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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT – I - SPECIAL ELECTRICAL MACHINES – SEE1307

SEE1307 SPECIAL ELECTRICAL MACHINES

UNIT 1

STEPPING MOTORS

Constructional features, principle of operation, types, modes of excitation, Torque production in Variable Reluctance (VR) stepping motor, Static and Dynamic characteristics, Introduction to Drive circuits for stepper motor, suppressor circuits, Closed loop control
of stepper motor- Applications.

UNIT 2

SWITCHED RELUCTANCE MOTORS

Principle of Operation, Constructional features, Torque equation, Power Semi Conductor Switching Circuits, frequency of variation of inductance of each phase winding - Control circuits of SRM-Torque - Speed Characteristics, Microprocessor based control of SRM Drive, Applications.

UNIT 3

SYNCHRONOUS RELUCTANCE MOTORS

Constructional features: axial and radial air gap Motors. Operating principle, reluctance torque
- Phasor diagram, Speed torque characteristics, Applications.

UNIT 4

PERMANENT MAGNET BRUSHLESS DC MOTORS

Commutation in DC motors, Electronic Commutation - Difference between mechanical and electronic commutators- Hall sensors, Optical sensors, Construction and principle of PMBL DC Motor, Torque and E.M.F equation, Torque-speed characteristics,
Power Controllers-Drive Circuits, Applications.

UNIT 5

PERMANENT MAGNET SYNCHRONOUS MOTORS
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Construction and types, Principle of operation, EMF and Torque equation, Phasor diagram-Torque Speed Characteristics, Power controllers- Self control, Vector control, Microprocessor Based Control, Applications.

UNIT I

STEPPER MOTOR

Stepper Motor is an electromechanical device which actuates a train of steps movements of shaft in response to train of input pulses. Each pulse moves the shaft through a fixed angle. The angle through which the motor rotates or shaft moves for each pulse is known as the step angle β expressed in degrees.

Let

$N_r \rightarrow$ Number of rotor poles.

$N_s \rightarrow$ Number of stator poles

$m \rightarrow$ Number of phases.

$$step\ Angle\ \beta = \frac{360}{m N_r}\ (or)\ \frac{N_s \approx N_r}{N_s\ N_r} \times 360$$

i. Smaller the step angle, greater the number of steps per revolution and higher the resolution (or) accuracy of positioning obtained.

ii. The step angle can be as small as 0.72^0 (or) as large as 90^0.

iii. Common step sizes are $1.8°, 2.5°, 7.5° \& 15°$.

Resolution is given by the number of steps needed to complete one revolution of the rotor shaft. Higher the resolution, greater the accuracy of positioning.

$$\therefore \mathrm{Re}solution = No\ of\ \ steps / revolution = \frac{360°}{\beta}$$

Operation of stepper Motor at high speeds is called "Slewing". If f is the stepping frequency (or) pulse rate in pulses per sec and β is step angle, then

$$Motor\ shaft\ speed(n) = \frac{\beta \times f}{360} rps$$

When stepping rate is increased quickly, the motor losses synchronism and stops.

Application of stepper Motor

1. Used for operational control in computer peripherals, textile industry, IC fabrications & Robotics etc.
2. It is also used in typewriters, line printers, tape drivers, floppy disk drives, CNC machines, X-Y plotters etc.
3. It is also used in commercial, military & medical applications.

Advantages of stepper Motor

1. No feedback is normally required for either position or speed control.
2. Positional error is not cumulative.
3. Stepper Motors are Compatible with digital equipments.
4. It requires less maintenance.
5. It is mechanically simple and free from contamination.

Types of stepper Motor

1. Variable Reluctance Stepper Motor
2. Permanent Magnet stepper Motor
3. Hybrid stepper Motor

2.1 VARIABLE RELUCTANCE STEPPER MOTOR

2.1.1 Construction:

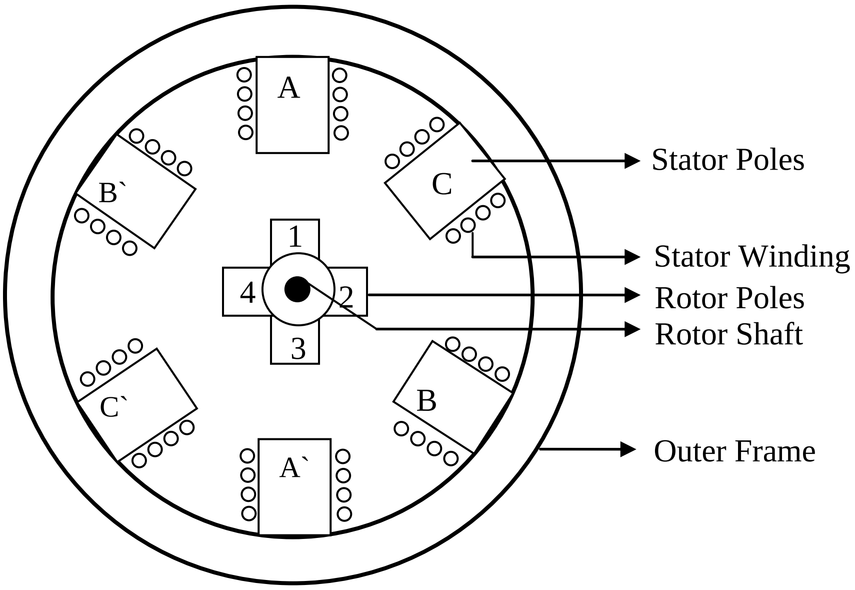
It is the most basic type of stepper Motor.

Two important parts of a stepper Motor are

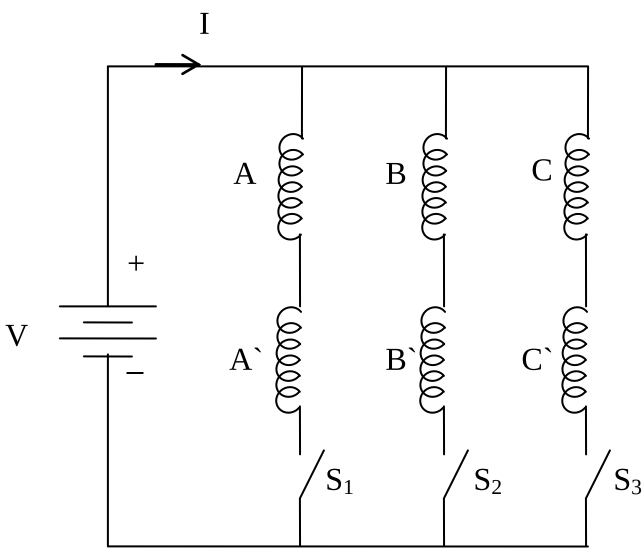
i. Stator

ii. Rotor

- The motor has a stator which is usually wound for three phases.
- The stator consists of common outer frame which is used to enclose the stepper motor and protect it.
- The salient poles of the stator are fixed under the stator outer frame. The stator poles are laminated and assembled in a single stack.
- The stator poles are usually made up of soft steel (or) high graded silicon content steel in order to reduce the hysteresis losses and they are laminated to reduce the eddy current loss in the stepper Motor.
- Usually there may be six stator poles and concentrated exciting windings are placed around each pole.
- The exciting windings are usually made up of copper material and pair of exciting windings form a phase in the stepper Motor. So there are 3 phases in the stepper Motor which is considered.
- Each phase is excited separately through a switch by the DC source, which is also shown in the Fig 2.1.
- The direction of rotation of the stepper Motor depends upon the sequence we excite the windings.
- The Rotor also has projecting poles which may be laminated (or) solid soft steel material. It is usually made up of ferromagnetic Material and it may be single (or) multi-stack type
- The multi-stack type rotor gives smaller step angle.
- Generally, number of stator poles will not be equal to number of rotor poles for proper operation. Here we consider four rotor poles. The rotor pole do not have windings.



Constructional View



Circuit Arrangement

Fig 2.1

2.1.2 Principle of Operation

- The operation is based on various reluctance positions of rotor with respect to stator.
- When any one phase of the stator is excited, it produces its magnetic field whose axis lies along the poles of the phase which is excited.
- Then the rotor moves to minimum reluctance position.
- Let us see the operation of the VR stepper Motor ,when the phases A,B,C are excited in sequence ie., one after the other with the help of switches S_1,S_2 and S_3.
- When the phase AA^1 is excited with the switch S_1 closed, then stator Magnet Axis exist along the poles formed due to AA^1 (ie) vertically.
- Then the rotor adjust itself in a minimum reluctance position and occupies along $AA^1 \rightarrow$ 1, 3, rotor poles. This is the initial position (ie) 0°.
- When the BB^1 phase is excited with the switch S_2 closed, and de-energise the AA^1 phase with the switch S_1 opened, then stator magnetic axis shifts along the poles formed due to BB^1 and the rotor tries to align itself in the minimum reluctance position and turns through 30° step angle in clockwise direction.
- Open the switch S_2 and de-energise the BB^1 phase and close the switch S_3 and energise the CC^1 phase.
- So that the stator magnetic axis shifts along the poles formed due to CC^1 and the rotor tries to align itself in the minimum reluctance position and rotor rotates by a step angle of 30° in the same direction.
- The stepper motor continues to move in steps of 30 degree for each excitation either in clockwise or counter clockwise direction.
- The Fig 2.2 gives the three step positions

The switching sequence continues as follows

A,B,C,A $\rightarrow$ for Clockwise rotation and

A,C,B,A $\rightarrow$ for Counter Clockwise rotation.

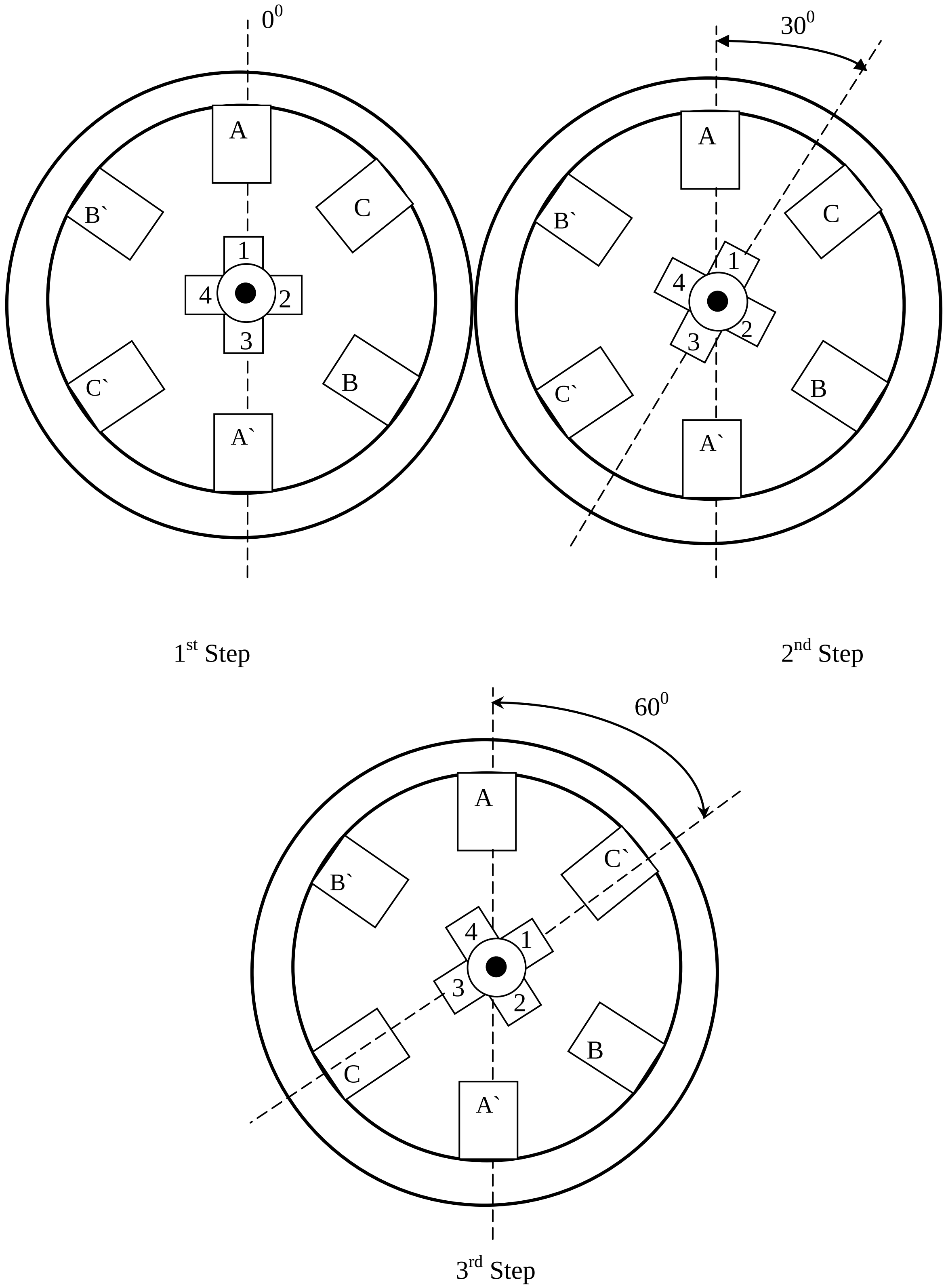


Fig 2.2

If i is the current passing through the phases which are excited then the torque developed by the motor is given as $T_m = \frac{1}{2} i^2 \frac{dL}{d\theta}$. Where L is the inductance in Henry and θ is the displacement angle in degree.

Advantages of VR stepper Motor:

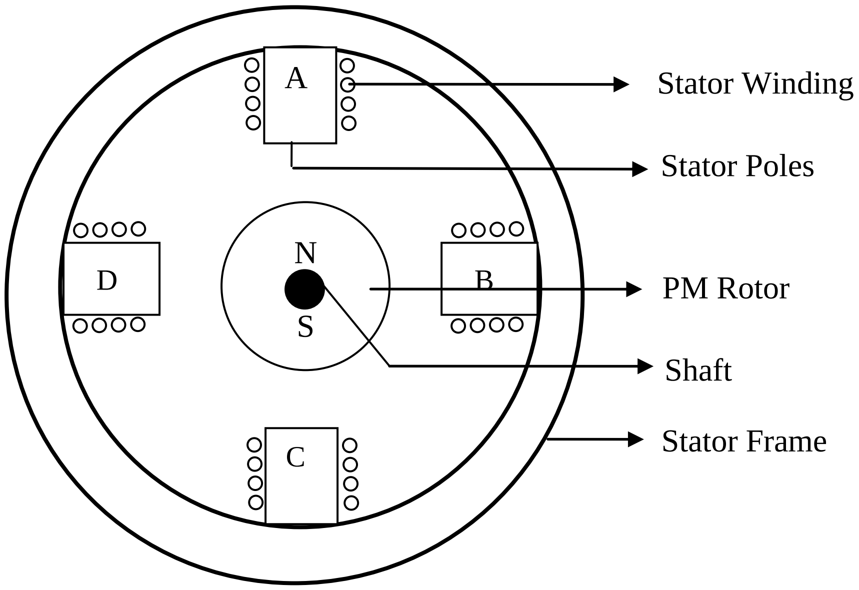
1. High torque to inertia ratio
2. High rates of acceleration.
3. Fast dynamic response
4. Simple & low cost
5. Rotor has no windings.

Disadvantages of VR stepper Motor:

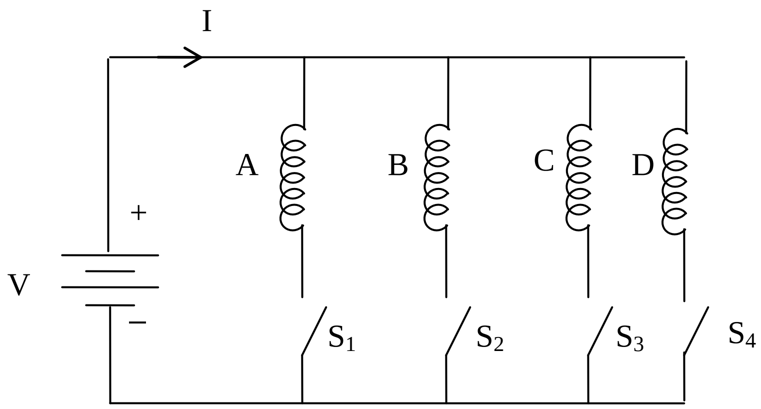
1. No detent torque
2. Low Efficiency at low voltages and stepping rate
3. Normally available in 3.6 degree to 30 degree

2.2 PERMANENT MAGNET STEPPER MOTOR

- This motor has got two important part (ie) stator & rotor.
- The stator of this type of motor is multi-polar. Assume that the stator has four poles. Its stator construction is similar to VR stepper Motor.
- It consists of stator outer frame, stator core and stator winding. The stator core is laminated and made of soft steel and has projecting poles.
- The stator winding is wound on each pole individually and form a phase and made of copper material.
- The rotor is also smooth cylindrical type or projecting pole type and it is made up of permanent magnet material like hard ferrite.
- Because of this construction, it is called as permanent magnet stepper Motor. Usually the rotor has only two poles. The exciting circuit with the constructional view is shown figure 2.3.



Constructional view

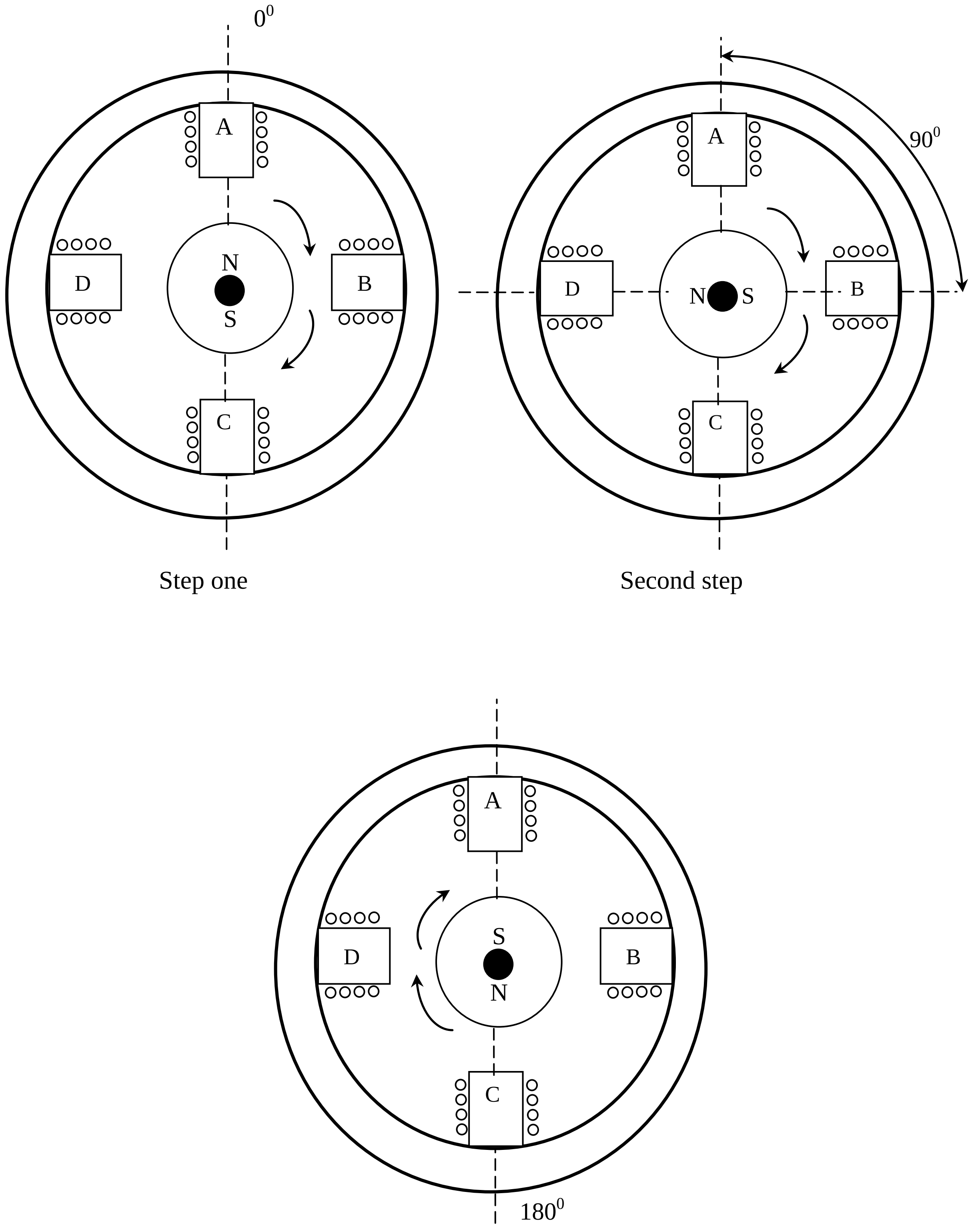


Equivalent Circuit

Fig 2.3

2.2.1 Working Principles

- The basic principle is when a particular stator phase is excited, the rotor magnetic poles move into alignment with the excited stator poles.
- Consider stator has 4 phases , 4 poles and rotor has ONE poles pair then the step angle $\beta = \frac{360}{mN_r} = \frac{360}{4 \times 1} = 90^\circ$.
- The proper switching of the stator poles is controlled by the driver circuit.



Step three

Fig 2.4

- When S_1 is closed then phase A is excited for a particular pole and the opposite pole of rotor will come into alignment. This is the initial (or) start position (ie) Zero degree
- When S_1 is opened and S_2 is closed then phase B is excited so that the rotor adjust itself to align with the stator magnetic axis by moving 90°.
- Similarly S_1 and S_1 switches are operated in such away that the stepper motor rotates in steps by 90° for each phase excitation. The direction of rotation depends upon the sequence of switching (ie)

    - A,B,C,D,................... CW rotation.
    - A,C,D,B,................... CCW rotation.

- Sometimes the direction of stator current also decides the direction of rotation of stepper motor.

Advantages of PM stepper Motor:

1. Low power requirement
2. High detent torque.
3. Rotor does not require external exciting current
4. It produces more torque per ampere stator current

Disadvantages of PM stepper Motor:

1. Motor has high inertia
2. Slower Acceleration
3. Step size is from 30 degree to 90 degree
4. The stepper motor with permanent magnet rotors with large number of poles cannot be manufactured in small size.
5. Hence small steps are not possible. Because of presence of permanent magnet, detent torque is present in the motor.

2.3 HYBRID STEPPER MOTOR

2.3.1 Construction

- It uses the principles of both variable reluctance and permanent Magnet stepper motor.
- Constructionally also, it has the combination of VR & PM stepper Motor. This motor has also got two important parts (ie) stator & Rotor.
- The stator has got outer frame, stator core, stator poles & stator pole teeths and stator winding. The outer frame covers the entire machine and protects it.
- Under the stator frame, stator core is fixed with solid or laminated soft steel material to reduce eddy current & hysteresis loses.
- The stator may be single or multi-stack configuration. Usually the stator has got 8 poles and each poles has 2 to 6 teeths.
- There is only two phases winding, made of copper material. The coils on poles, 1,3,5 & 7 are connected in series to form phase while the coils on poles 2,4,6 & 8 are connected in series to form phase B.
- The winding A & B are excited alternately.
- The constructional view is shown in the figure 2.5

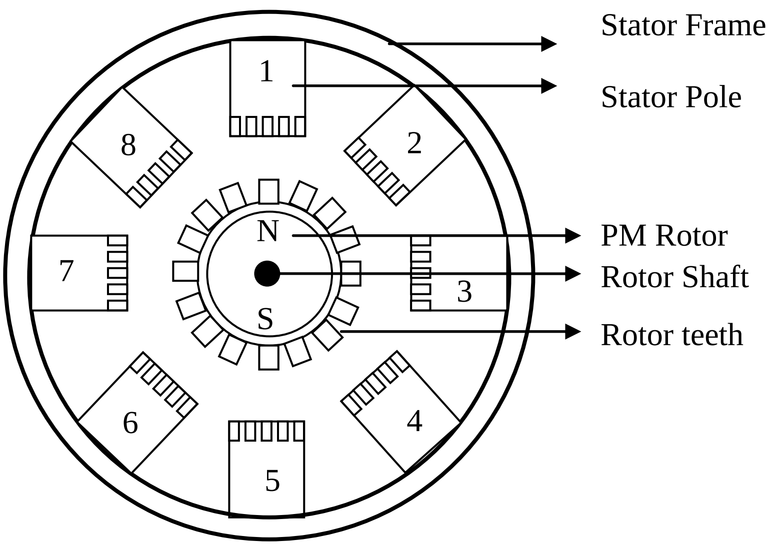


Fig 2.5

- In this motor, the rotor has permanent magnet which is fixed in the middle of the rotor and it is magnetised in the axial direction.
- Surrounding the rotor permanent magnet, rotor teeths are framed which are laminated and made up of soft steel material.
- The rotor teeths are selected according to the step angle required.

2.3.2 Working Principle

- This motor uses the permanent magnet & variable reluctance principle combined.
- In this motor, the rotor flux is produced by the permanent magnet and it is directed by the rotor teeths to the appropriate parts of the airgap.
- Consider the hybrid motor has two phase (ie) phase A & phase B. When phase A is excited by the positive stator current then stator poles 1 and 5 becomes south and 3 and 7 becomes north.
- Now the rotor teeths with north and south polarity will come into alignment with the stator pole teeths.
- Similarly when phase B is excited and phase A is unexcited then the rotor will move by one step angle.
- Suppose the rotor has 18 teeths then the step angle, $\beta = \frac{360}{m \times N_r} = \frac{360}{2 \times 18} = \frac{360}{36} = 10°$.
- The torque in a hybrid stepper motor is produced by the interaction of rotor and the stator produced fluxes.
- The rotor flux remains constant because it is produced by the permanent magnet. The motor torque T_m is proportional to the phase current in the stator.

Advantages of Hybrid stepper motor

1. We can achieve very small step angle up to 1.8°.
2. Torque per unit volume is more than VR motor.
3. Due to permanent magnet, the motor has some detent torque.
4. Better damping due to presence of rotor magnets
5. Higher holding torque

Comparison between VR and PM stepper Motor

VR Stepper Motor	**PM Stepper Motor**
The rotor is not magnetized.	The rotor is magnetized.
High Torque to inertia Ratio	Low torque to inertia ratio.
High rates of acceleration	Acceleration is slow.
Dynamic Response is fast	Very slow dynamic response.
It can be manufactured for large number of poles	It cannot be manufactured for large number of poles due to constructional difficulties.
Very small step angle is possible	Step angles are high in the range 30° to 90^0
It does not have detent Torque.	It has got detent Torque.
Rotor has salient pole construction	The rotor has mostly smooth cylindrical type of construction
Maximum stepping rate is as high as 1200 pulses per second	It is only 300 pulses per second.

2.4 MULTISTACK STEPPER MOTOR

Basically the stepper motors which we have discussed are single stack stepper motor. In single stack motor, there will be common stator and rotor for the poles or teeths on it. Which means that the only one stator core and rotor core on which the poles will be placed. The single stack more will have one winding only for a phase. The cross sectional view is shown in the figure 2.6.

The multi-stack motors are used to obtain small step size typically ranging between 2° to 15°.

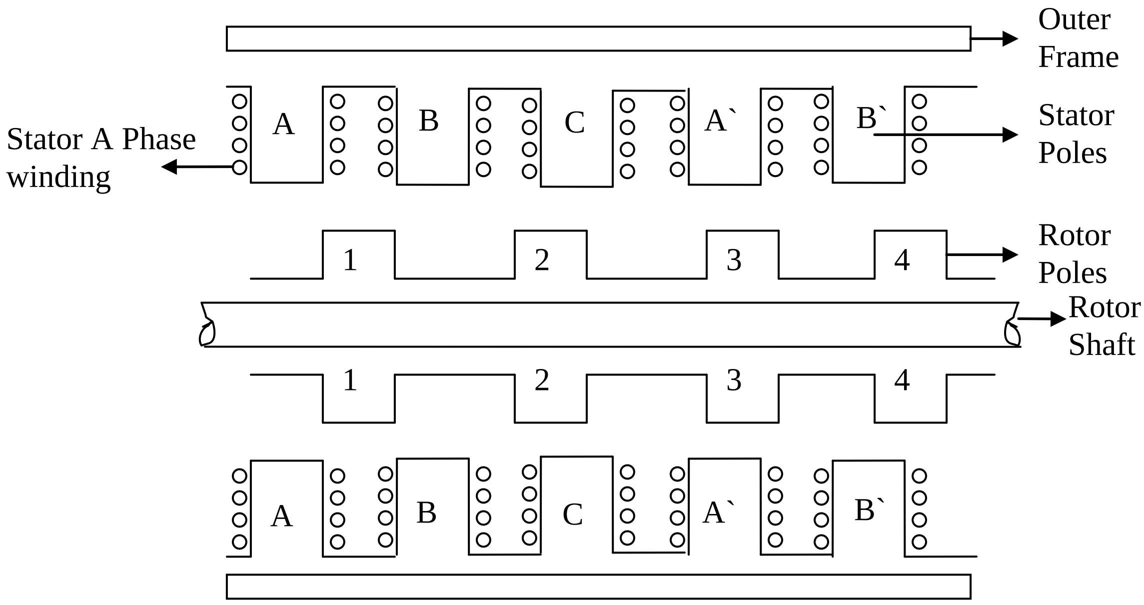


Fig 2.6

I In an 'm' stack motor, the motor is divided into a 'm' number of Magnetically isolated sections called as stacks along its axial length. The 'm' stacks of stator have a common outer frame while the rotors are mounted on a common shaft. The stator and rotor have the same number poles (or) teeths. The stator poles in motor are aligned equally while the rotor poles are shifted by 1/m of the pole pitch from one another. All the stator windings in a stack are excited simultaneously; hence each stator forms a phase. So the number of stator phases is equal to number of stator stacks.

Generally three stack stepper motor are used. In each stack, the stator and rotor laminations are provided and they have 12 poles. The poles of the stator are in one line while the rotor poles are aligned from each other by 1/3 of the pole pitch.

The various windings in one stack are excited simultaneously. When phase A of the stator is excited then rotor poles of stack A get aligned with the stator poles. But the rotor poles of stack B and C do not align. Now if phase A is unexcited and phase B is excited then rotor poles of stack B get aligned with the stator poles. Thus the rotor moves by 1/3 of pole pitch. Again phase B is unexcited and phase C is excited then the rotor again moves by 1/3 of the pole pitch and the process continuous.

The step angle $\beta = \frac{360}{m \times N_r}$ where m=3, N_r=12

$$\because \beta = \frac{360}{3 \times 12} = 10°$$

So we can achieve small step angle by the multi-stack structure.

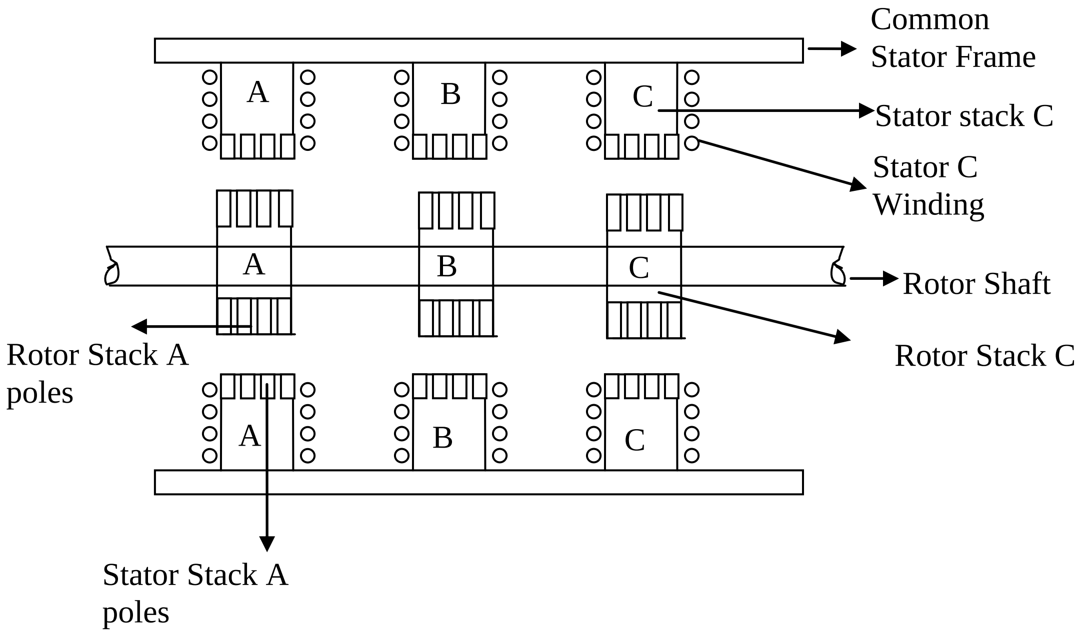


Fig 2.7

2.5 CHARACTERISTICS OF STEPPER MOTOR

The two important characteristics of stepper motor are:

1. Static characteristics

The characteristics relating to motors which are stationary are called static characteristics.

a. T/θ Characteristics:

The stepping motor is kept stationary at rest position by supplying a current in a specified mode of excitation. If an external Torque is applied to the shaft, an angular displacement will occur. The relation between the external Torque and displacement angle θ may be plotted as T/θ curve. The maximum of Static Torque is called as Holding Torque which occurs at $\theta = \theta_M$. After the θ_M, the rotor moves to the next equilibrium position. The Holding torque is defined as the maximum static Torque that can be applied to the shaft of an excited motor without causing continuous rotation. It is shown in the figure 2.8

b. T/I characteristics

The Holding Torque increases with the current and the curve drawn between the Holding Torque and the current is called T/I characteristics curve. For VR stepper motor, this curve starts from the zero point. But for PM & Hybrid stepper motor, the curve has a slight raise in the holding Torque (ie) Y-axis. This is due to the presence of detent Torque due to permanent magnet in the rotor when current is zero. It is shown in the figure 2.9

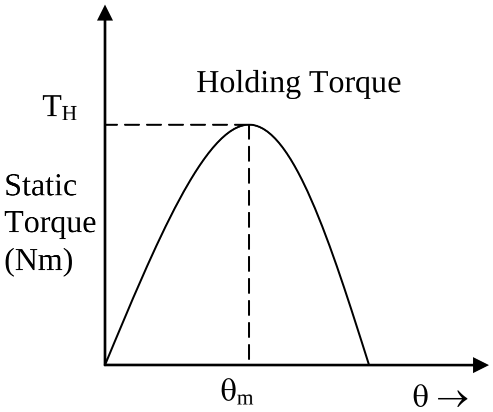


Fig 2.8

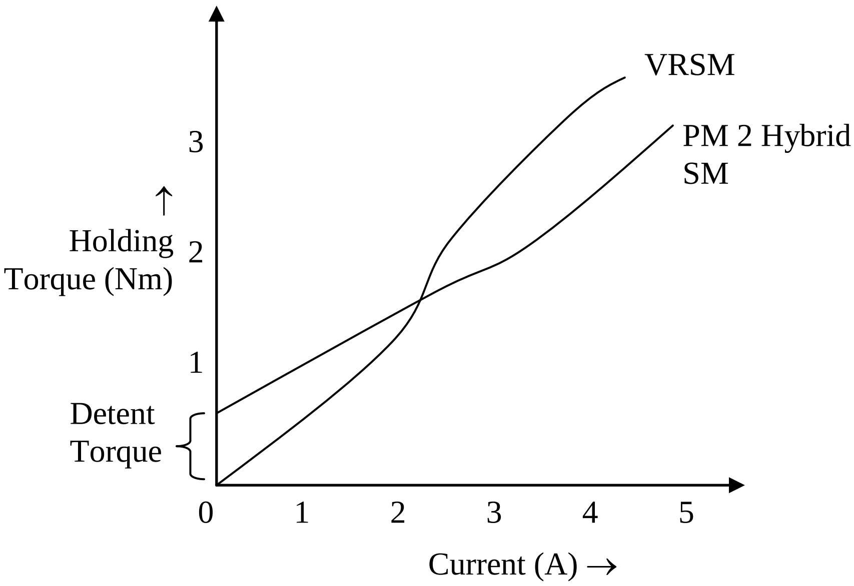


Fig 2.9

Definition:

Holding Torque :

It is defined as the maximum static torque that can b e applied to the shaft of an excited motor without causing continuous rotation.

Detent Torque Or Cogging Torque :

It is defined as the maximum load torque that can be applied to the shaft of an unexcited motor without causing continuous rotation

2. Dynamic characteristics:

The characteristics relating to stepper motor which are in motion (or) about to start are called dynamic characteristics. The curve drawn between the Torque & stepping rate gives the Dynamic characteristics which shown in the figure 2.10

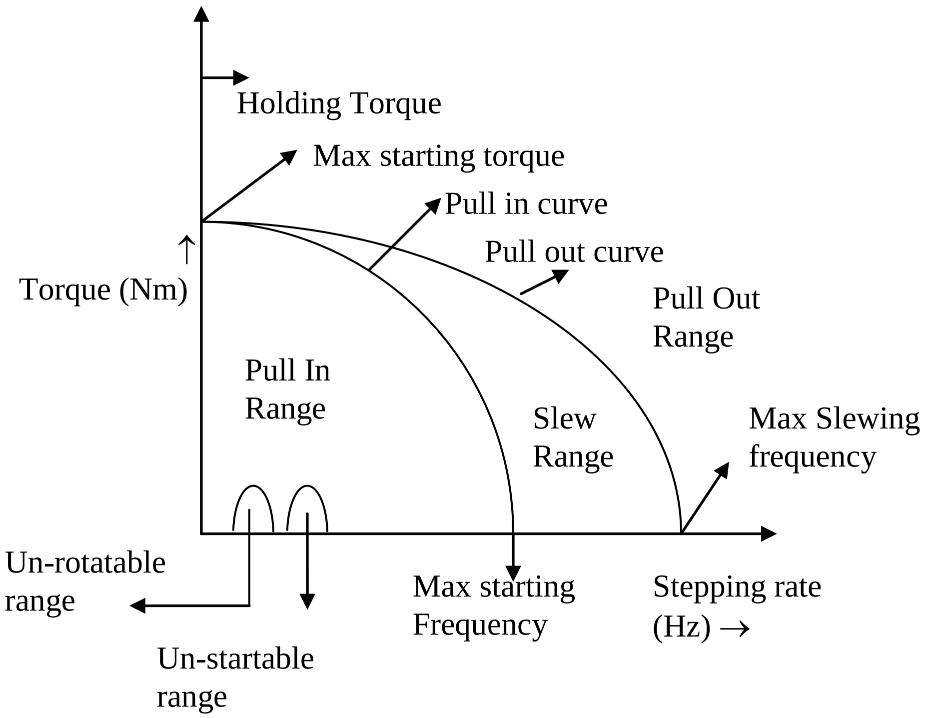


Fig 2.10

i. Pull - In Torque Curve

It is called starting characteristics and it is the range of frictional load Torque at which the motor can start & stop without losing steps for various frequencies in a pulse train.

ii. Pull - Out Torque Curve

It is called slewing characteristics. After the motor is started by giving specific excitation, the pulse frequency is gradually increased and during this increase in frequency the motor has to synchronize with the pulses. The relation between the frictional load Torque and max pulse rate with which the motor can synchronize is called pull -out curve. The pullout curve is greatly affected by the driver CKT, coupling, measuring devices and other conditions.

iii. Max Starting frequency

It is defined as maximum control frequency at which the unloaded motor can start & stop without losing steps.

iv. Max Pullout rate (or) Max Slewing frequency

It is defined as max: frequency at which the unloaded motor can run without losing steps.

v. Max starting Torque

It is also called as Max pullout Torque and it is defined as the Maximum frictional load Torque with which motor can start and synchronize with the pulse train of a frequency as low as 10 HZ.

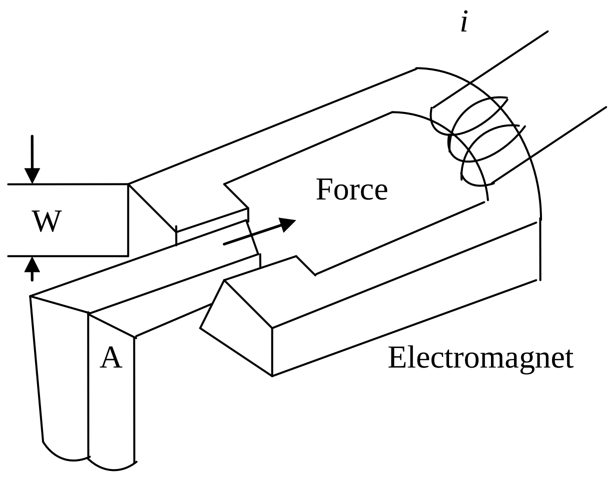
2.6 Static Torque Production in a VR stepper Motor

The torque developed in the stepper motor can be dealt in-terms of magnetic energy and co-energy. It has got three case.

I. Infinite Permeable Core

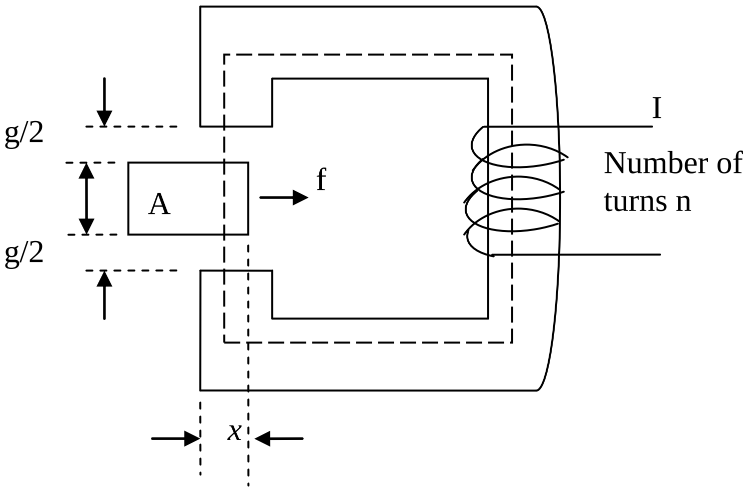
II. Constant Permeable Cores

III. Saturated Core



Iron Piece attracted by Electromagnet

Fig 2.11



Model of Stepping Motor

Fig 2.12

Case I :

Infinitely permeable cores:

To analyze the situation of an iron piece being attracted into a magnetic field created by a electromagnet as shown in the figure 2.11 and we use the model of stepper motor as shown figure 2.12.

A current I is flowing through the coil of "n" turns to yield magnetic flux and a force f is acting on the iron piece in the x - direction. First let us determine the magnetic flux density B_g in the air gap. Amperes circuital law along the dotted closed loop is expressed as

$$\oint H.dl = nI \qquad \text{(1)}$$

The left hand of this equation is rewritten as

$$\oint H.dl = H_g \, g/2 + H_g \, g/2 + H_i l = H_g g + H_i l \qquad \text{(2)}$$

Where H_g = Magnetic field intensity in the gaps

H_i = Magnetic field intensity in the cores

l = Total magnetic path in the cores.

When the permeability of core is extremely large, H_i is so low (ie) H_i=0. If H_i=0 and the core permeability μ is infinity. then $B_i = \mu H_i = \infty$ in the cores.

$$\therefore H_g g = nI$$

$$H_g = n \, I/g \qquad \text{(3)}$$

The gap flux density is $B_g = \mu_0 n \, I/g$ (4)

Where μ_o is the permeability in the air gap length.

Let the transverse length of iron piece be w, let the distance by which the rotor tooth and iron piece overlap be *x*. The overlapped area is now '*xw*'.

$\therefore$ Magnetic flux ϕ = Flux density x Area

$$= \mu_0 n \, I/g \, xw \qquad \text{(5)}$$

Hence the flux linkage ψ is given by

$$\psi = n\phi = xw\mu_0 n^2 \, I/g \qquad \text{(6)}$$

Let us assume that there is an incremental displacement Δx during time interval Δt. Then the incremental flux linkage is

$$\Delta\psi = \Delta x\, w\, \mu_0\, n^2\, I/g \qquad \text{\_\_\_\_\_ (7)}$$

The emf induced in the coils by the change in flux linkage is

$$e = \frac{-\Delta\Psi}{\Delta t} = \frac{-w\mu_0 n^2 I}{g} \times \frac{\Delta x}{\Delta t} \quad \text{Volts} \qquad \text{\_\_\_\_\_ (8)}$$

The minus sign in this equation implies that the direction of the emf is opposing the current. Since the current I is supplied by the power source for the time interval Δt to overcome the counter – emf and the work done Δp_i by the source is

$$\Delta p_i = I \times e \times \Delta t = \frac{w\mu_0 n^2 I^2}{g} \times \Delta x \qquad \text{\_\_\_\_\_ (9)}$$

Let the coil resistance is assumed zero for analysis. Δp_i can be expressed in terms of B_g as follows,

$$\Delta p_i = \frac{B_g^2 g w}{\mu_0} \times \Delta x \qquad \text{\_\_\_\_\_ (10)}$$

The work done by the source is converted partly to mechanical work and the rest is spent in increasing the magnetic field energy in the gaps. The increase in the gap field energy is given by

$$\Delta w_m = \frac{1}{2}\frac{Bg^2}{\mu_0}. \text{ (increase in the gap space)}$$

$$= \frac{1}{2} B_g^2 \frac{g\, w\, \Delta x}{\mu_o} \qquad \text{\_\_\_\_\_ (11)}$$

From (10) and (11) we find that half of Δp_i is converted into the magnetic field energy in the gaps and other half for mechanical work. Since the mechanical work is the force (f) multiplied by the displacement Δx, we obtain

$$\underset{\Delta p_o}{\text{Mechanical}} \quad work = f\,\Delta x = 1/2 \frac{B_g^2}{\mu_0} g\, w \Delta x \qquad \text{\_\_\_\_\_ (12)}$$

$$f = \frac{1}{2} B_g^2 \frac{g\, w}{\mu_o} \qquad \text{\_\_\_\_\_ (13)}$$

Other hand, the magnetic energy W_m in the gap is

$$W_m = \frac{1}{2} B_g^2 \frac{g\,w\,x}{\mu_o} \qquad \text{\_\_\_\_\_ (14)}$$

From (13) and (14) we derive

$$f = \frac{dw_m}{dx} \qquad \text{\_\_\_\_\_ (15)}$$

Assume that the current I is kept constant during the displacement, then

$$\therefore \quad f = \left(\frac{\partial w_m}{\partial x}\right) I \ = \text{constant} \qquad \text{\_\_\_\_\_ (16)}$$

Assume that the flux is kept constant during the displacement, then

$$f = -\left(\frac{\partial w_m}{\partial x}\right) \phi \ = \text{constant} \qquad \text{\_\_\_\_\_ (17)}$$

<u>Case II :</u>

Constant permeability of the cores:

In the previous case with infinite permeability, the magnetic field appears only in the gaps and its analysis is simple. When cores have some finite permeability, the magnetic energy not only appears in the gaps but also in the cores and other spaces and it is not easy to analysis this situation by electromagnetic field theory. So we will derive an expression for force in terms of circuitry parameters under some assumption.

If the coil inductance is L in the model, then flux linkage

$$\psi = L\,I \qquad \text{\_\_\_\_\_ (1)}$$

The magnetic energy W_m in the system is given as

$$W_m = \frac{1}{2} L\,I^2 \qquad \text{\_\_\_\_\_ (2)}$$

If the iron piece undergoes a displacement Δx during the time interval Δt, the inductance L will increase by ΔL.

The emf induced in the coil is

$$e = -\frac{\Delta\psi}{\Delta t} = \frac{\Delta(LI)}{\Delta t} \qquad \text{\_\_\_\_\_ (3)}$$

If the power supply is a current source and provides a current I during the displacement, then

$$e = -I \; \frac{\Delta L}{\Delta t} \qquad \text{\_\_\_\_\_ (4)}$$

The work done Δp_i by the source on the circuit is

$$\Delta p_i = I\, e\, \Delta t = I^2 \; \Delta L \qquad \text{\_\_\_\_\_ (5)}$$

On the other hand, the increase in the magnetic energy is

$$\Delta w_m = \frac{1}{2} I^2 \Delta L \qquad \text{\_\_\_\_\_ (6)}$$

From (5) and (6) it is seen that half of the work done by the source is converted into magnetic energy and other half is converted into mechanical work Δp_o given as

$$\Delta p_o = f\,\Delta x = \tfrac{1}{2} I^2 \Delta L \qquad \text{\_\_\_\_\_ (7)}$$

$$\therefore \; The\;\; force \;\; f = \frac{1}{2} I^2 \frac{\Delta L}{\Delta x} \qquad \text{\_\_\_\_\_(8)}$$

In the above analysis it was assumed that coil resistance is zero and the power supply was a current source. The force equation says that the force developed on the iron piece is in the direction which will increase the inductance (or) decrease the reluctance.

Case III:

Treatment of Magnetic saturated core

In most of the stepper motor the cores are subject to magnetic saturation. Let us assume that the motor is to be operated in the linear B/H characteristic region . we can discuss general theory for torque developed with magnetic saturation in cores.

Again using the model, let us analysis the energy conversion. The iron piece is drawn by a force *f* due to the magnetic field induced by the coil current I and travels from x_0 to $x_0 + \Delta x$ taking a time internal Δt .

The flux linkage is a function of the position x and the current i and expressed as $\psi(x, i)$. If the current i is kept at value I during the displacement, the work done Δp_i by the power supply for the interval Δt is

$$\Delta p_i = Ie\Delta t = I\frac{\Delta\psi}{\Delta t}\times\Delta t = I\Delta\psi \qquad (1)$$

The Mechanical work done on the iron piece during the interval Δt is

$$\Delta p_0 = f\,\Delta x \qquad (2)$$

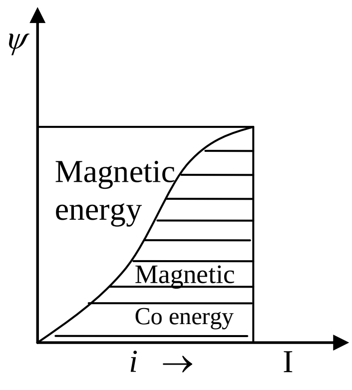
The increase in the magnetic energy during the displacement Δx is

$$\Delta w_m = \int_o^{\psi+\Delta\psi} id\psi(x_o+\Delta x, i) - \int_o^{\psi} id\psi(x_o, i) \qquad (3)$$

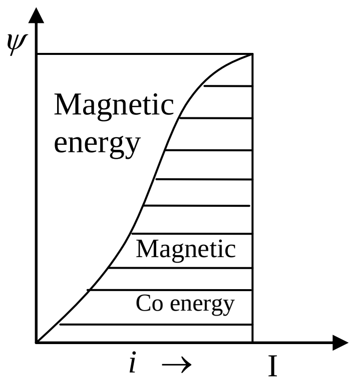
In the above equation the current i is treated as a variable which varies from 0 to I and the ψ varies from 0 to $\psi+\Delta\psi$ (or) ψ.

In the equation (3) each term is integrated by parts and we get

$$\Delta w_m = I\Delta\psi - \Delta\int_o^I \psi(x,i).di \qquad (4)$$



At $x = x_0$



At $x = x_o + \Delta x$

Since the first term on the right hand side is the work done by the power supply.

$$\therefore \Delta p_i = \Delta w_m + \Delta \int_0^I \psi(x,i).di \qquad \text{\_\_\_\_\_ (5)}$$

$$\therefore \Delta p_i = \Delta w_m + \Delta p_0 \qquad \text{\_\_\_\_\_ (6)}$$

$$Mechanical\ work\ done\ \Delta p_o = f\ \Delta x = \Delta \int_0^I \Psi(x,i)\,di \qquad \text{\_\_\_\_\_ (7)}$$

$$\therefore f = \frac{\Delta \int_0^I \psi(x,i).di}{\Delta x} = \frac{\partial(magnetic\ coenergy)}{\partial x}\Bigg|_{I = \text{constant}}$$

The corresponding Torque

$$T = \frac{\Delta \int_0^I \psi(\theta,i).di}{\Delta \theta} = \frac{\partial(magnetic\ co\,energy)}{\partial \theta}\Bigg|_{I = \text{constant}}$$

Where θ is the angular position of the rotor.

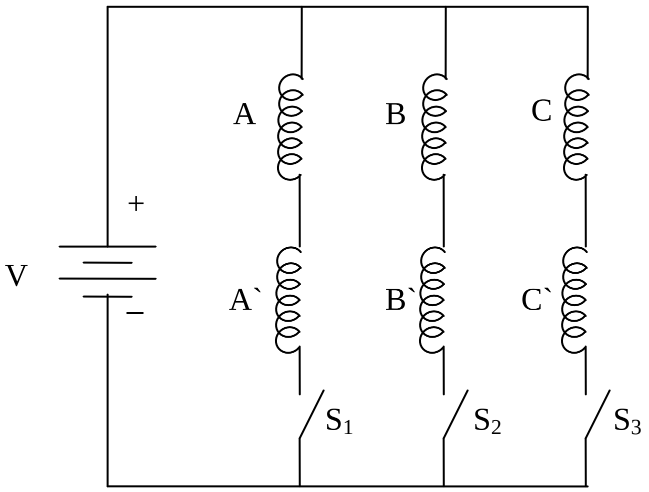
These are the fundamental equations necessary to calculate the force and torque produced in stepping motors due to magnetic saturation of the cores. When the system has ‘n’ coils then the Torque equation is expresses as

$$T = \frac{\partial}{\partial \theta} \sum_{i=1}^{n} \int_o^I \psi(\theta,i)di \qquad \text{\_\_\_\_\_ (8)}$$

2.7 VARIOUS MODES OF OPERATION OF STEPPER MOTOR

1. Single phase ON (or) Full step operation

In this mode of operation each phase is switched ON independently. Consider the VR stepper motor with 6 stator poles and 4 rotor poles. The equivalent circuit of Full step operation is shown in the figure 2.13 with the truth table.



Equivalent Circuit

A	B	C	θ
X	_	_	0^0
_	X	_	30^0
_	_	X	60^0
X	_	_	90^0
_	X	_	120^0

Truth table

Fig 2.13

The step angle $\beta = \frac{360}{mn_r} = \frac{360}{3 \times 4} = 30°$.

When m = number of phases.

The operation of single phase ON mode is as follows. When S_1 is closed, AA^1 phase is excited and the rotor will align (or) attracted into a position of minimum reluctance (ie) 0^0. Then S_1 is opened and S_2 is closed, the rotor rotates through a full step angle $30°$ in the clockwise direction. Similarly when S_2 is opened and S_3 is closed, the rotor again moves by an angle $30°$. So the rotor rotates by an angle of $30°$ for each phase when excited. The switching sequence is A,B,C,A........ , the rotor rotates in clockwise direction and when the switching sequence is A,C,B,A......... , the rotor rotates in counter- clockwise direction.

2. Two Phase ON Mode

In this mode of operation, two stator phases are excited simultaneously. When S_1 & S_2 are closed then phase A and B are energised together, the rotor experiences torque from both phases and comes to rest at point midway between the two adjacent full step position. So initially the rotor position will be at 15^0. When sequence of switching is carried out the rotor moves by full step angle.

The sequence of switching of clockwise rotation is AB,BC,CA................. The sequence of switching for counter clockwise rotation is AC,CB,BA.................. The truth table is given below.

A	B	C	θ
X	X	_	15^0
_	X	X	45^0
X	_	X	75^0
X	X	_	105^0
_	X	X	135^0
X	_	X	165^0

The 2 phase ON mode provides greater holding torque and a much better damped single stack response than the single phase ON mode of operation.

3. Half Step Operation

This mode of operation combines both single & two phase ON mode operation. It is also called as wave excitation and it causes the rotor rotate in steps of 15^0(ie) half the full step angle. The half stepping can be obtained by exciting the three phases in proper sequence so that the rotor rotates by half step.

The sequence of switching for clockwise rotation is A, AB, B, BC.. and the sequence of switching for counter clockwise rotation is A,AC,C,CB.......... The truth table is given below

A	B	C	θ
X	_	_	0^0
X	X	_	15^0
_	X	_	30^0
_	X	X	45^0
_	_	X	60^0

It will be seen that in half stepping mode, the step angle is halved thereby enabling the resolution. Moreover, continuous half stepping produces a smoother shaft rotation.

4. Micro stepping Operation

It is also known as mini - stepping. It utilizes two phases simultaneously as in 2 phase ON mode but with the two currents deliberately made unequal. The current in phase A is held constant while that in phase B is increased in very small increments until maximum current is reached. The current in phase A is then reduced to zero using the same very small increments. In this way, the resultant step becomes very small and is called micro step. Stepper motors employing micro stepping technique are used in printing and photo typesetting where very fine resolution is needed. Micro stepping provides smooth low speed operation and high resolution.

2.8 A CLOSED LOOP OPERATION SYSTEM USING MICROPROCESSOR

Now a days, microprocessors are available cheaply. Utilization of a microprocessor in control of stepping motors is a very interesting engineering problem. The choice of lead angles and the arrangement of switching points are based on the operation of the motor and selection of motor. The two curves of speed Vs distance under closed loop control of a stepper motor is shown in the figure 2.14

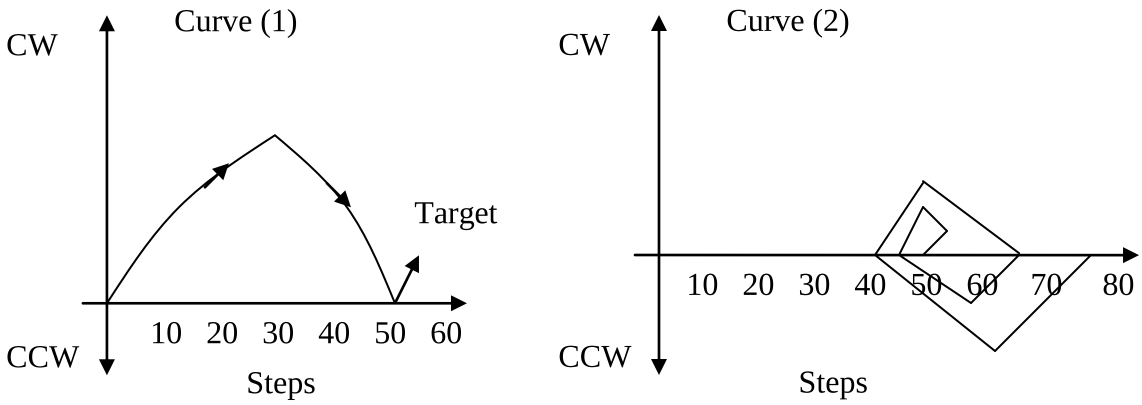


Fig 2.14

The curve 1 is an excellent pattern where the motor is started with an appropriate lead angle, accelerated with another lead angle and began to be decelerated at the best timing from which the speed is reduced most quickly and becomes zero just at the target. To start and accelerate a motor, a lead angle larger than one step is used, while zero (or) a negative lead angle is used for deceleration. On curve 2 which is an unskilled one, deceleration is initiated when the target position is detected. But the motor cannot stop at once and will overrun due to inertia. To accommodate the rotor at the current position, the motor is forced to move backward by setting the lead angle to a proper value. The speed Vs distance locus may be oscillatory as shown in the figure 2.15

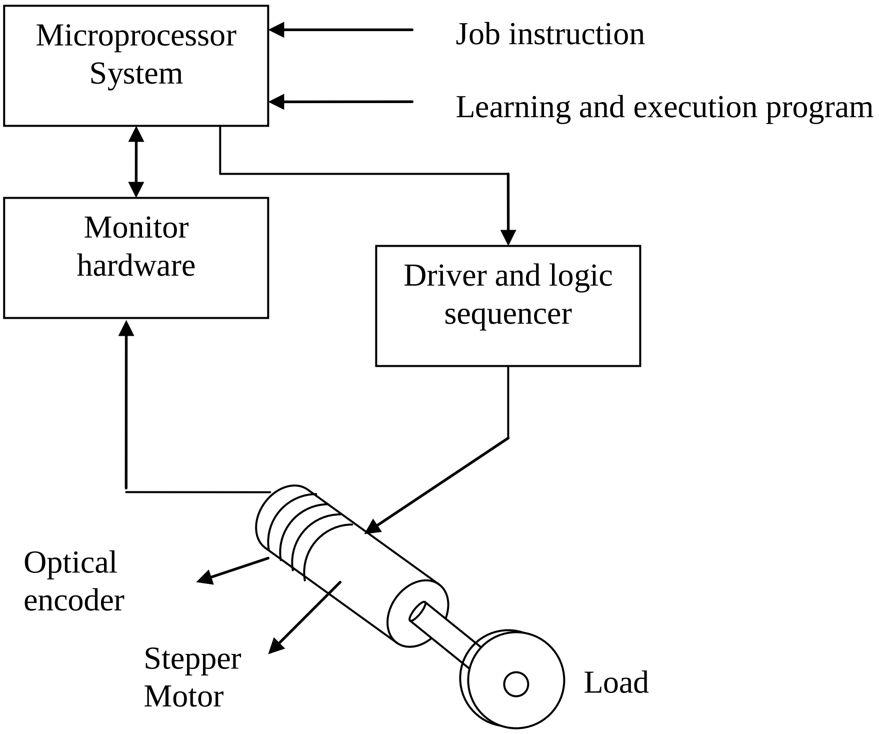


Fig 2.15

A microprocessor system is used here to find out the best timings to change lead angles to attain the curve 2 type motion, starting from the pattern of 2. The below figure illustrates the outline of the system which has a dedicated logic sequence outside the microprocessor. A positional signal is fed back to the block of hardware which monitors the rotor movement and exchanges information with the microprocessor. The software must be programmed so that the microprocessor determines better timings for changing lead angles, based on the previous experience and present position / speed data. The microprocessor will finally do several executions, and find the optimum timings for each motion used.

The microprocessor is also used for determining timings to set proper lead angles, based on the following information.

i. Present position

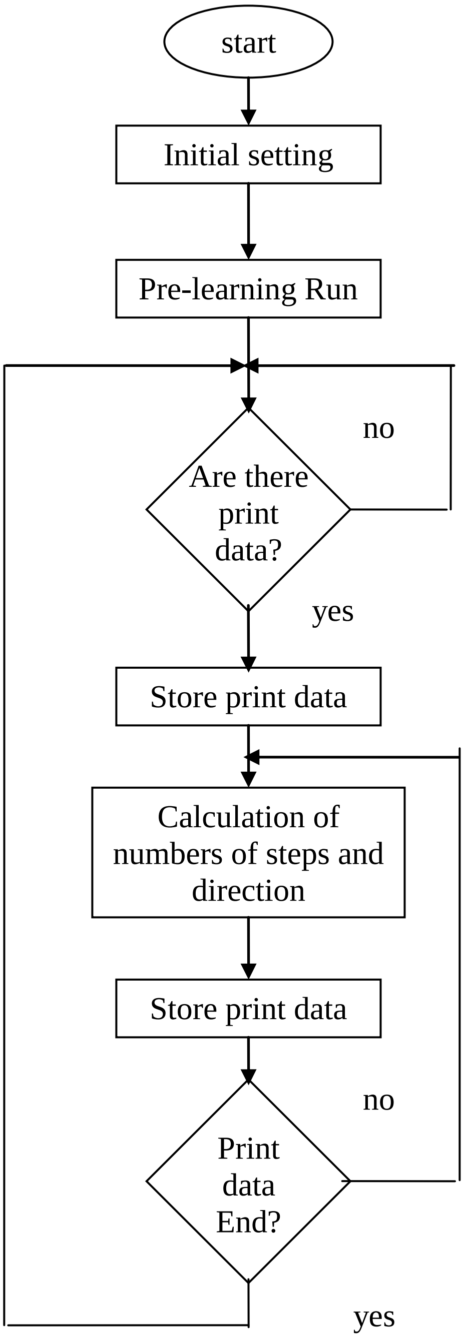
ii. Error steps from target.

iii. Signal to indicate that the rotor has passed the point a half step before target.

iv. Signal to indicate that motion has reversed.

v. Speed.

The flow chart of the programmed microprocessor is given below.



Initial Setting

At first, the motor is operated in the ordinary open loop mode for one revolution or to rotate by apart of one revolution in CW direction. The purpose of this is to reset the present position counter.

Pre-learning run

In this process, every kind of motion which may be commanded in the job processing is executed several times to train the microprocessor system before it learns the timings to change lead angle to yield optimum speed pattern for a given lead.

Are there print data? After 200 kinds of motions are trained, the system is ready to work for practical job processing. If the microprocessor receives any data to be printed, they are at once stored in RAMS.

Calculation of number of steps and direction

The distance between the present position and the target is calculated, and the result is sent out to the error counter. The position at which lead angle is to be changed from acceleration to deceleration is also sent out to the LACS generator.

Main program

Acceleration mode of lead angle and direction is set and putout from output port 2 to the gate, to start the motor. It is expected that every motion is performed in the shortest time. If however, any variation of load conditions happens, overshoots positive (or) negative will occur and the timings of changes in the lead angle are always corrected.

2.9 DRIVER SYSTEM

A simple driver system for a stepper motor is represented by the block diagram as shown in the figure 2.16 It consists of input controller, logic sequencer, Driver circuit and stepper motor.

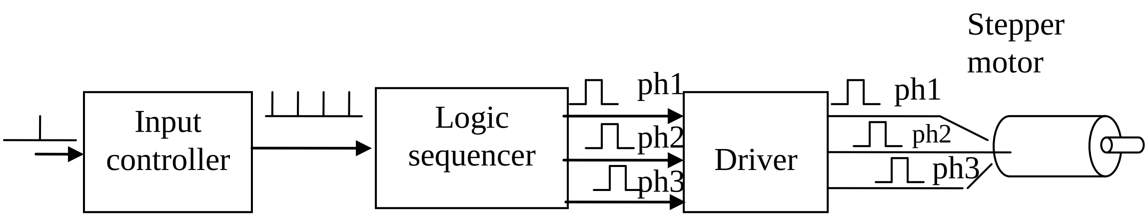


Fig 2.16

Input Controller

It is an electronic controller which is used to produce proper train of pulses needed to put before the logic sequencer. The purpose of input controller is, when an increment is performed by two or more steps, this will generate proper train of pulses with proper duration of time. The electronic devices such as micro controllers & microprocessor are used to generate pulse train to speed up, slew & slow the motor in the most efficient and reliable manner.

Logic Sequencer

When a command pulse is applied to the logic sequencer, the states of the output terminals are changed to control the motor driver so as to rotate the motor a step angle in the desired direction. The rotational direction is determined by the logic states at the direction, input (ie) H level for CW and L level for CCW direction. In some application the logic sequencer are unidirectional, having no direction signal terminal.

The logic sequencer is a logic circuit which controls the excitation of the windings sequentially, responding to step command pulse. It generally consists of shift registers and logical gates such as NAND, NOR etc. The logical sequences can be assembled by a proper combination of J-K Flip flops IC chips and logic gate IC chips. Nowadays built in logic sequencer are designed for stepper motors available in the market.

Motor Driver

The output from logic sequencer is given as input to the motor driver by which the switching of the motor winding is governed. To establish proper rotation of stepper motor, the driver circuit plays a vital role in driving the motor in proper step angle. The simple method of connection is the direct connection which is shown below. If the output currents from the sequencer are not enough to drive the power transistor, it is necessary to put a buffer for current amplification between the two stages.

The logical sequencer with the motor driver is shown in the figure 2.17

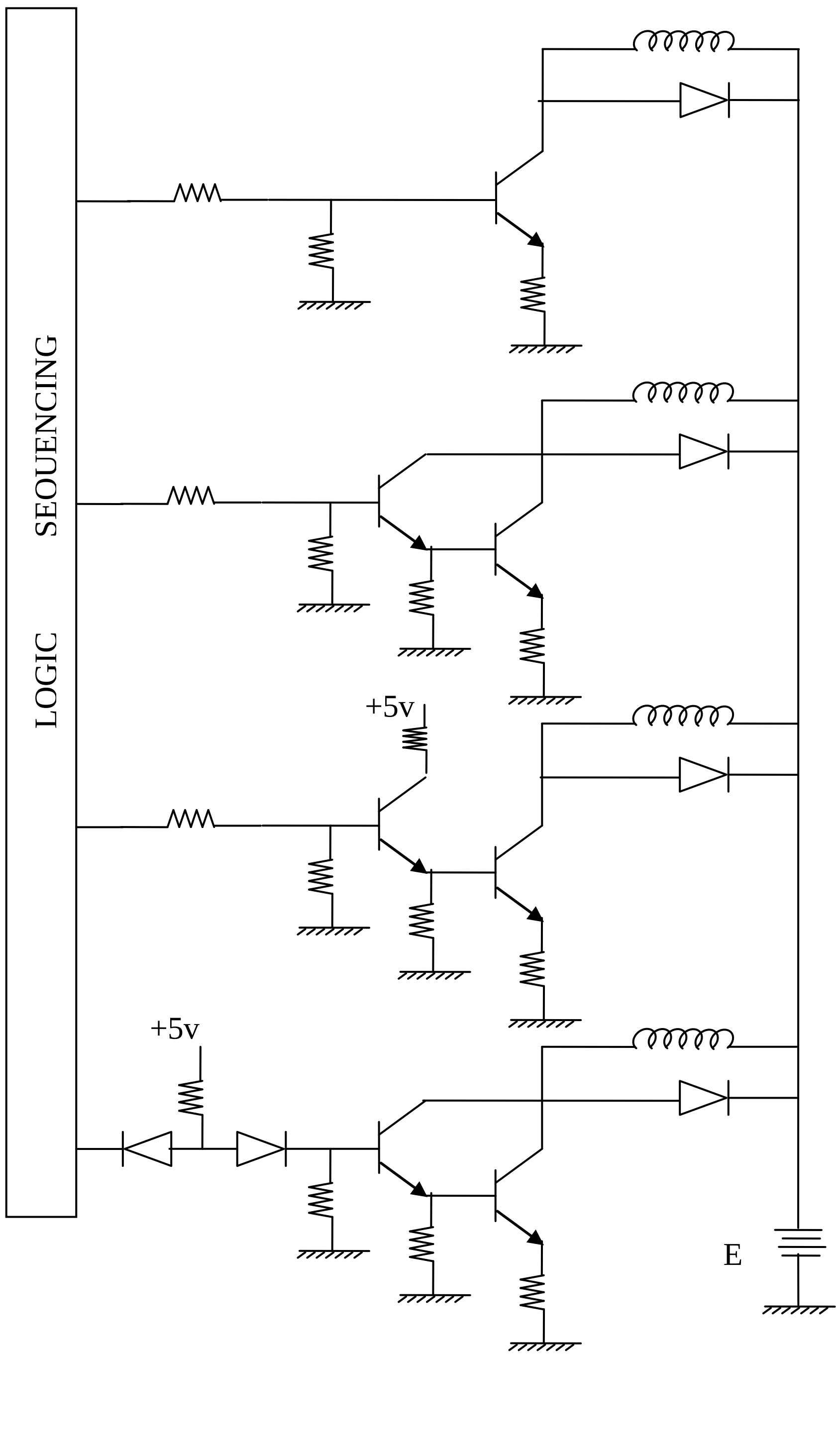


Fig 2.17

Problems with Motor Drivers

A winding on a stepper motor is inductive and appears as a combination of inductance and resistance in series. In addition, as a motor revolves, a counter emf is produces in the winding. The equivalent circuit is shown in the figure 2.18.

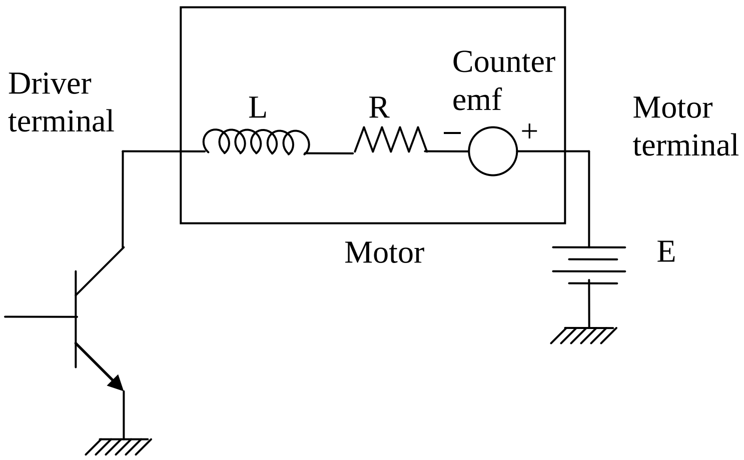


Fig 2.18

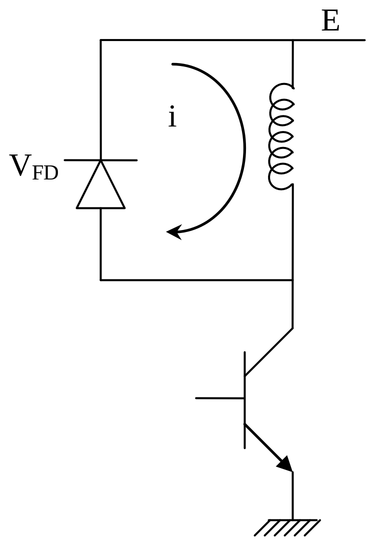
The motor parameters vary due to manufacturing tolerances and operating conditions. Since the stepper motors are designed to deliver the highest power from the smallest size, the temperature can be as high as 100^0c and the winding resistance therefore increases 20 to 25 percent.

2.10 SUPPRESSORS

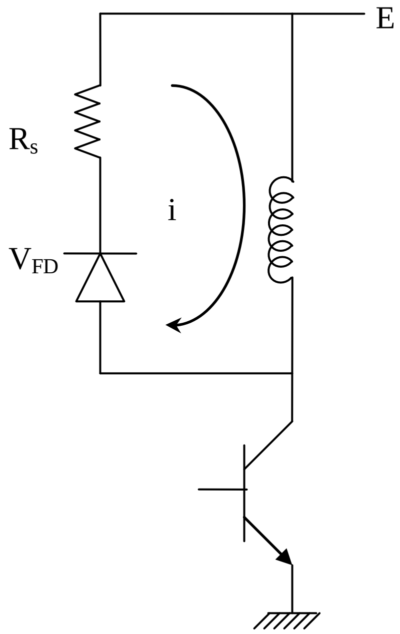
When the transistor is turned off, a high voltage builds up due to $L\,{}^{di}\!/_{dt}$ and this voltage may damage the transistor. There are several methods of suppressing this spike voltage and protecting the transistor.

i. **Diode suppressor:** If a diode is put in parallel with the winding in the polarity shown, a circulating current will flow after the transistor is turned off and the current will decay with time. The collector potential is $V_{CE} = E + V_{FD}$. This method is very simple but a drawback is that the circulating current lasts for a considerable length of time and produce a braking torque.

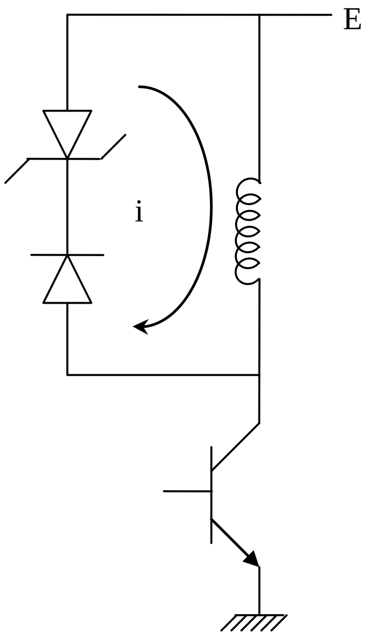
$$V_{CE} = E + V_{FD}$$

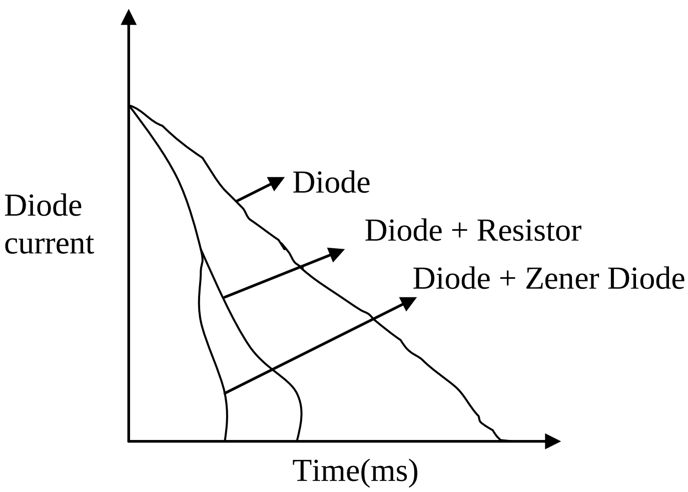


ii. **Diode / Resister Suppressor:** When a resister is connected in series with the diode as shown, quick damping of circulating current will take place. Then the collector voltage $V_{CE} = E + I\ R_S + V_{DF}$. The higher the resistance R_S, quicker the current decays after turn off, but the higher the collector potential. Therefore, a higher maximum voltage rating is required for fast Decay.



iii. **Zener Diode Suppressor:-** Zener Diodes are often used to connect in series with the ordinary diode as shown. Compared to the two cases discussed earlier, in this method the current decays more quickly after turn off. The collector potential is $V_{CE} = E + V_z$ which is independent of the current.





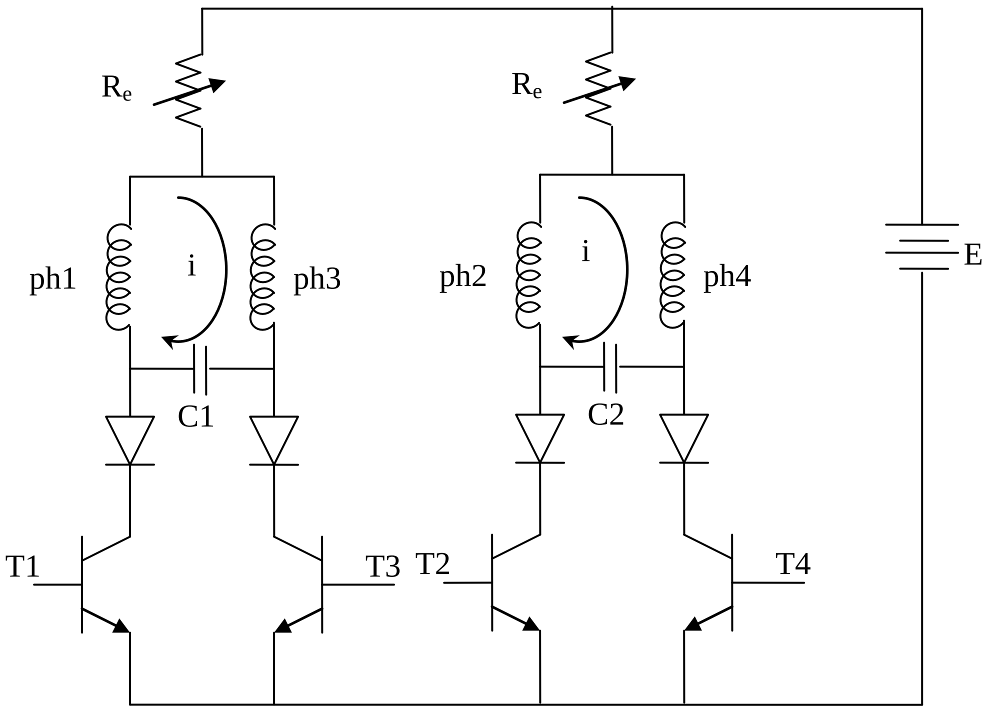
iv. **Condenser Suppressor:-** This scheme is employed for bifilar wound motor and four phase motor. A condenser is put between ph_1 & ph_3 and between ph_2 & ph_4. The condenser serves two purposes:

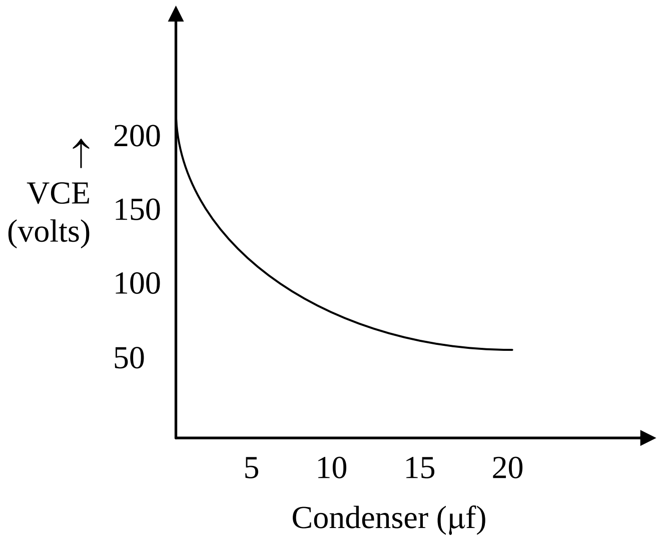
a. When a transistor is turned off, the condenser connected to it with the diode absorbs the decaying current from the winding to protect the transistor.

b. The condenser acts as an electrical Damper. That is a method of damping rotor oscillations is to provide a mechanism to convert kinetic energy into heat energy.

The oscillatory current will flow in the closed loop between the phases and condenser as shown and Joule heat is generated in the windings which means that the condenser works as an electrical damper.

The condenser suppressors are suited to drives in which the stepping rate is limited in a narrow region. The smaller the capacitance, the more the pullout Torque at higher stepping rate which is due to quick decay of current after turning off. The maximum potential applied to collector after turning off becomes higher with decreasing capacitance.


Re
Re
ph1
i
ph3
ph2
i
ph4
E
C1
C2
T1
T3
T2
T4


VCE
(volts)
200
150
100
50
5
10
15
20
Condenser (μf)

2.11 Input Controller:

The input controller which governs the number of step command pulses and their timings and in some applications the directional signal also.

2.11.1 Single step controllers

The simplest is the system which performs an increment with a single step. The step Vs time relation in this system will be such as shown in figure 2.19.

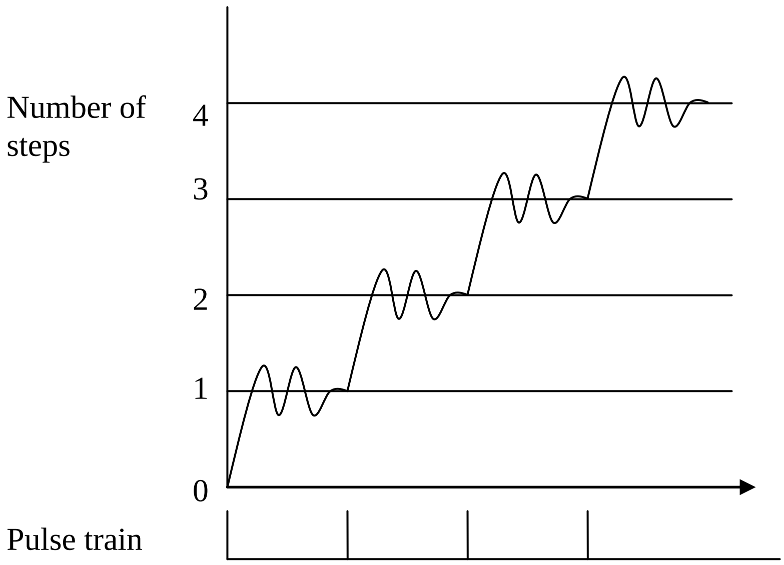


Fig 2.19 Single step response

The positioning profile is generally oscillatory and its damping depends on the motor and drive scheme used. The input controller is very simple, since its function is only to provide an output signal which is suitable as the input to the sequencer. The example for simple input controller is shown figure 2.20.

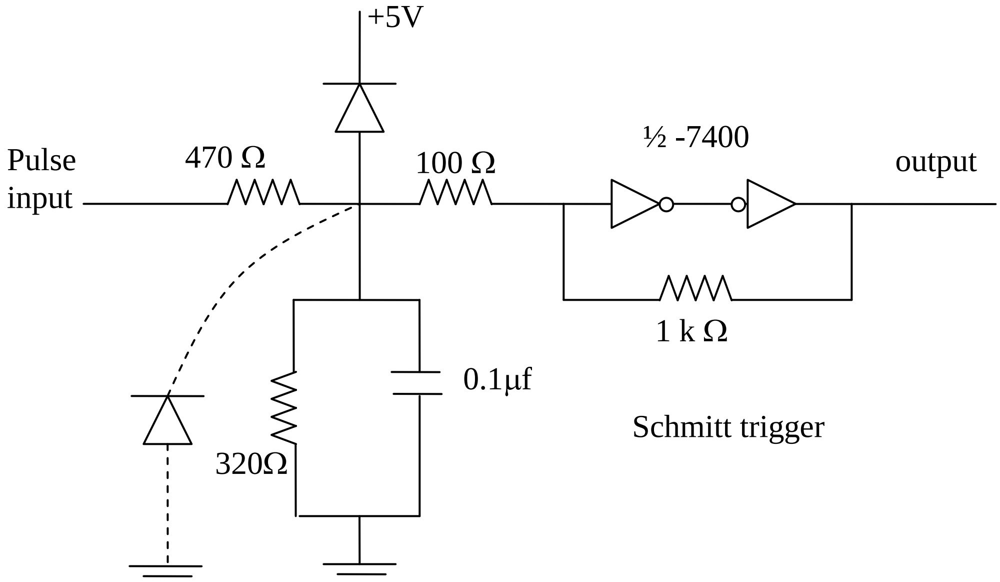


Fig 2.20

It has the following features:-

1. The input signal is clamped at a suitable H level. (5v)
2. Noise is absorbed in the condenser.
3. Since the input signal is deformed by the condenser, it is reformed by means of a Schmitt trigger. NAND & NOR gates may be used for the Schmitt trigger. If any part of the input signal can be less than the ground potential, a diode should be added as shown by the dotted curves. Mostly universal sequences have a Schmitt trigger inbuilt

2.11.2 Input controller for Electronic damper

To carryout a single step without oscillation, a method called "back phasing" is used. The relation between the position profile and pulse timing is illustrated in the below figure 2.21

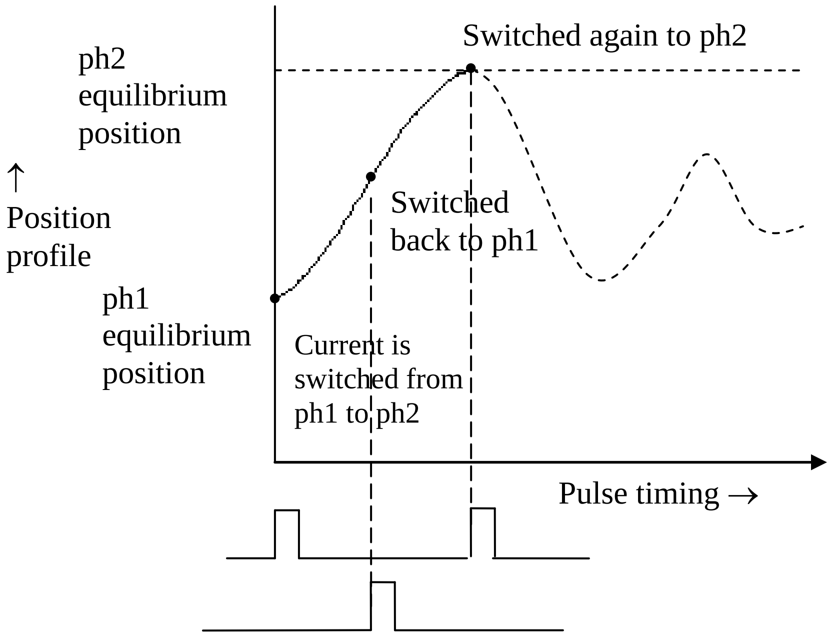


Figure 2.21 Rotational angle and pulse timing in back phasing damping.

The motor at rest on an equilibrium position with ph_1 excited, is commanded to move to the next equilibrium position. If the rotor continuous to be accelerated by the excitation of ph_2, it will overshoot exceeding the next equilibrium position. So as the rotor is moving towards the next phase equilibrium position, ph_2 is switched off and ph_1 is switched back ON. This produces a retarding torque which tends to slow down the rotor. When the rotor momentum is cancelled by the retarding torque, it will momentarily come to rest before reversing to go back to the previous position. At this moment, excitation is again switched to ph_2. The reversing pulse must be exactly timed so that the rotor reaches zero speed when it is on the equilibrium position of ph_2. Thus when the exciting current is switched back to ph_2, the rotor will lock in on the ph_2 equilibrium position with no overshoot or oscillations. This technique can be applied to more than one step of motion by the addition of more pulses preceding the back phasing pulse. it may be summarized as

i. Adjust the pulse preceding the back phasing to give minimum response.

ii. Adjust the back phasing pulse to retard the load motion such that it just reaches its step position.

iii. Adjust the last pulse to hold the load in its final position with minimum oscillation.

2.11.3 Damped incremental motion with multi-steps

Single step motion is generally oscillatory. But non - oscillatory incremental motions can be performed with several steps by proper pulse timing. Two examples are given here.

1. Delayed last step electronic damping

Assume that it is wished to move three steps. If a three pulse train is applied at a moderate rate ,the response will appear as shown in figure 2.22. However, if the period between the first and second pulses is adjusted such that the rotor will overshoot by exactly one step, its final step position will be ph_3. The last is then applied to hold the rotor in place at its point of zero speed as shown in figure 2.23. If the system friction is such that the rotor does not overshoot one step, this technique cannot be used, likewise this cannot be applied to less than three steps.

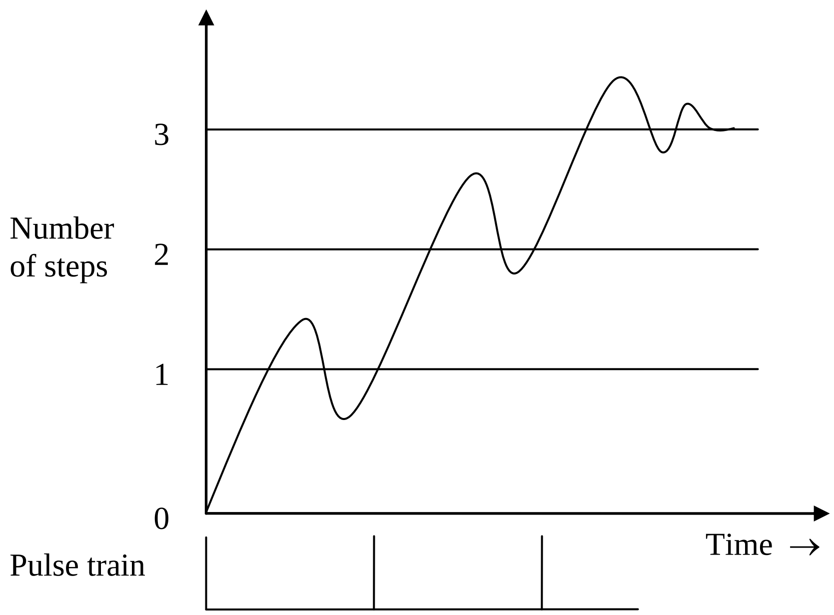


Figure 2.22

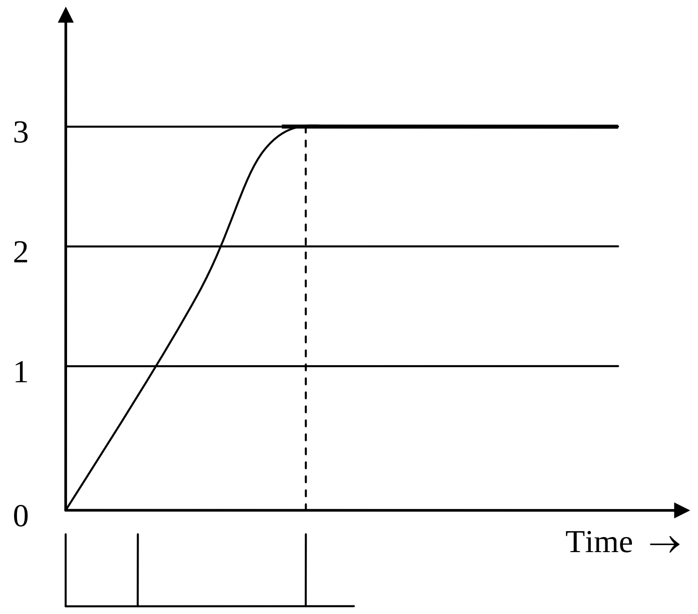


Figure 2.23

2. Constant pulse rate electronic damping

If a non - oscillatory incremental motion is performed with several pulses at equal intervals, the input controller may be simple. Here the pulses are generated at constant rate so that the oscillations at the equilibrium position are avoided. The below figure 2.24,2.25 & 2.26 shows the single step, three pulse and six pulse response of the stepper motor.

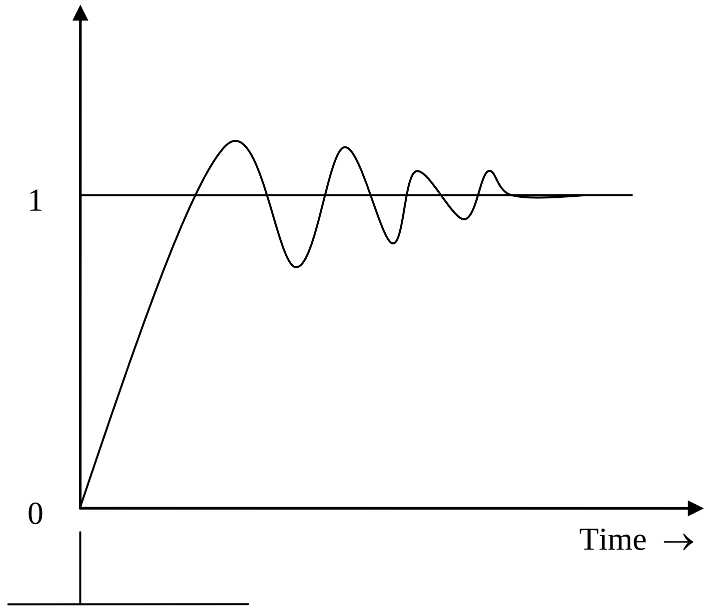


Fig 2.24 Single step response

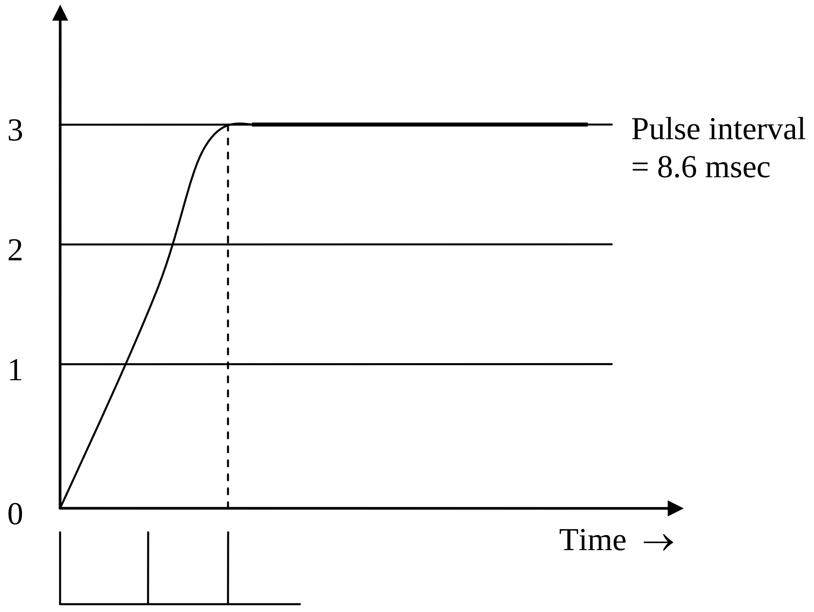


Fig 2.25 Three Pulse responses

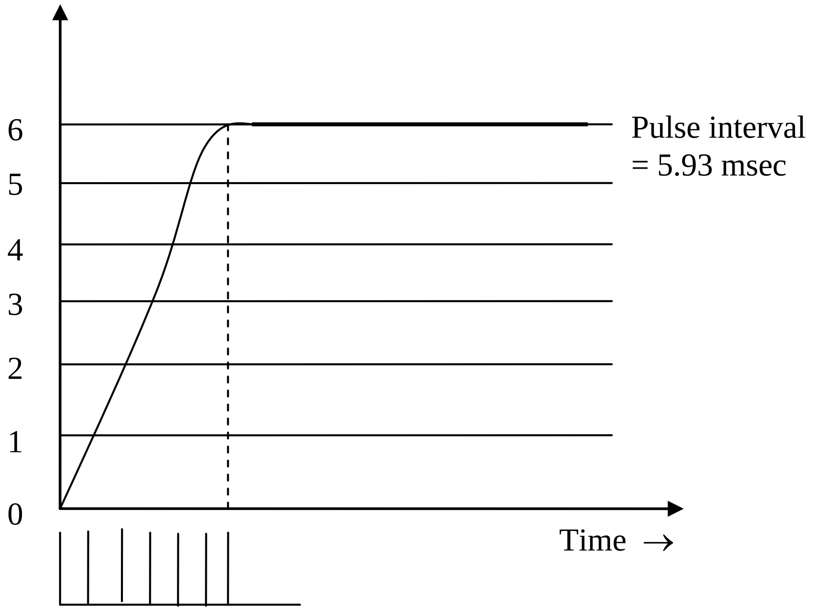


Fig 2.26 Six pulse response

2.12 Limitation of open loop operation & need for closed loop operation:

In the drive system, the step command pulses were given from an external source and it was expected that the stepping motor is able to follow every pulse. This type of operation is referred to as open loop drive. The open loop drive is attractive and widely accepted in applications of speed & position control. However, the performance of a stepping motor driven in the open loop is limited. It may fail to follow a pulse command when the frequency of the pulse train is too high or the inertia load is too heavy. Moreover the motor motion tends to be oscillatory in open loop drive.

The performance of a stepping motor can be improved to a great extent by employing position feedback (or) speed feedback to determine the proper phase to be switched at proper timings. This type of control is termed as closed loop drive. A position sensor is needed for detecting the motor position example-an optical encoder which is coupled to the motor shaft. In closed loop control, the motion of the motor is much quicker and smoother.The closed loop operation is shown in fig 2.27

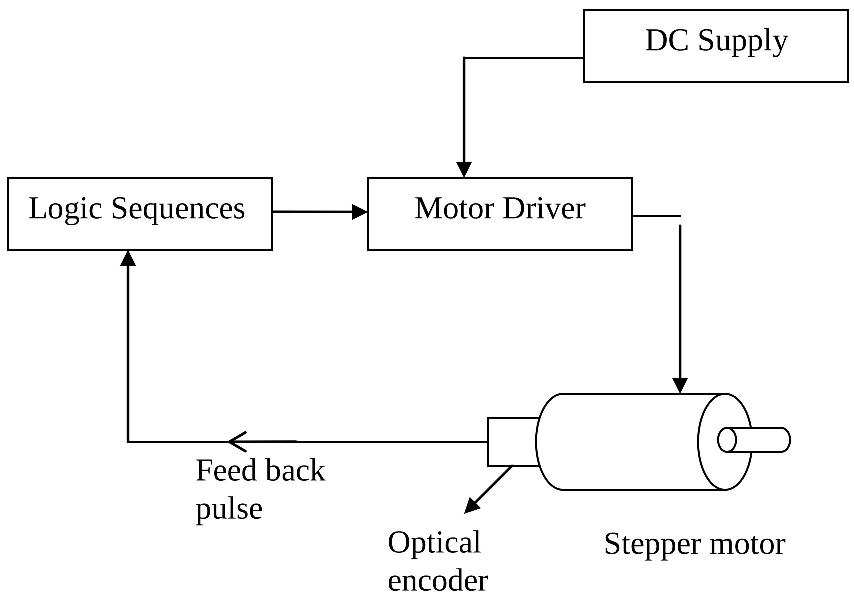


Fig 2.27 Simple closed loop control of Stepper Motor

PROBLEM

1. A 3 phase VR stepper motor has the following parameters: winding resistance is 1 Ω, average phase winding inductance is 30 mH and rated winding current is 3 amps. Design a simple unipolar drive circuit such that the electrical tie constant is 2 msec at phase turn on and 2 msec at turn off. The stepping rate is 300 steps per second

Jan 2006

Given data

Turn on time constant, τ_{on} = 2 msec

Turn off time constant τ_{off} = 1 msec

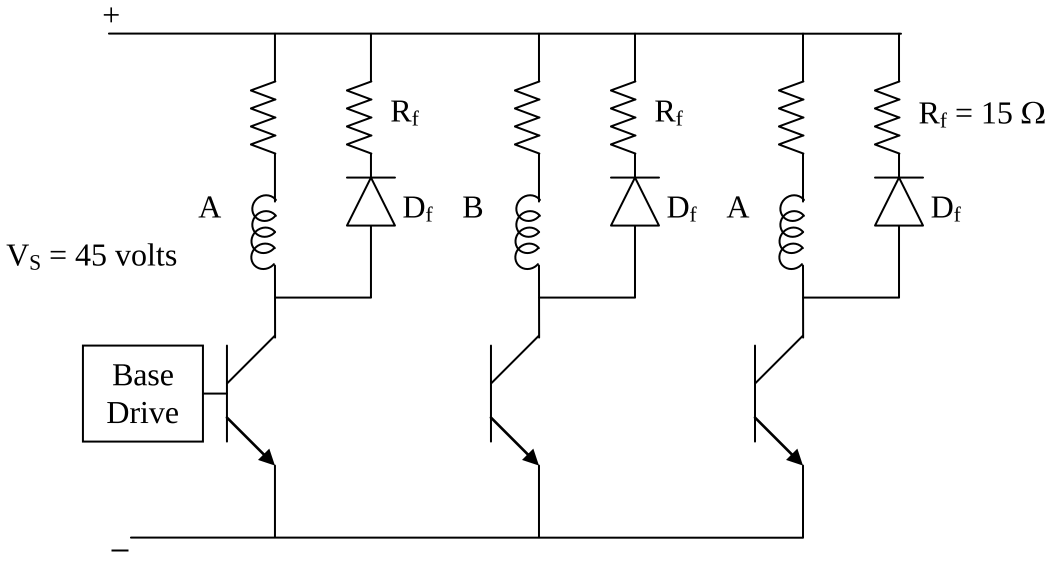
Winding resistance, R_w = 1 ohm

Winding inductance, L_w = 30 mH

Stepping rate ζ = 300 / second

To find : Design a simple unipolar drive circuit

Solution



The turn on time constant , $\tau_{on} = \dfrac{L_w}{R_w + R_{ext}}$

$$R_w + R_{ext} = \frac{L_w}{\tau_{on}}$$

$$R_{ext} = \frac{L_w}{\tau_{on}} - R_w$$

$$\Rightarrow \quad R_{ext} = \frac{30}{2} - 1$$

R

Power loss due to $P = I_w^2 \times R_{ext}$

= 3^2 x 14

P = 126 watts

The DC voltage V = I_w (R_w + R_{ext})

= 3 (1 + 14)

V = 45 volts

Turn off time constant $\tau_{off} = \dfrac{L_w}{R_w + R_{ext} + R_f}$

$$R_f = \frac{L_e}{\tau_{off}} - \left[R_w - R_{ext}\right]$$

$$= \frac{30}{1} - (15)$$

R_f = 15 ohm

Energy stored in the phase resistance at turn off $= \dfrac{1}{2} \times L_w \times i_w^2$

$$= \frac{1}{2} \times 30 \times 10^{-3} \times 3^2$$

w = 0.135 Joules

[∵ R_f = R_w + R_{ext} all the time]

Energy dissipated across R_f is $= \frac{0.135}{2} = 0.0675$ Joules

Number of turn off in each phase = $\frac{Stepping\ rate}{q}$

$$= \frac{300}{3} = 100$$

Average power dissipated in R_f = 100 x 0.0675 = 6.75 watts

$V_{CE(max)}$ = V + (q x R_f)

= 45 + (3 x 15)

$V_{CE(max)}$ = 90 V

Current rating of the transistor is 3 amps

2. A steeper motor driven by a polar drive circuit has 30mH winding inductance, 45 V DC supply, BA rated current and 15 Ω total resistance in each phase. When the resistors are turned off find i. time taken by phase current to decay to zero and ii. Properties of stored inductive energy returned to supply.

Nov/Dec 2003

Jan 2005

Given data

Winding Inductance L_w = 30mH

The DC supply = V_S = 45 volts

Total resistance in each phase R = 15 ohm

Rated current I_{rated} = 3 amps

To find

i. Time taken by phase current to decay to zero and

ii. Proportion of stored inductive energy returned to supply

Solution

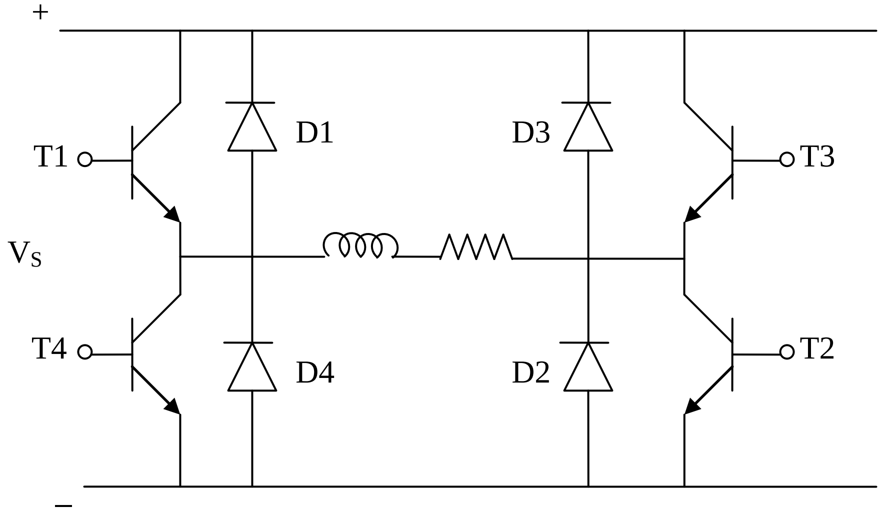
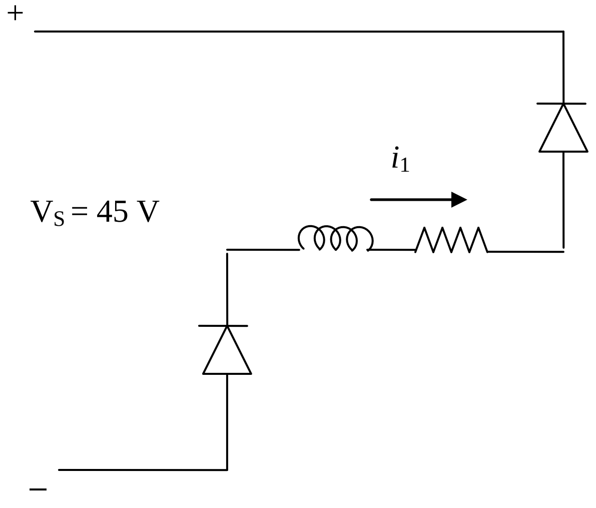
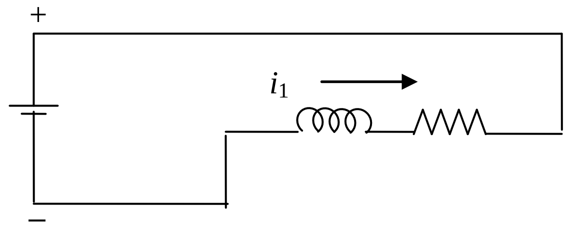
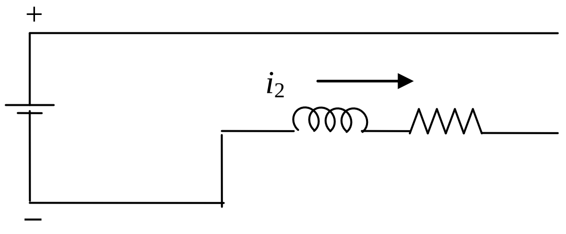


Fig Bipolar driven circuit for VRM

During the operation going on the equation circuit are drawn like this







$$i = 2e^{-t/\tau} - 3\left(1 - e^{-t/\tau}\right)$$

$$i = -3 + 6e^{-t/\tau}$$

$$\tau = \frac{L_w}{R} = \frac{30\times10^{-3}}{15}$$

$$\tau = 2\ m\text{sec}$$

i. Let i fall to zero in time t_1.

$$0 = -3 + 6e^{-t/\tau}$$

$$\ln\left(e^{-t/\tau}\right) = \ln\left(\frac{3}{6}\right)$$

$$-t_1/\tau = -0.7$$

$$t_1 = 0.7\times2\times10^{-3}$$

$$\mathbf{t_1 = 1.4\ msec}$$

ii. The energy returned to the supply W_s.

$$= \int_0^{t_1} V_s i\, dt$$

$$= \int_0^{t_1} 45\left(-3 + 6e^{-t/\tau}\right) dt$$

$$= -135\int_0^{t_1} dt + \int_0^{t_1} 270\, e^{-t/\tau} dt$$

$$= -135(t_1) + 270(-\tau)\left[e^{-t/\tau}\right]_0^{t_1}$$

$$= -135t_1 + 270(2)\left[e^{-t_1/\tau} - 1\right]$$

$t_1 = 1.4$ msec $\quad \tau = 2$ msec

$$W_s = -135\left(1.4\times10^{-3}\right) - 270\left(2\times10^{-3}\right)\left[e^{-1.4/2} - 1\right]$$

= 0.081 Joules

W_s = 81 mJ

Stored energy $= \frac{1}{2} i^2 L_w$

$= \frac{1}{2} \times 3^2 \times 30 \times 10^{-3}$

E = 135 mJ

Proportion of energy returned to supply

$= \frac{81}{135} \times 100$

= 60 %

3. A VR stepper motor has a 8 pole in the stator and they have five teeth in each pole. If the rotor has 50 teeth, calculate the step angle and resolution

Given data

Stator pole N_s = 8

Rotor teeth N_r = 50

To find

i. Step angle, ξ and

ii. Resolution, Z

Solution

i. Step angle , $\xi = \frac{N_s - N_r}{N_s N_r} \times 360^0$

$= \frac{40 - 50}{2000} \times 360^0 = 1.8^0$

ii. Resolution, $Z = \frac{360^0}{\xi} = \frac{360^0}{1.8^0}$

200 steps/ resolution

4. A steeper motor has a step angle of 2.5^0, determine a. resolution b. Number of steps per shaft to make 25 revolution c. shaft speed if starting stepping frequency is 3600 pulse/sec.

Given data

Step angle, ξ = 2.5^0

Stepping frequency = 3600 pulse/sec

To find

i. Resolution (Z)

ii. Number of steps to make 25 resolution and

iii. Shaft speed

Solution

i. Resolution $Z = \frac{360^0}{\xi} = \frac{360^0}{2.5^0}$

$= 144$ steps/revolution

ii. Number of steps for 25 revolution = 25 x 144 = 3600 steps

iii. Stepping frequency f = 3600 pulse/ sec

Step/angle/pulse = 2.5^0.

Angular displacement/sec = 3600 x 2.5

= 9600 angle/sec

Revolution/sec = $\frac{9600}{360} = 25$ revolution/sec

Shaft speed = 25 x 60 = 1500 rpm

5. What is the step angle of a 4 phase stepper motor with 12 stator teeth and 8 rotor teeth.

Solution

Number of phase m = 4

Number of rotor, Nr = 3

Step angle $\xi = \frac{360}{mN_r} = \frac{360}{3 \times 4} = 30^0$

TEXT / REFERENCE BOOKS

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2. **Kenjo.T**, "Stepping motors and their microprocessor control", Oxford University Press, 1995.

3. **R.Krishnan**, "Electric Motor Drives - Modeling, Analysis and Control", Prentice-Hall of India Pvt. Ltd., New Delhi, 2009.

4. **Kenjo.T and Naganori, S** "Permanent Magnet and Brushless DC motors", Clarendon Press, Oxford, 1989.

5. **B.K. Bose**, "Modern Power Electronics & AC drives", Dorling Kindersley India, 2006.

QUESTIONS:

UNIT – I STEPPING MOTORS

PART A

1 Define step angle and give its formula

2 State any 3 applications of stepper motors

3 Describe the resolution of a stepper motor & write the equation for it.

4 State the advantage of 2 ph excitation in a stepper motor?

5 Explain slewing in a stepper motor?

6 Examine the resolution of a stepper motor with a step angle of 2.5 degrees.

7 Solve for the no of stator poles for a 4 stack VR stepper motor has a step angle of 1.8 deg.?

8 Recognize the micro-stepping in a stepper motor.

9 A 3 stack VR stepper motor has a step angle of 10 deg. Identify the no of rotor teeth in each stack.

10 Examine step angle of a PM stepper motor with 8 stator poles & 4 rotor poles.

11 Classify the different modes of excitation of stepper motor.

12 Explain holding torque in stepper motor.

13 Compare variable reluctance and permanent magnet stepper motor.

14 Define the term detent torque.

15 List the functions of logic sequencer.

PART B

1 Explain the construction & principle of operation of a VR single stack stepper motor with different modes of operation.

2 Investigate on dynamic characteristics of a stepper motor.

3 Formulate the construction & principle of a PM type stepper motor with different modes of excitation.

4 A single stack VR type stepper motor has a step angle of 15 deg. Identify the two possible combinations of stator & rotor poles.

5 A stepper motor has a step angle of 1.8deg & is driven at 4000pps. Examine i) The resolution ii) Motor speed iii) Number of pulses required to rotate the shaft through 54deg.

6 Derive an expression for the torque generated in Variable Reluctance Stepper Motor.

7 Develop the drive circuits for stepper motor with neat diagram.

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UNIT – II - SPECIAL ELECTRICAL MACHINES – SEE1307

UNIT 2

SWITCHED RELUCTANCE MOTORS

Principle of Operation, Constructional features, Torque equation, Power Semi Conductor Switching Circuits, frequency of variation of inductance of each phase winding - Control circuits of SRM-Torque - Speed Characteristics, Microprocessor based control of SRM Drive, Applications.

3. SWITCHED RELUCTANCE MOTORS

3.1 INTRODUCTION

The switched reluctance motor (SRM) drives for industrial applications are of recent origin. Since 1969, a variable reluctance motor has been proposed for variable speed applications. The origin of this motor can be traced back to 1842, but the “reinvention” has been possible due to the advent of inexpensive, high-power switching devices. Even though this machine is a type of synchronous machine, it has certain novel features.

3.2 CONSTRUCTION OF SWITCHED RELUCTANCE MOTOR

SRM are made up of laminated stator and rotor cores with N_s=2mq poles on the stator and N_r poles on the rotor. The number of phases is m and each phase is made up of concentrated coils place on 2q stator poles. Most favored configuration amongst many more options are 6/4 three phase and 8/6 four phase SRM’s as shown in the figure 3.1(a).

These two configurations correspond to q=1(one pair of stator poles (and coils) per phase) but q may be equal to 2, 3 when, for the three phase machine, we obtain 12/8 or 18/12 topologies applied either for low speed high torque direct drives or for high speed stator generator systems for aircraft. The stator and rotor pole angles β_s and β_r are, in general, almost equal to each other to avoid zero torque zones.

It has wound field coils of a dc motor for its stator windings and has no coils or magnets on its rotor. Both the stator and rotor have salient poles, hence the machine is referred to as a doubly salient machine. Such a typical machine is shown in Figure 3.1a, and a modified version with two teeth per pole is shown in Figure 3.1b.

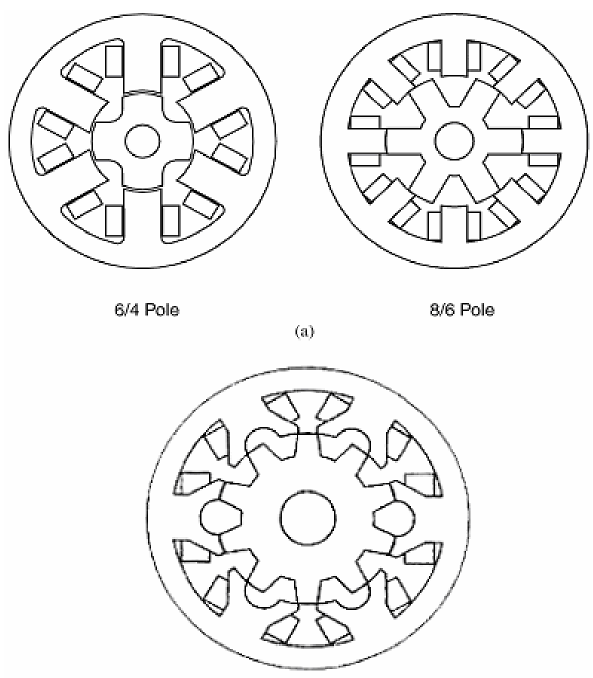


FIGURE 3.1 Switched reluctance motor configurations. (a) One tooth per pole. (b) Two teeth per pole (12/10 poles).

The rotor is aligned *whenever diametrically opposite stator poles are excited*. In a magnetic circuit, the rotating member prefers to *come to the minimum reluctance position at the instance of excitation*. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment. Likewise, by sequentially switching the currents into the stator windings, the rotor is rotated. The movement of the rotor, hence the production of torque and power, involves switching of currents into stator windings when there is a variation of reluctance; therefore, this variable speed motor drive is referred to as a switched reluctance motor drive.

3.3 ADVANTAGES AND DISADVANATGES OF SRM

3.3.1 ADVANTAGES

The SRM possess a few unique features that makes it a vigorous competitor to existing AC and DC motors in various adjustable-speed drive and servo applications. The advantages of an SRM can be summarized as follows:

- Machine construction ***is simple and low-cost because*** of the ***absence of rotor winding*** and permanent magnets.
- There are ***no shoot-through faults between the DC buses*** in the SRM drive converter because ***each rotor winding is connected in series with converter*** switching elements.
- ***Bidirectional currents are not necessary***, which facilitates ***the reduction of the number of power switches*** in certain applications.
- The bulk of the losses appear in the stator, which is relatively ***easier to cool***.
- The torque–speed characteristics of the motor ***can be modified to the application requirement more easily*** during the design stage than in the case of induction and PM machines.
- The starting torque can be ***very high without the problem of excessive in-rush current*** due to its higher self-inductance.
- The open-circuit voltage and short-circuit current at faults ***are zero or very small***.
- The maximum permissible ***rotor temperature is higher***, since there are no permanent magnets.
- There is ***low rotor inertia and a high torque/inertia ratio***.
- Extremely ***high speeds with a wide constant power region*** are possible.
- There are independent stator phases, ***which do not prevent drive operation*** in the case of loss of one or more phases.

3.3.2 DISADVANTAGES

The SRM also comes with a few disadvantages among ***which torque ripple and acoustic noise are the most critical***. The higher torque ripple also ***causes the ripple current in the DC supply*** to be quite large, ***necessitating a large filter capacitor***. The doubly salient structure of the SRM also causes ***higher acoustic noise compared with other machines***.

The absence of permanent magnets ***imposes the burden of excitation on the stator windings and converter***, which increases the ***converter KVA requirement***. Compared with PM brushless machines, the ***per unit stator copper losses will be higher, reducing the efficiency and torque per ampere***. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRMs.

3.4 APPLICATIONS OF SRM

The simple motor structure and inexpensive power electronic requirement have made the SRM an attractive alternative to both AC and DC machines in adjustable-speed drives. Few of such applications are listed below.

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

3.5 ELEMENTARY OPERATION OF THE SWITCHED RELUCTANCE MOTOR

Consider that the rotor poles r_1 and $r_1^{'}$ and stator poles c and $c^{'}$ are aligned. Apply a current to phase *a* with the current direction as shown in Figure 3.2a. 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 $r_2^{'}$ toward the stator poles a and $a^{'}$, respectively. When they are aligned, the stator current of phase *a* is turned off and the corresponding situation is shown in Figure 3.2b. Now the stator winding *b* is excited, pulling r_1 and $r_1^{'}$ toward b and $b^{'}$ 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 energizations in sequence to move the rotor by 90^0 and one revolution of rotor movement is effected 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 is seen with the aid of Figures 3.2a and b.

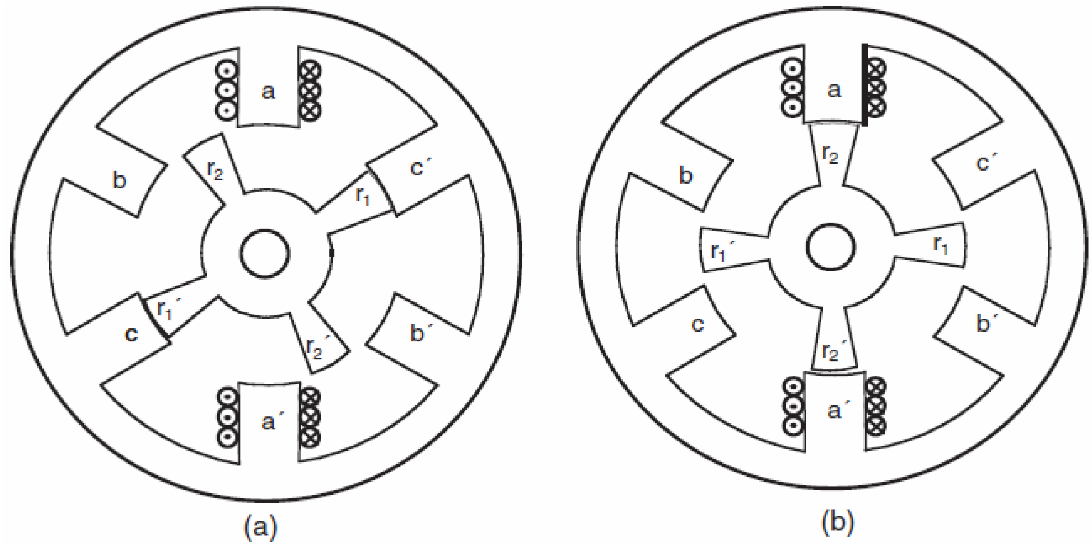


FIGURE 3.2 Operation of an SRM. (a) Phase *c* aligned. (b) Phase *a* aligned.

3.6 PRINCIPLE OF OPERATION OF THE SWTICHED RELUCTANCE MOTOR

The torque production in the switched reluctance motor is explained using the elementary principle of electromechanical energy conversion in a solenoid, as shown in Figure 3.3a. The solenoid has *N* turns, and when it is excited with a current *i* the coil sets up a flux ϕ.Increasing the excitation current will make the armature move towards the yoke, which is fixed. The flux vs. magneto motive force (mmf) is plotted for two values of air gap, x_1 and x_2, where $x_1 > x_2$ and is shown in Figure 3.3b.The flux vs. mmf characteristics for x_1 are linear because the reluctance of the air gap is dominant, making the flux smaller in the magnetic circuit. The electrical input energy is written as:

$$W_e = \int ei\,dt = \int i\,\mathrm{dt}\,\frac{\mathrm{dN}\phi}{\mathrm{dt}} = \int Ni\,d\phi = \int Fd\phi \text{............}(3.1)$$

Where *e* is the induced emf and *F* is the mmf. This input electrical energy, W_e is equal to the sum of energy stored in the coil, W_f, and energy converted into mechanical work, W_m. It is written as:

$$W_e = W_f + W_m \text{..}(3.2)$$

When no mechanical work is done, as in the case of the armature starting from position x_1, the stored field energy is equal to the input electrical energy given by equation (3.1). This corresponds to area OBEO in Figure 3.3b. The complement of the field energy, termed *co energy*, is given by area OBAO in Figure 3.3b and mathematically expressed as $\int \phi dF$ .Similarly, for the position x_2 of the armature, the field energy corresponds to area OCDO and the co energy is given by area OCAO. For incremental changes, equation (3.2) is written as:

$$\delta W_e = \delta W_f + \delta W_m \text{...}(3.3)$$

For a constant excitation of F_1 given by the operating point A in Figure 3.3b, the various energies are derived as:

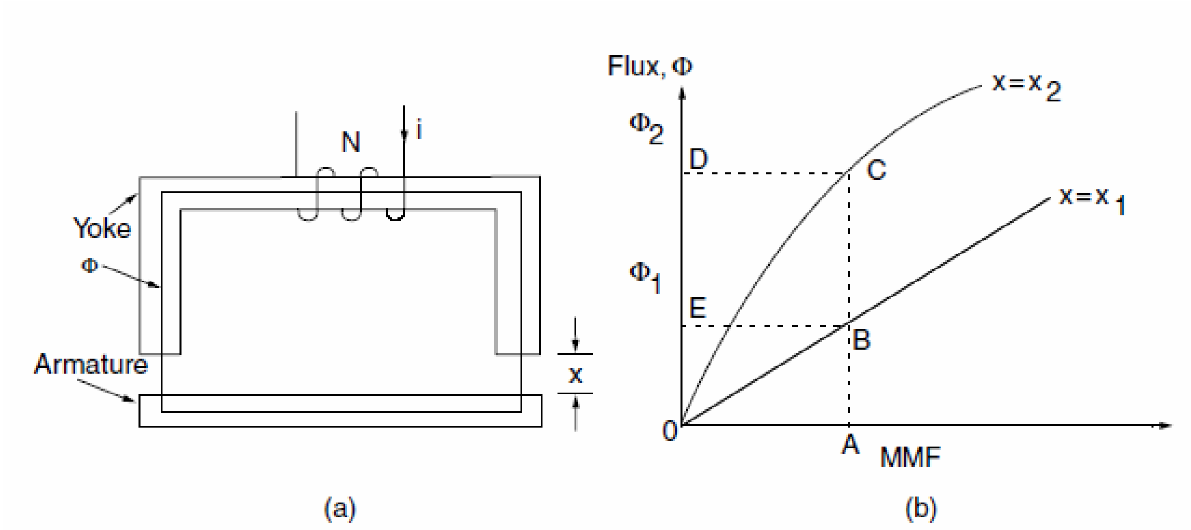


FIGURE 3.3 Solenoid and its characteristics. (a) A solenoid. (b) Flux v. mmf characteristics.

For a constant excitation of F_1 given by the operating point A in Figure 3.3b, the various energies are derived as:

$$\delta W_e = \int_{\phi_1}^{\phi_2} F_1 d\phi = F_1(\phi_2 - \phi_1) = area(BCDEB) \text{.........................}(3.4)$$

$$\delta W_f = \delta W_{f}\big|_{X=X_2} - \delta W_{f}\big|_{X=X_1} = area(OCDO) - area(OBEO) \text{......}(3.5)$$

Using Eqs. (3.3) to (3.5), the incremental mechanical energy is derived as:

$$\delta W_m = \delta W_e - \delta W_f = area(OBCO) \text{..}(3.6)$$

and that is the area between the two curves for a given magneto motive force. In the case of a rotating machine, the incremental mechanical energy in terms of the electromagnetic torque and change in rotor position is written as:

$$\delta W_m = T_e \delta\theta \text{...}(3.7)$$

Where T_e is the electromagnetic torque and $\delta\theta$ is the incremental rotor angle. Hence, the electromagnetic torque is given by:

$$T_e = \frac{\delta W_m}{\delta\theta} \text{..}(3.8)$$

For the case of constant excitation (i.e., when the mmf is constant), the incremental mechanical work done is equal to the rate of change of co energy, $W_f^{'}$ which is nothing but the complement of the field energy. Hence, the incremental mechanical work done is written as:

$$\delta W_m = \delta W_f^{'} \text{...}(3.9)$$

Where

$$W_f' = \int \phi dF = \int \phi d(Ni) = \int (N\phi) di = \int \lambda(\theta, i) di = \int L(\theta, i) i di \qquad (3.10)$$

Where the inductance, L, and flux linkages, λ, are functions of the rotor position and current. This change in co energy occurs between two rotor positions, θ_2 and θ_1. Hence, the air gap torque in terms of the co energy represented as a function of rotor position and current is

$$T_e = \frac{\delta W_m}{\delta \theta} = \frac{\delta W_f'}{\delta \theta} = \left.\frac{\delta W_f'(i, \theta)}{\delta \theta}\right|_{i=\text{constant}} \qquad (3.11)$$

If the inductance is linearly varying with rotor position for a given current, which in general is not the case in practice, then the torque can be derived as:

$$T_e = \frac{dL(\theta, i)}{d\theta} \cdot \frac{i^2}{2} \qquad (3.12)$$

Where

$$\frac{dL(\theta, i)}{d\theta} = \left.\frac{L(\theta_2, i) - L(\theta_1, i)}{\theta_2 - \theta_1}\right|_{i=\text{constant}} \qquad (3.13)$$

and this differential inductance can be considered to be the torque constant expressed in N. m/A^2. It is important to emphasize at this juncture that this is not a constant and that it varies continuously. This has the implication that the switched reluctance motor will not have a steady-state equivalent circuit in the sense that the dc and ac motors have.

The following are the implications of equation (3.12)

1. The torque is ***proportional to the square of the current***; hence the current can be ***unipolar to produce unidirectional torque***. Note that this is quite contrary to the case for ac machines. This unipolar current requirement has a distinct advantage in that only ***one power switch is required for control of current in a phase winding***. Such a feature greatly reduces the number of power switches in the converter and thereby makes the drive economical.
2. The torque constant is given by the slope of the ***inductance vs. rotor position*** characteristic. It is understood that the inductance of a stator winding is a function of both the rotor position and current, thus making it nonlinear. Because of its nonlinear nature, ***a simple equivalent circuit development for this motor is not possible.***
3. Since the torque is proportional to the square of the current, this machine resembles a dc series motor; hence, ***it has a good starting torque***.
4. A ***generating action*** is made possible with unipolar current due to its operation on ***the negative slope of the inductance profile***.

5. The direction of rotation can be ***reversed by changing the sequence of stator excitation***, which is a simple operation.

3.7 COMPARISION BETWEEN SRM AND STEPPER MOTORS

From the above description, it is deduced that the switched reluctance motor is similar to the step motor except that it has

1. Fewer poles
2. Larger stepping angle
3. Usually one tooth per pole
4. Higher power output capability
5. The SRM motor is normally operated with shaft position feed back to synchronize the commutation of the phase currents with precise rotor positions, where as stepper motor is normally run in open loop, i.e with out shaft position feed back.
6. SRM is normally designed for efficient conversion of significant amounts of power, stepper motors are more usually designed to maintain step integrity in position controls.

The comparison should not be carried too much further due to the nonlinearity of the magnetic circuit.

3.8 DERIVATION OF THE RELATIONSHIP BETWEEN INDUCTANCE AND ROTOR POSITION-*NON LINEAR ANALYSIS*

Since the torque characteristics are dependent on the relationship between flux linkages and rotor position as a function of current, it is worthwhile to conceptualize the control possibilities and limitations of this motor drive. For example, a typical phase inductance vs. rotor position is shown in Figure 3.4 for a fixed phase current. The inductance corresponds to that of a stator-phase coil of the switched reluctance motor neglecting the fringe effect and saturation. The significant inductance profile changes are determined in terms of the stator and rotor pole arcs and number of rotor poles. The rotor pole arc is assumed to be greater than the stator pole arc for this illustration, which is usually the case. From Figures 3.4a and b, the various angles are derived as:

$$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{P_r} - (\beta_s + \beta_r)\right] \quad \text{(3.14}a\text{)}$$

$$\theta_2 = \theta_1 + \beta_s \quad \text{(3.14}b\text{)}$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s) \quad \text{(3.14}c\text{)}$$

$$\theta_4 = \theta_3 + \beta_s \quad \text{(3.14}d\text{)}$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r} \quad \text{(3.14}e\text{)}$$

Where β_s and β_r are stator and rotor pole arcs, respectively, and P_r is the number of rotor poles.

Four distinct inductance regions emerge:

1. $0 - \theta_1$ and $\theta_4 - \theta_5$: The stator and rotor poles are not overlapping in this region and the flux is predominantly determined by the air path, thus making the inductance minimum and almost a constant. Hence, these regions do not contribute to torque production. The inductance in this region is known as unaligned inductance, L_u.

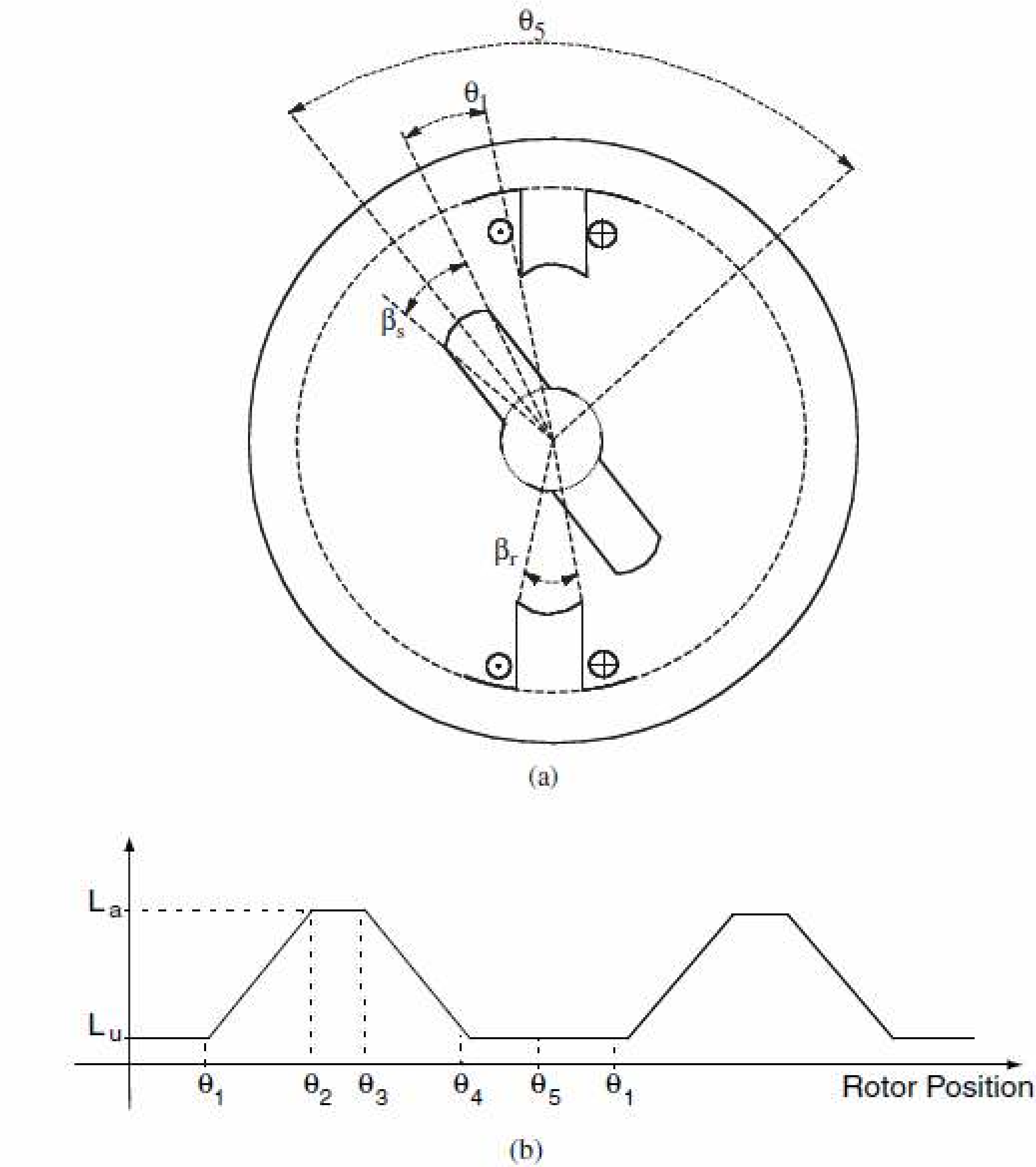


FIGURE 3.4 Derivation of inductance vs. rotor position from rotor and stator pole arcs for an unsaturated switched reluctance machine. (a) Basic rotor position definition in a two pole SRM. (b) Inductance profile.

2. $\theta_1 - \theta_2$: Poles overlap, so the flux path is mainly through stator and rotor laminations. This increases the inductance with the rotor position, giving it a positive slope. A current impressed in the winding during this region produces a positive (i.e., motoring) torque. This region comes to an end when the overlap of poles is complete.
3. $\theta_2 - \theta_3$: During this period, movement of rotor pole does not alter the complete overlap of the stator pole and does not change the dominant flux path. This has the

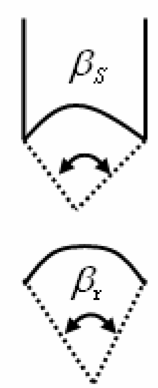
effect of keeping the inductance maximum and constant, and this inductance is known as aligned inductance, L_a. As there is no change in the inductance in this region, torque generation is zero even when a current is present in this interval. In spite of this fact, it serves a useful function by providing time for the stator current to come to zero or lower levels when it is commutated, thus preventing negative torque generation for part of the time if the current has been decaying in the negative slope region of the inductance.

4. $\theta_3 - \theta_4$: The rotor pole is moving away from overlapping the stator pole in this region. This is very much similar to the $\theta 1 - \theta 2$ region, but it has decreasing inductance and increasing rotor position contributing to a negative slope of the inductance region. The operation of the machine in this region results in negative torque (i.e., generation of electrical energy from mechanical input to the switched reluctance machine).

It is not possible to achieve the ideal inductance profiles shown in Figure 3.4 in an actual motor due to saturation. Saturation causes the inductance profile to curve near the top and thus reduces the torque constant. Hence, saturating the machine beyond a point produces a diminishing return on torque and power output.

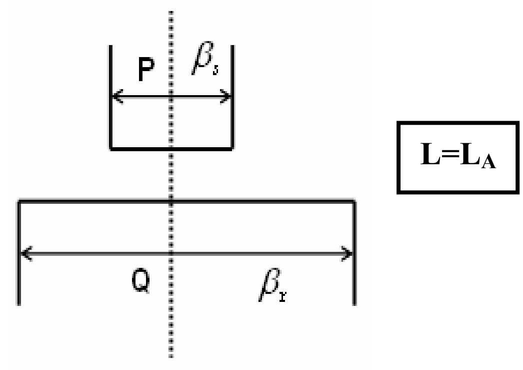
DETAILED DERIVATION

Let L_A be the aligned inductance of a coil/Phase and L_U be the unaligned inductance of the coil / phase. β_s and β_r are stator and rotor pole arcs, respectively. Let us assume that $\beta_r > \beta_s$ and $L_A > L_U$.



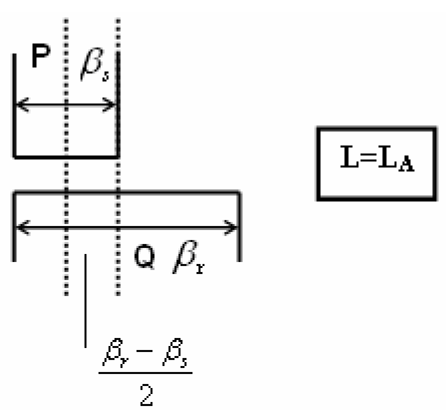
Case 1: When θ=0^0

Axis of the stator pole is in alignment with the stator pole as shown in the figure below. Therefore the inductance of the coil is L_A, because the stator reference axis and rotor reference axis are in alignment. At this position flux linkage of phase winding of stator has maximum value and hence inductance of phase winding has maximum value for given current.



<u>CASE II: When</u> $\theta = \frac{\beta_r - \beta_s}{2}$

The rotor reference axis makes angular displacement of $\frac{\beta_r - \beta_s}{2}$ stator reference axis one edge of rotor pole is along the edge of stator pole. At this position reluctance is minimum. Then the inductance of the coil continues to be L_A. When θ varies from 0 to $\frac{\beta_r - \beta_s}{2}$**.** At this position also $\mathbf{L=L_A}$.



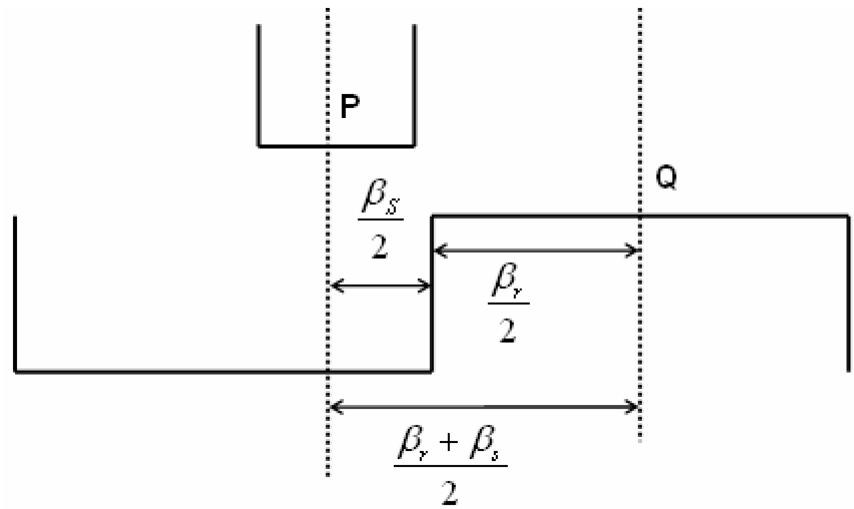
<u>CASE III: WHEN</u> $\theta = \frac{\beta_r + \beta_s}{2}$

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

Half the pole pitch of the rotor = $\frac{\pi}{N_r}$ Assume $\theta = \frac{\beta_r + \beta_s}{2} < \frac{\pi}{N_r}$

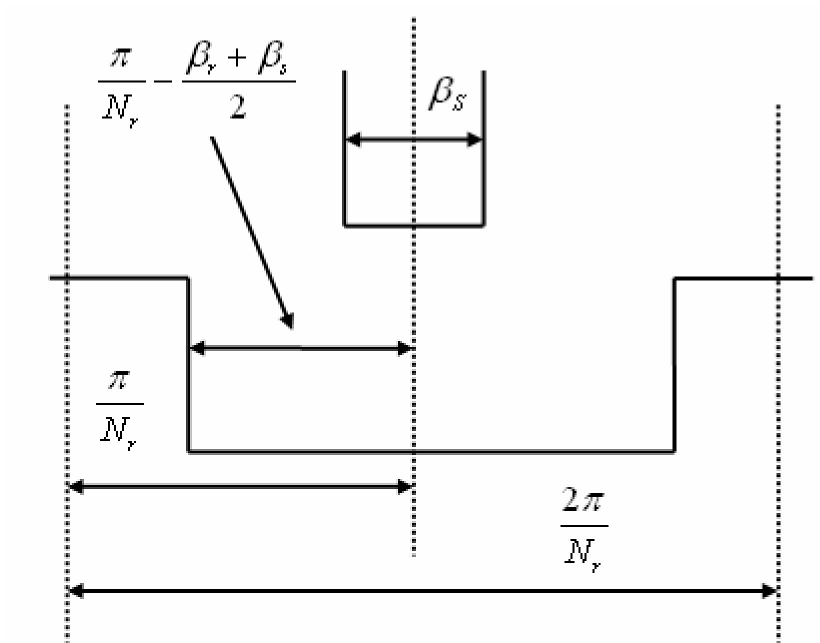
In this position, the flux pattern is such that the flux linkages / unit current of the stator is less than the previous case but not minimum. Therefore $L < L_A$ and $L > L_U$.

$\mathbf{L_U < L < L_A}$ At $\frac{\beta_r - \beta_s}{2} < \theta < \frac{\beta_r + \beta_s}{2}$

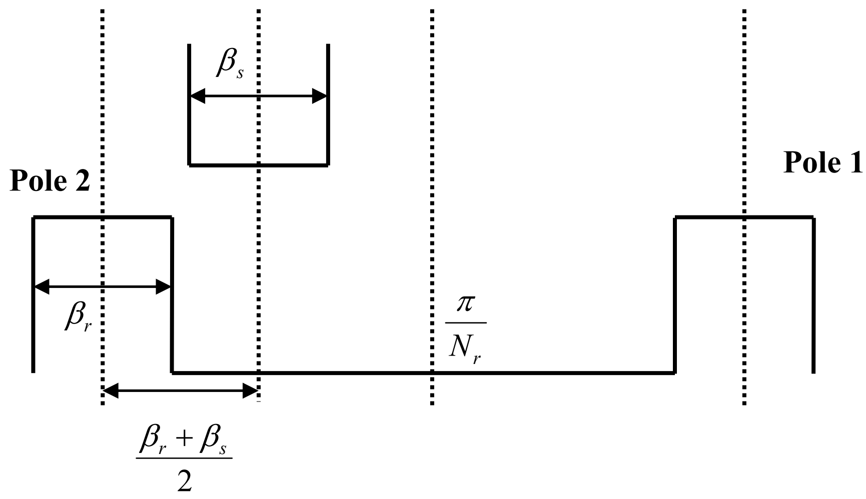


CASE IV: WHEN $\theta = \frac{\pi}{N_r}$

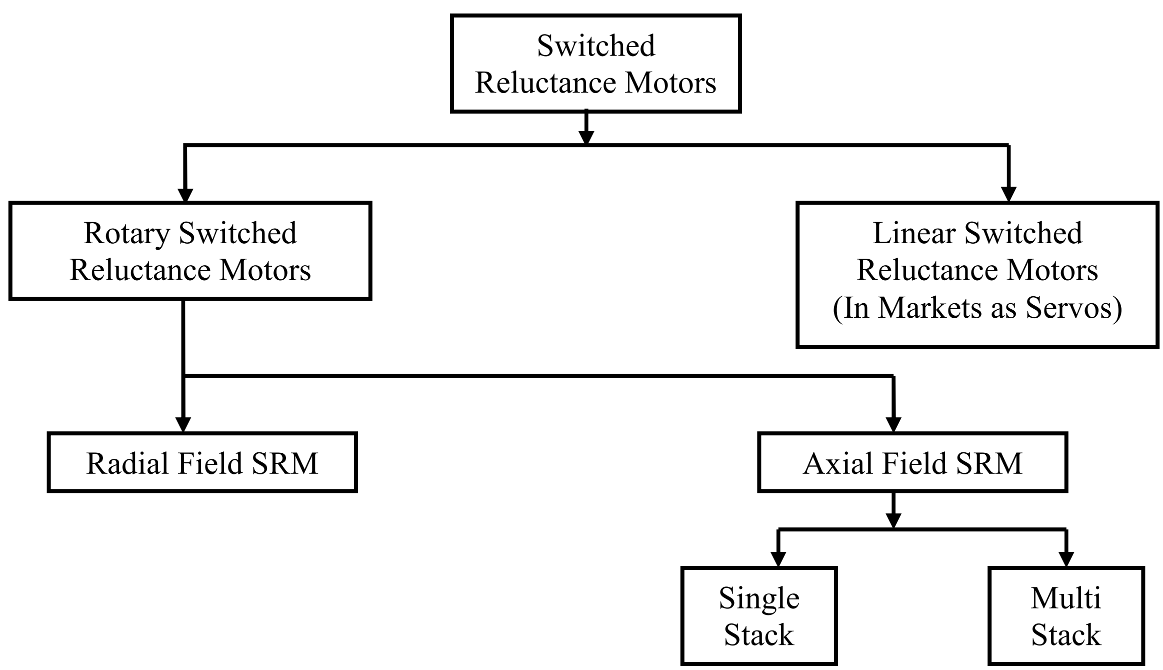
For $\frac{\beta_r+\beta_s}{2} \le \theta \le \frac{\pi}{N_r}$ **$L=L_U$**



CASE V: WHEN $\theta = \frac{\beta_r+\beta_s}{2}$ after $\frac{\pi}{N_r}$ **(or)** $\theta = \frac{2\pi}{N_r} - \frac{\beta_r+\beta_s}{2}$ as far as the rotor pole is considered. After which stator pole comes under the influence of the rotor pole 2. Now the inductance variation is from L_U to L_A as the rotor pole moves towards so as to cover the stator pole.



3.9 TYPES OF SRM



3.10 CONVERTERS FOR SRM DRIVES

Since the torque in SRM drives is independent of the excitation current polarity, the SRM drives require only one switch per phase winding. This is contrary to the ac motor drives where at least two switches per phase are required for current control. Moreover, the windings are not in series with the switches in ac motor drives, leading to irreparable damage in shoot-through faults. The SRM drives always have a phase winding in series with a switch.

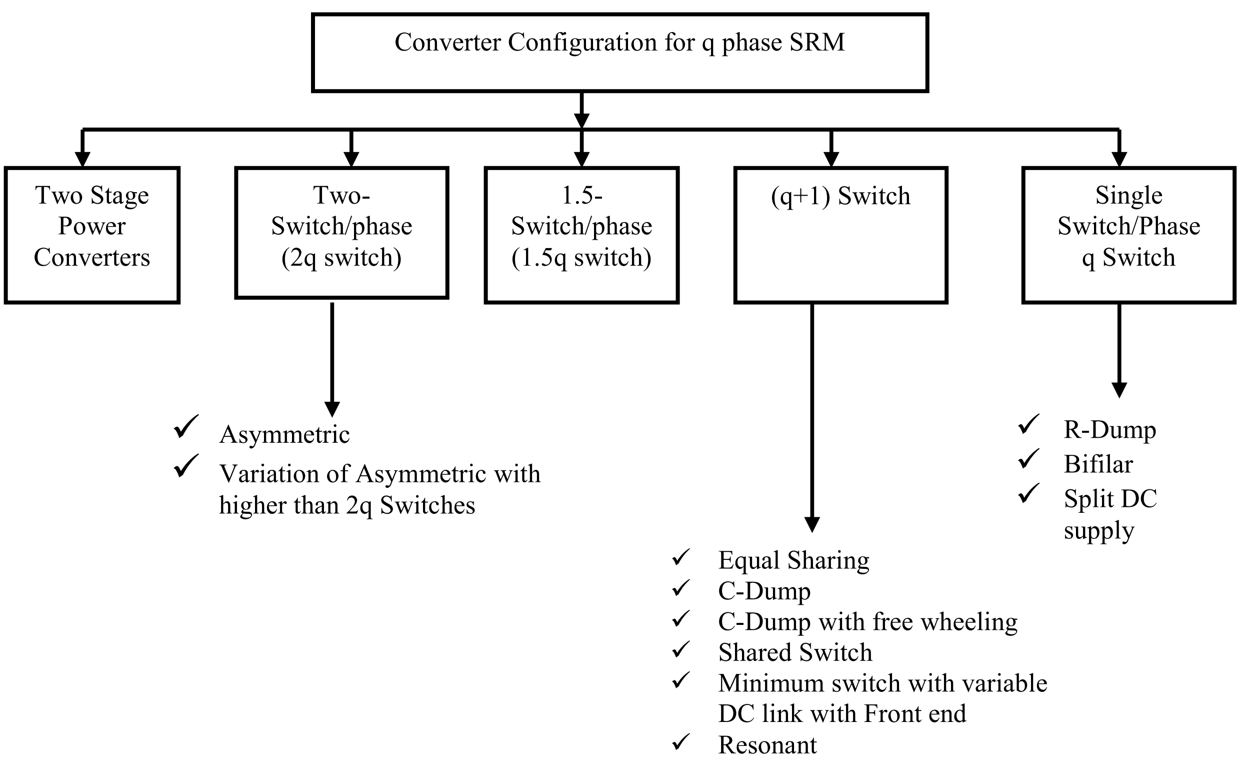
In case of a shoot-through fault, the inductance of the winding limits the rate of rise in current and provides time to initiate protective relaying to isolate the faults. The phases of the

SRM are independent and, in case of one winding failure, uninterrupted operation of the motor drive operation is possible, although with reduced power output.

3.10.1 CONVERTER CONFIGURATIONS

The mutual coupling between phases is negligible in SRMs. This gives complete independence to each phase winding for control and torque generation. While this feature is advantageous, a lack of mutual coupling requires a careful handling of the stored magnetic field energy. The magnetic field energy has to be provided with a path during commutation of a phase; otherwise, it will result in excessive voltage across the windings and hence on the power semiconductor switches leading to their failure. The manner in which this energy is handled gives way to unique but numerous converter topologies for SRM drives. The energy could be freewheeled, partially converting it to mechanical/electrical energy and partially dissipating it in the machine windings. Another option is to return it to the dc source either by electronic or electromagnetic means. All of these options have given way to power converter topologies with q, $(q+1)$, $1.5q$, and $2q$ switch topologies, where q is the number of machine phases.

3.10.1.1 Classification of Converter Configurations



3.10.2 ASYMMETRIC BRIDGE CONVERTER

Figure 3.5a shows the asymmetric bridge converter considering only one phase of the SRM. The rest of the phases are similarly connected. Turning on transistors T_1 and T_2 will circulate a current in phase A of the SRM. If the current rises above the commanded value, T_1 and T_2

are turned off. The energy stored in the motor winding of phase *A* will keep the current in the same direction until it is depleted. Hence, diodes D_1 and D_2 will become forward biased leading to recharging of the source. That will decrease the current, rapidly bringing it below the commanded value. This operation is explained with the waveforms of Figure 3.5b. Assuming that a current of magnitude Ip is desired during the positive inductance slope for motoring action, the *A* -phase current command is generated with a linear inductance profile. Here, phase advancing both at the beginning and during commutation are neglected. The current command i_a^* is enforced with a current feedback loop where it is compared with the phase current, i_a. The current error is presumed to be processed through a hysteresis controller with a current window of Δi. When the current error exceeds $-\Delta i$, the switches T_1 and T_2 are turned off simultaneously. Hysteresis current controller is considered here due to its simplicity in concept and implementation. At that time, diodes, D_1 and D_2 take over the current and complete the path through the dc source.

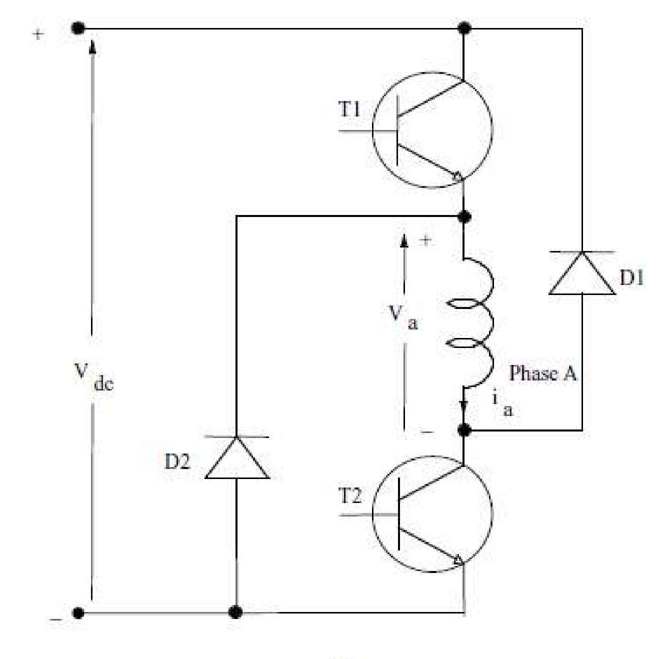


FIGURE 3.5 (a) Asymmetric converter for SRM with freewheeling and regeneration capability.

Note that the voltage of phase *A* is then negative and will equal the source voltage, *Vdc*. During this interval, the energy stored in the machine inductance is sent to the source, thus exchanging energy between the load and source repeatedly in one cycle of a phase current. After the initial startup, during turn-on and turn-off of T_1 and T_2, the machine phase winding experiences twice the rate of change of dc link voltage, resulting in a higher deterioration of the insulation. This control strategy (strategy I) hence puts more ripples into the dc link capacitor, thus reducing its life and also increasing the switching losses of the power switches due to frequent switching necessitated by energy exchange. These can be ameliorated with an alternate switching strategy.

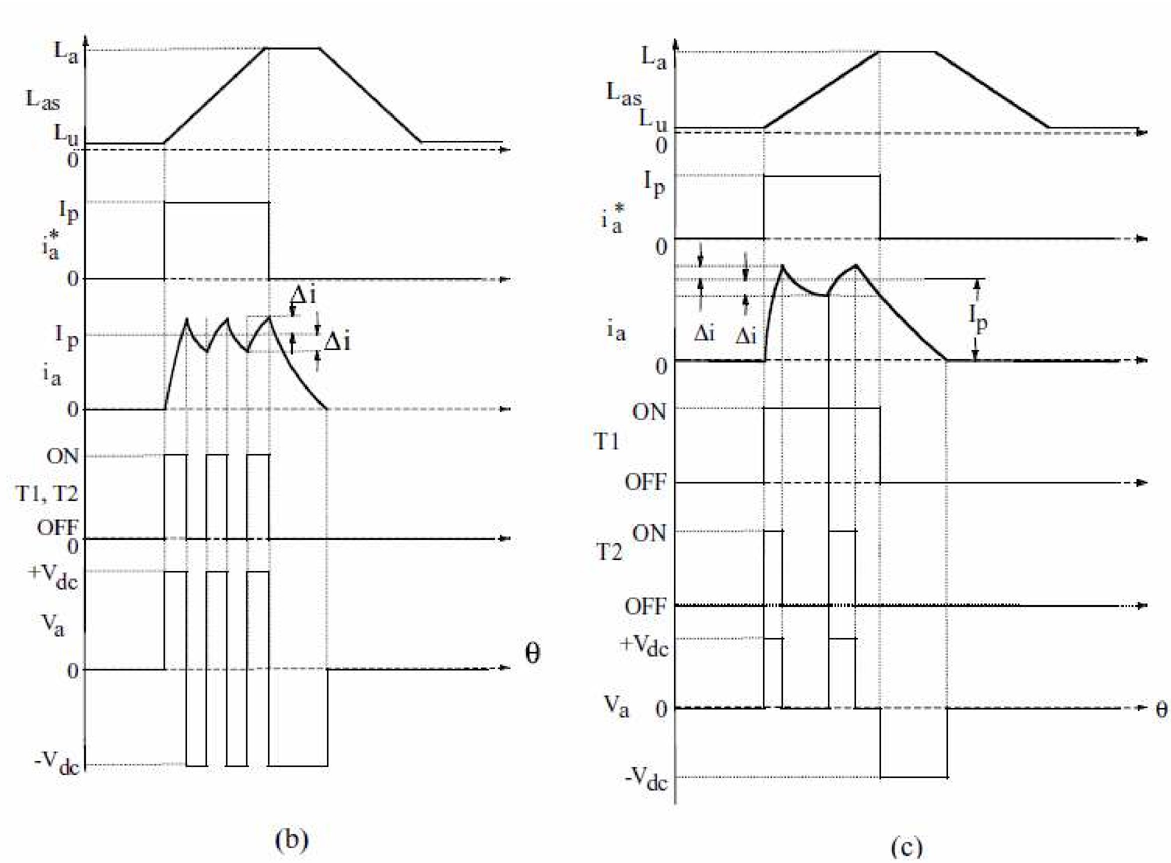


FIGURE 3.5 (b) Operational waveforms of the asymmetric bridge converter (strategy I); (c) Operational waveforms of the asymmetric bridge converter (strategy II).

The energy stored in the phase *A* can be effectively circulated in itself by turning off, say, T_2 only (strategy II). In that case, the current will continue to flow through T_1, phase *A*, and D_1, the latter having forward biased soon after T_2 is turned off. The voltage across the winding becomes zero if the diode and transistor voltage drops are neglected as shown in Figure 4.2c. That will take the phase current from $Ip + \Delta I$ to $Ip - \Delta i$ in a time greater than had it been forced against the source voltage using the previous strategy. This particular fact reduces the switching frequency and hence the switching losses. When the current command goes to zero, both T_1 and T_2 are turned off simultaneously. During this interval, the voltage across the winding is $-V_{dc}$ as long as D_1 and D_2 conduct (i.e., until i_a goes to zero) and thereafter the winding voltage is zero. The voltage across T_2 during its off time and when T_1 is on is equal to the source voltage, V_{dc}. Hence, the power switches and diodes have to be rated to a minimum of source voltage at least. The current ratings of the switches are equal to or less than $I_p/\sqrt{q}$ by interchanging the off times between *T*1 and *T*2 in one cycle of phase conduction. Similarly, the current rating of the diodes can be evaluated. While such a self-circulation will keep the current going for a longer time compared to recharging the source voltage, it has the advantage of converting the stored energy to useful mechanical work.

While this form of control can be used for current control, the recharging of the source is advantageous when the current has to be turned off rapidly. Such an instance arises when the inductance profile becomes flat or is starting to have a negative slope. Any further conduction of current in such regions entails a loss of energy or production of negative torque, thus reducing the average motoring torque. Note that this converter requires two transistors and two diodes for each phase, resembling the conventional ac motor drives.

3.10.3 SINGLE-SWITCH-PER-PHASE CONVERTERS

Single-switch-per-phase converters are appealing due to their compactness of converter package and hence a possible reduction in their cost compared to other converters. They also have the disadvantage of being unable to apply zero voltage across the machine phase during current conduction. Such an operational constraint increases the circulation of energy between the machine and dc link, resulting in higher losses and reduced system efficiency

3.10.3.1 R-DUMP

Figure 3.6 shows a converter configuration with one transistor and one diode per phase of the SRM. When T_1 is turned off, the current freewheels through D_1, charging C_s, and later flows through the external resistor R. This resistor partially dissipates the energy stored in phase A. This has the disadvantage that the current in phase A will take longer to extinguish compared to recharging the source. The energy, in addition, is dissipated in a resistor, thus reducing the overall efficiency of the motor drive.

Figure 3.6b shows the timing waveforms of the circuit in detail. The hysteresis current controller turns off T_1 when the phase current exceeds the current command, by Δi. Turning off T_1 will reduce the current, which in turn induces an emf in the winding to sustain i_a in the same direction. This emf forward biases diode D_1. The voltage across the resistor R is $i_a R$. Note that the voltage across the resistor has a positive polarity with respect to the positive rail of the source voltage. The voltage across T_1 during off time is then the sum of the source voltage and the voltage drop across the resistor is expressed as:

$$V_{T1} = V_{dc} + i_a R \qquad (3.15)$$

Design considerations such as the turn-off transient voltage have to be included in the rating of the switch T_1. The selection of R not only determines the power dissipation but also the switch voltage. A lower value of R increases the fall time of the current. If the current comes under the negative slope region of the phase inductance, negative torque will be generated, decreasing the average motoring torque. A high value of R increases the voltage drop across the winding and hence across T_1.

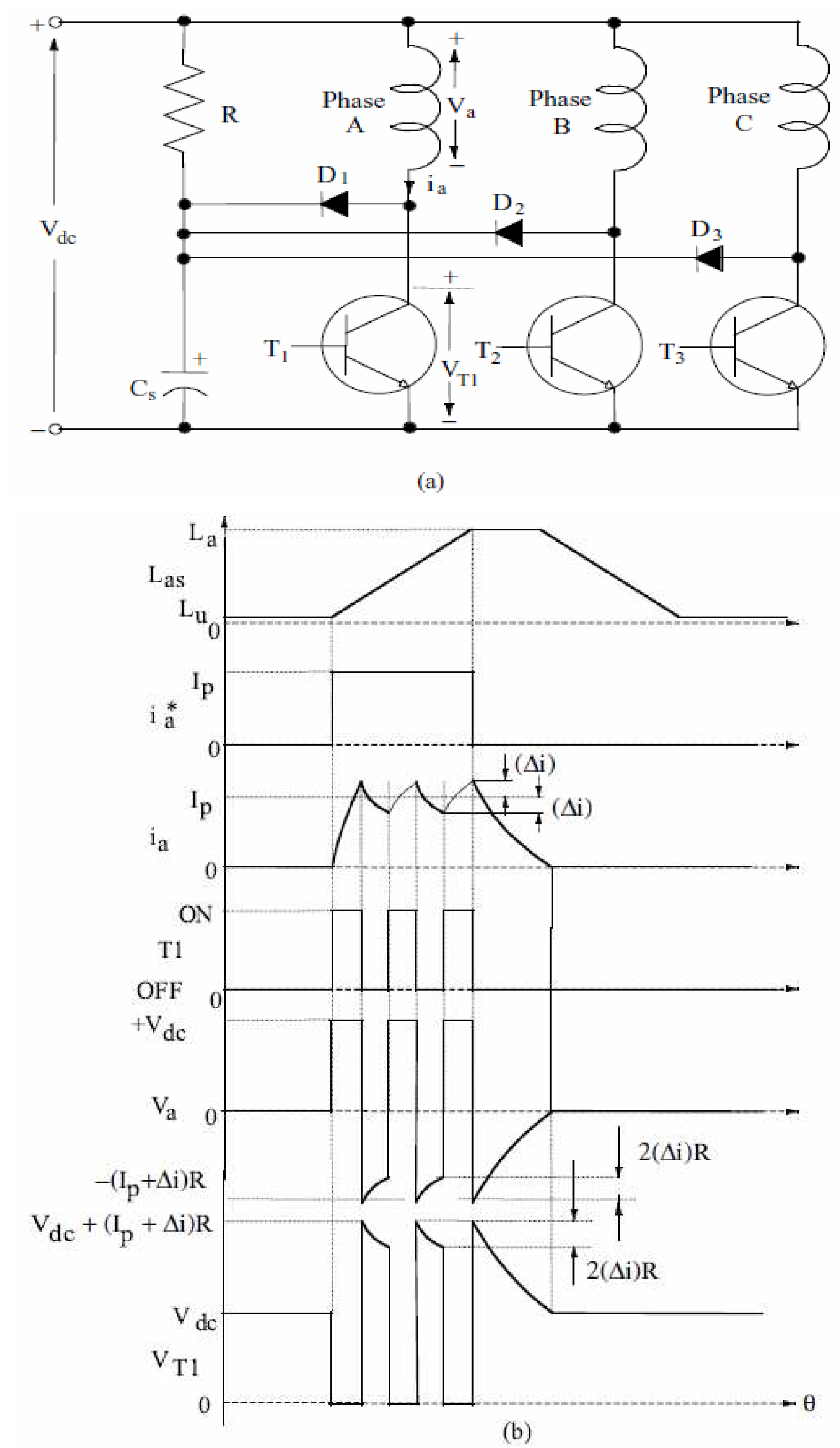


FIGURE 3.6 (a) Converter for SRM with freewheeling path; (b) operational waveforms of R-dump converter

3.10.3.2 BIFILAR TYPE

Figure 3.7a shows a converter configuration with one transistor and one diode per phase but regenerating the stored magnetic energy to the source. This is achieved by having a bifilar winding with the polarity as shown in the figure. When the phase-*A* current is turned off by removing the base drive signal to T_1, the induced emf in the winding is of such polarity that

D_1 is forward biased. This leads to the circulation of current through D_1, the bifilar secondary winding, and the source, thus transferring energy from the machine winding to the source.

The various timing waveforms of the circuit are shown in Figure 3.7b. During current turn-off, the applied voltage across the bifilar secondary winding is equal to the dc link voltage. The voltage reflected into the main winding is dependent upon the turns ratio of the windings. Considering the turns ratio between the main winding in series with the power switch and the auxiliary winding in series with the diode as *a*, the voltage across the power switch is

$$V_{T1} = V_{dc} + aV_{dc} = (1 + a)V_{dc} \quad (3.16)$$

This shows that the voltage across T_1 can be very much greater than the source voltage. One switch per phase comes with a voltage penalty on the switch. The volt ampere (VA) capability of the switch will not be very different for one switch compared to two switches per phase circuit. The disadvantage of this drive is that the SRM needs a bifilar winding and such a form of winding is not economical for large motors. Also, the bifilar windings require additional slot volume, reducing the power density of the SRM.

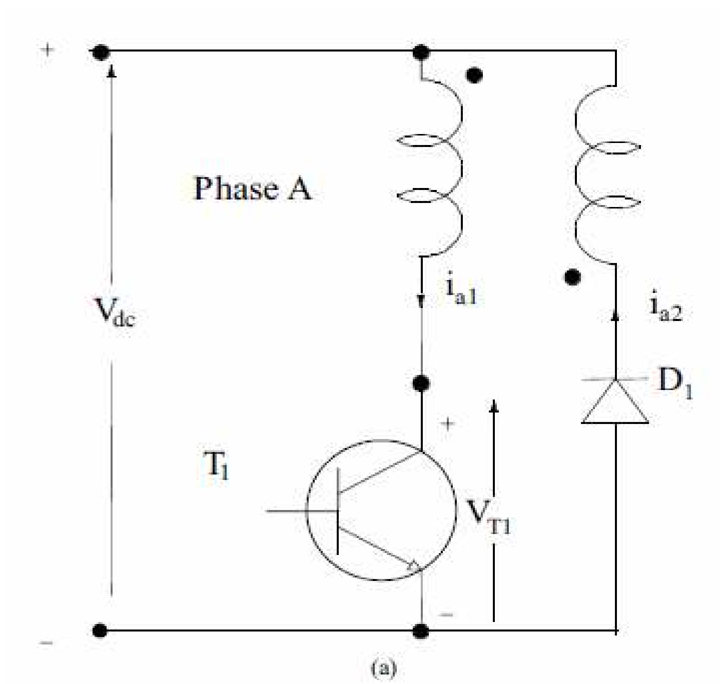


FIGURE 3.7 (a) Converter for an SRM with bifilar windings

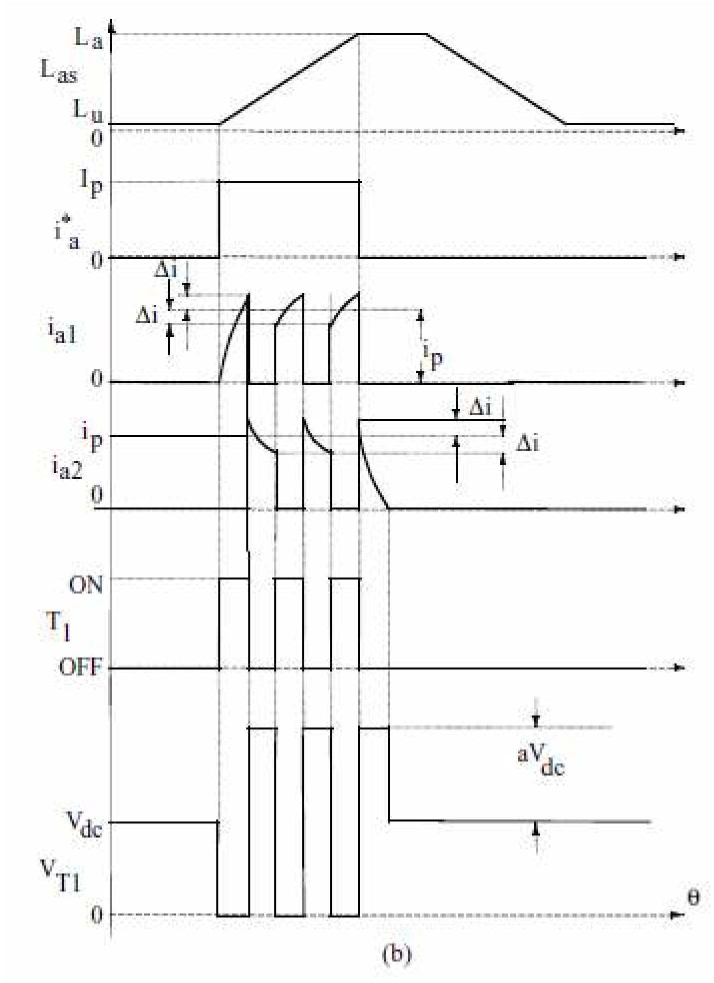


FIGURE 3.7 (b) operational waveforms of bifilar converter.

3.10.3.3 SPLIT DC SUPPLY CONVERTER

A split dc supply for each phase allows freewheeling and regeneration, as shown in Figure 3.8a. This topology preserves one switch per phase; its operation is as follows. Phase *A* is energized by turning on T_1. The current circulates through T_1, phase *A*, and capacitor C_1. When T_1 is turned off, the current will continue to flow through phase *A*, capacitor C_2, and diode D_2. In that process, C_2 is being charged up and hence the stored energy in phase *A* is depleted quickly. Similar operation follows for phase *B*. The operation of this circuit for phase *A* is shown in Figure 3.8b. A hysteresis current controller with a window of Δi is assumed. The phase voltage is V_{dc} /2 when *T*1 is on, and when it is turned off with a current established in phase *A*, the phase voltage is $-V_{dc}/2$. The voltage across the transistor T_1 during the on time is negligible, and it is V_{dc} when the current is turned off. That makes the switch voltage rating at least equal to the dc link voltage. As the stator current reference, goes to zero, the switch T_1 is turned off regardless of the magnitude of i_a. When the winding current becomes zero, the voltage across T_1 drops to 0.5 V_{dc} and so also does the voltage across D_2. Note that this converter configuration has the disadvantage of derating the supply dc voltage,

V_{dc}, by utilizing only half its value at any time. Moreover, care has to be exercised in balancing the charge of C_1 and C_2 by proper design measures.

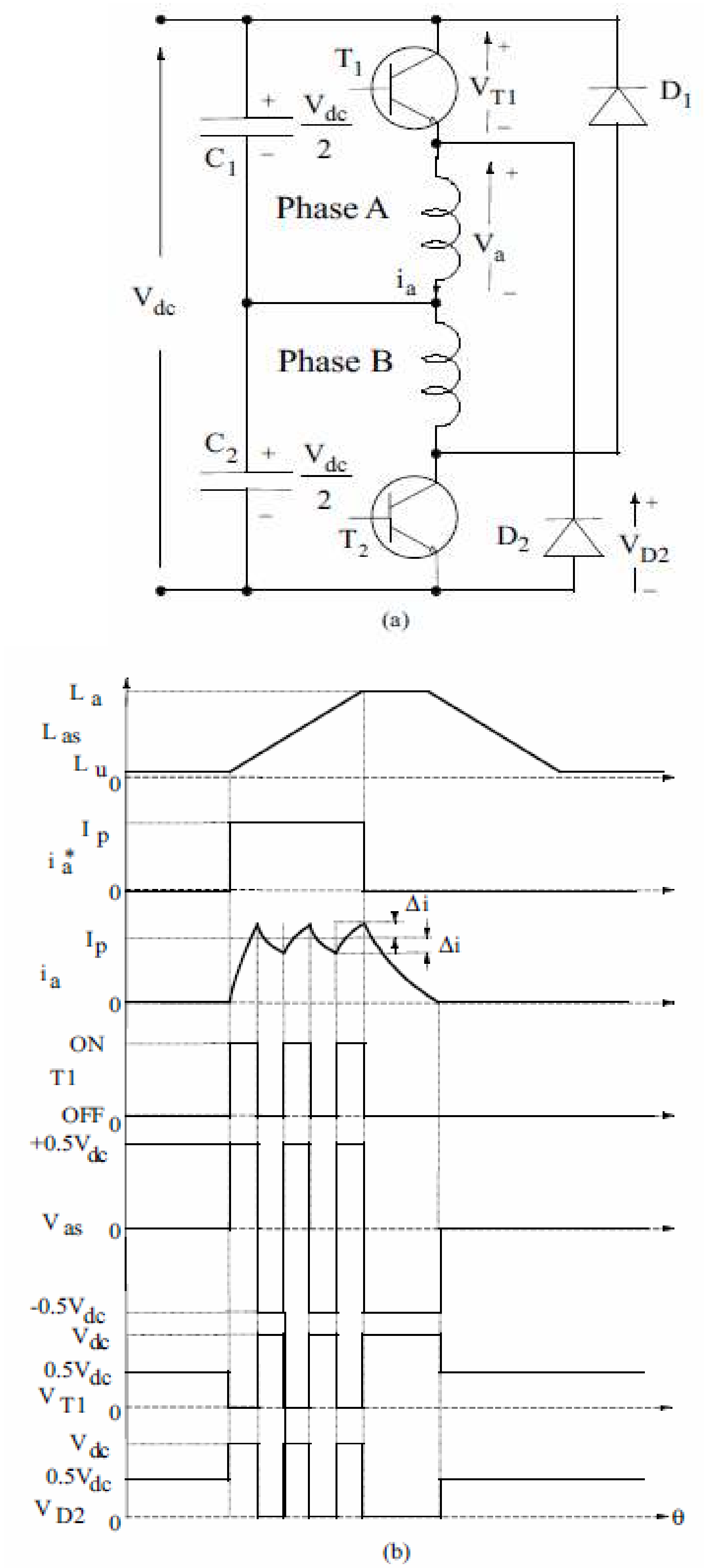


FIGURE 3.8 (a) Converter for SRM with split dc supply; (b) Operational waveforms of split dc supply converter.

For balancing the charge across the dc link capacitors, the number of machine phases has to be even and not odd. In order to improve the cost-competitive edge of the SRM drive, this converter was chosen in earlier integral horse power (hp) product developments, but its use in fractional hp SRM drives supplied by a single phase 120-V ac supply is much more justifiable; the neutral of the ac supply is tied to the midpoint of the dc link and so capacitors can be rated to 200 V dc, thus minimizing the cost of the converter.

3.10.4 (q + 1) SWITCH AND DIODE CONFIGURATIONS

3.10.4.1 C-DUMP CONVERTER

The C-dump converter is shown in figure 3.9 with an energy recovery circuit. The stored magnetic energy is partially diverted to the capacitor C_d and recovered from it by the single quadrant chopper comprising of T_r, L_r, and D_r and sent to the dc source. Assume that T_1 is turned on to energize phase A and when the A-phase current exceeds the reference, T_1 is turned off. This enables the diode D_1 to be forward biased, and the current path is closed through C_d which increases the voltage across it. This has the effect of reducing the A-phase current, and, when the current falls below the reference by Δi (i.e., current window), T_1 is turned on to maintain the current close to its reference. When current has to be turned off completely in phase A, T_1 is turned off, and partially stored magnetic energy in phase A is transferred to energy dump capacitor, C_d. The remaining magnetic energy in the machine phase has been converted to mechanical energy. Figure 3.9(b) shows the variables of interest in this converter.

This converter has the advantage of minimum switches allowing independent phase current control. The main disadvantage of this circuit is that the current commutation is limited by the difference between voltage across C_d, v_o, and the dc link voltage. Speedy commutation of currents requires larger v_o, which results in increasing the voltage rating of the power devices. Further, the energy circulating between C_d and the dc link results in additional losses in the machine, T_r, L_r, and D_r, there by decreasing the efficiency of the motor drive.

The energy recovery circuit is activated only when T_1, *T2, T3 orT4* switches are conducting to avoid freewheeling of the phase currents. The control pulses to T_r end with the turn-off of the phase switches. The control pulse is generated based on the reference and actual value of E with a window of hysteresis to minimize the switching of T_r.

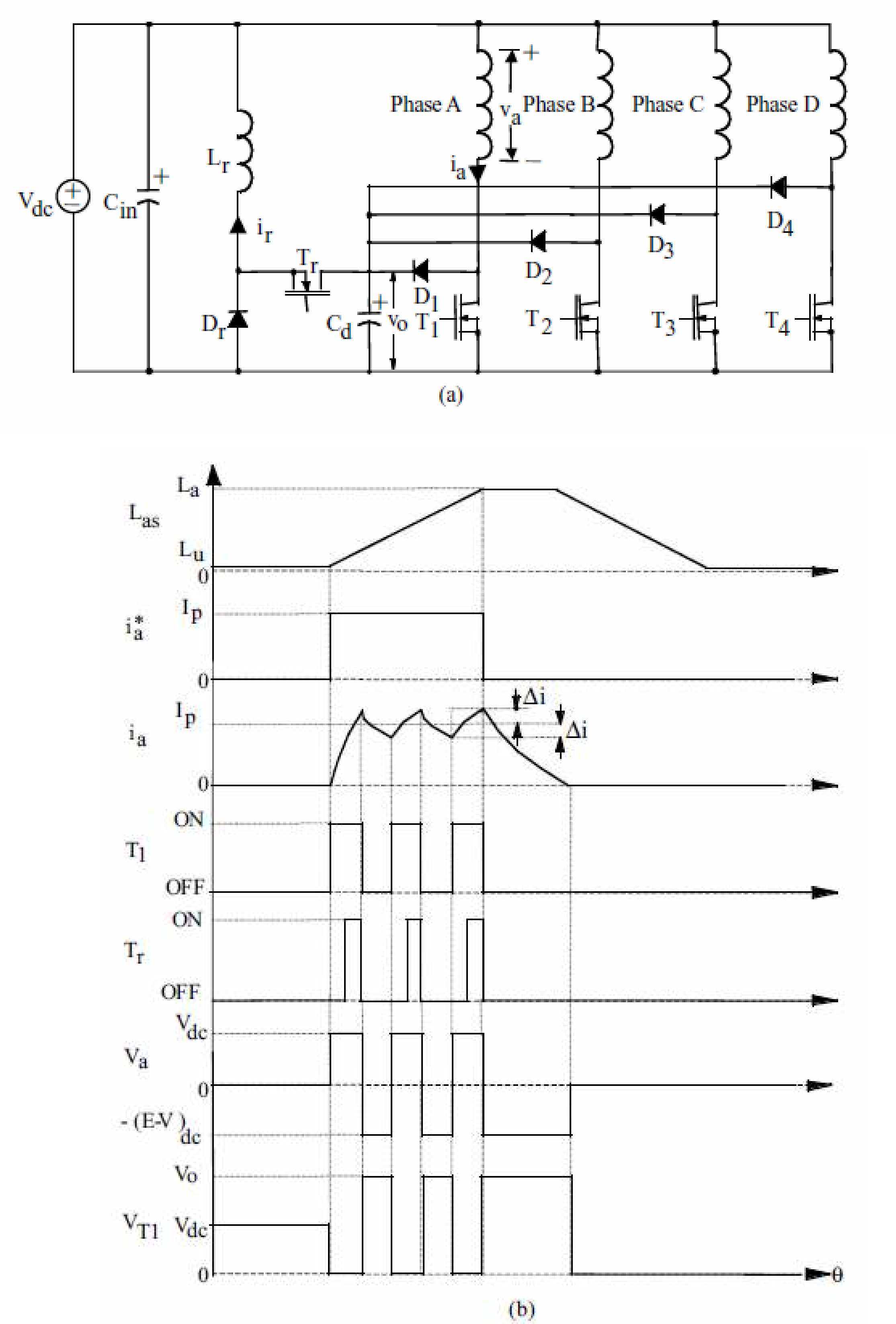


FIGURE 3.9 (a) C-dump converter with energy recovery circuit;
(b) Waveforms of C-dump converter with energy-recovery circuit.

3.11 MICROPROCESSOR BASED CONTROL OF SRM

This section describes a general purpose microprocessor controlled closed loop-switched reluctance motor (SRM) drive system. The system is designed to drive a four phase SRM with minimum number of switches, while achieving maximum flexibility. This section also describes the hardware for driving the motor, the techniques used to measure control parameters and how they are fed to the microprocessor. The operation of the microprocessor software to provide the user interface and control on the operation is given in detail.

The main objective of this microprocessor based control of SRM is to develop Software controllability of various modes of operation; here a microprocessor based control philosophy is adopted to achieve flexibility of adapting the controller-driver for various applications.

3.11.1 System Concept

Figure 3-10 shows the principal block diagram of the system concept for the switched reluctance motor.

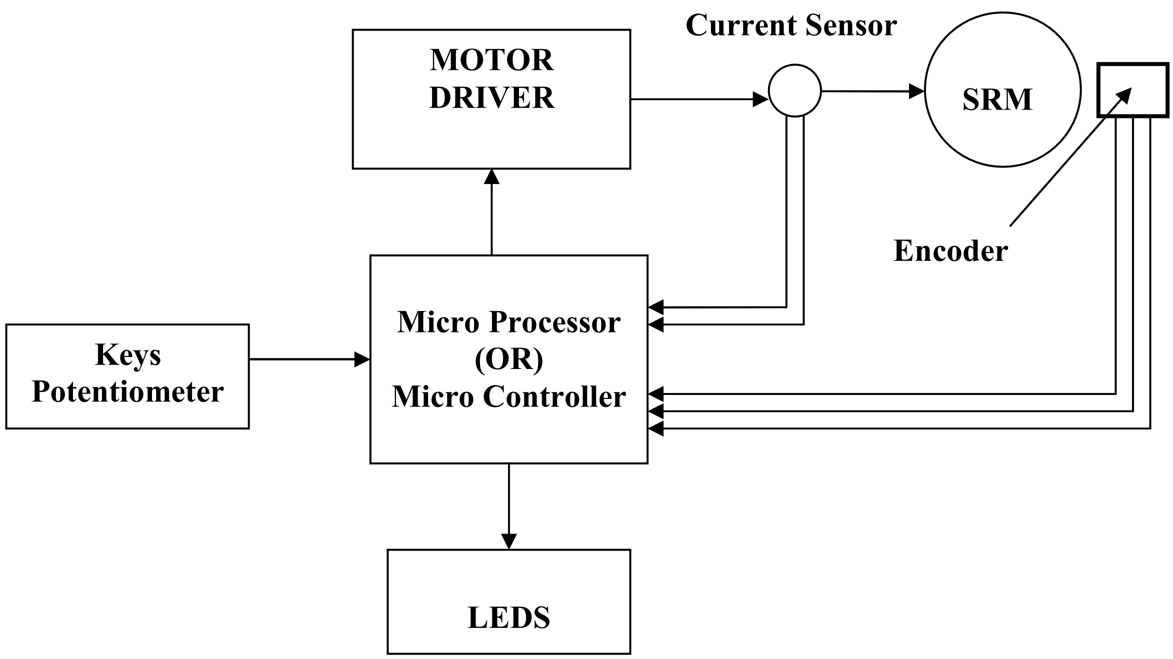


Figure 3.10 Principle Block Diagram of Microprocessor based SRM

This system can be designed to drive a SR motor. The application should meet the following performance specifications:

- ✓ Speed control of SR motor with encoder position sensor
- ✓ Variable line voltage up to rated 42V DC
- ✓ Control techniques incorporates
  - ❖ Voltage SRM control with speed closed loop.
  - ❖ Motor starts from any position with rotor alignment.
  - ❖ Two directions of rotation.
  - ❖ Motoring mode.
  - ❖ Minimal speed 600 rpm (can be set by user).
  - ❖ Maximal speed depended 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.

3.11.2 System Configuration

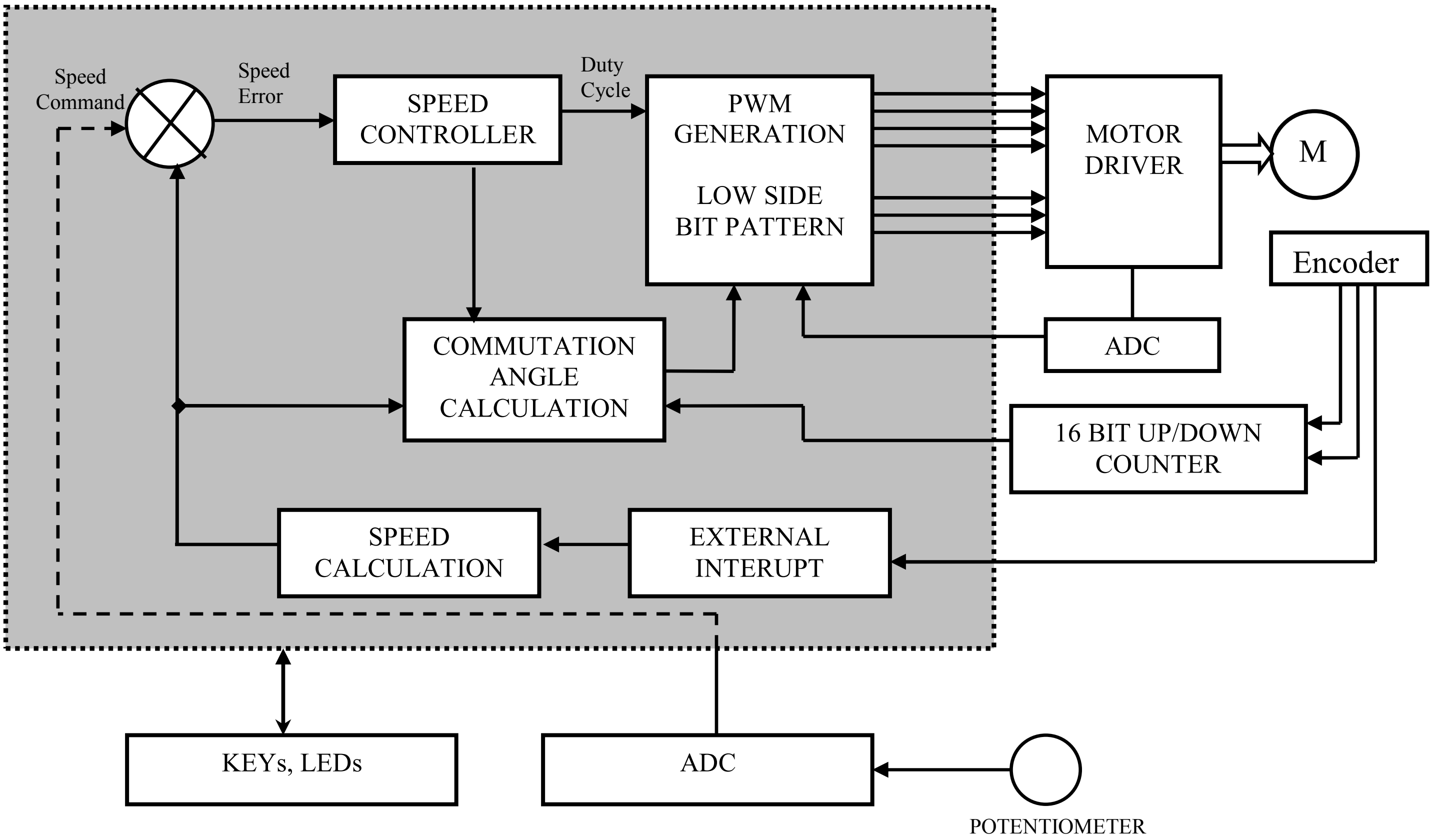


Figure 3.11 Microprocessor Based Control of SR motor

The microprocessor runs the main control algorithm. It generates 4-Phase PWM output signals for the SR motor power stage according to the user interface input and feedback signals. The required speed is set by a potentiometer, furthermore a start/stop and right/left switch is provided. When the start command is given the start-up sequence with the rotor alignment is performed and the motor is started in the desired direction. The rotor position is evaluated using the external encoder and the commutation angle is calculated. When the actual position of the motor is equal to the reference position, the commutation of the phases in the desired direction of rotation is done; the actual phase is turned off and the following phase is turned on. For the speed calculation no additional velocity sensor is needed, motor speed is derived from the position information. The reference speed is calculated from user defined potentiometer value. The speed error between commanded speed and actual speed is used in the speed controller to manipulate the voltage applied to each phase winding and the firing angles. As mentioned earlier PWM Voltage regulation is used in low- and mid speed regions, whereas advancing the turn-on angle in the single-pulse control comes active in the high speed area. The control algorithm is build up in such a matter, when the PWM regulation reaches its limits the single-pulse regulation takes over. Then during the PWM cycle, the actual phase current is compared with the absolute maximum value for the rated current. As soon as the actual current exceeds this value the PWM duty cycle is restricted. The procedure is repeated for each commutation cycle of the motor.

3.12 Torque–Speed Characteristics

The torque–speed plane of an SRM drive can be divided into three regions as shown in Fig. 3.12. The constant torque region is the region below the base speed ω_b, which is defined as the highest speed when maximum rated current can be applied to the motor at rated voltage with fixed firing angles. In other words, ω_b is the lowest possible speed for the motor to operate at its rated power.

Region 1

In the low-speed region of operation, the current rises almost instantaneously after turn-on, since the back-emf is small. The current can be set at any desired level by means of regulators, such as hysteresis controller or voltage PWM controller.

As the motor speed increases, the back-emf soon becomes comparable to the DC bus voltage and it is necessary to phase advance-the turn-on angle so that the current can rise up to the desired level against a lower back-emf. Maximum current can still be forced into the motor by PWM or chopping control to maintain the maximum torque production. The phase excitation pulses are also needed to be turned off a certain time before the rotor passes alignment to allow the freewheeling current to decay so that no braking torque is produced.

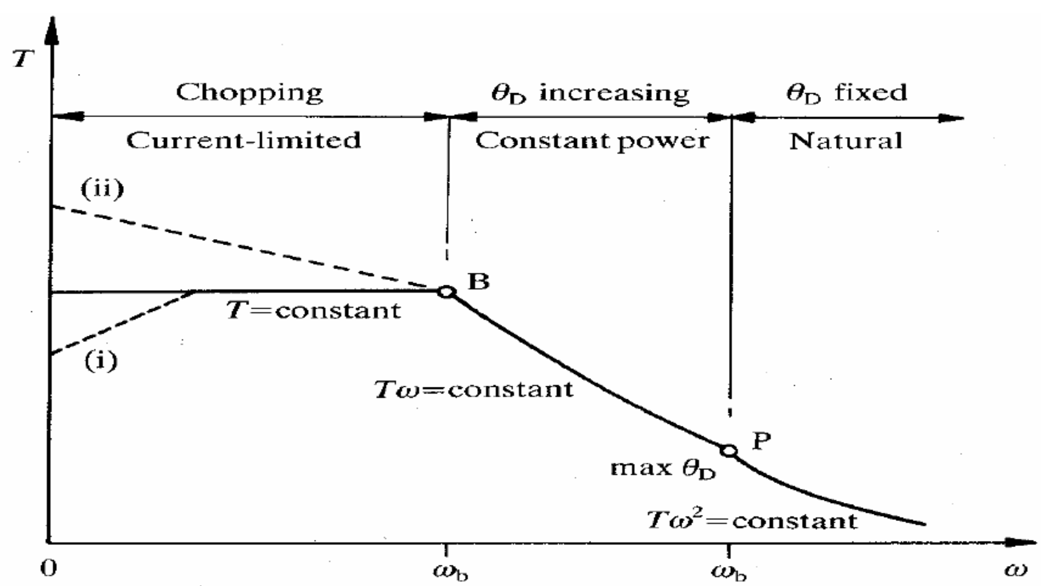


Fig 3.12 Torque Speed Characteristics of SRM

Region 2

When the back-emf exceeds the DC bus voltage in high-speed operation, the current starts to decrease once pole overlap begins and PWM or chopping control is no longer possible. The natural characteristic of the SRM, when operated with fixed supply voltage and fixed conduction angle θ_{dwell} (also known as the dwell angle), is that the phase excitation time falls off inversely with speed and so does the current. Since the torque is roughly proportional to the square of the current, the natural torque–speed characteristic can be defined by $T \alpha 1/\omega^2$. Increasing the conduction angle can increase the effective amps delivered to the phase. The torque production is maintained at a level high enough in this region by adjusting the conduction angle θ_{dwell} with the single-pulse mode of operation. The controller maintains the torque inversely proportional to the speed; hence, this region is called the constant power region. The conduction angle is increased by advancing the turn-on angle until the θ dwell reaches its upper limit at speed ω_p. The medium speed range through which constant power operation can be maintained is quite wide and very high maximum speeds can be achieved.

Region 3

The θ_{dwell} upper limit is reached when it occupies half the rotor pole-pitch, i.e., half the electrical cycle. θ_{dwell} cannot be increased further because otherwise the flux would not return to zero and the current conduction would become continuous. The torque in this region is governed by the natural characteristics, falling off as $1/\omega^2$. The torque–speed characteristics of the SRM are similar to those of a DC series motor, which is not surprising considering that the back-emf is proportional to current, and the torque is proportional to the square of the current.

3.13 SR MOTOR CONTROL

For motoring operation the pulses of phase current must coincide with a period of increasing inductance, i.e. when a pair of rotor poles is approaching alignment with the stator poles of the excited phase. The timing and dwell of the current pulse determine the torque, the efficiency, and other parameters. In d.c. and brushless d.c. motors the torque per ampere is more or less constant, but in the SR. motor no such simple relationship emerges naturally. With fixed firing angles, there is a monotonic relationship between average torque and r.m.s. phase current, but in general it is not very linear. This may present some complications in feedback-controlled systems although it does not prevent the SR motor from achieving 'near-servo quality' dynamic performance, particularly in respect of speed range, torque/inertia, and reversing capability.

At low speeds the self-e.m.f. of the winding is small and the current must be limited by chopping or p.w.m. of the applied voltage. The regulating strategy employed has a marked effect on the performance and the operating characteristics.

3.13.1 Hysteresis Type Regulator

Figure 3.13(a) shows schematically the method of control. As the current reference increases, the torque increases. At low currents the torque is roughly proportional to current squared, but at higher currents it becomes more nearly linear. At very high currents saturation decreases the torque per ampere again. This type of control produces a constant-torque type of characteristic as indicated in Fig. 3.14. With loads whose torque increases monotonically with speed, such as fans and blowers, speed adjustment is possible without tachometer feedback, but in general feedback is needed to provide accurate speed control. In some cases the pulse train from the shaft position sensor may be used for speed feedback, but only at relatively high speeds. At low speeds a larger number of pulses per revolution is necessary, and this can be generated by an optical encoder or resolver, or alternatively by phase-locking a high-frequency oscillator to the pulses of the commutation sensor (Bose 1986). Systems with resolver-feedback or high-resolution optical encoders can work right down to zero speed. The 'hysteresis-type' current regulator may require current transducers of wide bandwidth, but the SR drive has the advantage that they can be grounded at one end, with the other connected to the negative terminal of the lower phase leg switch. Shunts or Hall-effect sensors can be used, or alternatively, 'Sensefets' with in-built current sensing. Much of the published literature on SR drives describes this form of control.

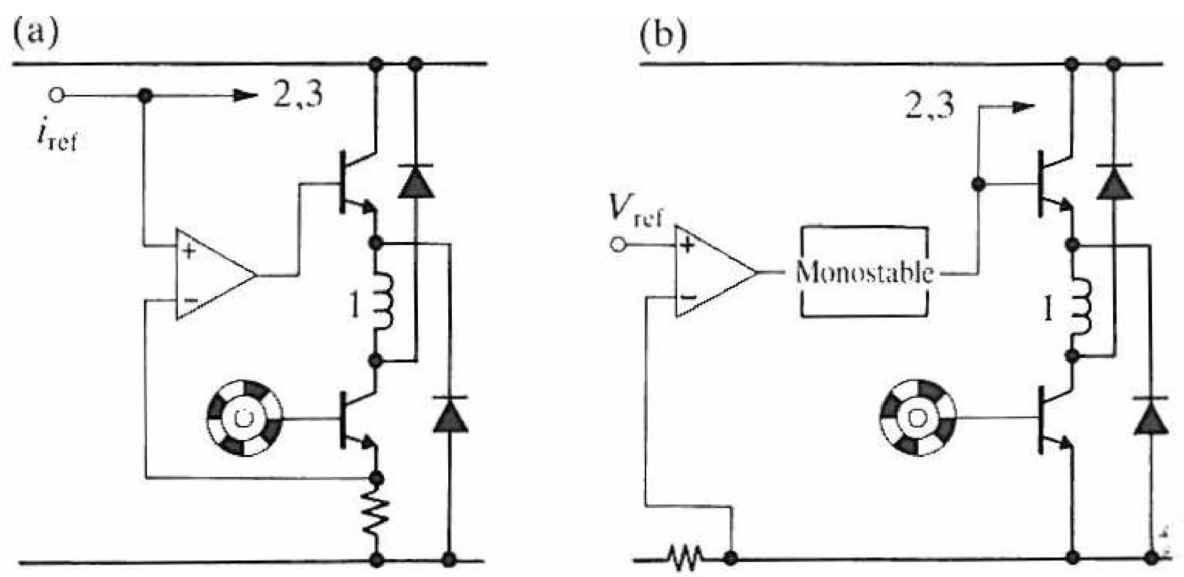


Fig 3.13 Schematic of Current regulated for one Phase

(a) Hysteresis Type (b) Voltage PWM Type (duty-cycle control)

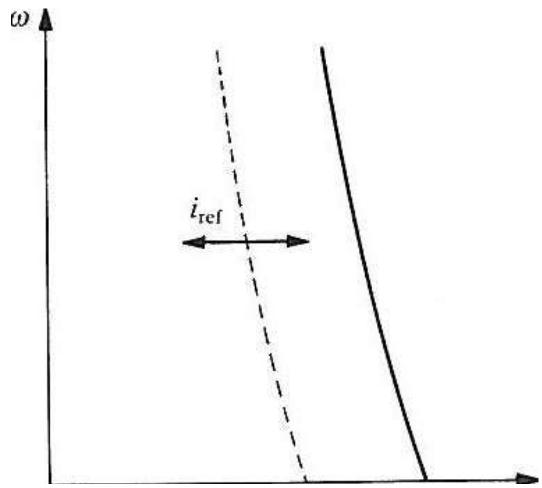


Fig. 3.14. Constant-torque characteristic obtained with regulator of Fig. 3.13(a)

3.13.2 Voltage PWM Type

Figure 3.13(b) shows an alternative regulator using fixed-frequency p.w.m. of the voltage with variable duty-cycle. Current feedback can be added to the circuit of Fig. 7.20(b) to provide a signal which, when subtracted from the voltage reference, modulates the duty cycle of the p.w.m. and 'compounds' the torque-speed characteristic. It is possible in this way to achieve under-compounding, over-compounding, or flat compounding just as in a d.c. motor with a wound field. For many applications the speed regulation obtained by this simple scheme will be adequate. For precision speed control, normal speed feedback can be added. The current feedback can also be used for thermal over current sensing.

A desirable feature of both the 'hysteresis-type' current-regulator and the voltage p.w.m. regulator is that the current waveform tends to retain much the same shape over a wide speed range. When the p.w.m. duty cycle reaches 100 per cent the motor speed can be increased by increasing the dwell (the conduction period), the advance of the current-pulse relative to the rotor position, or both. These increases eventually reach maximum practical values, after which the torque becomes inversely proportional to speed squared, but they can typically double the speed range at constant torque. The speed range over which constant power can be maintained is also quite wide, and very high maximum speeds can be obtained, as in the synchronous reluctance motor and induction motor, because there is not the limitation imposed by fixed excitation as in PM motors.

TWO MARKS QUESTIONS AND ANSWERS

1. Define Switched Reluctance Motor

SRM is a doubly salient and singly excited motor. That means both the stator and rotor has salient poles but only one usually stator carries the winding which operates based on the reluctance principle.

2. Write two distinguished points between Switched Reluctance and stepper motor.

- The SRM motor is normally operated with shaft position feed back to synchronize the commutation of the phase currents with precise rotor positions, where as stepper motor is normally run in open loop, i.e. without shaft position feedback.
- SRM is normally designed for efficient conversion of significant amounts of power, stepper motors are more usually designed to maintain step integrity in position controls.

3. Write the advantages of SRM.

- Machine construction ***is simple and low-cost because*** of the ***absence of rotor winding*** and permanent magnets.
- There are ***no shoot-through faults between the DC buses*** in the SRM drive converter because ***each rotor winding is connected in series with converter*** switching elements.
- ***Bidirectional currents are not necessary***, which facilitates ***the reduction of the number of power switches*** in certain applications.
- The bulk of the losses appear in the stator, which is relatively ***easier to cool***.
- The torque–speed characteristics of the motor ***can be modified to the application requirement more easily*** during the design stage than in the case of induction and PM machines.
- The starting torque can be ***very high without the problem of excessive in-rush current*** due to its higher self-inductance.
- The open-circuit voltage and short-circuit current at faults ***are zero or very small***.
- The maximum permissible ***rotor temperature is higher***, since there are no permanent magnets.
- There is ***low rotor inertia and a high torque/inertia ratio***.
- Extremely ***high speeds with a wide constant power region*** are possible.
- There are independent stator phases, ***which do not prevent drive operation*** in the case of loss of one or more phases.

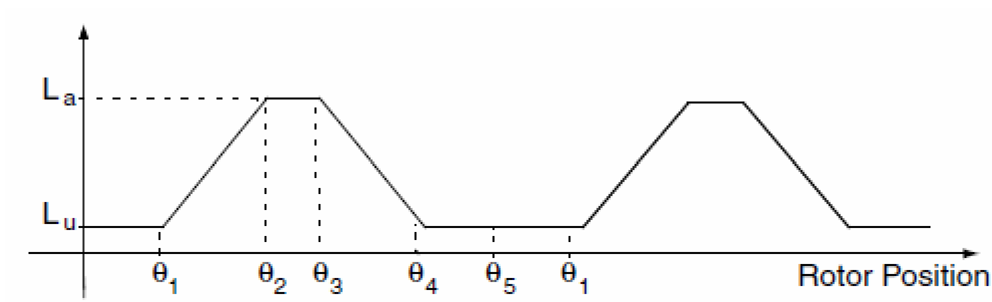
4. **List the disadvantages of SRM.**
   - The SRM also comes with a few disadvantages among ***which torque ripple and acoustic noise are the most critical***. The higher torque ripple also ***causes the ripple current in the DC supply*** to be quite large, ***necessitating a large filter capacitor***. The doubly salient structure of the SRM also causes ***higher acoustic noise compared with other machines***.
   - The absence of permanent magnets ***imposes the burden of excitation on the stator windings and converter***, which increases the ***converter KVA requirement***. Compared with PM brushless machines, the ***per unit stator copper losses will be higher, reducing the efficiency and torque per ampere***. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRMs.
5. **Define aligned and unaligned inductance**
   - The inductance measured at the position as the conjunction of any rotor inter pole axis with the axis of the stator poles of the phase is called as unaligned inductance.
   - The inductance measured at the position as the conjunction of any rotor pole axis with the axis of the stator poles of the phase is called as aligned inductance.
6. **Write the instantaneous torque equation of switched reluctance motor.**

$$T_e = \frac{dL(\theta,i)}{d\theta} \cdot \frac{i^2}{2}$$

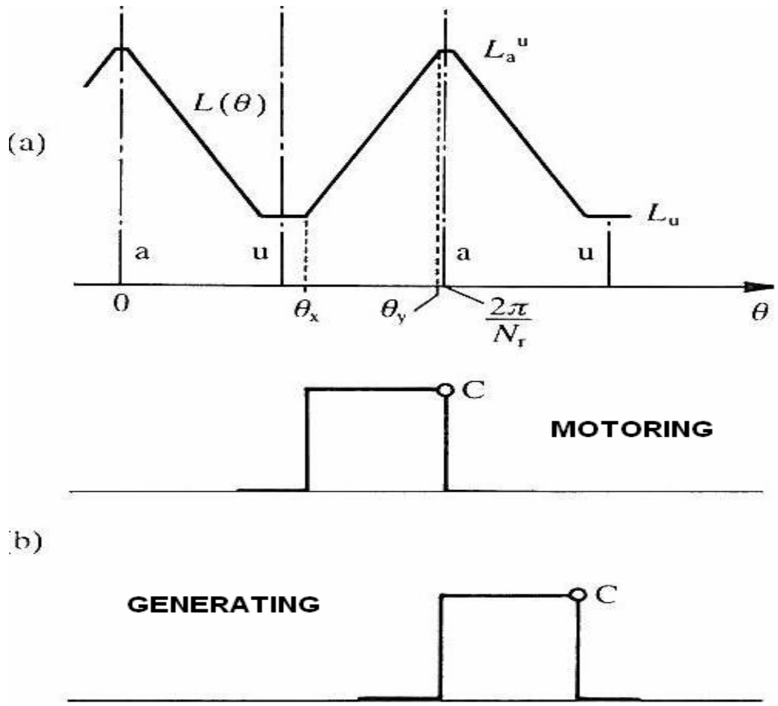
Where

$$\frac{dL(\theta,i)}{d\theta} = \left.\frac{L(\theta_2,i) - L(\theta_1,i)}{\theta_2 - \theta_1}\right|_{i=\text{constant}}$$

7. **Draw the inductance variation with respect to the rotor position in SRM.**



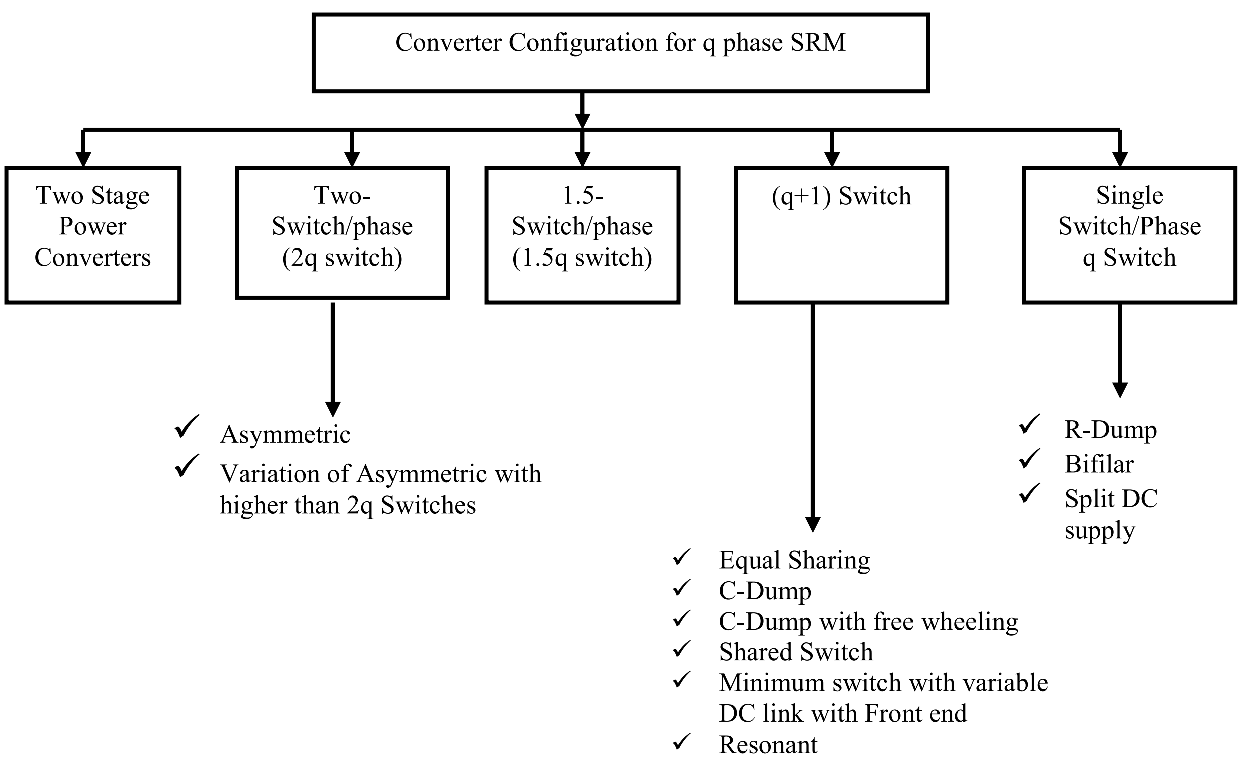
8. Draw the ideal current wave form for motoring and generating



9. Bring out the requirements to get the maximum torque per ampere.

- Unsaturated aligned inductance should be as large as possible by implying a small air gap with wide slots.
- Smallest possible unaligned inductance can be achieved by a large inter polar arc on the rotor, narrow stator poles and deep slotting on both stator and rotor
- The highest possible saturation flux density.

10. What are the types of converters used to drive SRM?



11. Which makes the SRM to use unipolar controller circuit?

The torque is independent of the direction of the phase current which can therefore be unidirectional. This permits the use of unipolar controller circuit for SRM.

12. Write the advantages of 2n transistor converter circuit

- This circuit provides the maximum control flexibility and efficiency, with a minimum of passive components.
- By controlling the upper and lower transistors independently all possible firing angles can be used.
- In small drives PWM control over the entire speed range is possible.

13. How the phase windings of the SRM are connected with the converter circuit and compare it with the normal inverter with windings.

The phase winding is connected in between the two control switches on the same leg. But in inverter the windings are connected from the mid points of adjacent phase legs. No simultaneous switching ON process of the switches in the same leg.

14. State the advantages and limitations of bifilar winding converter circuit.

Advantages:

To reduce the number of switching devices bifilar winding is used.

Limitation:

- Double the numbers of connections are used.
- Poor utilization of copper
- Voltage spikes due to imperfect coupling

15. What is C dump converter circuit?

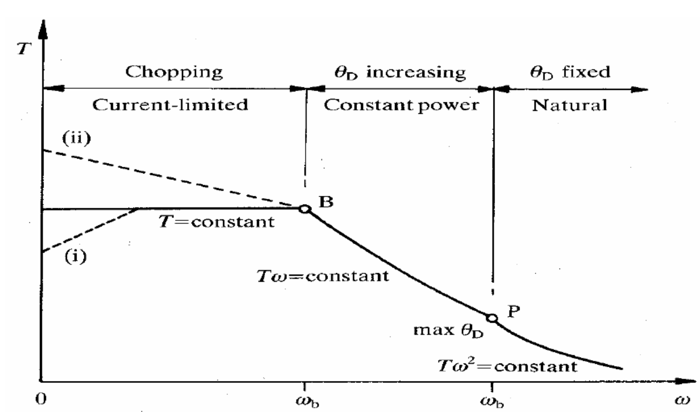
One capacitor is used in the circuit with one more phase to bleed the stored energy in the capacitor.

16. What are the types of control method used to control SRM?

(a) Hysteresis Type

(b) Voltage PWM Type (duty-cycle control)

17. Draw the torque speed characteristics of SRM



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5. **B.K. Bose**, “Modern Power Electronics & AC drives”, Dorling Kindersley India, 2006.

QUESTIONS:

UNIT – II SWITCHED RELUCTANCE MOTOR

PART – A

1 Describe a switched reluctance motor.

2 List out the advantages of switched reluctance motor.

3 Weigh the rotor position sensor for the operation of switched reluctance motor.

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

5 Defend on hysteresis current control.

6 Relate the switched reluctance motor as doubly salient motor.

7 Argue on the Switched reluctance motor is singly exited motor. (5)

8 Solve the torque exerted by an SRM with the instantaneous value of stator current 2A & $dL/d\theta=1$.

9 Compare SRM and stepper motor.

10 Sketch the speed-Torque characteristics of SRM.

11 List any four application of SRM.

12 Describe the modes of operation of SRM.

13 Sketch the inductance variation with respect to the rotor position in SRM.

PART B

1 Describe the construction and working principle of switched reluctance motor.

2 (a) Develop the torque equation of switched reluctance motor. (6)
(b) Explain the speed-torque characteristics of switched reluctance motor.

3 Examine the step angle of a 3 phase SR motor having 12 stator poles &8 rotor Poles. State the commutation frequency in such phase at a speed of 600 Rpm.

4 Explain any two power controller circuit for switched reluctance motor.

5 Describe any three power converters used in Switched Reluctance Motor with suitable waveform.

6 Demonstrate on the control of SRM using microprocessor based controller.

7 Examine the control of a Switched Reluctance motor using a microprocessor based controller.

8 Explain the control circuits for SRM with neat diagram.

9 Investigate on the relationship between inductance and rotor position with relevant diagram.

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT – III - SPECIAL ELECTRICAL MACHINES – SEE1307

UNIT III

SYNCHRONOUS RELUCTANCE MOTOR

The Synchronous Reluctance Motor is completely free of magnets and their operational problems. It is inexpensive to make and can operate at extensively high speed and at higher temperature than the PM motors. However, its power factor and efficiency are not as high as those of a PM motors and the converter KVA requirement is higher.

The Synchronous Reluctance Motor offers many of the advantages of the Switched Reluctance Motor. But the Synchronous Reluctance Motor has two added advantages

i) it can operate from essentially standard PWM AC inverter and has lower torque ripple.

ii) It can also be built with a standard induction motor stator and winding.

1.1 CONSTRUCTION OF SYNCHRONOUS RELUCTANCE MOTOR

- Its construction is very similar to induction motor The two important parts of the motor are stator and rotor as in Induction motor. It is shown in the figure 1.1
- The stator construction is similar to induction motor (ie) it has outer frame which covers the whole machine. Beneath the frame stator core which are laminated and made up of silicon steel material are fixed to reduce Hysteresis & Eddy current loss in the motor.
- The stator core has stator slots which are used for housing the stator winding, usually three phase winding is provided.
- Here the rotor does not have any magnets (or) field winding for excitation.
- The rotor has very simple construction such that salient pole rotor core which are laminated (or) solid steel material.
- The machine is low cost, rugged and have high efficiency and are capable of operating at very high speeds.

- The traditional Synchronous Reluctance Motor has low saliency (ie) a low L_{dm}/L_{qm} ratio, which gives poor torque density, low power factor and poor efficiency.
- The Synchronous Reluctance Motor is similar to the sinusoidal PM machine, except that the field flux $\psi_f = 0$ and $L_{dm} \neq L_{qm}$.

1.1.1 Working Principle

- The motor works on the basic principle of minimum reluctance position.
- When the stator winding is excited by the AC supply, it produces the rotating magnetic field in the airgap which cuts the rotor and induces magnetic field in the rotor.
- The rotor tries to align itself with the minimum reluctance position by developing reluctance torque between the stator and rotor.
- Ideally there is no core (or) copper loss in the rotor, but the inverter fed harmonics will cause some copper loss in the damper winding if present.
- The simplest operation of a Synchronous Reluctance Motor is a line start motor where the machine starts like an induction motor with the help of a cage winding, but pulls into synchronism at synchronous speed.

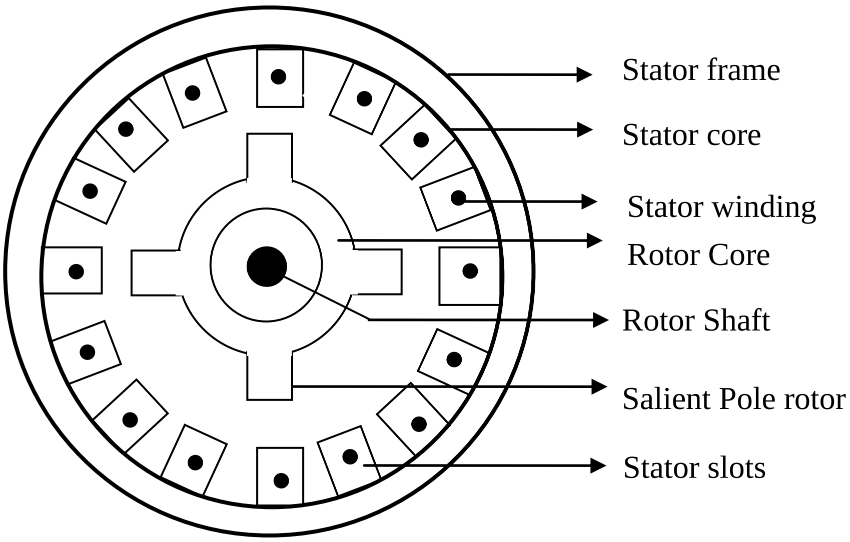

Fig1.1

Useful properties of Synchronous Reluctance Motor:

i. Combined reluctance and magnet alignment torque.

ii. Field weakening capability

iii. High Inductance

iv. High Speed capability

v. High temperature capability

vi. Under excited operation for most load condition.

Applications

i. Pumps and Conveyors

ii. Synthetic fiber spinning mills

iii. Wrapping and folding machines

iv. Motor pumps

Types of Synchronous Reluctance Motor:

i. Line start Synchronous Reluctance Motor (cage type)

ii. Cageless PM / Synchronous Reluctance hybrid motor

iii. Brushless Synchronous Reluctance Motor

Depending upon the rotor construction the Synchronous Reluctance Motor is two types.

i. Radial airgap motor

ii. Axial airgap motor

1.2 RADIAL AIRGAP MOTOR

- In this type of motor, the stator construction remains the same but the rotor has projecting pole laminations of steel core. It is shown in the figure 1.2
- Therefore the length of the magnetic core in a radial motor is less than the total active magnetic length due to the presence of end turns at each end of the motor.

- The magnetic working radius set the torque for the motor and is directly related to the torque production of a motor. The larger the radius is, the more torque the motor produces.
- The working radius of the magnet in a radial motor is usually considered the outside dimension of the magnet.
- Since this is a cylindrical structure this is easily defined and is commonly used.
- The working radius is smaller than the axial motor. So torque production in radial motor is smaller than the axial motor.
- The total magnetic surface area in radial motor design is set by the magnet diameter and the magnet length. The magnet surface area is increasing linearly with magnet length surface area is more than the axial motor.
- In radial motor, the effective airgap area is less than the maximum airgap area since there are gaps between the field poles to reduce the flux leakage and allow for insertion of windings.
- The core area for a radial motor is limited by the smallest radius of the core, the winding thickness and the gap necessary to allow for winding the motor windings.
- An advantage to the radial motor design is that more core area can be incorporated into the motor. Generally radial motors have a limited value of copper fill since the windings need to be done through the slots between the pole shoes.

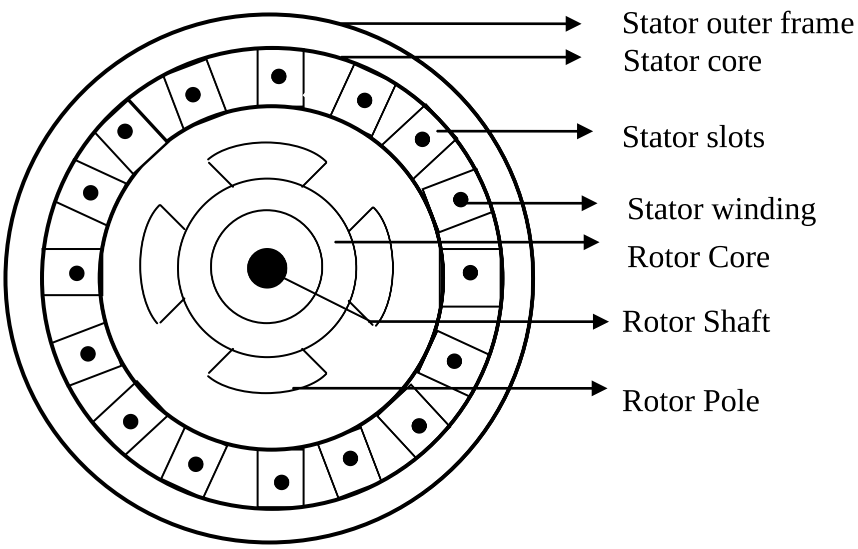

Fig 1.2

1.3 AXIAL AIRGAP MOTOR

- In this type of motor, the length of the laminated core of rotor is L_c which is essentially the same as the length of the winding.
- For axial motor, the magnet working radius is harder to define since the radius varies over the area of the air gap.
- Typically the magnet working radius can be larger since the magnet outside diameter is limited only by the motor shell thickness and a clearance gap for rotation and in some case the winding thickness.
- The axial motor has 1.4 times torque improvement compared to the radial motor. For the axial motor, the magnet surface area is set by the inner and outer radii of the magnet and then doubled since this surface has one magnet at each end of the motor.
- The air gap area for a traditional axial motor is just the area of a slice of the field poles that is perpendicular to the axis of rotation.
- The effective air gap area is less than maximum area since some areas are left between the field poles to reduce flux leakage between the field poles and some area to the windings.
- The core area for a traditional axial motor is just the area of a perpendicular slice of the field poles. The axial motor has a constant core area and it has maximum torque for any given diameter independent of length.
- The increase in length of an axial motor changes the power dissipation of the motor but does not change the maximum torque. Axial motor has high copper fill ratio because of the simple coil design.
- If the length were not constrained, the axial motor could be lengthened so that additional copper could be added.
- The axial motors do not increase torque by extending motor length. Extending the motor length in an axial motor increase the length of the winding but does not change the torque value produced.
- The constructional view is shown in the figure 1.3

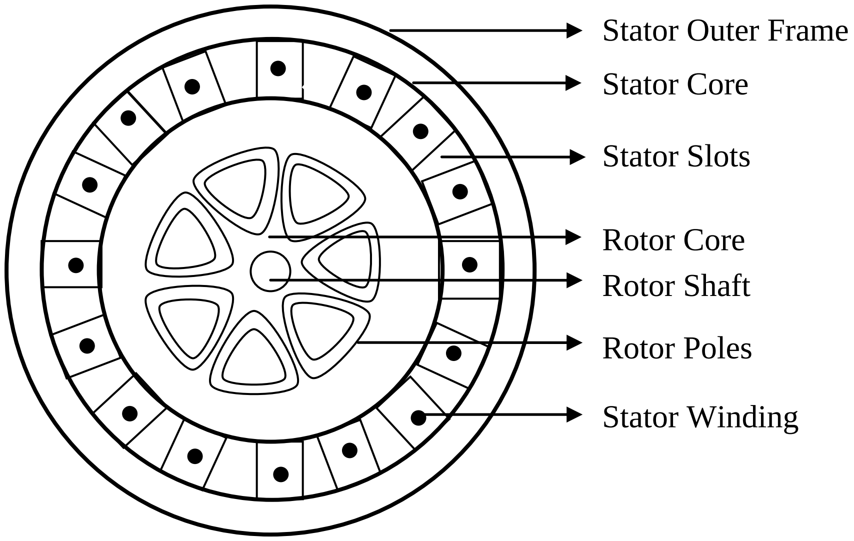

Fig 1.3

1.4 SYNCHRONOUS RELUCTANCE

In this type of motor where magnets are absent (or) removed under the no load condition (or) open circuit condition and when there is not torque, all the flux is the q-axis flux and there is no d-axis flux. Usually the case is that $X_d < X_q$ which is opposite to the ordinary synchronous machines.

In many respects, the Synchronous Reluctance Motor is similar to the sinusoidal PM machines, except that the field flux $\psi_f = 0$ and $L_{dm} \neq L_{qm}$. The $d^e - q^e$ equivalent circuits of the machines are simple and they are shown in the figure 1.4.

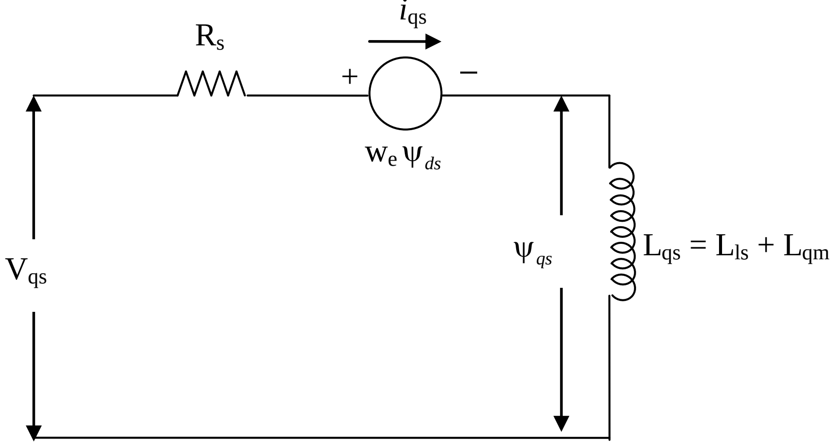

Fig 1.4

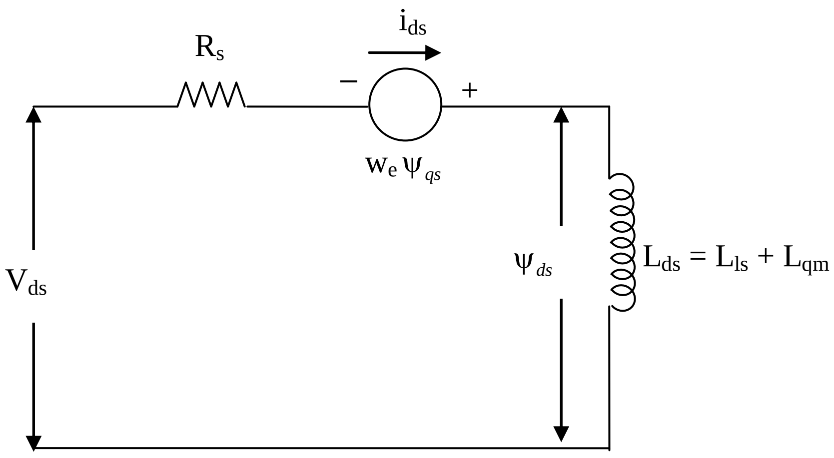

Fig1.4

The machine may or may not have a cage (or) damper winding. Ideally there is no core (or) copper loss in the rotor, but the inverter fed harmonics will cause some copper loss in the damper winding if present. The simplest operation of the Synchronous Reluctance Motor is as lie start motor where the machine starts like an induction motor with the help of a cage winding, but pulls into synchronism at synchronous speed. One traditionally popular application of a Synchronous Reluctance Motor is the multi motor drive by open loop volts/Hz speed control.

1.5 PHASOR DIAGRAM OF SYNCHRONOUS RELUCTANCE MOTOR

The phasor diagram of the motor is drawn to obtain the performance parameters of the motor. The phasor diagram is shown in the figure 1.5 with their standard symbols where $\psi_{ds} = L_{ds} i_{ds}$, $\psi_{qs} = L_{qs} i_{qs}$ and $V_s = w_e \psi_s$

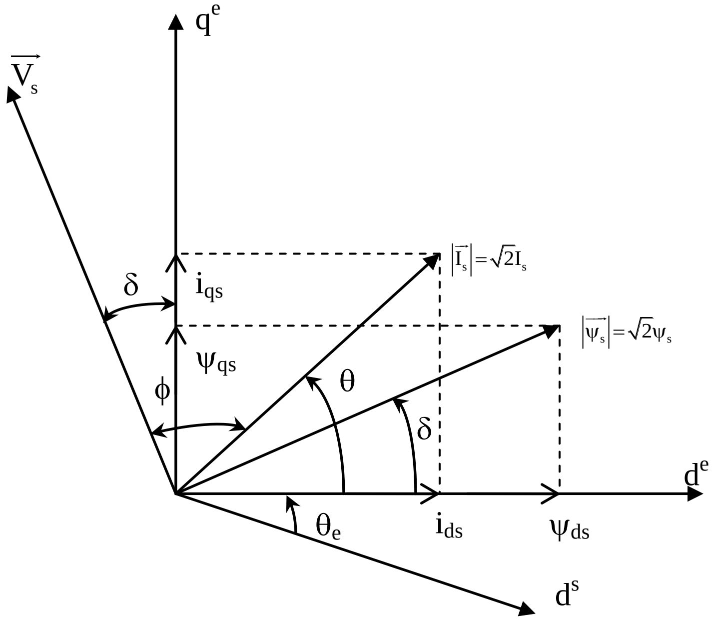

Fig 1.5

The flux ψ_{ds} tends to saturate at i_{ds}. In fact there is some cross saturation effect of L_{ds} due to i_{qs} current. The stator resistance drop has been neglected for simplicity. Note that ψ_f phasor and corresponding V_f phasor are absent. Since the stator supplies magnetizing current like an induction motor, the stator power factor angle ϕ is large. So the power factor is low in the synchronous reluctance motor.

The torque developed by the motor is called as synchronous reluctance torque which is given by

$$T_e = 3\left[\frac{P}{2}\right]\psi_s^2\left[\frac{L_{ds}-L_{qs}}{2L_{ds}L_{qs}}\right]\sin 2\delta$$

Where $\psi_s = \dfrac{\hat{\psi}_s}{\sqrt{2}}$

$$\therefore \qquad T_e = \left(\frac{3}{2}\right)\left[\frac{P}{2}\right]\hat{\psi}_s^2\left[\frac{L_{ds}-L_{qs}}{2L_{ds}L_{qs}}\right]\sin 2\delta$$

Where

$\hat{\psi}_s \rightarrow$ space vector flux magnitude

P $\rightarrow$ umber of poles

$\delta \rightarrow$ torque angle

Put sin 2δ = 2 sinδ cosδ and where $\sin\delta = \frac{\Psi_{qs}}{\hat{\Psi}_s}$ and $\cos\delta = \frac{\Psi_{ds}}{\hat{\Psi}_s}$

$$\therefore \qquad T_e = \left(\frac{3}{2}\right)\left[\frac{P}{2}\right]\left[\frac{L_{ds} - L_{qs}}{L_{ds}L_{qs}}\right]\Psi_{ds}\Psi_{qs}$$

$$\therefore \qquad T_e = \left(\frac{3}{2}\right)\left[\frac{P}{2}\right]\left[L_{ds} - L_{qs}\right]i_{ds}i_{qs}$$

From the above equation we say that the torque can be controlled by i_{ds} , i_{qs}(or) both components. The above equation can also be rewritten as

$$T_e = \left(\frac{3}{2}\right)\left[\frac{P}{2}\right]\left[\Psi_{ds}i_{qs} - \Psi_{qs}i_{ds}\right]$$

1.6 SYNCHRONOUS RELUCTANCE MOTOR CHARACTERISTICS

The characteristics of the motor depends upon the torque angle δ and speed of the motor with respect to the torque developed. The torque equation is given as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\psi_s^2\left[\frac{L_{ds} - L_{qs}}{2L_{ds}L_{qs}}\right]\sin 2\delta$$

Generally $L_{qs} > L_{ds}$ and the torque has a maximum value at $\delta = 45^0$ (or) $\frac{\pi}{4}$ radians in the motoring region. The torque follows the sinusoidal distribution in the motoring and generating region and it is shown in the figure 1.6.

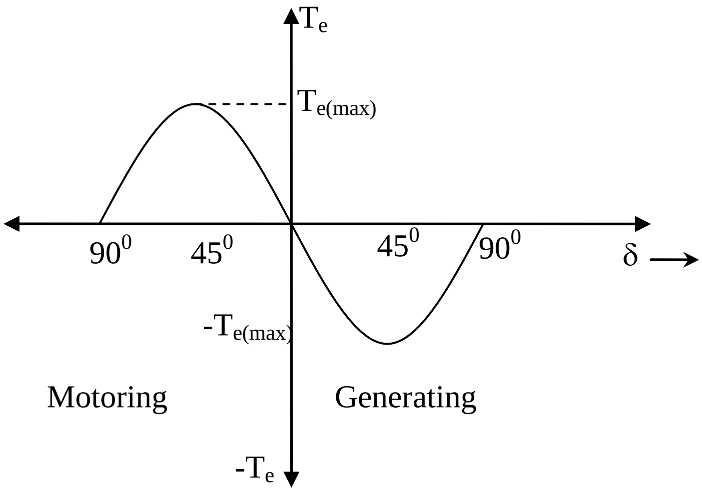

Fig 1.6

The next important characteristics are the speed torque characteristics of the motor. Usually the synchronous motor is the constant speed motor and it runs only at synchronous speed. The speed control of the motor can be achieved by combined volts/Hz control. The speed torque characteristics of the motor are shown in the figure 1.7.

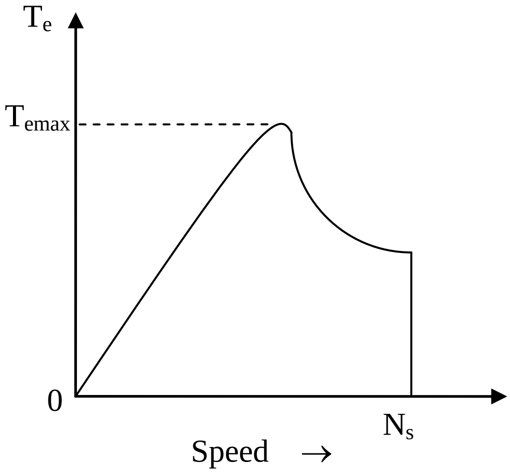

Fig 1.7

The characteristics takes the natural shape (ie) as the speed is increased from initial value, the torque also increase and reaches its maximum value and then the motor tries to pull into synchronism and runs at synchronous speed with normal reluctance torque. The variable load on the motor does not affect the speed of the motor but it controls the developed torque in the motor for the fixed frequency operation. The motor goes out of synchronism when it is subjected to overload condition and the motor stops. The speed torque characteristics is also affected by the sudden loading and unloading of motor which leads to oscillatory motion of the rotor which may sometime lead to asynchronous operation.

1.7 VERNIER MOTOR

A vernier motor is an unexcited inductor synchronous motor in which a small displacement of the rotor produces a large displacement of the axes of permeance. It runs at a slow speed as if it were geared down the speed of the rotating field set up by the stator. To design a vernier motor is equivalent to designing a polyphase reluctance motor with an odd shaped rotor. So that the air gap permeance distribution is a displaced triangular wave. The motor is so named because it operates on the principle of a vernier. The peculiar feature of this kind of motor is that a small displacement of the rotor produces a large displacement of the axes of maximum and minimum permeance. When a rotating magnetic field is introduced in the air gap of the machine, the rotor will rotate slowly and at a definite fraction of the speed of the rotating field. This rotating field can be produced either by feeding poly phase current to the stator winding or by exciting the stator coil groups in sequence. As the rotor speed steps down from the speed of the rotating field, the motor torque steps up. Therefore, the motor works as an electric gearing. This kind of motor is attractive in applications which require low speed and high torque and where mechanical gearing is undesirable.

1.7.1 Construction

- The construction of vernier motor is similar to poly phase induction motor as shown in the figure 1.8
- The two important parts are stator and rotor. The stator has laminated stator core made up of silicon steel to reduce eddy currents and hysteresis loss in the stator.
- At the inner periphery of the stator core, stator slots are provided and the slots are used for housing the stator winding.
- The stator winding is distributed in the slots just like the ordinary poly phase induction motor. When the stator winding is excited by the poly phase supply, the rotating magnetic field is produced in the air gap.
- The rotor has laminated core made up of iron material without any winding.
- The outer periphery of the rotor has rotor slots Number of stator slots will be more than the number of rotor slots.
- Because of this construction the air gap permeance varies between the stator and rotor slots in the horizontal and vertical direction.

1.7.2 Principle of operation

- The stator of a vernier motor has slots and a distributed winding just like the stator of an ordinary polyphase induction motor.
- The rotor is slotted iron core without winding. To understand the principle of operation of a vernier motor refer the below figure.

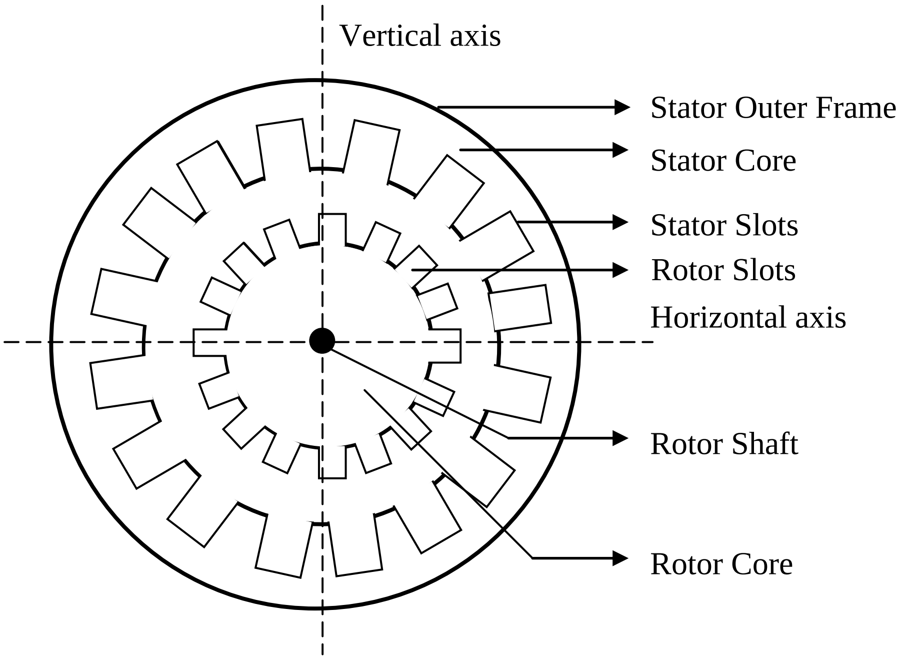

Fig 1.8

- The figure 1.8 shows a two pole machine with 12 stator slots and 10 rotor slots. Small numbers of slots are purposely chosen as an example to facilitate the explanation.
- At the position shown in figure, the stator and the rotor teeth are facing each other in the vertical axis. The stator teeth are facing rotor slots in the horizontal axis.
- At this position, the maximum permeance is along the vertical axis and the minimum permeance is along the horizontal axis.
- When the rotor is rotated one half of its slots pitch, the rotor slots will face stator teeth in the vertical axis. The stator and rotor teeth will face each other in the horizontal axis.
- The axis of maximum permeance is now horizontal and the axis of minimum permeance is now vertical.
- Thus the rotor movement of one half rotor slot pitch results in a 90 degree displacement of the permeance.

- Suppose that a magnetic field is rotating in the machine. Whenever the rotating field rotates 90 degree, the rotor will rotate one half of its slot pitch.

- When the rotating field completes one revolution, the rotor will rotate through an angle corresponding to two rotor slot pitches. For the example given, the rotor speed is one fifth of the speed of the rotating field.

1.8 Airgap Permeance Distribution in Vernier motor

The first step in the design is to study the permeance distribution along the air gap. Assume that fluxes fringing from the edges of the teeth will be neglected and the fluxes in the air gap flows in the radial direction. The permeance of air space between the stator and rotor at any location is inversely proportional to the radial length of air space at that location. Since the stator and rotor slot depths are much larger in comparison with the air gap length, the permeance of air space can be considered as zero, except where stator tooth surface is facing rotor tooth surface. The permenace distribution along the circumference of air gap for the given figure is shown below. Figure 1.9

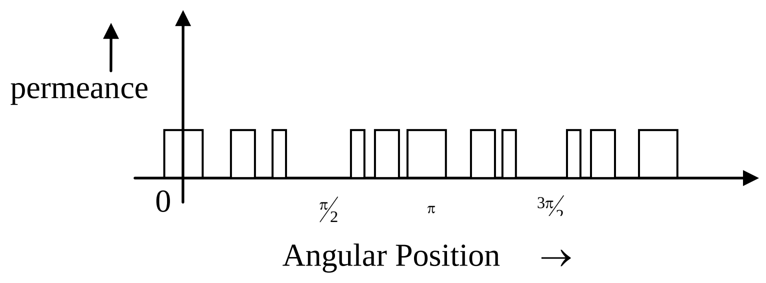

Figure 1.9 Airgap permeance distribution of motor

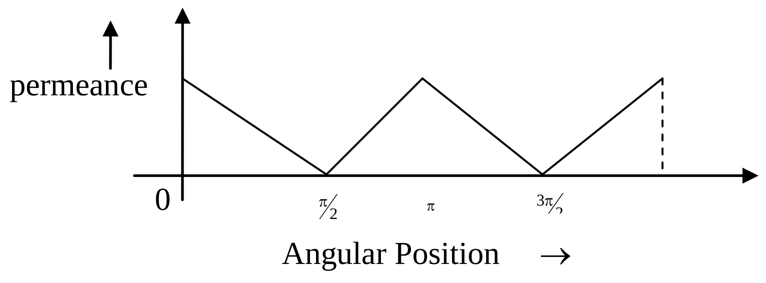

Figure 1.10. Equivalent permeance distribution

In figure 1.9, the widths of rectangular blocks are the widths of overlap between the stator and rotor teeths. These widths of overlap vary linearly from a maximum to a minimum and back to a maximum as shown. The area of overlap is maximum for the top and bottom stator teeth where the rotor teeth are directly opposite. The area of overlap is reduced a constant amount for each successive stator tooth until a minimum (zero) is reached. After that the area of overlap is increased successively back to the maximum and cycle repeats.

A permeance distribution curve shown in figure1.9 is not convenient to use because it cannot be represented by a simple mathematical function. The equivalent permeance distribution curve of the figure 1.10 is therefore drawn. The figure1.10 represents the periodic linear variation of permeance per unit area from a maximum to minimum and back to a maximum. When the rotor rotates, this permeance wave rotates at a much faster speed. The axes at which maximum and minimum permeance occur are the direct and quadrature axes respectively of the vernier motor. The technique of replacing a permeance curve of figure1.9 by an equivalent permeance curve of figure 1.10 is an accepted practice in electrical machine design.

1.9 DESIGN OF VERNIER MOTOR

In a poly phase reluctance motor, the rotor has the same number of poles as the stator mmf wave. Similarly, in a vernier motor, the air gap permeance wave should have the same number of poles as the stator mmf wave. Therefore, the number of stator and rotor slots should have the following relation.

$$N_1 = N_2 \pm P$$

Where N_1 $\rightarrow$ number of stator slots

N_2 $\rightarrow$ number of rotor slots

P $\rightarrow$ number of poles of the rotating magnetic field

As we have seen before, when the rotor rotates through an angle corresponding to one rotor slot pitch, the permeance wave rotates through an angle corresponding to one pole pitch. The pole pitch of the permeance wave is the same as the pole pitch of the stator mmf wave, because they have the same number of poles.

Also in a reluctance machine, the speed of the permeance wave is the same as the speed of rotating mmf.

Therefore,

$$\frac{Rotor\ \ speed}{Rotating\ \ field\ \ speed} = \frac{Rotor\ \ slot\ \ pitch}{mmf\ \ pole\ \ pitch} = \frac{P}{N_2}$$

(or)

$$Rotor\ \ Speed = \frac{120\,f}{N_2} \quad rpm$$

And the electric gear ratio is given as

$$\text{Electric Gear Ratio} = \frac{N_2}{\pm\left(N_2 - N_1\right)}$$

It can be seen from rotor speed equation that the rotor speed is independent of the number of poles of the machine, when the speed of the rotating field is reduced by increasing the number of poles of the machine. It cannot be expected that the speed of the rotor be reduced proportionally because when P is increased the difference between N2 and N1 should also be increased and the electric gear ratio is reduced in the inversed proportion. Thus, the rotor speed is not affected by the number of poles but depends on the number of rotor slots.

The main step in design is to calculate the direct and quadrature axes reactance X_d and X_q.

$$X_d = X_l + X_{ad}$$

$$X_q = X_l + X_{aq}$$

Where

$X_l \rightarrow$ stator leakage reactance

$X_{ad} = X_{aq} \rightarrow$ direct and quadrature axis reactance of armature reaction.

The X_{ad} is the ratio of the fundamental component of reactive armature voltage produced by the mutual flux due to the fundamental direct axis component of armature current to this component under steady state conditions and at rated frequency. Similarly X_{aq} is the ratio of the fundamental component of relative armature voltage produced by the mutual flux due to the fundamental quadrature axis component of armature current to this component of current under steady state condition and at rated frequency.

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QUESTIONS:

UNIT – III - SYNCHRONOUS RELUCTANCE MOTORS

PART – A

1 List the applications of synchronous reluctance motor.

2 Classify the synchronous reluctance motor.

3 State the main parts of synchronous reluctance motor.

4 State synchronous reactance.

5 Develop an expression for reluctance torque.

6 Argue on the type of synchronous reluctance motor to operate at high speeds.

7 Explain how the torque ripples are reduced in synchronous reluctance motor?

8 Distinguish between permanent magnet synchronous motor and synchronous reluctance motor.

9 Differentiate axial air gap and radial air gap motor.

10 Defend on the type of rotor in synchronous reluctance motor.

11 List the three types of laminations in synchronous reluctance motor.

PART B

1 Explain the constructional details of the axial air gap Synchronous Reluctance Motor and state the principle of operation.

2 Sketch the phasor diagram of synchronous reluctance motor and explain.

3 Develop the expression for reluctance torque from phasor diagram of synchronous reluctance motor.

4 Investigate on the torque-speed characteristics of a synchronous reluctance motor.

5 Explain the constructional details of the axial air gap Synchronous Reluctance Motor and state the principle of operation.

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UNIT – IV - SPECIAL ELECTRICAL MACHINES – SEE1307

UNIT IV

PERMANENT MAGNET BRUSHLESS D.C. MOTORS

4.1 INTRODUCTION

Conventional DC motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawbacks that they need a commutator and brushes which are subject to wear and require maintenance.

When the functions of commutator and brushes were implemented by solid state switches, maintenance free motors were realized. These motors are known as brushless DC motors. The function of magnets is the same in both brushless motor and the dc commutator motor. The motor obvious advantage of brushless configuration is the removal of brushes. Brush maintenance is no longer required, and many problems associated with brushes are removed.

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

4.2 CONSTRUCTIONAL FEATURESB OF BLPM MOTORS

4.2.1 Construction

The stator of the BLPM dc motor is made up of silicon steel stampings with slots in its interior surface. These slots accommodate either a closed or opened distributed armature winding usually it is closed. This winding is to be wound for a specified number of poles. This winding is suitably connected to a dc supply through a power electronic switching circuitry (named as electronic commutator).

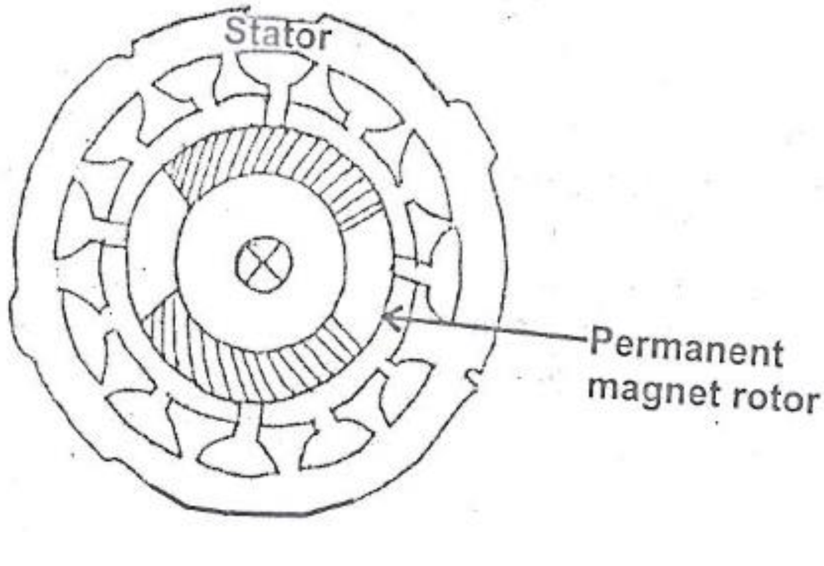


Fig 4.1 Arrangement of permanent magnet in the rotor

Rotor is made of forged steel. Rotor accommodates permanent magnet. Number of poles of the rotor is the same as that of the stator. The rotor shaft carries a rotor position sensor. This position sensor provides information about the position of the shaft at any instant to the controller which sends suitable signals to the electronic commutator.

4.2.2 Merits and Demerits

Merits

- There is no field winding. Therefore there is no field
- cu loss. The length of the motor is less as there is no
- mechanical commutator. Size of the motor becomes
- less.
- It is possible to nave very high speeds.
- It is self-starting motor. Speed can be controlled.
- Motor can be operated in hazardous atmospheric condition. Efficiency is better.

Demerits

- Field cannot be controlled.
- Power rating is restricted because of the maximum available size of permanent magnets.
- A rotor position sensor is required.
- A power electronic switch circuitry is required.

4.2.3 Comparison of brushless dc motor relative to induction motor drives

- In the same frame, for same cooling, the brushless PM motor will have better efficiency and p.f and therefore greater output. The difference may be in the order of 20 – 50% which is higher.
- Power electronic converter required is similar in topology to the PWM inverters used in induction motor drives.
- In case of induction motor, operation in the weakening mode is easily achieved providing a constant power capability at high speed which is difficult in BLPM dc motor.
- PM excitation is viable only in smaller motors usually well below 20 kw also subject to speed constraints, In large motors PM excitation does not make sense due to weight and cost.

4.2.4 Commutator and brushes arrangement

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

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

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

4.2.5 Construction of Mechanical Commutator

Commutator Segment

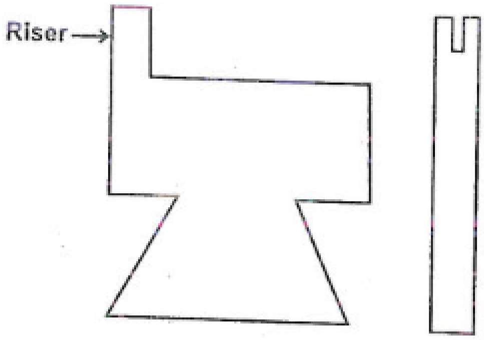


Fig 4.2 Commutator Segment

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

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

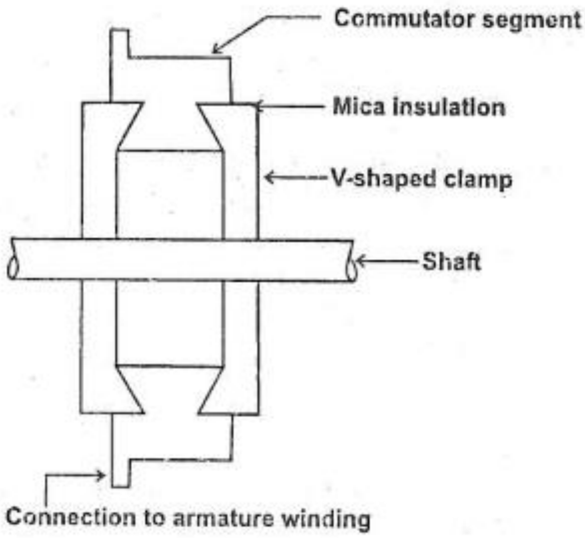


Fig 4.3 connection of commutator segments to shaft

4.2.6 Mechanical Commutator and Brushes Arrangement

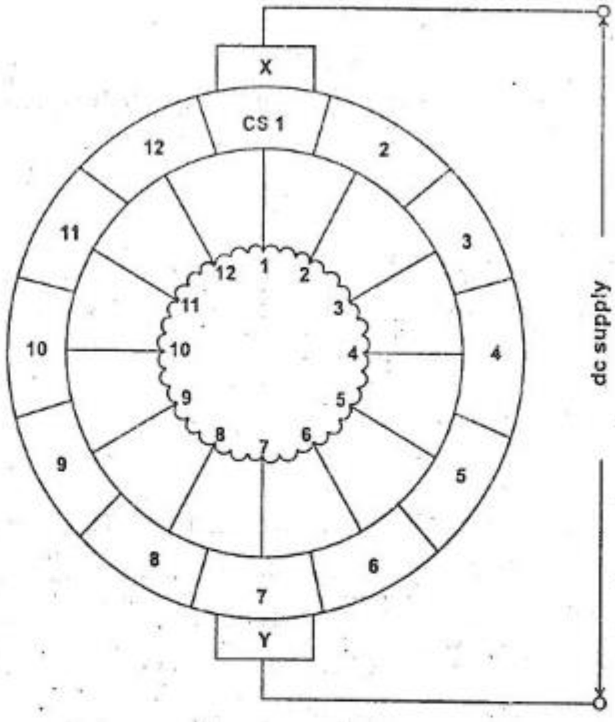


Fig 4.4 Mechanical Commutator and Brushes Arrangement

It represents a case with 2poles and 12 commutator segments.

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

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

(i) 2–3–4–5–6–7–8
(ii) 2–1–12–11–10–9–8

Now the mmf set up by the armature winding is form tapping 8 to 2 along the brush axis YX Thus the armature mmf direction is always along the brush axis YX, even though the current distribution in the armature winding gets altered.

In a normal dc machine brushes are kept in the interpolar axis. Therfore, the axis of the armature mmf makes an angle 90˚elec with the main field axis.

The function of commutator and brushes arrangement in a conventional dc machine is to set up an armature mmf always in quadrature with the main field mmf respectively of the speed of rotation of the rotor.

4.2.7 Electronic commutator

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

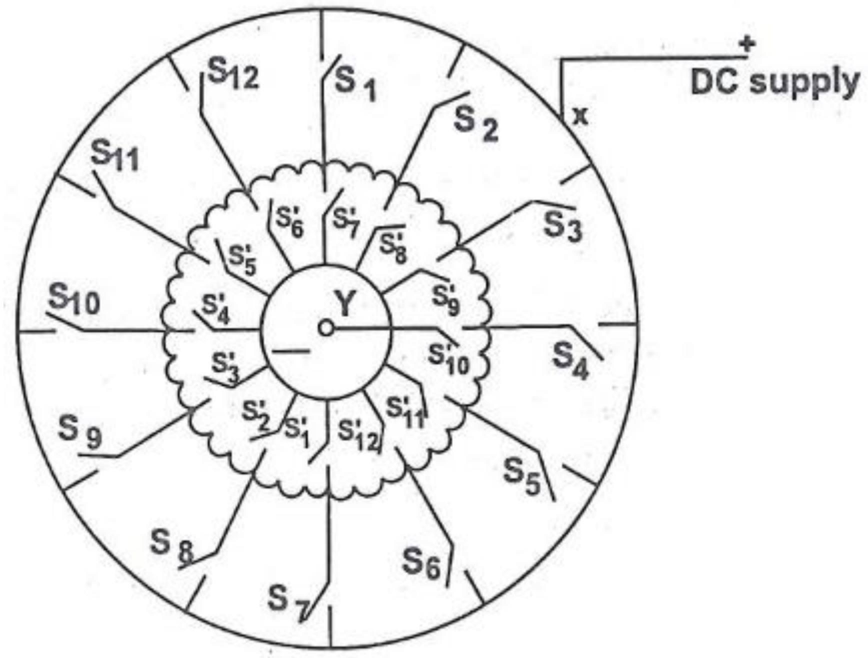


Fig 4.5 Electronic Commutator

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

(i) 1–2–3–4–5–6–7

(ii) 1–12–11–10–9–8–7

They set up armature mmf along the axis 7 to 1.

After a small interval S1 and S‘1 are kept open and S2 and S‘2 are closed. Then dc current passes from tapping 2 to 8 sets up mmf in the direction 8 – 2.

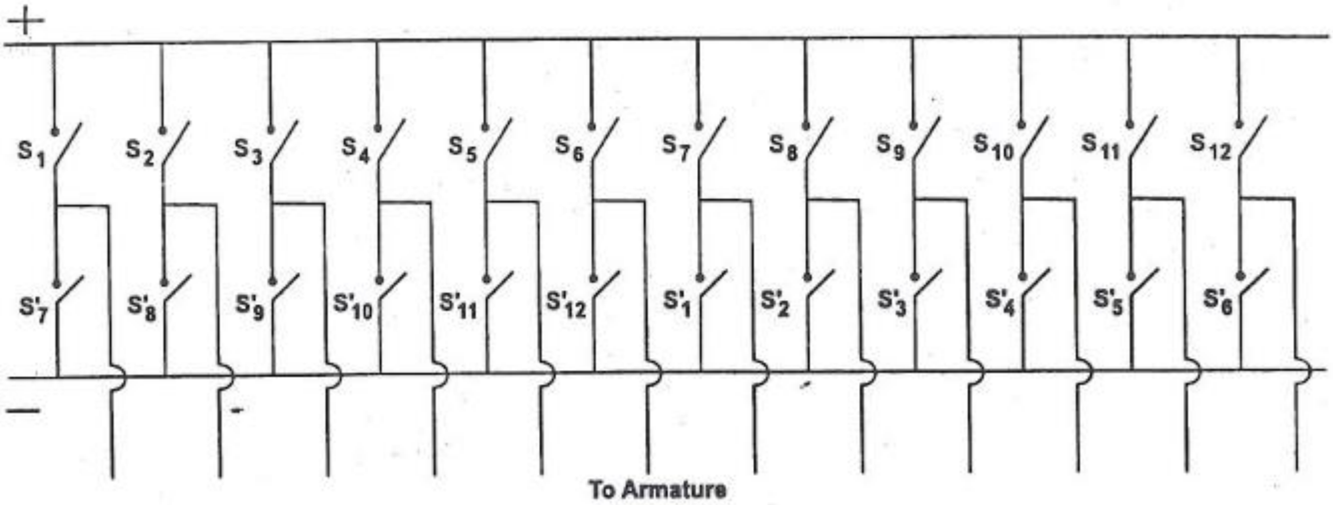


Fig 4.6 switching circuit of electronics commutator

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

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

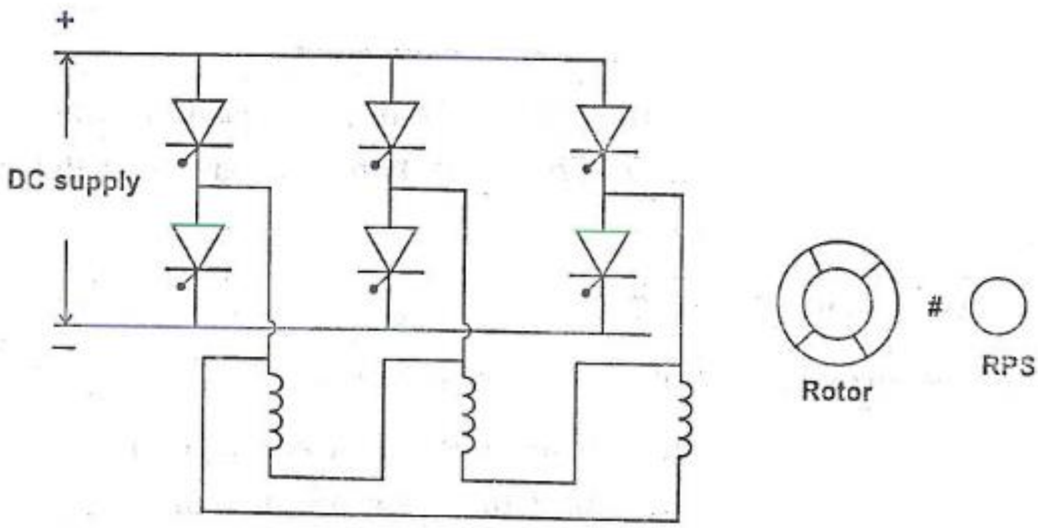


Fig 4.7 Delta Connected Stator Armature Winding

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

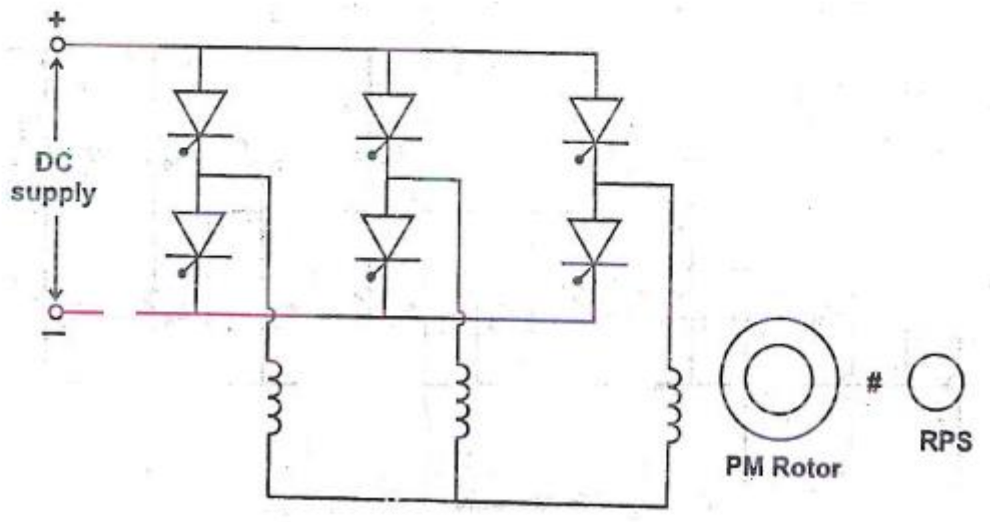


Fig 4.8 Star Connected Armature Winding

4.2.8 Comparison between mechanical Commutator and brushes and Electronic Commutator

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

4.3 PRINCIPLE OF OPERATION OF BRUSHLESS PM DC MOTOR

Starting

When dc supply is switched on to the motor the armature winding draws a current. The current distribution within the stator armature winding depends upon rotor position and the devices turned on. An emf perpendicular to the permanent magnet field is set up. Then the armature conductors experience a force. The reactive force develops a torque in the rotor. If this torque is more than the opposing frictional and load torque the motor starts. It is a self-starting motor.

Demagnetization curve

As the motor picks up speed, there exists a relative angular velocity between the permanent magnet field and the armature conductors. AS per faradays law of electromagnetic induction, an emf is dynamically induced in the armature conductors. This back emf as per len‘s law opposes the cause armature current and is reduced. As a result the developed torque reduces. Finally the rotor will attain a steady speed when the developed torque is exactly equal to the opposing frictional load torque. Thus the motor attains a steady state condition.

Electromechanical transfer

When the load – torque is increased, the rotor speed tends to fall. As a result the back emf generated in the armature winding tends to get reduced. Then the current drawn from the mains is increased as the supply voltage remains constant. More torque is developed by the motor. The motor will attain a new dynamic equilibrium position when the developed torque is equal to the new torque. Then the power drawn from the mains V *I is equal to the mechanical power delivered $\frac{2\pi NT}{60}$ = Pm =ωT and the various losses in the motor and in the electronic switching circuitry.

4.4 CLASSIFICATION OF BLPM DC MOTOR

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

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

(a) BLPM Square wave motor

These are two types: 180Ʈ pole arc.

120Ʈ pole arc.

Air gap flux density distribution in 180Ʈ BLPM SQW motor as shown in fig.

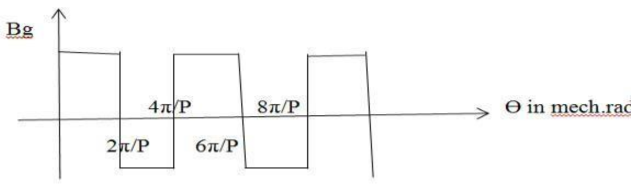


Fig 4.11 Air gap flux density distribution in 180Ʈ BLPM SQW motor.

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

fig.

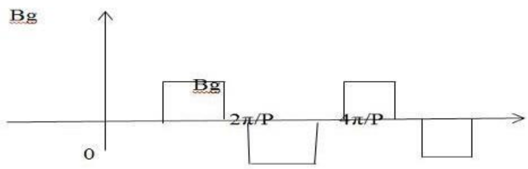


Fig 4.12 Air gap flux density distribution in 120Ʈ BLPM SQW motor

(b)BLPM Sine wave DC Motor

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

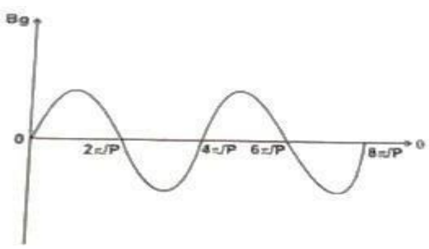


Fig 4.13 Flux density distribution of BLPM DC sine wave motor

4.5 EMF EQUATION OF BLPM SQW DC MOTORS

The basic torque emf equations of the brushless dc motor are quite simple and resemble those of the dc commutator motor.

The co-ordinate axis have been chosen so that the center of a north pole of the magnetic is aligned with the x-axis at Θ = 0 .the stator has 12 slots and a three phasing winding. Thus there are two slots per pole per phase.

- Consider a BLPM SQW DC MOTOR

Let ‗p‘be the number of poles (PM)

‗B_g‘ be the flux density in the air gap in wb/m^2.

B_k is assumed to be constant over the entire pole pitch in the air gap (180° pole arc)

‗r‘ be the radius of the airgap in m.

‗l‘ be the length of the armature in m.

‗T_c‘ be the number of turns per coil.

‗ω_m‘ be the uniform angular velocity of the rotor in mechanical rad/sec.

$\omega_m = 2\pi N/60$ where N is the speed in rpm.

Flux density distribution in the air gap is as shown in fig 4.14.At t=0(it is assumed that the axis of the coil coincides with the axis of the permanent magnet at time t=0).

Let at $\omega_m t=0$,the centre of N-pole magnet is aligned with x-axis.

At $\omega_m t=0$,x-axis is along PM axis.

Therefore flux enclosed by the coli is

$$\Phi_{max}=B \times 2\pi r/p \times l \quad \text{.......... (4.1)}$$

$$=\text{flux/pole}$$

$$\Phi_{max}=rl\int_0^{\pi} B(\theta)d\theta$$

$$=B_g\, rl[\theta]_0^{\pi}$$

$$=B_g rl[\pi]$$

At $\omega_m t=0$,the flux linkage of the coil is

$$\Lambda_{max}= (B_g \times 2\pi r/p \times l)T_c \ \omega b\text{-}T \quad \text{.......... (4.2)}$$

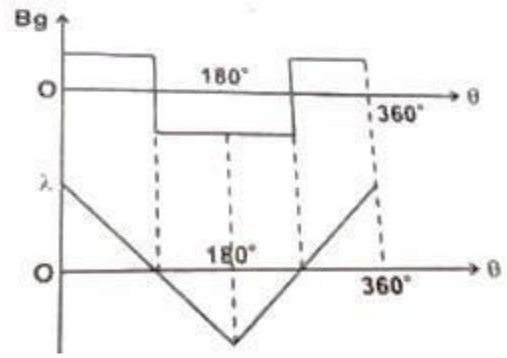


Fig 4.14 Magnetic Flux Density around the Air gap.

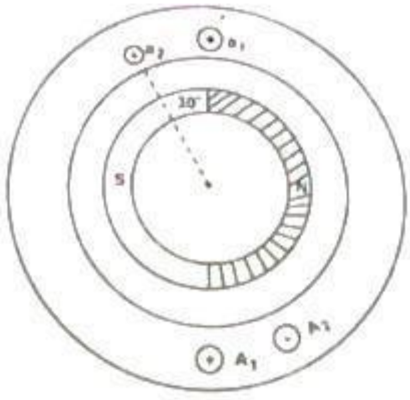


Fig 4.15 Motor Showing two Coils of One Phase.

Let the rotor rotating in ccw direction and when $\omega_{mt}=\pi/2$, the flux enclosed by the coil Φ, Therefore λ=0.

The flux linkages of the coil vary with θ variation of the flux linkage is as shown above.

The flux linkages of the coil changes from $B_g rlTc\pi/p$ at $\omega_{mt}=0$ (i.e) t= 0 t0 θ at

$t=\pi/p\omega_m$. Change of flux linkage of the coil (i.e) Δλ is

Δλ/Δt =Final flux linkage – Initial flux linkage/time.

$=0- (2B_g rlTc\pi/p)/ (\pi/p\omega_m)$

$= -(2B_g rlTc\omega_m)$……………………………………………………………………………………(4.3)

The emf induced in the coil $e_c= - d\lambda/dt$

$e_c =2B_g rlTc\omega_m$……………………………………………………………………………………(4.4)

Distribution of e_c with respect to t is shown in fig 4.16

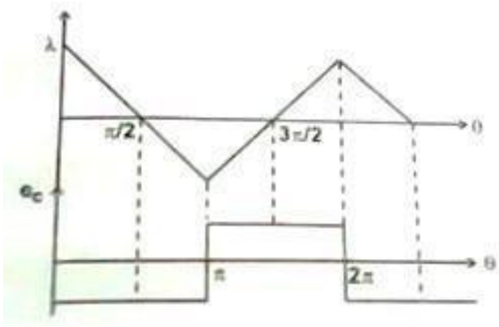


Fig 4.16 Emf waveform of coil 1

It is seen that the emf waveform is rectangular and it toggles between + e_c to - e_c. The period of the wave is $2\pi r/p\omega_m$ sec and magnitude of e_c is

$e_c = 2B_g r l T c \omega_m$ volts...(4.5)

Consider two coils a1A1 and a2A2 as shown in fig 5.15.Coil a2A2 is adjacent to a1A1 is displaced from a1A1 by an angle 30°(i.e.) slot angle γ .

The magnitude of emf induced in the coil a1A1

$e_{c2} = B_g r l T c \omega_m$ volts ....(4.6)

The magnitude of emf induced in the coil a2A2

$e_{c2} = B_g r l T c \omega_m$ volts ....(4.7)

Its emf waveform is also rectangular but displaced by the emf of waveform of coil e_{c1} by slot angle γ .

If the two coils are connected in series, the total phase voltage is the sum of the two separate coil voltages.

$e_{c1} + e_{c2} = 2B_g r l T c \omega_m$ ....(4.8)

Let n_c be the number of coils that are connected in series per phase $n_c T_c = T_{ph}$ be the number of turns/phase.

$e_{ph} = n_c\, [2B_g r l T c \omega_m\,]$...(4.9)

$e_{ph} = 2B_g r l T_{ph} \omega_m$ volts..(4.10)

e_{ph}=resultant emf when all n_c coils are connected in series.

The waveforms are as shown in fig 4.17

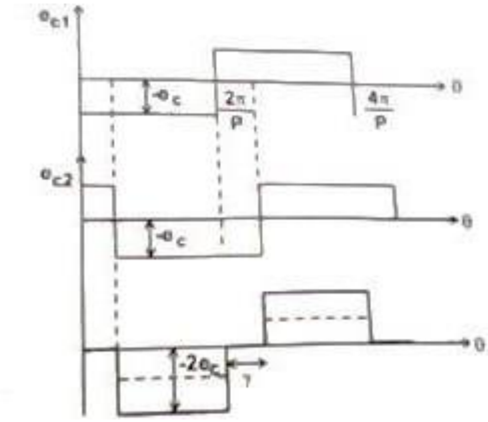


Fig 4.17 Emf waveform of phase a

The waveform of e_{ph} is stepped and its amplitude is $2B_{g}rlT_{ph}\omega_{m}$ volts.

At any instant 2-phase windings are connected in series across the supply terminals as shown in fig 4.18.

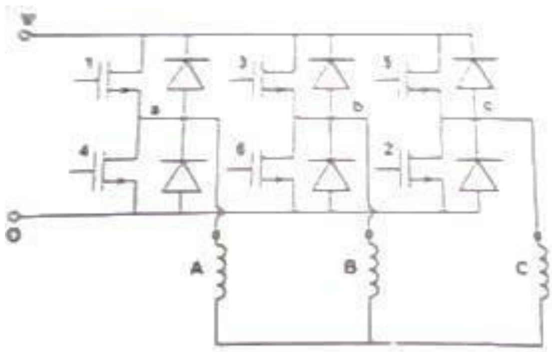


Fig.4.18 converter of brushless dc motor with star connected phase winding.

Assumption

- Armature winding is Y connected.
- Electronic switches are so operated using rotor position sensor that the resultant emfs across the winding terminals is always = 2 eph.
- Amplitude of back emf generated in Y connected armature winding E = 2 eph.

4.6 BASIC VOLTAGE EQUATION OF BLPMDC MOTOR

Let V be the dc supply voltage

I be the armature current

R_{ph} be the resistance per phase of the λ connected armature winding.

V_{dd} be the voltage drop in the device (it is usually neglected)

e_{ph} be the back emf generated per phase of Y connected armature winding .

$V = 2\,e_{ph} + 2IR_{ph} + 2V_{dd}$ ……………………………………...(4.11)

If V_{dd} is neglected

$V = 2\,e_{ph} + 2\,I\,R_{ph}$

$I = \frac{V \quad 2\,eph}{2Rph}$

$I = \frac{V \quad E}{R}$ ……………………………………….(4.12)

(a) Starting condition

Speed is zero $\omega_m = 0$

Supply voltage is V

Since ω_m=0; $e_{ph} = 0$

Starting current $I_{stg} = \frac{-}{2Rph} = \frac{V}{2Rph} = \frac{V}{R}$ …………………………...(4.13)

$R = 2\,R_{ph}$ is Y connected

This current is also known as starting current.

(b) NO load condition

Current is very very small

Then $V = 2\,e_{ph} + 2\,I\,R_{ph}$

$2I\,R_{ph}$ – negligible

$V = 2\,e_{pho}$ …………………………….…(4.14)

$= 2\,[2\,B_g\,r\,l\,\omega_{mo}\,T_{ph}]$

$= 4\,[B_g\,r\,l\,\omega_{mo}\,T_{ph}]$

$V = k_e\,\omega_{mo}$ ………………………….…(4.15)

No load speed, $\omega_{mo} \cong \frac{V}{4\,Bg\,\,r\,l\,Tph}$ …………………………....(4.16)

$= \frac{V}{ke}$ …………………………..…..(4.17)

No load current I_o=0

(c) ON load condition:

$V = 2\,eph + 2\,I\,Rph$

$= 4\,Bg\,r\,l\,\omega m\,tph + 2\,I\,Rph$ …………………...(4.18)

On load current

$I = \frac{V - 2\,eph}{2Rph} = \frac{V - 4\,Bg\,r\,l\,\omega m\,tph}{2Rph}$ ....(4.19)

$= \frac{V - ke\,\omega m}{2\,Rph}$ ……………..…(4.20)

$I = \frac{V - ke\,\omega m}{2\,Rph}$ ....(4.21)

I vs ωm curve is shown in fig 4.19

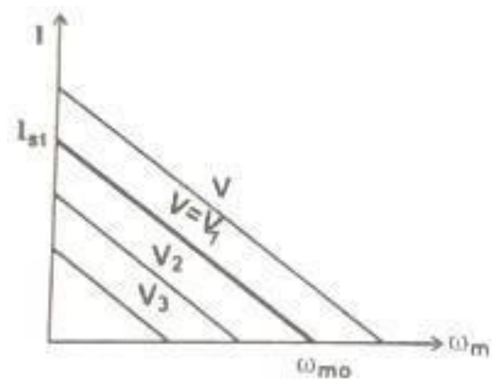


Fig.4.19 I Vs. ωm Curve

4.7 TORQUE EQUATION OF BLPM SQUARE WAVE MOTOR

Power input = VI

=[2 eph + 2 I Rph + 2 Vdd] I ....(4.22)

VI=[2 eph + 2 I Rph + 2 Vdd] I..(4.23)

VI= electrical power input

2 eph I = power converted as mechanical

2 I2 Rph = power loss in the armature winding

2 Vdd I = power loss in the device

Mechanical power developed= 2 eph I ....(4.24)

eph= 2(2BgrlTphωm)I

eph= 4BgrlTphωm ....(4.25)

Mechanical power = (2πN/60)T.. (4.26)

= ωmT.. (4.27)

Where N=Speed in rpm

T=Torque in N-m

ωm=Speed in rad/sec

Therefore T=4BgrlTphI ....(4.28)

=KtT...(4.29)

Where Kt = 4BgrlTph=Ke ....(4.30)

(a) Case1: Starting Torque

ωm=0

Istg=(V/2Rph) ………………………….…(4.31)

Tstg=4BgrlTph(V/2Rph) ………………………....(4.32)

Tstg=Kt(V/2Rph) …………………………...(4.33)

Starting torque or stalling torque depends upon V.

To vary the starting torque the supply voltage is to be varied.

(b) Case 2: On load condition

$T = K_t I$ ……………………………(4.34)

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

$I = (V-2e_{ph})/(2R_{ph})$ …………………………….. (4.35)

$2e_{ph} = V-2I\ R_{ph}$

$4\ B_g\ r\ l\ T_{ph}\ \omega_m = V-2I\ R_{ph}$ …………………………….. (4.36)

$K_e\ \omega_m = V-2I\ R_{ph}$

$\omega_m = (V-2I\ R_{ph})/\ K_e$ …………………………….. (4.37)

$\omega_{m0} = V/\ K_e$ ………………………………(4.38)

$\omega_m/\ \omega_{m0} = (\ (V-2I\ R_{ph})/\ K_e)\ (V/\ K_e\ )$

$=(V-2I\ R_{ph})/\ V$

$\omega_m/\ \omega_{m0} = 1-\ ((V-2I\ R_{ph})/\ V)$ …………………………… (4.39)

$I/(T_{stg}) = (K_t I)/(K_t I_{stg})$

$= I.(2R_{ph}/V)$

$T/\ T_{stg} = 2I\ R_{ph}/V$ ………………….. (4.40)

Substituding eqn. 5.40 in eqn. 5.39

$\omega_m/\ \omega_{m0} = 1-(\ T/\ T_{stg})$ ………………….. (4.41)

$\omega_m/\ \omega_{m0} = 1-(I-I_{stg})$ ………………… (4.42)

4.8 TORQUE- SPEED CHARACTERSISTICS OF BLPM SQM DC MOTOR

Let the supply voltage V be constant. A family of torque speed characteristics for various constant supply voltages is as shown in figure 4.20

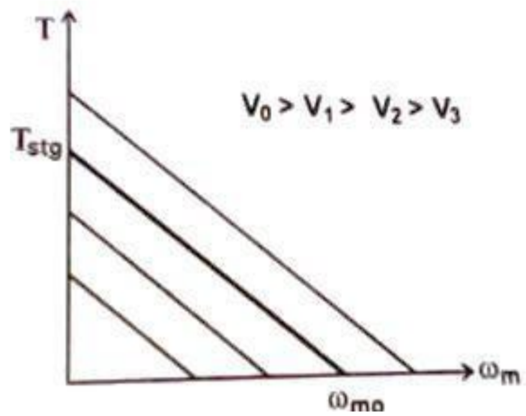


Fig 4.20 T-ω_m curve for various supply voltages

Permissible region of operation in T-ω_m plane

Torque speed characteristics of BLPM square wave motor is shown in fig.4.21. The constraints are

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

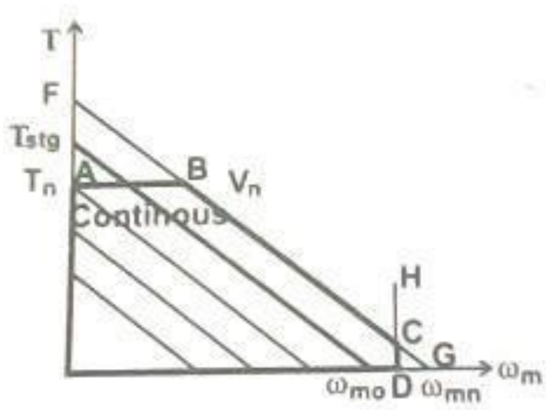


Fig. 4.21 Torque-speed characteristics

Line AB

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

Line FG

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

Line DH

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

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

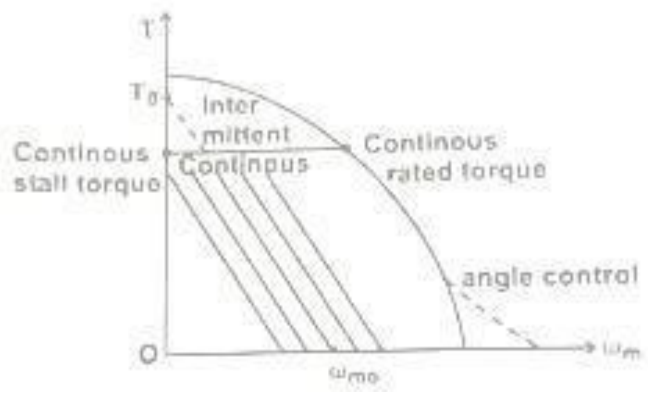


Fig.4.22 Torque speed characteristics of ideal brushless DC motor

- If the phase resistance is small as it should be in an efficient design, then the characteristics to that of a shunt dc motor. The speed is essentially controlled by the voltage V and may be changed by changing the supply voltage. Then the current drawn just to drive the torque at its speed.
- As the load torque is increased, the speed drops and the drop is directly proportional to the phase resistance and the torque.
- The voltage is usually controlled by chopping or PWM. This gives rise to a family of torque speed characteristics as shown in fig. 4.22. The boundaries of continuous and intermittent limits are shown.

Continuous limit - determined by the heat transfer and temperature rise.

Intermittent limit – determined by the maximum ratings of semiconductor devices in circuit.

In practice the torque speed characteristics deviates from the ideal form because of the effects of inductance and other parasitic influences.

Also the speed range can be extended by increasing the dwell of conduction period relative to the rotor position.

4.9 COMMUTATION IN MOTORS WITH 120° AND 180° MAGNET ARC

BLPM dc motor with 180° magnet arcs and 120° square wave phase currents arc shown in fig. 4.23 and 4.24.

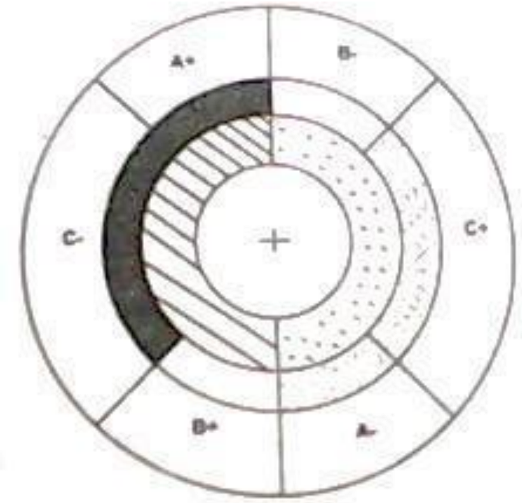


Fig.4.23 BLDC motor with 180° magnet arc and 120° square wave phase currents

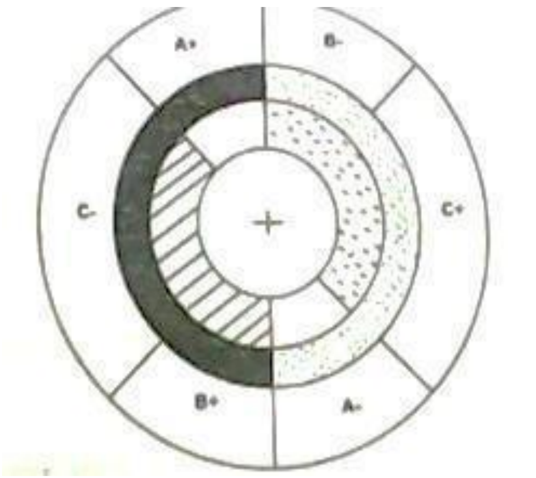


Fig.4.24 BLDC motor with 120° magnet arcs and 180° square wave phase currents

In Fig. 4.26 the rotor magnet poles are shaded to distinguish north and south. The phase belts are shaded us complete 60° sector of the stator bore. There are two slots in each of these phase belts. The current in these two slots are identical and conductors in them are in series

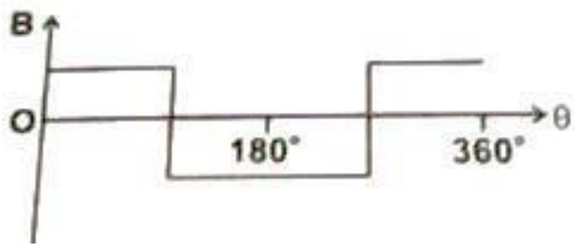


Fig.4.25 Flux density around air gap

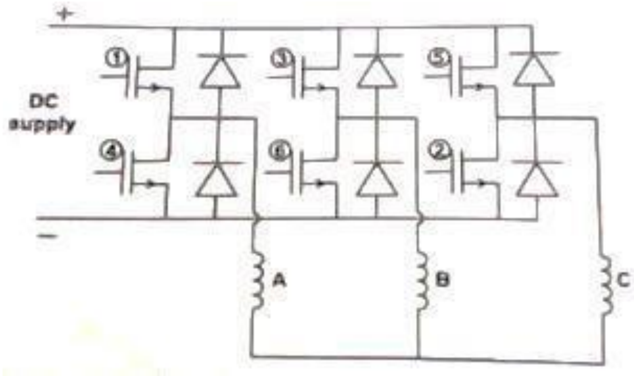


Fig.4.26 Converter of brushless DC motor for star connected phase winding

Between the rotor ring and the stationary belt ring in fig. 4.26 there is a third ring called the ‖mmf ring‖. This represents the mmf distribution of the stator currents at a particular instant.

- At the instant shown wt=0, phase A is conducting positive current and phase C is conducting negative current. The resulting mmf distribution has the same shading as the N and S rotor poles to indicate the generation of torque,
- Where the mmf distribution has like shasing, positive torque is produced. Where mmf and flux shading are unlike, negative torque is produced. Where one is zero, no torque is zero, no torque is produced. The total torque is the integral of the contributions from around the entire air gap periphery.

The rotor is rotating in the clockwise direction. After 60º of rotation, the rotor poles start to ‗uncover' the C phase belts and the torque contribution of phase C starts to decrease linearly.

During this period, the magnet poles, have been ‗covering' the B phase belts. Now if the negative current is commutated from C to B exactly at then point 60º, then the torque will be unaffected and will continue constant for a further 60º. After 120º, positive current must be commutated from A to C.

Commutation tables for three-phase brushless dc motors.

TABLE 4.1 180º Magnet-Star Winding. 120º Square wave phase Currents

Rotor Position	A	B	C	au(1)	aL(4)	bu(3)	bL(6)	cu(5)	cL(2)
0–60	+1	0	-1	1	0	0	0	0	1
60 – 120	+1	-1	0	1	0	0	1	0	0
120 – 180	0	-1	+1	0	0	0	1	1	0
180 – 240	-1	0	+1	0	1	0	0	1	0
240 – 300	-1	+1	0	0	1	1	0	0	0

300 - 360	0	+1	1	0	0	1	0	0	1

- The production of smooth, ripple free torque depends on the fact the magnet pole arc exceeds the mmf arc by 60º.
- Here only 2/3 of the magnet and 2/3 of the stator conductors are active at any instant

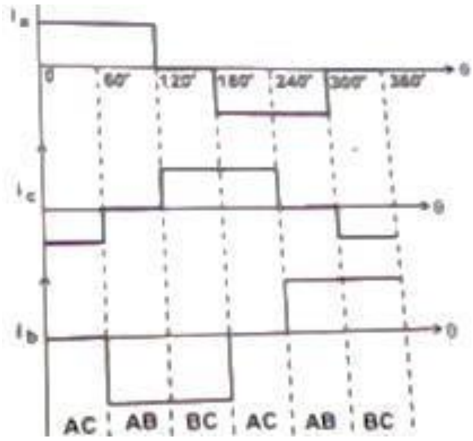


Fig. 4.27 phase current waveforms of BLDC motor with 180º pole arc.

In a practical motor the magnet flux-density distribution cannot be perfectly rectangular as shown in fig.4.27. for a highly coercive magnets and full 180º magnet arcs there is a transition section of the order of 10-20º in width. This is due to fringing effect. Likewise on the stator side, the mmf distribution is not rectangular but have a stepped wave form as shown in fig.4.28 that reflects the slotting.

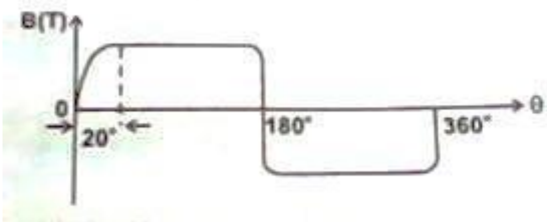
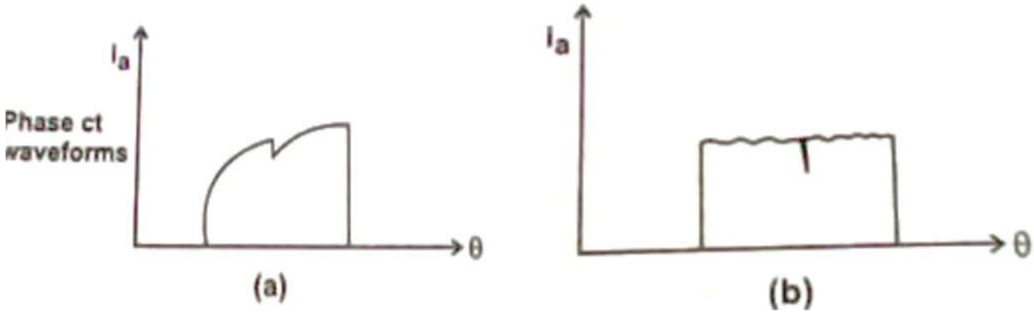


Fig 4.28 Air Gap Flux Density on Open Circuit

To some extent these effects cancel each other so that s that satisfactory results are obtained with a magnet arc as short as 150º, and two slots per pole per phase.

But there is always dip in the torque in the neighborhood of the commutation angles. This torque dip occurs every 60º elec degrees, giving rise to a torque ripple component with a fundamental frequency equal to 6P times the rotation frequency where P is the number of pole pairs. The magnitude and width of the torque dip depends on the time taken to commutate the phase current.

Phase current waveforms corresponding to high speed and low speed operations are as shown in fig. 4.29 (a & b)



(a) High speed, full voltage. Note the dip caused by commutation of other 2 phases,
(b) Low speed with current controlled by chopping.

Fig.4.29 Phase current wave forms.

- The back emf is of equal value in the incoming phase and is in such a direction as to oppose the current build up.
- While the flux distribution of the magnet rotates in a continuous fashion, the mmf distribution of the stator remains stationary for 60º and then jumps to a position 60º ahead.

Similar analysis is made with a motor having 120 º pole arc magnets with delta connected armature winding.

Table 4.2 120º Magnet Delta Winding, 180º Square Wave Phase Currents.

Rotor Position	A	B	C	ab u (1)	ab L (4)	bc u (3)	bc L (6)	ca u (5)	ca L (2)
0–60	+1	+1	-1	0	0	1	0	0	1
60 – 120	+1	-1	-1	1	0	0	0	0	1
120 – 180	+1	-1	+1	1	0	0	1	0	0
180 – 240	-1	-1	+1	0	0	0	1	1	0
240 – 300	-1	+1	+1	0	1	0	0	1	0
300 - 360	-1	+1	1	0	1	1	0	0	0

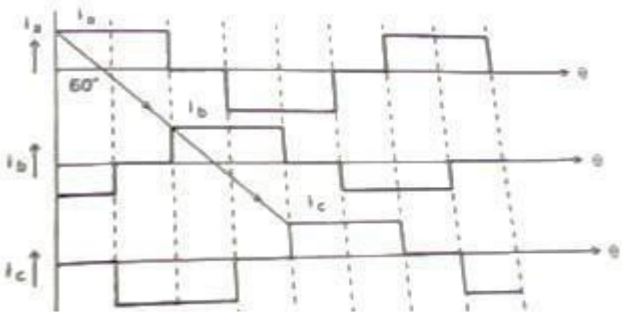


Fig.4.30 phase currents wave forms of BLDC motor with120º pole arc

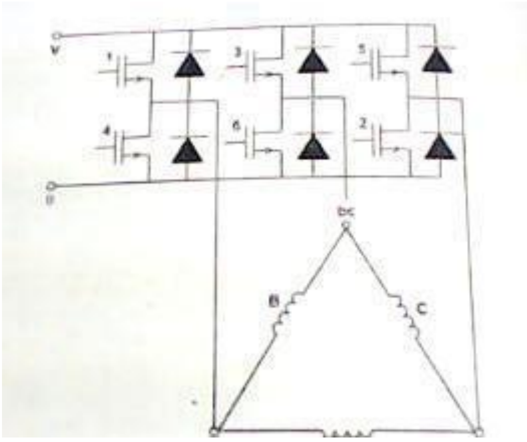


Fig 4.31 converter of brushless dc motor for delta connected phase winding

- C phase belt remains covered by the magnet poles. While the coverage of A phase belt increases thereby decreasing that of B phase belt.
- Since all the conductors are varying same current the increasing torque contribution of phase A is balancing by the decreasing contribution of phase B. Therefore, the total torque remains constant.
- Similarly there is a linear increase in the back emf of A and equal and oppoaite decrease in the back emf in phase B, Therefore the back emf at the terminals remains constant.
- Line current divides equally between two paths
  One-phase C Second-phase A & B series.

This balance is not perfect in practice because of the resistance and inductance of the windings.But the current balance should be maintained, otherwise circulating current may produce excessive torque ripple and additional losses.

When compared with 180° pole arc machine.

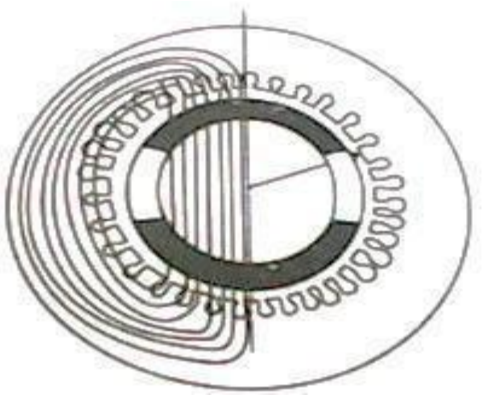
- For the same ampere-conductors per slot and for the same peak flux density, the 120° pole arc machine has 1.5 times copper losses, but produces the same torque.
- Also the ampere-conductors per slot would have to be reduced because the duty cycle is 1.0 instead of 2/3.

Merits

- For the same magnet flux density the total flux is only 2/3 of that of 180° pole arc motor, so that only 2/3 of the stator yoke thickness is required. If the stator outside diameter is kept the same, the slots can be made deeper so that the loss of ampere conductors can be at least partially covered .consequently the efficiency of the motor may not be very much less than that of 180° pole arc machine.
- In this machine also, the effects of fringing flux, slotting and communication overlap combine to produce torque ripple.
- Only emf and torque are discussed. The concept of hanging flux-linkage and energy balance can also be used to analyze the operation.

4.10 MAGNETIC CIRCUIT ANALYSIS ON OPEN CIRCUIT

Cross section of a 2 pole brushless dc motor having high energy rare earth magnets on the rotor and the demagnetization curve are as shown in fig 4.32 (a & b)



(a) Motor cross section and flux pattern (b)magnet demagnetization curve

Fig 4.32 magnetic circuit analysis of BLDC motor

First step to analyze a magnetic circuit is to identify the main flux paths and the reluctance or permeances assigned to them.

The equivalent magnetic circuit is shown in fig 4.33.only half of the equivalent circuit is shown & the lower half is the mirror image of the upper half about the horizontal axis, which is at equipotential. This assumption is true only if the two halves are balanced. If not the horizontal axis might still be an equipotential but the fluxes and the magnetic potentials in the two halves would be different and there could be residual flux in the axial direction .along the shaft. The axial flux is undesirable because it can induce current to flow in the bearing.

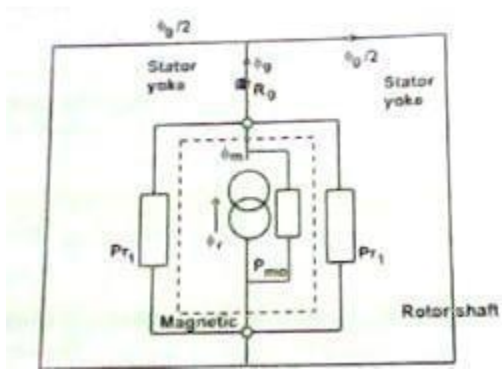


Fig .4.33 magnetic equivalent circuit.

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

Each magnet is represented by a ‗Norton' equivalent circuit consisting of a flux generator in parallel with an internal leakage permeance p_{mo}.

υr=BrAm …….(4.43)

Pmo=μ0μrecAm/lm …….(4.44)

where Am – pole area the magnet

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

Br- remanent flux density

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

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

with a magnet arc of 120°

$A_m = 2/3 \pi [r_1 – g - l_m/2] l$ ....(4.45)

r1- radius of the rotor

g- air gap length

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

$R_g = g'/\mu_0 A_g$ ………..(4.46)

g'- equivalent air gap length allowing for slotting.

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

$g' = K_c g$ ....(4.47)

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

$A_g = [2/3 \pi (r_1 - g/2) + 2g](l + 2g)$ …..(4.48)

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

  $p_m = p_{mo} + p_{rl}$ ....(4.49(a))

  $p_m = p_{mo}(1 + p_{rl})$ ....(4.49(b))

prl-normalized rotor leakage permeance

4.11 A controller for BLPM SQW DC Motor

4.11.1 Power Circuit

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

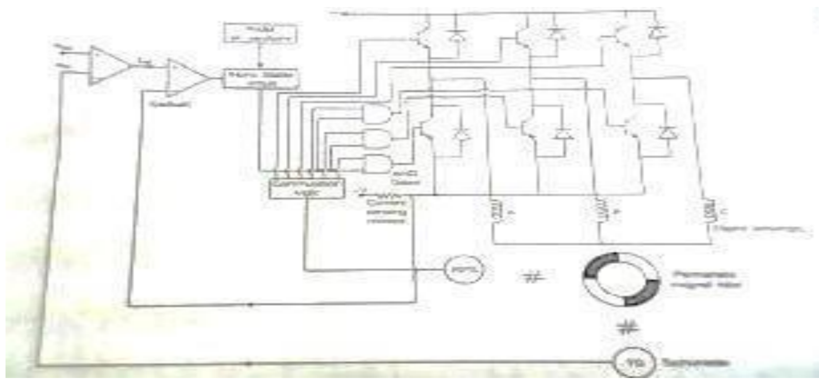


Fig 4.34 structure of controller for brushless PM DC Motor

4.11.2 Control circuit

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

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

Rotor Position sensors for BLPM motor

It converts the information of rotor shaft position into suitable electrical signal. This signal is utilized to switch ON and OFF the various semiconductor devices of electric switching and commutation circuitry of BLPM motor.

Two popular rotor sensors are

Optical Position Sensor.

Hall Effect Position Sensor.

(a) Optical position sensor

This makes use of six photo transistors. This device is turned into ON state when light rays fall on the devices. Otherwise the device is in OFF state the schematic representation is shown in fig.

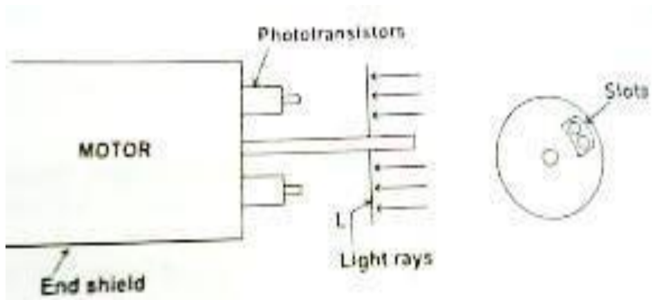


Fig 4.35 Optical position sensor

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

As the shaft rotates, the devices of electronic commutation which are turned into ON are successively changed.

(b) Hall effect position sensor

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

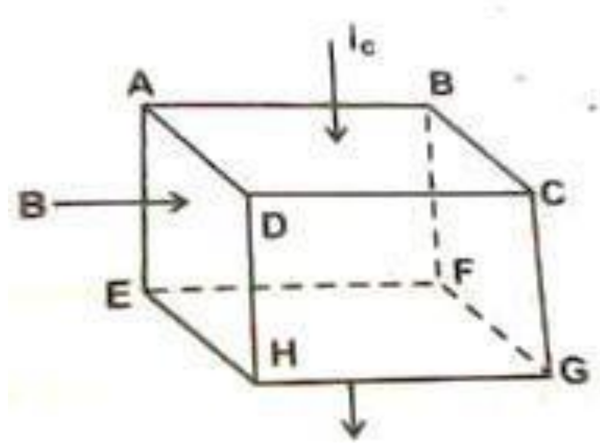


Fig 4.36 Hall Effect

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

It has been experimentally shown that emf due to hall effect is V_H is given by

$V_H = R_H(i_C / d)$ volts

Where i_C current through the pellet in amps
B- Flux density in tesla
d- Thickness of the pellet in m.
R_H – Constant which depends upon the physical dimensions or physical properties of the pellet. If the polarity of B is changed from North Pole to South Pole the polarity of the emf due to Hall Effect also get changed.

4.11.3 Hall Effect Position Sensor

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

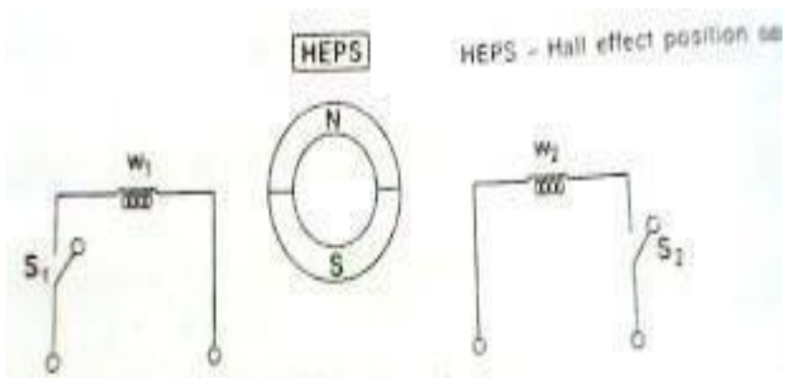


Fig 4.37 2 pole BLPM motor

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

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

4.12 Types of BLPM motor

BLPM motor is classified on the basis of number of phase windings and the number of pulses given to the devices during each cycle.

4.12.1 One phase winding one pulse BLPM motor

The stator has one phase winding as shown in fig4.38.

It is connected to the supply through a power semiconductor switch. When the rotor position sensor is influenced by say n pole flux, the stator operates and the rotor developed a torque. When the RPS is under the influence of S pole, the transistor is in off state. The rotor gets torque whenever the rotor position is under the influence of n pole.

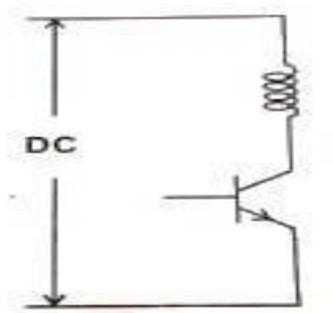


Fig. 4.38 one phase one pulse BLPM motor.

The current and torque are approximated as sinusoidally varying as shown in fig. 4.39.

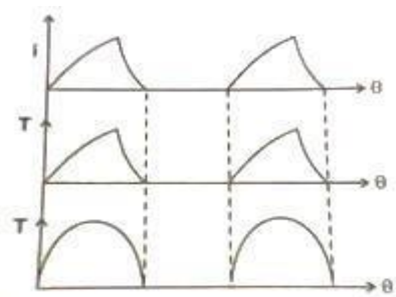


Fig.4.39 Current and torque waveform

Advantage

- One transistor and one position sensor is sufficient.
- Inertia should be such that the rotor rotates continuously.
- Utilization of transistor and winding are less than 50%.

4.12.2 One phase two pulse BLPM motor

Stator has only one winding. It is connected to DC three wire supply through two semiconductor devices as shown in fig. 4.40.

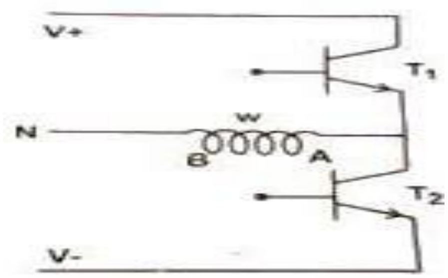


Fig. 4.40 One phase two pulse BLPM motor

There is only one position sensor. When the position sensor is under the N-pole influence,T_1 is in on-state and T_2 is in off-state. When it is under the influence of S-pole, T_2 is on and T_1 is off.

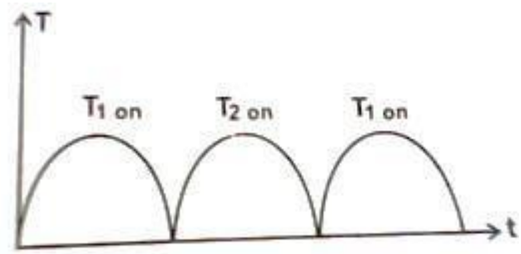


Fig. 4.41 Torque waveform

In the first case, the winding carries current from A to B and when T_2 is on, the winding carries current from B to A. The polarity of the flux setup by the winding gets alerted depending upon the position of the rotor. This provides the unidirectional torque as shown in fig. 4.41.

Advantages

- Winding utilization is better.
- Torque developed is more uniform.

Demerit

- Transistor utilization is less
- The current needs a 3-wire dc supply.

4.12.3 Two phase winding and two pulse BLPM motor

Stator has two phase windings which are displaced y 180° electrical. Electrical connections are as shown in fig. 4.42. It makes use of two semiconductor switches.

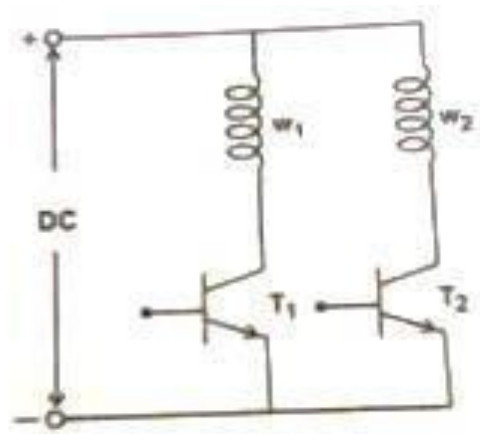


Fig. 4.42 two phase winding and two pulse motor

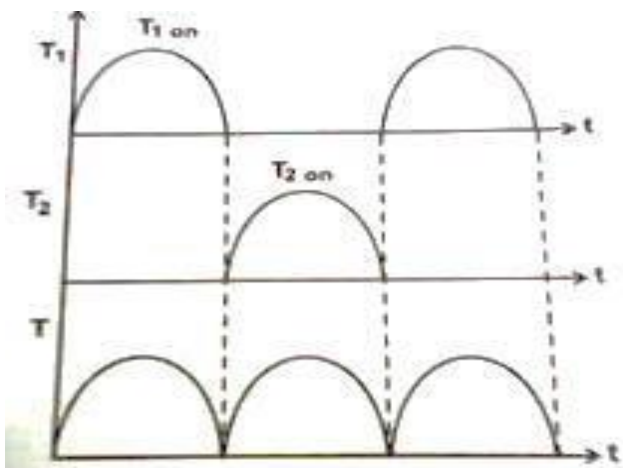


Fig. 4.43 torque waveform

Performance of this type is similar to one phase 2 pulse BLPM motor. Torque waveform are as shown in fig. 4.43. However it requires two independent phase windings.

Merit

- Better torque waveform.

Demerit

- Their utilization is only 50% which is less.
- Cabling with rotor position sensor should be made proper.

4.12.4 Three phase winding and three pulse BLPM motor

The stator has 3Φ windings as shown in fig. 4.44. Whose areas are displaced by 120°elec. apart. Each phase windings is controlled by a semiconductor switch which is operated depending upon the position of the rotor. Three position sensors are required for this purpose.

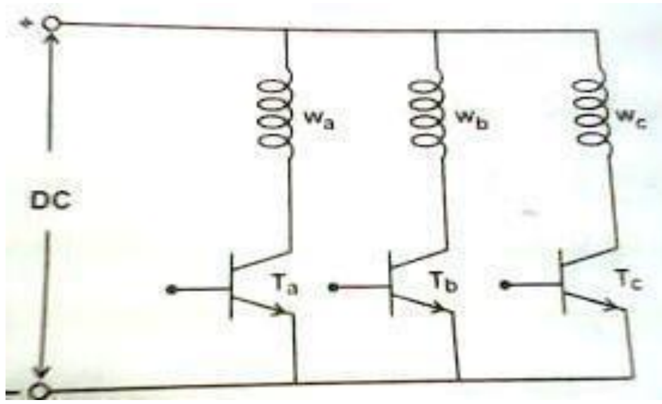


Fig. 4.44 3 phase, 3 pulse BLPM motor.

4.12.5 Three phase six pulse BLPM motor

Most commonly used. It has 3 phase windings and six witching devices as shown in fig. 4.45.

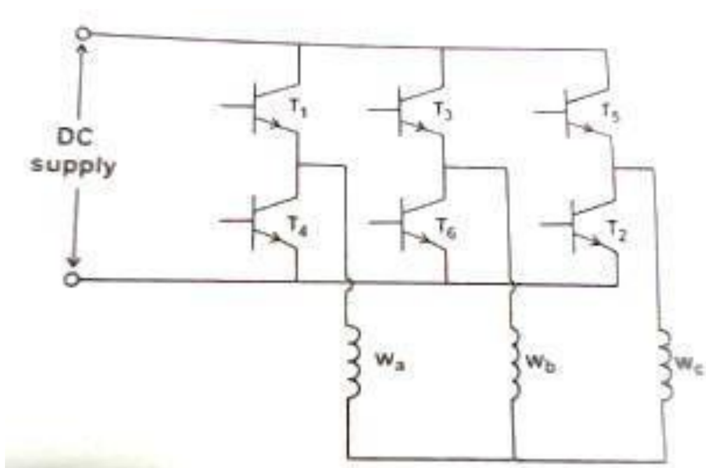


Fig. 4.45 3-phase six pulse BLPM motor.

Glossary

1.	Brushless PM D.C.Motor	--	It is similar to salient pole D.C.Motor except that there is no field winding on rotor and is provided by PM. It reduces losses. Complexity in construction is reduced.
2.	Magnetic Remanence	--	The magnetic flux density which persists in magnetic materials even though the magnetizing forces are completely removed.
3.	Coercivity Forces	--	The demagnetizing force which is necessary to neutralize completely themagnetism in an electromagnet after the magnetizing force becomes zero.
4.	Position Sensors	--	The position sensors detect the position of rotating magnets and send logic codes to commutation decoder.
5.	Energy Product	--	The absolute value of product of flux density and field intensity at each point along the demagnetization curve is called energy product.
6.	Electronic Commutator	--	It is to transfer the current to the armature. Power semiconductors are used as switching devices. Armature has three tappings, which can be connected either in star or in delta.
7.	Commutator	--	A commutator is a rotary electrical switch in certain types of electric motors or electrical generators.
8.	Friction	--	A force that resists motion between two objects that are in contact with each other. Smoother surfaces exhibit less friction, while rougher surfaces exhibit more friction.
9.	Magnet	--	A device or object that attracts iron and produces a magnetic field.
10.	Magnitude	--	The measurement of the amount of an applied force.
11.	Rotary Speed	--	A measure of circular motion found by counting the number of revolutions that occur in a specific amount of time.

13. Atmospheric Hazard -- A confined space hazard that is present in the environment. Atmospheric hazards are categorized as flammable, toxic, irritant, and asphyxiating.

14. Remanence The ability of a material to retain magnetization, equal to the magnetic flux density of the material after the removal of the magnetizing field Also called: retentivity

15. Permeance, In general, is the degree to which a material admits a flow of matter or energy.

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QUESTIONS:

UNIT – IV - PERMANENT MAGNET BRUSHLESS DC MOTOR

PART- A

1 Argue on the type of commutation is used in PMBLDC motors.

2 Describe about the Permanent magnet Brushless DC motor.

3 List any two applications of PMBLDC motors.

4 Describe the reason for PMBLDC motors are used in servo motor applications.

5 List any two advantages of a PMBLDC motor.

6 Compare conventional DC motor and PMBLDC motor.

7 List the types of PMBL square wave motor.

8 Describe Electronic commutator.

9 Argue on the efficiency improvement in PMBLDC motors compared to ordinary DC motors.

10 State an equation for the EMF induced/phase of a PMBLDC motor.

11 State an equation for the torque of a PMBLDC motor.

12 Explain about the position sensors that are used in PMBLDC motor.

13 List any four permanent magnetic material used in a PMBLDC motor.

14 Sketch the speed-torque characteristics of a PMBLDC motor.

15 List the application of PMBLDC motor.

PART B

1 (a)Distinguish the mechanical & electronic commutation.

(b)Sketch the torque speed characteristics of PMBL dc motor and Explain.

2 Describe the expression for EMF induced for a square wave PMBLDC motor.

3 The PMBLDC motor has a no-load speed of 6000rpm when connected to 120V DC supply. The armature resistance is 2Ω. The rotational and iron losses may be neglected. Determine the speed when the supply voltage voltage is 60V and the torque is 0.5N-m.

4 Explain the different types of rotor position sensor. Discuss the use of Hall sensors for position sensing in PMBLDC motor.

5 Explain the switching circuit of electronic commutator.

6 Explain the construction & working principle of PMBLDC motor.

7 Describe the operation of power controller for PMBL square wave motor with neat diagram.

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UNIT – V - SPECIAL ELECTRICAL MACHINES – SEE1307

UNIT-5

PERMANENT MAGNET SYNCHRONOUS MOTOR

5.1 INTRODUCTION

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

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

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

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

5.2 CONSTRUCTION AND PRINCIPLE OF OPERATION

Permanent magnet synchronous machines generally have same operating and performance characteristics as synchronous machines. A permanent magnet machine can have a configuration almost identical to that of the conventional synchronous machines with absence of slip rings and a field winding.

Construction

Fig. 5.1 shows a cross section of simple permanent magnet synchronous machines. It consists of the stationary member of the machine called stator. Stator laminations for axial air gap machines are often formed by winding continuous strips of soft steel. Various parts of the laminations are the teeth slots which contain the armature windings. Yoke completes the magnetic path. Lamination thickness depends upon the frequency of the armature source voltage and cost.

Armature windings are generally double layer (two coil side per slot) and lap wound. Individual coils are connected together to form phasor groups. Phasor groups are connected together in series/parallel combinations to form star, delta, two phase (or) single windings.

AC windings are generally short pitched to reduce harmonic voltage generated in the windings.

Coils, phase groups and phases must be insulated from each other in the end-turn regions and the required dielectric strength of the insulation will depend upon the voltage ratings of the machines.

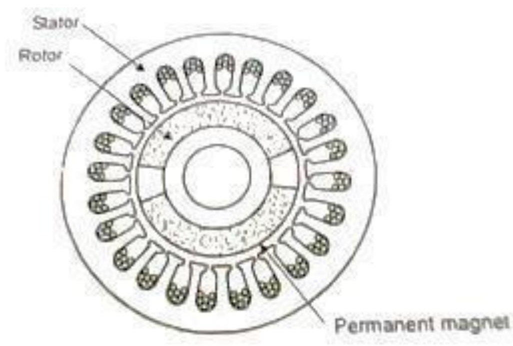


Fig. 5.1 structure of the stator and rotor

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

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

Many permanent magnet synchronous machines may be cylindrical or ―smooth rotor‖ physically but electrically the magnet is still equivalent to a salient pole structure. Some of the PMSM rotors have the permanent magnets directly facing the air gap as in fig. 5.2.

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

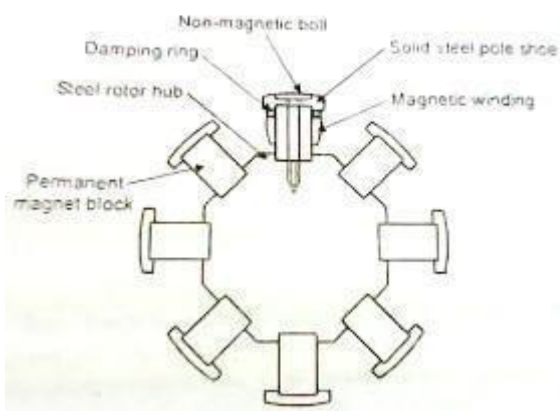


Fig. 5.2 PMSM rotor

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

The main purpose is to dampen the oscillations about synchronous speed, but the bars are also used to start synchronous motors in many applications.

The design and assembly of damper bars in permanent magnet machines are similar to the other types of synchronous machines.

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

1. Peripheral rotor
2. Interior rotor
3. Claw pole or lundell rotor.
4. Transverse rotor.

- **Peripheral rotor**

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

- **Interior rotor**

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

- **Claw pole or Lund ell**

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

- **Transverse rotor**

  In this type the permanent magnets are generally between soft iron poles and the permanent magnet flux is circumferential. In this soft iron poles at as damper bars. Magnetically this configuration is similar to a reluctance machine rotor, since the permeability of the permanent magnet is very low, almost the same as that of a non-magnetic material. Therefore, reluctance torque as well as torque resulting from the permanent magnet flux is developed.

  Thus BLPM sine waves (SNW) motor is construction wise the same as that of BLPM square wave (SQW) motor. The armature winding and the shape of the permanent magnet are so designed that flux density distribution of the air gap is sinusoidal(i.e.) .The magnetic field setup by the permanent magnet in the air gap is sinusoidal

5.3 EMF EQUATION OF BLPM SINE WAVE MOTOR

5.3.1 Flux density distribution

$= \hat{B}\sin\theta$ or $\hat{B}\cos p\theta$ or $\hat{B}\sin(p\theta+\alpha)$ or $\hat{B}\cos(\rho\theta+\alpha)$,2p=p,(i.e)p-no of pole pairs depending upon the position of the reference axis as shown in fig6.3

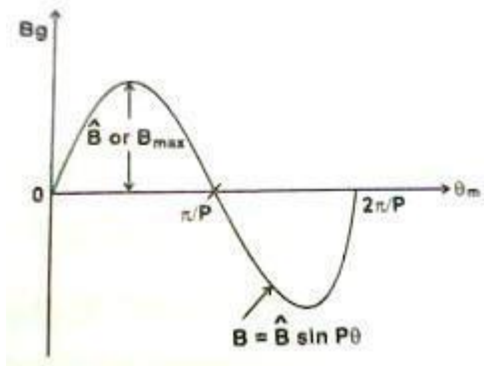


Fig 5.3 flux density distribution

Consider a full pitched single turn armature coil as shown in fig 5.4.Let the rotor be revolving with a uniform angular velocity of $\dot{\omega}_m$ mech.rad/sec.

At time t = 0, let the axis of the single turn coil be along the polar axis.

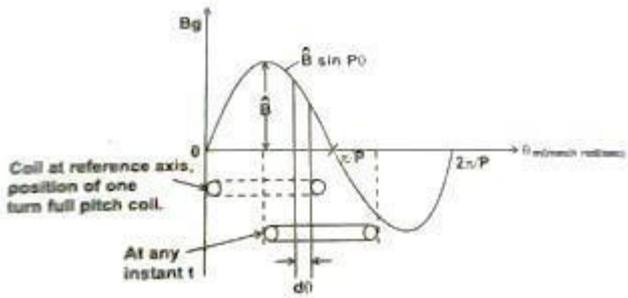


Fig 5.4 full pitched single turn armature coil

Consider a small strip of dθ mech.radians at a position θ from the reference.

$= \hat{B}\sin p\theta$

Incremental flux in the strip dθ = B X area swept by the conductor

$d\theta = \hat{B}\sin p\theta \times lr\, d\theta$

B lr dθ weber

Where

L – Length of the armature in m

r – Radians of the armature

$d\,\theta = \hat{B}\sin p\theta \times lr\, d\theta$

$= \hat{B}\, lr \sin p\theta \times d\theta$

Flux enclosed by the coil after lapes of t sec is

$\phi = \int_{0}^{\omega m+\frac{\pi}{p}} \hat{B}\, lr \sin P\theta\, d\theta$ .... (5.1)

$\phi = (2\ B\urcorner lr/p) \cos p\theta\ \omega_m t$

5.3.2. EMF Equation of an ideal BLPM sine wave motor

As per faradays law of electromagnetic induction, emf induction in the single turn coil.

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

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

$= - d\phi /dt ((2\ B\urcorner lr/p) \cos p\theta\ \omega_m t)$

$= (2\ B\urcorner lr/p)\, p\, \omega_m \sin p\, \omega_m t$

$e = 2\ B\lrcorner\, lr\, \omega_m \sin p\, \omega_m t$ ……..(5.2)

let the armature winding be such that all turns of the phase are concentrated full pitched and located with respect to pole axis in the same manner.

Let T_{ph} be the number of turns connected in series per phase. Then the algebraic addition of the emfs of the individual turns gives the emf induced per phase as all the emf are equal and in phase.

e_{ph} $lr\, \omega_m \sin p\, \omega_m t)T_{ph}$ ……..(5.3)

$= (2= 2B\urcorner\, lr\, \omega_m T_{ph} \sin p\, \omega_m t$

$= \breve{E}_{ph} \sin p\, \omega_m t$ where $p\, \omega_m t = \omega_e$ angular frequency in red/sec

$= \breve{E}_{ph} \sin \omega_e t$

……..(5.4)

$\breve{E}_{ph} = 2\ B\urcorner\, lr\, \omega_m T_{ph}\, \omega_m$

$\breve{E}_{ph}$ = rms value of the phase emf

$= \breve{E}_{ph}/ \sqrt{2}$

$= \sqrt{2}\ B\urcorner\, lr\, \omega_m T_{ph}\, \omega_m$

$\omega_m = \omega_e/\rho$

ϕ_m – sinusoidal distributedflux / pole

……..(5.5)

$\phi = B_{av}\, \tau\, l$

$= B_{av} \times (2\pi r / 2p) \times l$

Average value of flux density for sinewave =2/π

$= (2/\pi)\, B\square$

$\phi_m = (2/\pi)\, B\urcorner \times (\pi r / P).\, l$

$\phi_m = (2\, B\urcorner\, r\, l / P)$

$B\urcorner\, r\, l = (P\, \phi_m / 2)$ ……..(5.6)

$E_{ph} = \sqrt{2}\, B\square\, lr\, \omega_m\, T_{ph}$ .volt

Sub equ

$E_{ph} = \sqrt{2}\, (P\, \phi_m / 2)\omega_m\, T_{ph}$

$= \sqrt{2}\, (P\, \phi_m / 2)\, (\omega/p)\, T_{ph}$

$= \sqrt{2}\, (P\, \phi_m / 2)\, (2\pi f/p)\, T_{ph}$

$E_{ph} = 4.44\, f\, \phi_m\, T_{ph}$. Volt ……..(5.7)

5.3.3 EMF equation of practical BLPM sine wave motor

In a practical BLPM sine wave motor at the time of design it is taken care to have the flux density is sinusoidal distributed and rotor rotates with uniform angular velocity. However armature winding consists of short chorded coils properly distributed over a set of slot.

These aspect reduce the magnitude of E_{ph} of an ideal winding by a factor K_{w1} which is known as the winding factor the fundamental component of flux.

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

K_{s1} =slew factor

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

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

σ – Skew angle in elec. Radians.

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

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

Where m = coil span/pole pitch

= fraction < 1

π(1 - m) = ρ

[Coil span = τ

= π elec rad

= π/ρ mech. Rad]

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

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

K_{b1} = Distribution factor or width factor

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

Where v = slot angle in elec. Radians

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

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

= slots/pair of poles/phase

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

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

Thus rms value of the per phase emf is

$E_{ph} = 4.44\, f \Phi_m T_{ph} K_{w1}$ volts. ……..(5.9)

5.4. TORQUE EQUATION OF BLPM SINE WAVE MOTOR

5.4.1. Ampere conductor density distribution

Let the fig. 5.5 shows the ampere conductor density distribution in the air gap due to the current carrying armature winding be sinusoidal distributed in the airgap space.

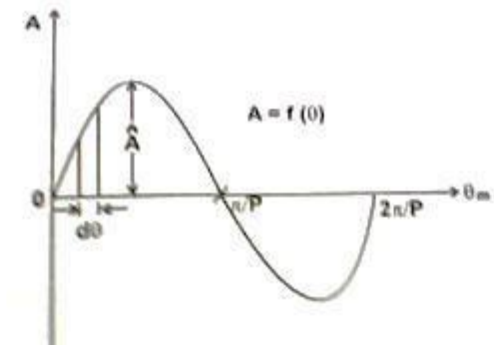


Fig. 5.5 Ampere conductor density distribution

$A = \hat{A} \sin p\,\theta$

Where A = ampere conductor density

= ampere conductor/degree

Consider a strip of d θ at an angle θ from the reference axis.

Ampere conductor in the strip d θ = A dθ ……..(5.10)

$= \hat{A} \sin P\theta\, d\,\theta$

Ampere conductor per pole = $\int_0^{\pi/p} \hat{A} \sin P\,\theta\, d\,\theta$ ……..(5.11)

$= -\hat{A}\left[\frac{\cos P\,\theta}{P}\right]$

$= -\frac{\hat{A}}{P}\,[\cos\pi - \cos 0]$

$= \frac{2}{P}\,A$

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

Let i be the current

i T_{ph} be the total ampere turns which is assumed to be θ sine distributed.

Total ampere conductors [sine distributed] = 2i T_{ph}

Sine distributed ampere conductors/pole = $\frac{2i}{2P}\,Tph$

Equating eqn. 6.30 and eqn. 6.32

$\frac{2}{P}\,A = \frac{2i}{2P}\,Tph$

$\mathbf{A}^{\wedge} = \frac{iTph}{2}$ ……..(5.12)

5.4.2. Torque equation of an ideal BLPM sine wave motor:

Let the ampere conductor distribution of ideal BLPM sine wave motor be given

by $A = A^{\wedge} \sin P\ \theta$

Let the flux density distribution set up by the rotor permanent magnet be also sinusoidal.

Let the axis of armature ampere conductor distribution be displaced from the axis of the flux density distribution by an angle $(\frac{\pi}{2}\_\alpha)$ as shown in fig 5.6

$$[\ B = B^{\wedge} \sin\left(P\ \theta + \left(\frac{\pi}{2} - \alpha\right)\right) \quad \text{.........(5.13)}$$

$$= B^{\wedge} \sin\left[\frac{\pi}{2} - (P\ \theta\_\alpha)\right]$$

$$= B^{\wedge} \cos\ (P\ \theta\_\alpha)$$

$$B = B^{\wedge} \cos\ (P\ \theta - \alpha) \quad \text{……..(5.14)}$$

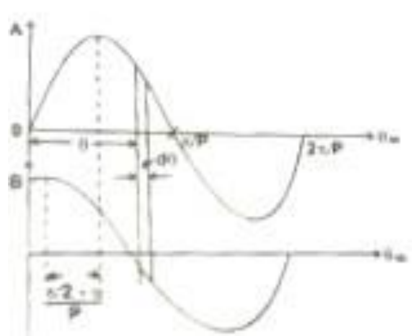


Fig. 5.6 Ampere conductor and flux density distribution.

Consider a small strip of width d θ at an angle θ from the reference axis.

Flux density at the strip B =B^ cos(pΘ-α)

Ampere conductors in the strip =AdΘ

=A sinPΘ dΘ ……..(5.15)

Force experienced by the armature conductors in the strip dΘ= BIAdΘ

dF=B^ cos(PΘ-α)1.A^B^1.A^sin PΘ.dΘ

dF=A^B^I sinPΘ cos(PΘ-α) dΘ.

Let _r‘ be the radial distance of the conductors from the axis of the shaft.

Torque experienced by the ampere conductors of the strip=dF*r

dT=AB r1 sin PΘ cos(PΘ-α) Dɵ N-m

Torque experienced by the ampere conductors/pole T/Pole = $\int_0^{\pi/p} dT$

T=$\int_0^{\pi} A\, B\ \ rl$ sin P θ cos (P θ – α) d θ ……..(5.16)

= A B rl/2 $\int_0^{\pi} /p\, (\sin P\,\theta + P\,\theta\_\alpha + \sin\alpha)\, d\,\theta$

= A B rl/2 $\left[\_\frac{\cos(}{2p} 2P\theta\_\alpha) + \theta\ sin\alpha\right]$

=A B rl/2 – $\left[\frac{cos\alpha}{2p} + \frac{cos\alpha}{2p} + \frac{\pi}{p}\ sin\alpha\right]$

T=A B rl/2.$\frac{\pi}{p}\ sin\alpha$ N-m ……..(5.17)

The total torque experienced by all the armature conductors

=2P x torque/pole

=2P x $\frac{\pi}{P} \times \frac{ABrl}{2} \sin\alpha$

T= π A B rl sin α N-m… …..(5.18)

As the armature conductors are located in stator of the BLPM SNW motor, the rotor experiences an equal and opposite torque.

= Torque developed by the rotor

= -π A B rl sin α

= π A B rl sin β where β= -α ……..(5.19)

B is known as power angle or torque

angle. T= π A B rl sin β in an ideal motor.

Consider the case of an armature winding which has three phases. Further the winding consists of short chorded coils and the coils of a phase group are distributed. The 3 phase armature winding carries a balanced 3 phase ac current which are sinusoidally varying. The various phase windings are ph a, ph b and ph c.

The axis of phase winding are displaced by 2π/3p mechanical radians or 2π/3 elec. Radians. The current in the winding are also balanced. An armature winding is said to be balanced if all the three phase winding are exactly identical in all respects but there axes are mutually displaced by 2π/3p mech radians apart.

A three phase armature current is said to be balanced when the 3 phase currents are exactly equal but mutually displaced in phase by 120 degree.

Let

$i_a = Im \cos \omega t$ $\overline{(i.\quad}$ $I \cos \omega t$

$I_{b=}$ $Im \cos\left(\omega t - \frac{2\pi}{3}\right) = \sqrt{2}I \quad (\omega t - 2\pi/3)$

$i_c = Im \cos \left(\omega t + \frac{2\pi}{3}\right) = \sqrt{2}I \quad (\omega t - 4\pi/3)$

When the 3 phase ac current passes through the 3 phase balanced winding it sets up an armature mmf in the air gap.

Space distribution of the fundamental component of armature ampere conductors can be written as.

$f_a = F_m \cos P\,\theta$ ……..(5.23)

$f_b = F_m \cos [P\,\theta - 2\pi/3]$ ……..(5.24)

$f_c = F_m \cos [P\,\theta - 4\pi/3]$ ……..(5.25)

5.4.3 Torque developed in a practical BLPM SNW motor:

- Ampere turn distribution of a phase winding consisting of full pitched coil is rectangular of amplitude I T ph. But the fundamental component of this distribution is the fundamental component of this distribution is 4/πi Tph.
- In a practical motor, the armature turns are short chorded and distributed .Further they may be accomonadated in skewed slots. In such a case for getting fundamental component of ampere turns distribution the turns per phase is modified as Kw1 Tph where Kw1 is winding factor which is equal to Ks1 Kp1 Kd1

Ks1 = Skew factor

$= \frac{\sin\sigma/2}{\sigma/2}$; σ = skew angle in elec. rad.

Kp1 = $\sin\frac{m\pi}{2}$ $m\pi$ = coil span in elec. Rad

Kd = distribution factor

= $\frac{\sin q\ v/2}{q \sin\frac{v}{2}}$ v-slot angle in electrical.rad, q-slot per pole for 60degree phase spread.

Fundamental component of ampere turns per phase of a practical one

=4/π I Tph Kw1 ……..(5.26)

- when a balanced sinusoidally varying 3 phase ac current pass through a balanced 3 phase winding it can be shown that the total sinusoidally distributed ampere turns is equal to 3/2.4/π Imax Kw1 Tph.

= 4/π.3/2 $\sqrt{2}$ Iph Kw1 Tph ……..(5.27)

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

Therefore Ā in a practical 3 phase motor = $\frac{\frac{4}{\pi}.3/2.\sqrt{2}}{2}$ Iph Kw1 Tph

Electromagnetic torque developed in a practical BLPL SNW motor

=π A B rl sin β ……..(5.28)

$=\pi\left[3\sqrt{\frac{2}{\pi}}Iph\ Kw1\ Tph\right]$ B r l sin β

= 3($\sqrt{2}$Kw1 Tph B rl)$Iph\ sin\beta$

$=3\,\frac{Eph}{\omega m}\ Iph \sin\beta$ ……..(5.29)

$i_a\,T_{ph} = I_{max}$ cosωt cosθ ……..(5.30)

$i_b\,T_{ph} = I_{max}\cos\left(\omega t-\frac{2\pi}{3}\right)\cos\left(\theta-\frac{2\pi}{3}\right)$ ……..(5.31)

$i_c\,T_{ph} = I_{max}\cos\left(\omega t-\frac{4\pi}{3}\right)\cos\left(\theta-\frac{4\pi}{3}\right)$ ……..(5.32)

$i\ \ T_{ph} = i_a\,T_{ph}+i_b\,T_{ph}+i_c\,T_{ph}$ ……..(5.33)

$= I_{max}\left(\frac{\cos(\omega t+\theta)+\cos(\omega t\ \ \theta)}{2}\right) + I_{max}\left(\frac{\cos(\omega t+\theta-4\pi/3)+\cos(\omega t\ \ \theta)}{2}\right) +$
$I_{max}\left(\frac{\cos(\omega t+\theta-8\pi/3)+\cos(\omega t-\theta)}{2}\right)$

$=\frac{1}{2} I_{max} . 3 \cos(\omega t-\theta)+\frac{1}{2} I_{max}[\cos(\omega t+\theta) \cos 240+\sin(\omega t+\theta) sin 240+\cos(wt+\theta) \cos 480+\sin(wt+\theta) sin 480]$

$=\frac{3}{2} I_{max} \cos(\omega t-\theta)+\frac{1}{2} I_{max}[\cos(\omega t+\theta)-\cos(\omega t+\theta)-0.866 \sin(\omega t+\theta)-0.5 \cos(\omega t+\theta)+0.866 \sin(\omega t+\theta)]$

$=\frac{3}{2} I_{\max T_{ph}} \cos(\omega t-\theta)$ ……..(5.34)

Properties of ‗A‘ (Ampere conductor density);

- Ampere conductor density is sinusoidally distributed in space with amplitude Â. This distribution has 2p poles (i.e) same as the rotor permanent magnetic field.
- The ampere conductor distribution revolves in air gap with uniform angular velocity $ώ_m$ rad /sec .or ώelec.rad/sec.(Ns rpm). This is the same speed as that of rotor magnetic field.
- The direction of rotation of armature ampere conductor distribution is same as that of rotor. This is achieved by suitably triggering the electronic circuit from the signals obtained from rotor position sensor.
- 4. The relative angular velocity between sine distributed permanent magnetic field and sine distributed armature ampere conductor density field is 0. Under such condition it has been shown an electromagnetic torque is developed whose magnitude is proportional to sin β.

β-torque angle or power angle.

Angle between the axes of the two fields is π/2-α and β=-α

Torque developed by the motor = $3E_{ph}I_{ph}\sin\beta/ώ_m$ N-m

Where ώm-angular velocity in rad/sec.

ώm=2πNs/60 where N_S is in rpm

T=60/2πNs (3EphIphsinβ)

$=3E_{ph}I_{ph}\sin\beta$ syn.watts.

1 syn.watt=60/2πNs N-m

It is a machine dependent conversion factor

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

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

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

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

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

1. V - supply voltage per phase across each winding of the armature .
   The magnitude of this voltage depends upon dc voltage and switching techniques adopted .
2. E_f - emf induced in the armature winding per phase due to sinusoidally varying permanent magnetic field flux.
   Magnitude of $E_f = 4.44 \upsilon_m f K_{w1} T_{ph} = I\ E_f I$
   As per Faradays law of electromagnetic induct5ion, this emf lags behind υ_{mf}- permanent magnet flux enclosed by armature phase winding by 90°.
3. E_a - emf induced in the armature phase winding due to the flux υ_a set up by resultant armature mmf $\upsilon \infty I_a$

$$I\ E_a I = 4.44 f \upsilon_a K_{w1} T_{ph}$$

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

$$I\ E_a I = I\ I_a X_a I \text{ where } X_a = 4.44 f K K_{w1} T_{ph}$$

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

Therefore $E_a = -jX_a I_a$

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

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

$\emptyset_{al}$ is the leakage flux and is directly proportional to I_a.

Therefore $|E_{al}|$ = 4.44 f ($K_{al} I_{al}$ $K_{w1} T_{ph}$)

$|E_{al}| = I_a X_{al}$

Where = 4.44 f $K_{al} K_{w1} T_{ph}$ in the leakage inductance. E_{al} lags behind $\emptyset_{al}$

Or I_a, by 90º

Therefore $E_{al} = -jI_a X_{al}$

Voltage equation:

The Basic voltage equation of the armature circuit is

$\dot{V} + \dot{E}f + \dot{E}al = \dot{I}a\,Ra$ ……..(5.35)

Where Ra is the resistance per phase of the armature winding.

$\dot{V} + \dot{E}f - j\,\dot{I}a\,Xa - j\,a\,Xal = \dot{I}\;a\,Ra$

$\dot{V} + \dot{E}f - j\,\dot{I}a\,(Xa + Xal) = \dot{I}\;a\,Ra$

$\dot{V} + \dot{E}f - j\,\dot{I}a\,Xs = \dot{I}a\,Ra$ ……..(5.36)

Where Xs =Xa+Xl

Xs is knowen as synchronous reactance per phase or fictious reactance.

V=(-Ef)+Ia(Ra+jXs)

$\dot{V} = \dot{E}q + \dot{I}a\,Zs$

Where Zs is the synchronous impedance.

Let Eq be the reference phasor. Let it be represented by OA.

Let I be the current phasor.OB represents I.

Ef be the emf induced in the armature winding by permanent magnet flux = -Eq

OC represents Ef

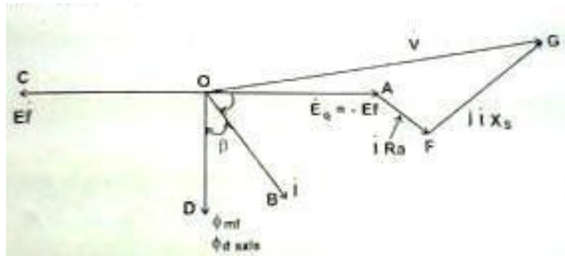


Fig 5.7 phasor diagram of BLPM sine wave motor

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

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

AF represents IaRa

FG represents Ia Xs; FG is perpendicular to I phasor

OG represents V

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

Power input = 3VI

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

= 3 Eq.Ia+3 I^2 Ra+O ……..(5.37)

3Eq I – electromagnetic power transferred as mechanical power.

3I^2Ra – copper losss.

Mechanical power developed = 3 Eq.I ……..(5.38)

= 3 Eq I cos(90-β)

= 3 Eq I sin β

= 3 Ef I sin β ……..(5.39)

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

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

= P/ω_m

= 3Eq Isin β/ω_m ……..(5.40)

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

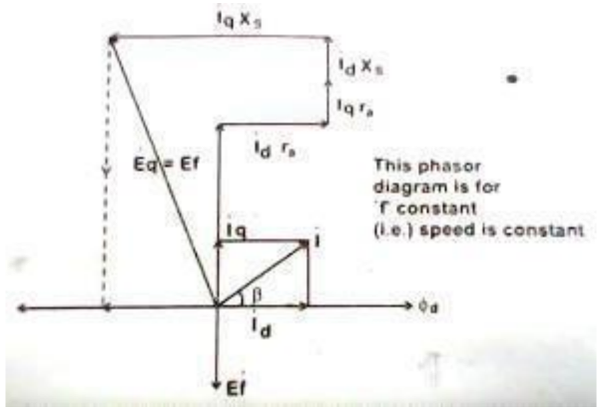


Fig 5.8 Phasor Diagram of BLPM sine wave motor with Φ d or Φ mf as reference axis

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

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

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

V = Eq +I Ra + j I Xs .... (5.41)

I = Iq + Id .... (5.42)

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

V can be represented as a complex quantity.

V = (V_r + j V_{IP})

From the above drawn phasor.

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

I can also be represented as a complex quantity

I = Id + j Iq

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

= Re(3((Id r_a - Iq Xs)+j (Eq+ Iq r_a + Id Xs)) ((Id-j IQ))) (i,e) power input = Re(3($_d$ ra – Id Iq Xs) + (-j Id Iq ra + j I_q^2 Xs) + j(Eq Id + Iq Id ra+ I_d^2 Xs) + (Eq Iq + $_q$ ra + Id Iq Xs))

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

= 3 Eq Iq + 3(I_d^2 + I_q^2) r_a

= 3 Eq Iq + 3 $I^2_d r$ ……..(5.43)

Electromagnetic power transferred = 3 Eq Iq

= 3 EI sin β

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

Electromagnetic Torque developed = 3 Eq Iq/ $_m$ N-m

Note:

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

From eqn. (5.43)

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

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

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

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

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

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

Torque developed for a salient pole machine is given by

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

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

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

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

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

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

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

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

In the phasor diagram shown in fig. 5.10.

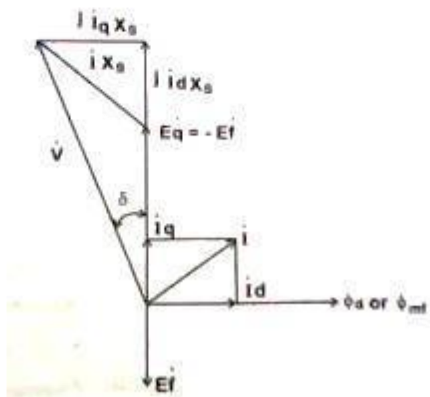


Fig 5.9 Phasor Diagram neglecting the effect of resistance

Neglecting the effect of resistance, the basic voltage equation of BLPMSNW motor

(i.e.,) $\dot{V} = \dot{E}_q + j X_s$

As the effect of resistance is neglected

$\frac{\dot{V}}{jX_s} = \frac{\dot{E}_q}{jX_s} + \dot{I}$ ……..(5.44)

$\dot{I} = \frac{\dot{V} \quad \dot{E}_q}{jX_s}$ ……..(5.45)

For a particular frequency of operation the phasor diagram can be drawn as shown in figure.

5.6. PERMISSIBLE TORQUE-SPEED CHARACTERISTICS

The torque-speed characteristics of BLPM sine wave motor is shown in fig. 5.10

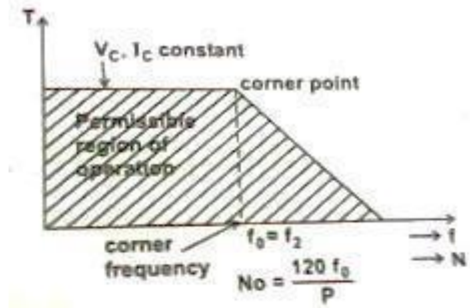


Fig 5.10 torque-speed characteristics of BLPM sine wave (SNW) motor.

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

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

Effect of over speed

In the torque speed characteristics, if the speed is increased beyond the point D, there is a risk of over current because the back emf E_q continues to increase while the terminal voltage remains constant. The current is then almost a pure reactive current flowing from the motor back to the supply. There is a small q axis current and a small torque because of losses in the motor and in the converter. The power flow is thus reversed. This mode of operation is possible only if the motor ‗over runs' the converter or is driven by an external load or prime mover.

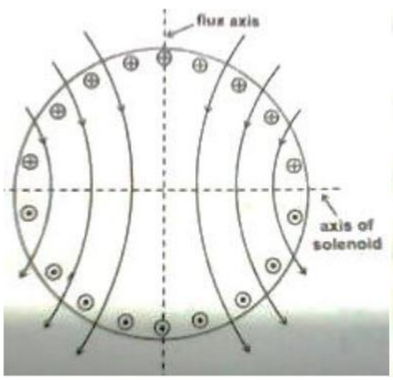
In such a case the reactive current is limited only by the synchronous reactance. As the speed increase further, it approaches the short circuit current $\frac{E}{X_s}$ which is many times larger than the normal current rating of the motor winding or the converter. This current may be sufficient to demagnetize the magnets particularly if their temperature is high. Current is rectified by the freewheeling diodes in the converter and there is a additional risk due to over voltage on the dc side of the converter, especially if a filter capacitor and ac line rectifiers are used to supply the dc. But this condition is unusual, even though in the system design the possibility should be assessed.

Solution

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

5.7. VECTOR CONTROL OF BLPM SNW MOTOR

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



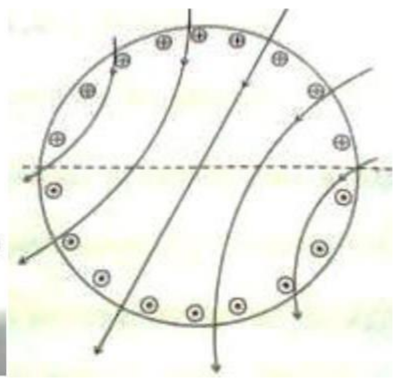


Fig. 5.11 Quadrature position of air gap flux and armature mmf axis.

Fig. 5.12 Non- Quadrature position of air gap flux and armature mmf axis.

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

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

In this case also each and every armature conductor experiences a force and contributes to the torque. But in this case the direction of the torque experienced by the conductors is not the same. Since conduction develops torque in one direction while the others develop in the opposite direction. As a result, the resultant torque gets reduced; consequently it is observed that both the steady state and dynamic performance of such a motor is poorer.

For a BLPM motor to have better steady state and dynamic performance, it is essential that the armature mmf axis and the axis of PM are to be in quadrature for all operating condition.

5.7.1. Principle of vector control

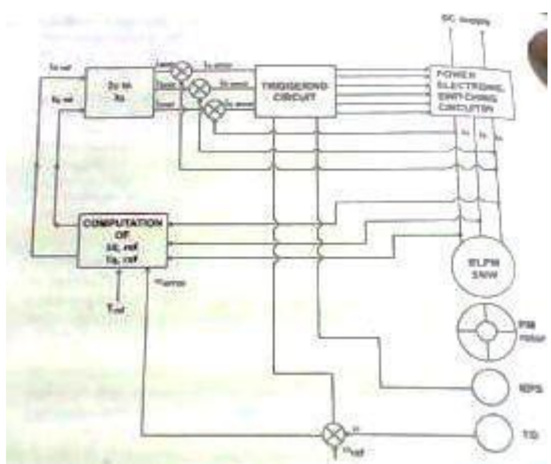
BLPM SNW motor is usually employed for variable speed applications. For this we keep V/f constant and vary V and f to get the desired speed and torque.

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

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

5.7.2. Schematic Diagram of Vector Control

The schematic block diagram of vector control is as shown in figure 5.13Knowing the value of the desired torque and speed and also the parameters and the voltage to which the motor is subjected to, it is possible to complete the values of $i_{d\ .ref}$ and $i_{q\ .ref}$ for the desired dynamic and steady state performance.



RPS – Rotor position sensor, TG – Tachogenerator

Fig.5.13 Schematic diagram of vector control

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 BLPM SNW motor is achieved.

5.8 SELF CONTROL OF PMSM

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

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

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

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

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

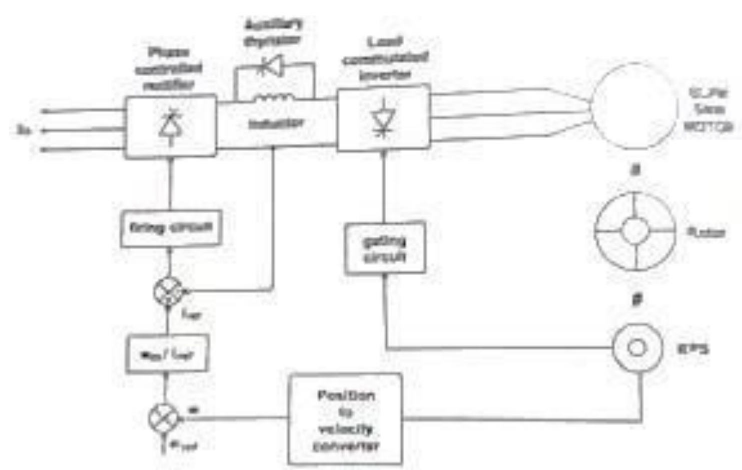


Fig 5.14 Schematic diagram of self-control

At high power levels the most common power converter configuration is the current fed DC link converter which is shown in fig. 5.14.

5.8.1 Inner current and outer speed loop

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

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

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

This reference current is compared with the sensed dc link current which provides control signals for the rectifier thyristor. The sensed shaft position is used as gating signal for inverter thyristor.

5.8.2Commutation at low speed

Load commutation is ensured only at high speeds. Whereas at low speeds the emf generated is not sufficient for load commutation. The inverter can be commutated by supplying pulsating on and off dc link current. This technique produces large pulsating torque but this is not suitable for drives which require smooth torque at low speed.

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

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

5.8.3 Four Quadrant Operations

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

Regenerative braking is accomplished by shifting the gate signal, so that machine side inverter acts as a rectifier and supply side rectifier as a inverter, hence the power is return to the ac utility network. The direction of rotation

Of the motor is also reversible by alternating the gate sequence of the motor side converter. Thus four quadrant operations are achieved, without additional circuitry.

5.9 MICROPROCESSOR BASED CONTROL OF PMSE

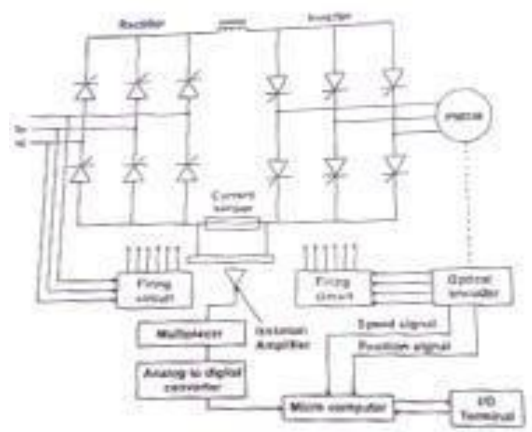


Fig.5.15 Microprocessor Based Control of PMSM

Fig 5.15 shows the block diagram of microprocessor based permanent magnet synchronous motor drive.

The advent of microprocessor has raised interest in digital control of power converter systems and electronics motor drives since the microprocessor provides a flexible and low cost alternative to the conventional method.

For permanent magnet synchronous motor drive systems, microprocessor control offers several interesting features principally improved performance and reliability, versatility of the controller, reduced components and reduced development and manufacturing cost. In the block diagram of the microprocessor controller PMSM shown in fig 5.15, the permanent magnet synchronous motor is fed from a current source d.c link converter system, which consists of a SCR invertor through rectifier and which is operated from three phase a.c supply lines, and its gating signals are provided by digitally controlled firing circuit.

The optical encoder which is composed of a coded disk attached to the motor shaft and four optical sensors, providing rotor speed and position signals. The invertor triggering pulses are synchronized to the rotor position reference signals with a delay angle determined by an 8-bit control input. The inverter SCR‘s are naturally commutated by the machines voltages during normal conditions. The speed signals, which is a train of pulses of frequency, proportional to the motor speed, is fed to a programmable counter used for speed sensing.

The stator current is detected by current sensor and amplified by optically isolated amplifier. The output signals are multiplexed and converted to digital form by a high speed analog to digital converter.

The main functions of the microprocessor are monitoring and control of the system variables for the purpose of obtaining desired drive features. It can also perform various auxiliary tasks such as protection, diagnosis and display. In normal operation, commands are fetched from the input-output terminals, and system variables (the dc link current, the rotor position and speed) are sensed and fed to the CPU. After processing, the microprocessor issues control signal to the input rectifier, then the machine inverter, so as to provide the programmed drive characteristics.

Glossary

1. Permanent Magnet Synchronous Motor -- It is also called as brushless permanent magnet sine wave motor. It has Sinusoidal magnetic flux in the air gap, Sinusoidal current wave forms, and Quasi-sinusoidal distribution stator windings.

2. Flux density -- The intensity of this flux

3. Vector Control -- Also called field-oriented control (FOC), isa variable frequency drive (VFD) control method which controls three-phase AC electric motor

4. Self-Control -- Self-control is the ability to controlone's , behavior, and desires in order to obtain some reward.

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

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

7. Resistivity -- Also known as specific resistance, the measure of a material's natural resistance to current flow. Resistivity is the opposite of conductivity, so it follows that good conductors have low resistivity per circular mil foot.

8. Specific Resistance -- Another term for resistivity. Every material has a set specific resistance per circular mil foot at a specific temperature.

9. Temperature Coefficient -- A ratio of increased conductor resistance per degree Celsius rise in temperature. Most metals increase in resistance as temperature increases, giving them a positive temperature coefficient.

10. Pole -- One of two ends of the axis of a sphere. Poles also refer to the opposite ends of a magnet.

11. Reluctance -- A material's resistance to becoming magnetized.

12. Residual Magnetism -- The attractive force that exists in an object or substance after it has been removed from a magnetic field.

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QUESTIONS:

UNIT – V - PERMANENT MAGNET SYNCHRONOUS MOTOR

PART – A

1 Compare the stator windings of square wave PMBL D.C motor &sine wave PMBL D.C motor.

2 Distinguish PMBLDC motor and PM synchronous motor.

3 Discuss about the self control in PMSM.

4 List the applications of the permanent magnet synchronous motor.

5 Describe the expression for3 phase torque of a permanent magnet synchronous motor.

6 Sketch the phasor diagram of the permanent synchronous motor for lagging p.f when I_d is negatve.

7 Sketch and explain speed torque characteristics of PMSM.

8 List the advantages of load commutation.

9 Describe the features of PMSM.

10 Compare self and vector control of PMSM.

PART B

1 Explain the torque-speed characteristics of PMSM.

2 Derive an expression for the torque generated Torque equation of PMSM.

3 With a neat block diagram explain the control of a PMSM using a microprocessor based controller.

4 With the neat Block Diagram explain the Vector Control operation of PM Synchronous Motor.

5 With the neat Block Diagram explain the self Control operation of PM Synchronous Motor.

6 Explain the principle of operation of a sine wave Permanent Magnet Synchronous Machine. Draw its phasor diagram and derive its EMF equation.