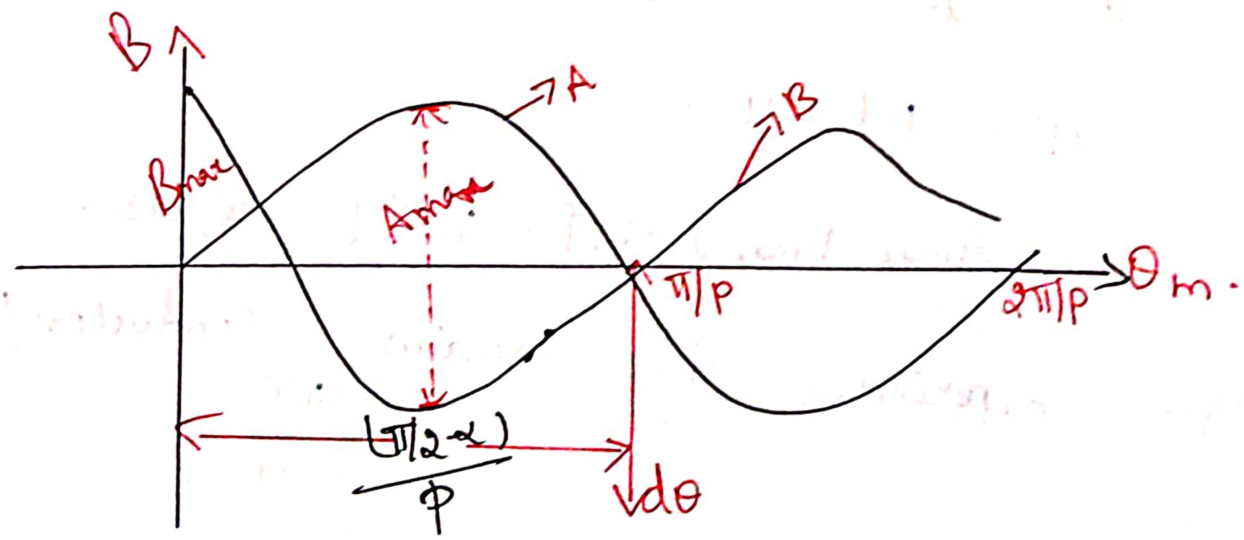
$= \sqrt{2}\pi f \varphi T_{ph}$

$E_{ph} = 4.44 f \varphi T_{ph}$.

1.8

Torque equation of PMSM :-

when a balanced three - phase voltage is applied to the armature, a three Phase current flows through the armature conductors. This current Produces armature flux for deriving the torque equation, the concept of armature ampere conductor density is used. A sinusoidally distributed ampere conductor density is assumed as Shown in below figure,



Let the operation point of PMSM is Such that the ampere conductor density and the flux density are Shown in the fig.

The angle between the axes of ampere conductor and flux density is $(\pi/2 - \alpha)$. A strip of width $d\theta$ is considered at θ.

$$B = B_{max} \cdot \sin\left[p\theta + (\pi/2 - \alpha)\right].$$

$$= B_{max} \cdot \sin\left[\pi/2 + (p\theta - \alpha)\right].$$

$$B = B_{max} \cdot \cos\left[p\theta - \alpha\right].$$

$$A = A_{max} \cdot \sin p\theta.$$

Force experienced by the armature Conductors in $d\theta$ is,

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

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

Torque Experienced by armature conductor / pole

$$\int_{\theta=0}^{\theta=\pi/p} dt.$$

$$= A_{max} \cdot B_{max} r l \int_0^{\pi/p} \sin p\theta \cos(p\theta - \alpha) d\theta.$$

$$= \frac{A_{max} \cdot B_{max}}{2} r l \int_0^{\pi/p} [\sin(p\theta + p\theta - \alpha) + \sin\ldots d\theta.$$

$$= \frac{A_{max} \cdot B_{max}\, r l}{2} \left[\frac{-\cos(2p \times \pi/p - \alpha)}{2p} + \pi/p \sin\alpha + \frac{\cos(-\alpha)}{2p} \right].$$

$$= \frac{A_{max} \cdot B_{max}\, r l}{2} \left[\frac{-\cos\alpha}{2p} + \frac{\cos\alpha}{2p} + \pi/p \sin\alpha \right]$$

$$= \frac{A_{max} \cdot B_{max} \cdot r l}{2} \; \pi/p \sin\alpha .$$

Total electromagnetic torque developed by all the armature conductors = $2p \times$ Torque per Pole.

$$= 2p \; \pi/p \; \frac{A_{max} \cdot B_{max}\, r l \sin\alpha}{2}$$

$$= \cancel{2} \pi \frac{A_{max} B_{max} \cdot r l \sin\alpha}{\cancel{2}}$$

$$= \pi A_{max} \cdot B_{max} \cdot r l . \sin\alpha .$$

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

$$T = -\pi A_{max} B_{max}\, r l \sin\alpha .$$

where 'β' is the torque angle (or) Power angle.

~~Armature mmf of PMSM :-~~

Phasor Diagram of PMSM :-

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

It is assumed that the motor acts as a balanced 3-φ system. Therefore, it is sufficient to draw the phasor diagram for only one phase.

V = Supply voltage.

E_f = emf induced in the armature winding per phase.

$$E_f = 4.44\, V_m f\, k_{w_1} T_{ph} = |E_f|.$$

E_a → Emf induced in the armature phase.

$$|E_a| = 4.44\, f\, V_a\, k_{w_1} T_{ph}$$

$$= 4.44\, (k I_a)\, k_{w_1} T_{ph}.$$

$$|E_a| = |I_a X_a|.$$

where, $X_a = 4.44\, f k\, k_{w_1} T_{ph}$.

This lags behind V_a by $90°$ (or) in other words E_a lags behind I_a by $90°$.

Therefore,

$$E_a = -j X_a I_a.$$

Voltage Equation:-

$$V' = E_f' + E_{al}' = I_a R_a .$$

where R_a is the resistance per phase of the armature winding.

$$V' + E_f' - j I_a X_a - j I_a X_{al} = I_a R_a$$

$$V' + E_f' - j I_a (X_a + X_{al}) = I_a R_a .$$

$$V' + E_f' - j I_a X_s = I_a R_a$$

where,

$$X_s = X_a + X_l .$$

X_s is known as synchronous reactance Per phase (or) fictious reactance.

$$V = (-E_f) + I_a (R_a + j X_s)$$

$$V' = E_q' + I_a Z_s$$

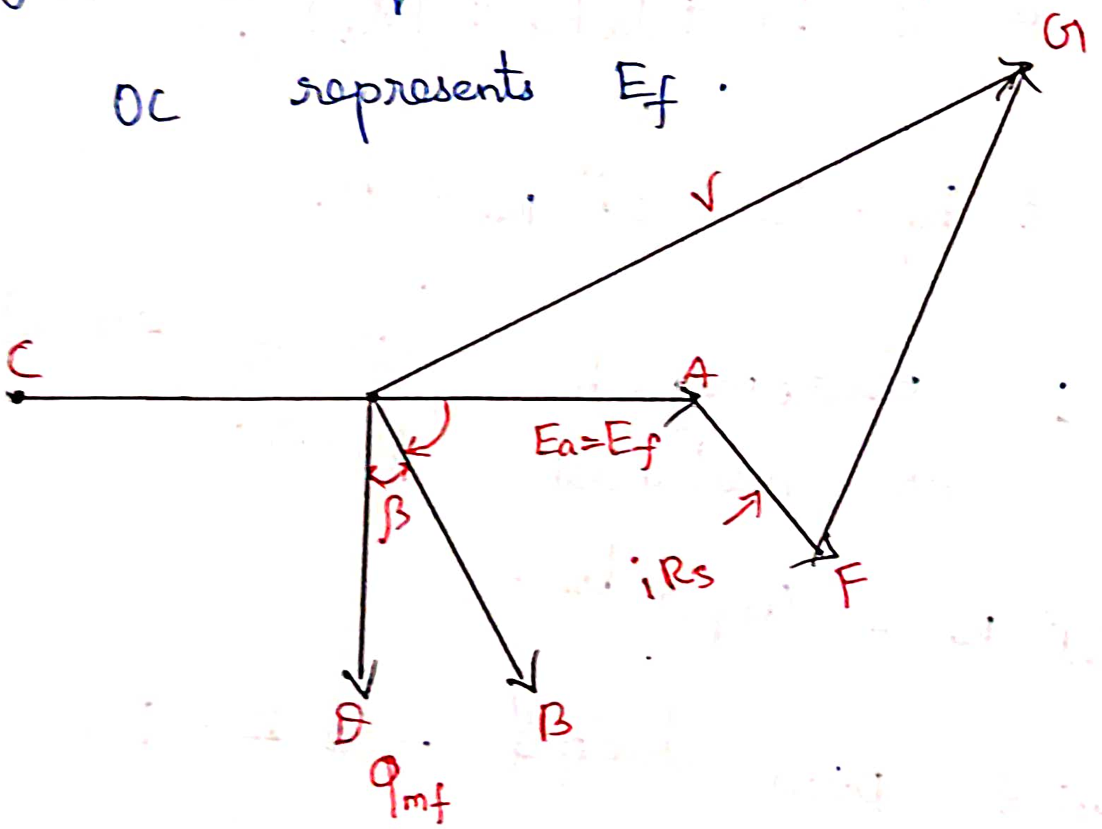
where, 'Z_s' is the synchronous impedance

Let 'E_q' be the reference phasor. Let it be represented by OA.

Let I be the current Phasor. OB represents I.

E_f be the emf induced in the armature winding by permanent magnet flux $= -E_q$.

OC represents E_f.



E_f lags behind,

$\varphi_{mf} = \varphi_d$.

AF represents $I_a R_a$,

FG represents $I_a X_s$; FG is perpendicular to I Phasor.

OG represents V.

Angle between the I and ϕ_{mf} is β the torque (or) power angle,

Power input $= 3VI$

$= 3(E_q + I_a R_a + j X_s I) \cdot I$

$= 3 E_q \cdot I_a + 3I^2 R_a + 0.$

$3 E_q I$ - electromagnetic power transferred as mechanical power.

$3I^2 R_a$ - copper loss.

Mechanical power developed $= 3 E_q \cdot I.$

$= 3 E_q I \cos(90-\beta)$

$= 3 E_q I \sin\beta$

$= 3 E_f I \sin\beta.$

The motor operates at N_s rpm (or $120f/2p$ rpm.

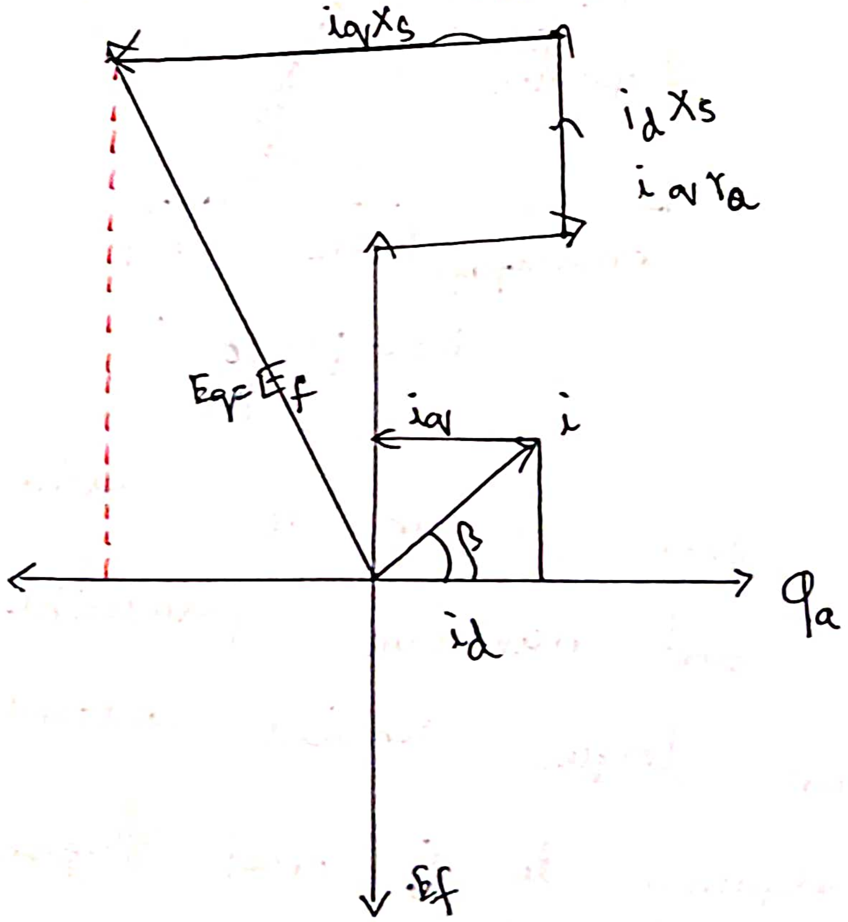
Therefore electromagnetic Torque developed

$$= 60/2\pi N_s \times 3 E_q I \sin\beta .$$

$$= P/\omega_m$$

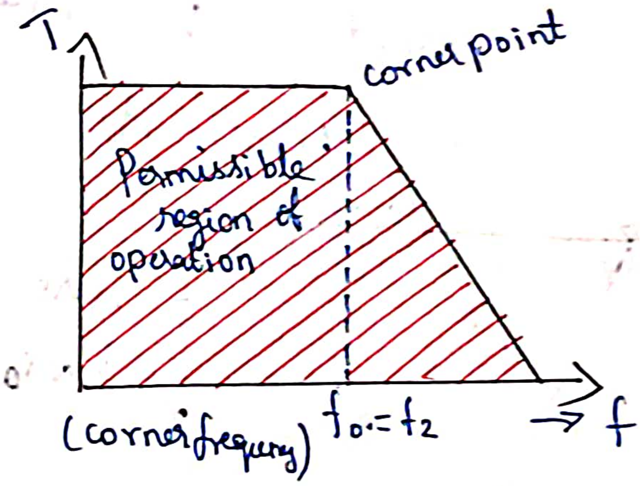
$$= 3 E_q I \sin \beta / \omega_m .$$

Further the current I phasor is resolved into 2 components I_d and I_q, I_d.



TORQUE - SPEED. CHARACTERISTICS OF PMSM :

The Torque Speed characteristics of PMSM sine wave motor is shown in below,



$$N_o = \frac{120 f_o}{P}.$$

For a given V_s and I_s maximum permissible voltage and maximum permissible current, maximum torque remains constant from a low frequency to f_o (corner frequency).

Any further increase in frequency decreases the maximum torque. At, $f = f_{10}$ or f. Torque developed is zero.

Effect of over speed :-

In the torque speed characteristics, if the speed is increased beyond the Point D, there is a risk of over current because the back emf E_b continuous to increase while the terminal voltage remains constant. The current is then almost a Pure reactive current flowing from the motor back to the supply. There is a small q axis current and a small torque because of losses in the motor and in the converter. The Power flow is thus reversed. This mode of operation is possible only if the motor and is the Converter. The power flow is thus reversed. This mode of operation is possible only if the motor over runs, the converter (or) is driven by an external load (or) Prime mover.

Solution:-

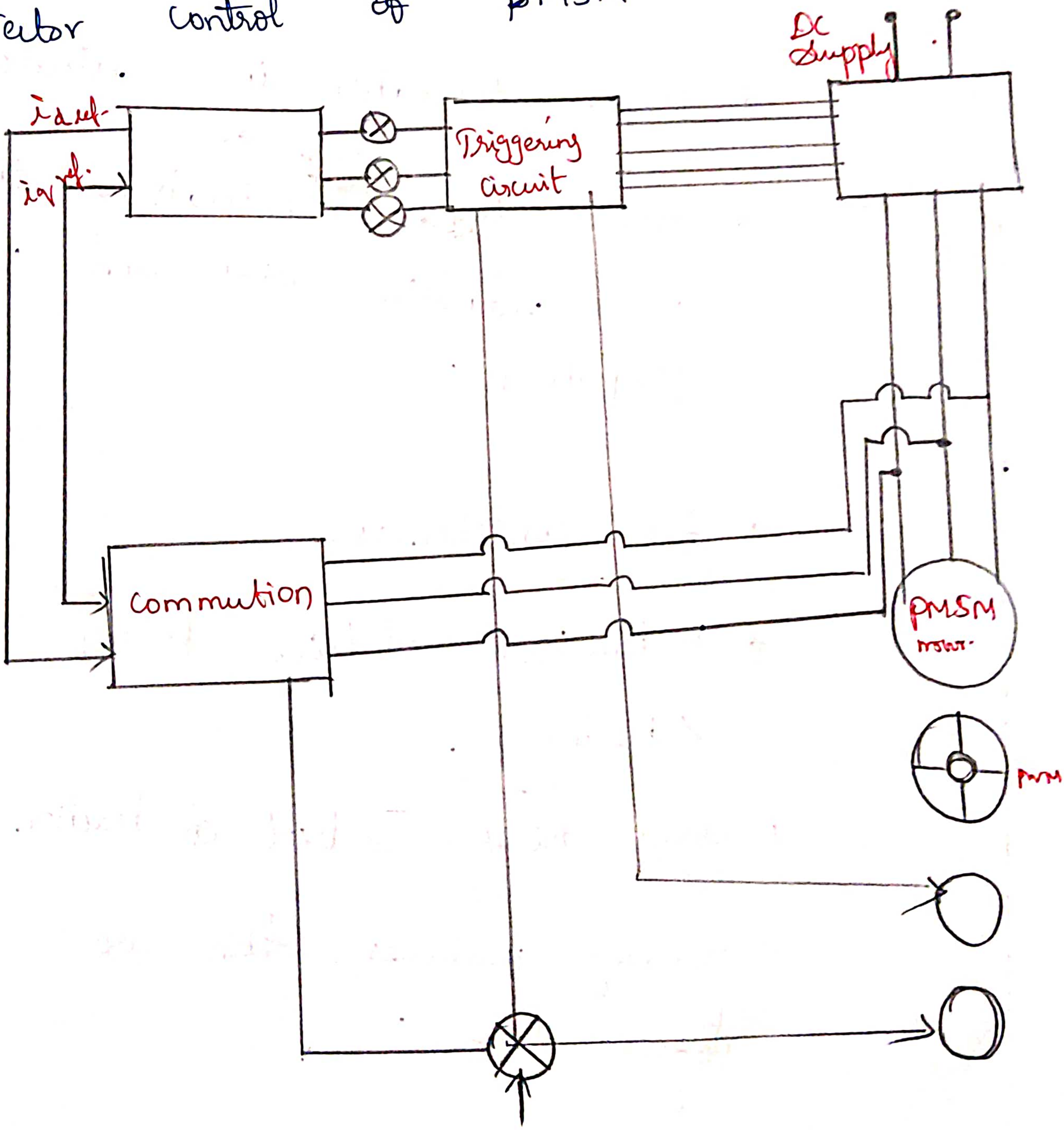
An effective solution is to use an over speed relay to short circuit the 3φ winding in a resistor (or) a short circuit to produce a braking Torque without actually releasing the converter.

Digital controller of PMSM:-

The value of desired torque and speed and also the parameters and the voltage to which the motor is subjected to, it is possible to complete the values of i_d. ref and i_q, for the desired dynamic and steady state performance.

The reference values of i_d and i_q are transformed into reference values of currents namely i_a ref, i_b ref and

i_c ref. These currents are compared with the actual currents and the error values actuate the triggering circuitry which is also influenced by the rotor position sensor and speed. Thus the vector control of PMSM is achieved.



Application of PMSM:-

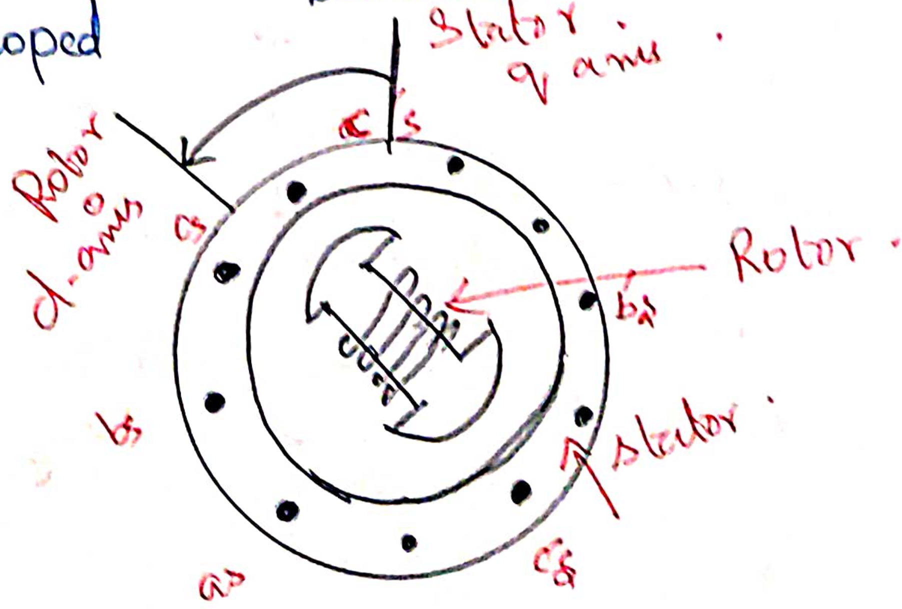
* It is widely used in Robotics.
* Machine tools.
* It is used in machine tools,
* Major Application is actuatators.
* High power Applications such as Industrial drives and vehicle Propulsion.
* Air Conditioners.
* Automotive electrical Power steering.
* Servo drives, control of traction.
* Washing machines, which are direct- drive.

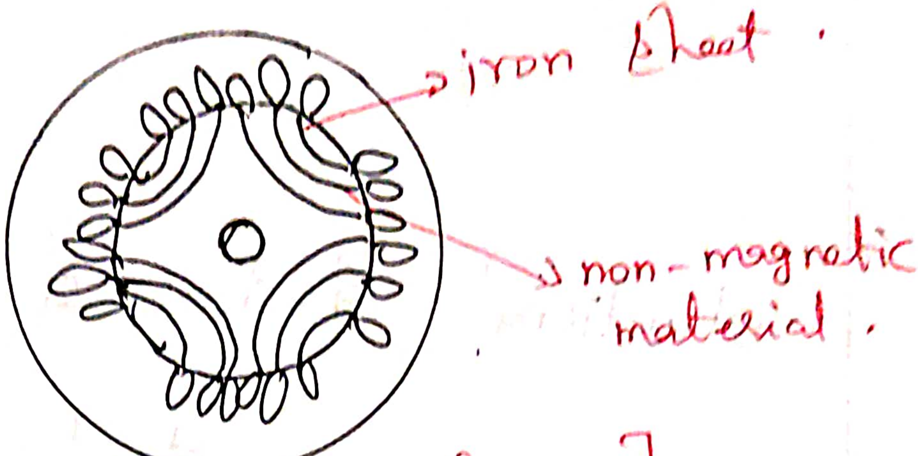
UNIT-V.

Other Special Machines.

Constructional features of SYRM:-

The structure of reluctance motor is same as that of salient pole synchronous machine. rotor does not have any field winding. The stator has 3-φ symmetrical winding, which creates sinusoidal rotating magnetic field in the air gap, and the reluctance torque is developed because the induced magnetic





[Cross sectional view of SYRM].

The rotor of the modern reluctance machine is designed with iron lamination in the axial direction speated by non-magnetic material. The performance of the reluctance motor may approach that of Induction machine. with high saliency ratio a power factor of 0.8 can be reached. The efficiency of reluctance machine may be higher than an induction motor, because there is no ~~rotor~~ copper loss.

The synchronous reluctance motor has no synchronous starting torque and runs up from stand still by induction action. There is an auxillary starting winding. This has increased the pull out torque, the power factor and the efficiency.

Synchronous reluctance motor is designed for high power generation.

Reluctance motors can deliver very high power density at low cost, making them ideal for many applications. Dis-advantages are high torque ripples, when operated at low speed, and noise caused by torque ripple. Until the early twenty - first century Their use was limited by the complexity.

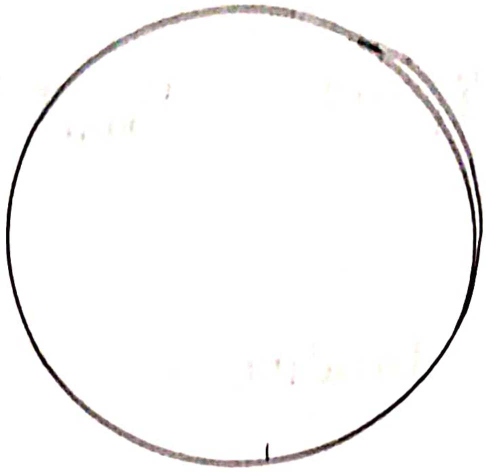
cost embedded system for control, typically based on microcontrollers, using control algorithms and real-time computing to tailor drive waveforms according to rotor position and current (or) voltage feedback.

Before the development of large-scale integrated circuits the control electronics would have been prohibitively costly.

Applications :-

* Some washing machine designs.
* control rod drive mechanism of nuclear reactors.

Torque and Em.f Equation:-



Each Phase winding is displaced by 30°,

Distributed ⇒.

fractional pitch $= 5/6$.

ψ_1 = flux linkage in coil $a_1 A_1$. This flux linkage is linear due to constant airgap.

maximum +ve flux linkage at 0°

maximum -ve flux linkage at 180°

$$\psi_{1\,max} = \phi * \text{no. of. turns.}$$

$$= N_1 \cdot \int_0^{\pi} B(\theta)\, r_1\, d\theta \times l.$$

$$\psi_{1\,max} = N_1 B_g \pi r_1 l$$

flux linkage is linear ⇒ $y = mx + c$

$$m = \text{Slope} = \frac{\psi_{1\,max}}{\pi/2}$$

$$\psi(\theta) = -\frac{\psi_{1\,max}}{\pi/2} \cdot \theta + \psi_{1\,max}.$$

$$= \left[1 - \theta / (\pi/2)\right] \varphi_{1\,max}$$

$$= \left(1 - 2\theta/\pi\right) \varphi_{1\,max} = \varphi_{max} - \frac{2\theta}{\pi} \varphi_{1\,max} \quad \text{— (1)}$$

EMF Equation :-

let,

$P \rightarrow$ no. of Poles,

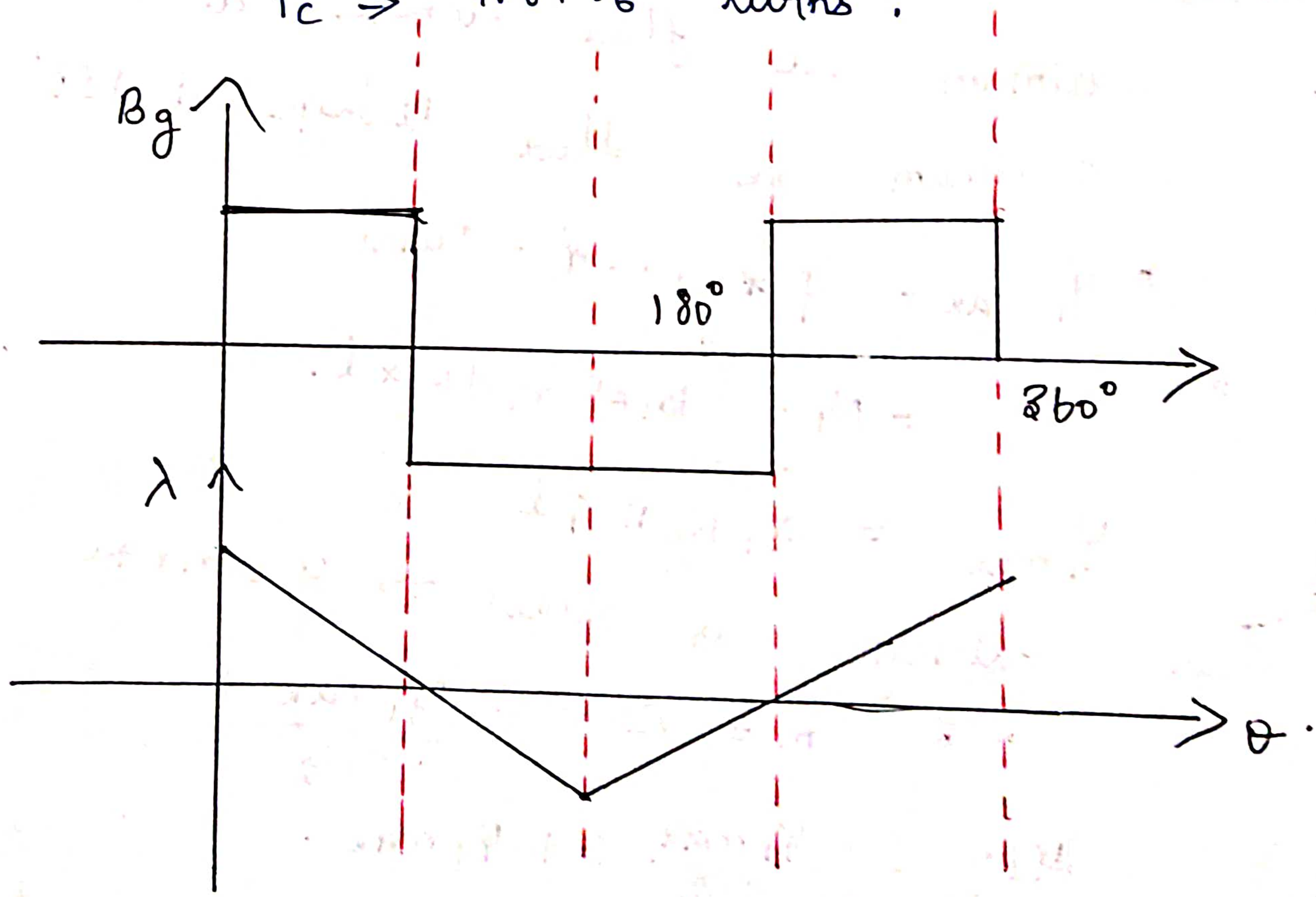
$B_g \rightarrow$ flux density in the airgap,

$r \rightarrow$ radius of the airgap.

$l \rightarrow$ Length of the armature

$\omega_m \rightarrow$ Angular velocity

$T_c \rightarrow$ No. of turns.



Consider PM-BL Square wave DC motor

flux/pole,

$$\phi_m = B_g \times \frac{2\pi r}{P} \times l$$

flux linkage,

$$\lambda_m = B_g \cdot \frac{2\pi r}{P} \cdot l \cdot T_c$$

rate of change of flux linkage,

$$\frac{\Delta\lambda}{\Delta t} = \frac{\text{final flux linkage} - \text{Initial flux linkage}}{\text{final time} - \text{Initial time}}$$

$$= \frac{0 - 2 B_g r l T_c \pi/P}{\pi/P\omega_m - 0}$$

$$\Delta\lambda/\Delta t = \frac{-2 B_g r l T_c \pi/P}{\pi/P \omega_m}$$

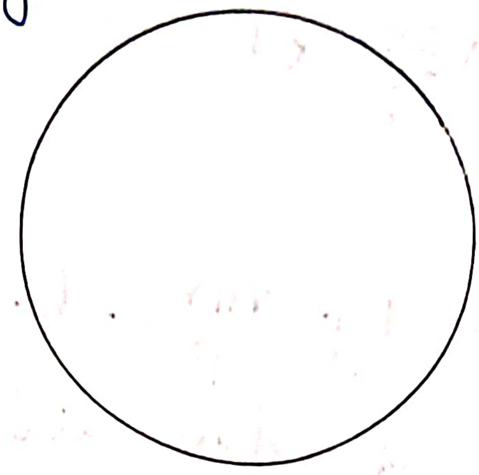
$$\frac{\Delta\lambda}{\Delta t} = -2 B_g r l T_c \omega_m \quad \text{—— (1)}$$

According to Faraday's law, emf induced in a coil,

$$e = -\frac{d\lambda}{dt} \quad \text{—— (2)}$$

Sub ① in ②,

$$e = 2 B_g r l T_c \omega_m$$



Here No. of slots / pole / phase = 2

∴ Consider 2 coils R_1R_1' & R_2R_2' both coil have same magnitude of emf.

$$\therefore \text{Emf} = e_{R_1R_1'} + e_{R_2R_2'}$$

$$= 2 \times 2 B_g r l T_c \omega_m$$

$$e_{ph} = 4 B_g r l T_{ph} \omega_m$$

Torque Equation:-

The torque,

$$T = P/\omega_m \quad \text{—— ①}$$

Power = Voltage x Current.

Hysterisis Motor :

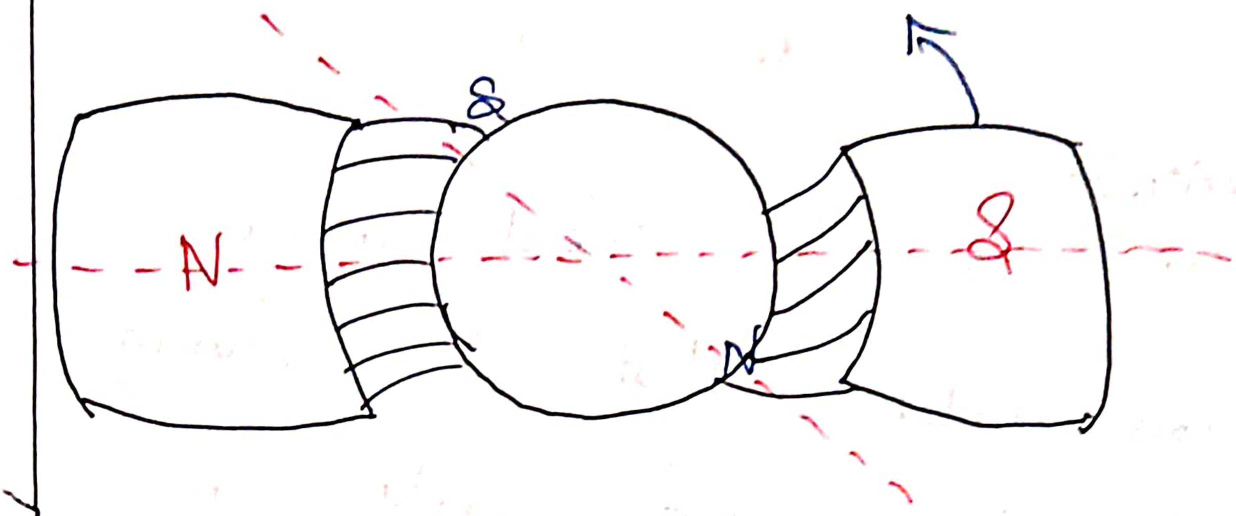
Introduction :-

Hysterisis motor is defined as a synchronous motor that is having cylindrical rotor and works on "Hysterisis losses" induced in the rotor of hardened steel with high retentivity. It is a single phase motor and its rotor is made up of "ferromagnetic material" with magnetic support over the shaft.

Construction :-

A hysterisis motor is constructed of five main components.

1) Stator
2) Single phase stator winding
3) Rotor
4) Shaft
5) Shading coil.



The a most important components of Hysterisis motor are, Stator and rotor.

Stator:-

Stator of Hysteris motor is designed in a particular manner to produce Synchronous revolving field from single Phase Supply.

Stator carries two windings.

a) main winding, b) auxillary winding.

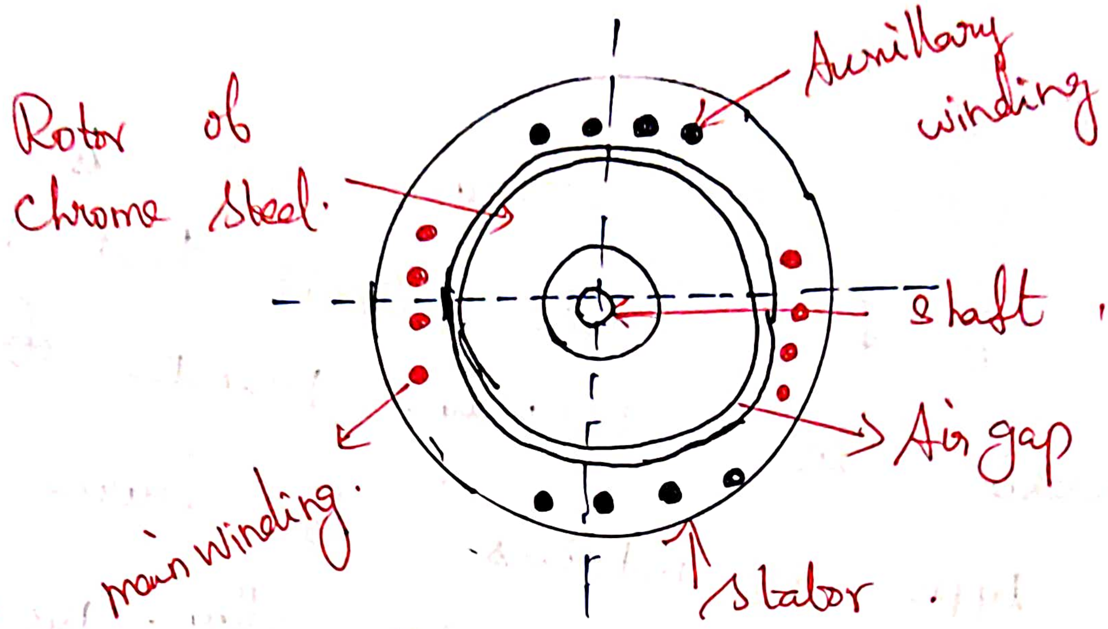
In another type of design of Hysterisis motor.

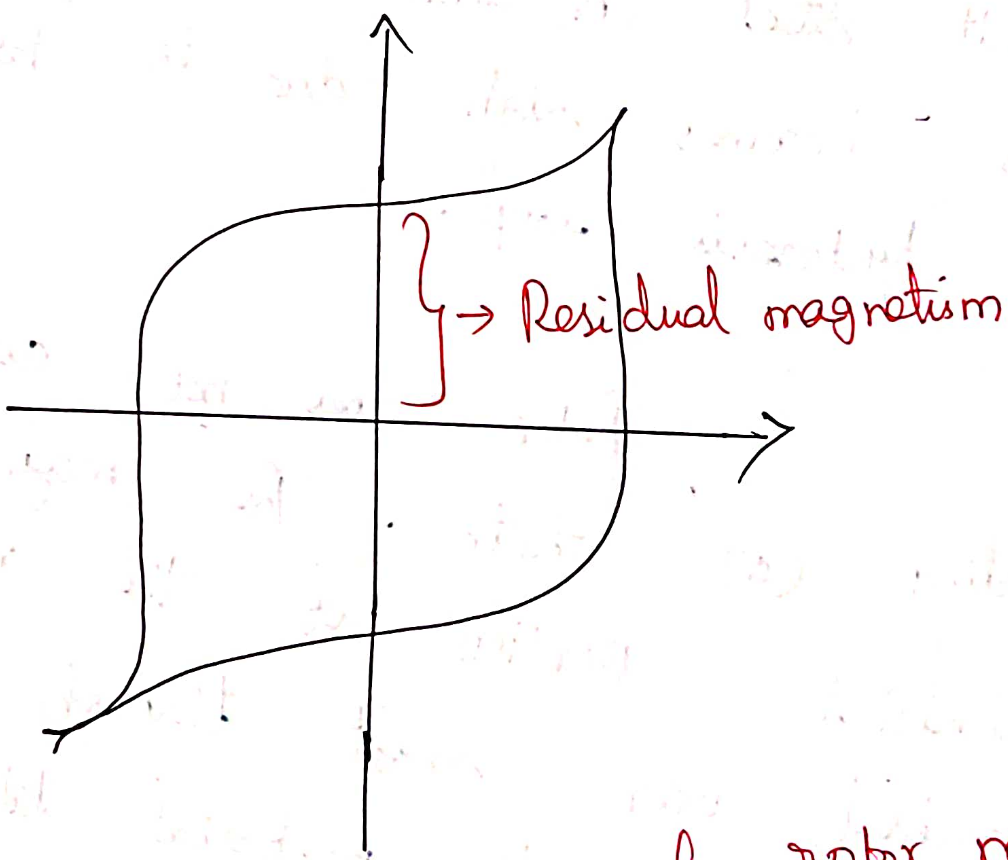
Rotor:-

"Rotor of Hysteresis motor" is made up of magnetic circuit that has hysteresis loss property. Example of this type of materials is chrome, cobalt steel (or) alnico (or) alloy. Hysteresis loss becomes high due to large area of "hysteresis loop".

Rotor does not carry any winding (or) teeth. The magnetic cylindrical portion of the rotor is assembled over shaft through arbor of non-magnetic material like brass.

Rotor is provided with high resistance to reduce "eddy current loss".





(Hysteresis loop of rotor material)

working principle:-

Starting behaviour of a Hysteresis motor is like a single phase

Induction motor. Step by step its behaviour can be realized in the working principle.

When stator is energized with single phase AC supply, rotating "magnetic field" is produced in the stator. To maintain the rotating magnetic field the main and auxillary windings must be supplied continuously at start as well as in running conditions.

At the starting, by "induction phenomenon" secondary voltage is induced in the rotor by "stator rotating magnetic field". Hence eddy current is generated to flow in the rotor and it develops rotor.

Hysteresis power :

$$P_h = k_h f_r B_{max}^n$$

where,

$f_r \rightarrow$ frequency of flux reversal in the rotor.

$B_{max} \rightarrow$ is the value of flux density in the airgap.

$P_h \rightarrow$ is the heat-power loss due to hysteresis (W).

$K_h \rightarrow$ is the hysteresis constant.

Advantages :-

i) It's operation is noiseless.

ii) There is no vibration.

iii) Multi-speed operation can be achieved by employing gear train.

Dis- Advantages :-

i) Low Efficiency.

ii) Low torque and low power Factor.

Applications :-

i) Sound producing Equipment

ii) Sound Recording instrument

iii) Timing Devices.

iv) Electronic Clocks.

Linear Induction Motor.

Introduction :-

A Linear induction motor is a special type of "Induction Motor" used to achieve rectilinear motion rather than rotational motion as in the case of conventional motors. linear Induction motors are quite an engineering marvel, to convert a general motor for a special purpose with more (or) less similar working principle

Working Principle :-

A linear Induction motor is a special type of Induction motor used to achieve rectilinear motion. rather than rotational motion as in the case of conventional motors. Linear induction motors are quite an engineering marvel.

When the primary of LIM gets excited by a balanced 3 - φ Power Supply. a flux strats travelling along the entire length primary. This linearly travelling magnetic field is Equivalent to the "rotating magnetic field" is equivalent. Electric Current gets induced in the conductor of the secondary due to the relevant relative motion, between the travelling flux and the conductors. Then the induced current interacts with the travelling flux wave to produce linear motion (or) thrust.

$$V_s = 2 \tau f_s \text{ m/sec.}$$

Applications :-

i) Automatic sliding doors in electric trains

ii) Propulsion of a train of tubs along a certain route.

iii) metallic conveyor belts.

iv) Pumping of liquid metal, material handling in cranes, etc.

v) mechanical handling equipment.