Constructional features – Principle of operation – Variable reluctance motor – Hybrid motor – Single and multi stack configurations – Torque equations – Modes of excitation – Characteristics – Drive circuits – Microprocessor control of stepper motors – Closed loop control - Concept of lead angle – Applications

2.1 INTRODUCTION

It is an electrodynamics and electromagnetic equipment.

These motors are also referred to as step motors or stepping motors.

On account of its unusual construction, operation and characteristics it is difficult to define a stepper motor.

A stepper motor is brushless dc motor whose rotor rotates in discrete angular displacements when its stator windings are energized in a programmed manner. Rotation occurs because of magnetic interaction between rotor poles and poles of the sequentially energized winding. The rotor has no electrical windings, but has salient and magnetic/or magnetized poles.

The stepper motor is a digital actuator whose input is in the form of digital signals and whose output is in the form of discrete angular rotation. The angular rotation is dependent on the number of input pulses the motor is suitable for controlling the position by controlling the number of input pulses. Thus they are identically suited for open position and speed control.

Applications:

- Printers
- Graph plotters
- Tape driver
- Disk Drives
- Machine Tools
- X-Y Recorders
- Robotics space Vehicle
- IC Fabrication and Electric Watches

2.2 CLASSIFICATION OF STEPPER MOTORS

As construction is concerned stepper motors may be divided into two major groups.

1. **Without Permanent Magnet**
   (a) Single Stack
   (b) Multi Stack

2. **With Permanent Magnet**
   (a) Claw Pole Motor
   (b) Hybrid Motors

2.3 SINGLE STACK VARIABLE RELUCTANCE STEPPER MOTOR

2.3.1 Construction:

The VR stepper motor characterized by the fact there is no permanent magnet either on the rotor or the stator. The construction of a 3-phase VR stepper motor with 6 poles on the stator and 4-pole on the rotor as shown.

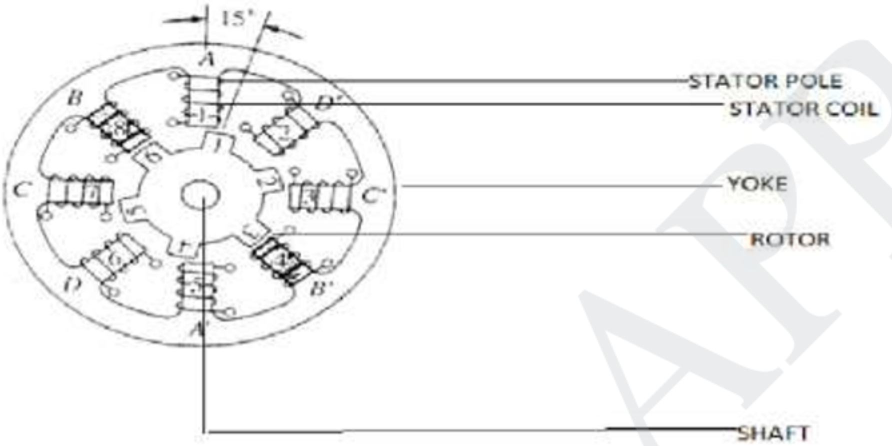


Fig 2.1 Single Stack Variable Reluctance Stepper Motor

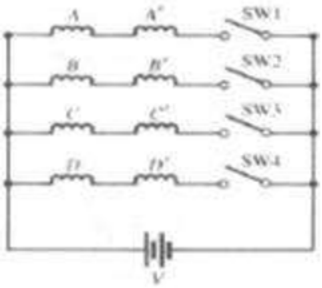
The Stator is made up of silicon steel stampings with inward projected even or odd number of poles or teeth. Each and every stator poles carries a field coil an exciting coil. In case of even number of poles the exciting coils of opposite poles are connected in series. The two coils are connected such that their MMF gets added .the combination of two coils is known as phase winding.

The rotor is also made up of silicon steel stampings with outward projected poles and it does not have any electrical windings. The number of rotor poles should be different from that of stators in order to have self-starting capability and bi direction. The width of rotor teeth should be same as stator teeth. Solid silicon steel rotors are extensively employed. Both the stator and rotor materials must have lowering a high magnetic flux to pass through them even if a low magneto motive force is applied.

2.3.2 Electrical Connection

Electrical connection of VR stepper as shown fig. Coil A and A' are connected in series to form a phase winding. This phase winding is connected to a DC source with the help of semiconductor switch S1.Similary B and B' and C and C' are connected to the same source through semiconductor switches S2 and S3 respectively. The motor has 3 –phases a, b and c.

- a phase consist of A and A' Coils
- b phase consist of B and B' Coils
- c phase consist of C and C' Coils



2.3.3 Principle of Operation

It works on the principle of variable reluctance. The principle of operation of VR stepper motor explained by referring fig.

(a).Mode 1 : One phase ON or full step operation

In this mode of operation of stepper motor only one phase is energized at any time. If current is applied to the coils of phase _a‘ (or) phase _a‘ is excited, the reluctance torque causes the rotor to run until aligns with the axis of phase a. The axis of rotor poles 1 and 3 are in alignment with the axis of stator poles _A‘ and _A‘‘. Then angle θ = 0° the magnetic reluctance is minimized and this state provides a rest or equilibrium position to the rotor and rotor cannot move until phase _a‘ is energized.

Next phase b is energized by turning on the semiconductor switch S2 and phase _a‘ is de – energized by turning off S1.Then the rotor poles 1 and 3 and 2 and 4 experience torques in opposite direction. When the rotor and stator teeth are out of alignment in the excited phase the magnetic reluctance is large. The torque experienced by 1 and 3 are in clockwise direction and that of 2 and 4 is in counter clockwise direction. The latter is more than the former. As a result the rotor makes an angular displacement of 30° in counterclockwise direction so that B and B‘ and 2 and 4 in alignment. The phases are excited in sequence a, b and c the rotor turns with a step of 30° in counter clockwise direction. The direction of rotation can be reversed by reversing the switching sequence in which are energized and is independent of the direction of currents through the phase winding.

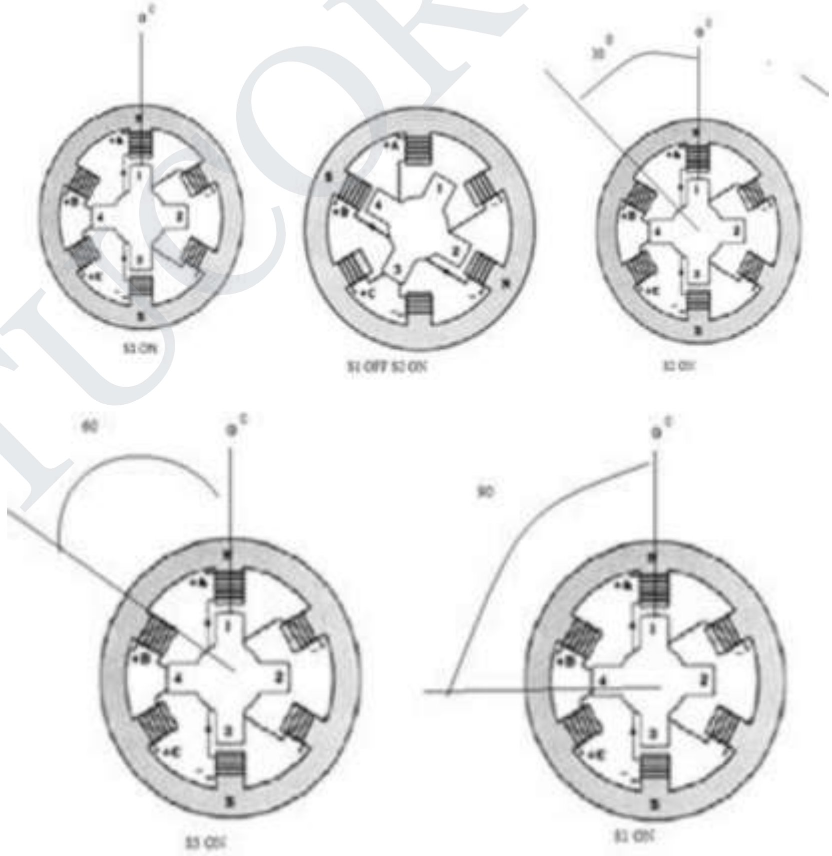


Fig 2.3 step motions as switching sequence process in a three phase VR motor

The truth table for mode I operation in counter and clockwise directions are given in the table

Table 2.1: Counter Clockwise Rotation (CCW)

S1	S2	S3	θ
*	-	-	0
-	*	-	30
-	-	*	60
*	-	-	90
-	*	-	120
-	-	*	150
*	-	-	180
-	*	-	210
-	-	*	240
*	-	-	270
-	*	-	300
-	-	*	330
*	-	-	360

(b).Mode II: Two Phase on Mode

In this mode two stator phases are excited simultaneously. When phases a and b are energized together, the rotor experiences torque from both phases and comes to rest in a point mid-way between the two adjacent full step position. If the phases b and c are excited, the rotor occupies a position such that angle between AA‘ axis of stator and 1-3 axis of rotor is equal to 45°.To reverse the direction of rotation switching sequence is changed a and b,a and c etc. The main advantage of this type of operation is that torque developed by the stepper motor is more than that due to single phase ON mode of operation.

The truth table for mode II operation in counter clockwise and clockwise directions is given in a tableTable

2.3: Counter Clockwise Rotation (CCW)

Mode III: Half step Mode

S1	S2	S3	θ°	
*	*	-	15°	AB
-	*	*	45°	BC
-	*	-	75°	CA
*	*	-	105°	AB
-	*	*	135°	BC
-	*	-	165°	CA
*	*	-	195°	AB
-	*	*	225°	BC
-	*	-	255°	CA
*	*	-	285°	AB

Table 2.4: Clockwise Rotation (CW) **(C)**

	S1	S2	S3	θ
AC	-	*	-	**15°**
CB	-	*	*	**45°**
BA	*	*	-	**75°**
AC	-	*	-	**105°**
CB	-	*	*	**135°**
BA	*	*	-	**165°**
AC	-	*	-	**195°**
CB	-	*	*	**225°**
BA	*	*	-	**255°**
AC				**285°**

In this type of mode of operation on phase is ON for some duration and two phases are ON during some other duration. The step angle can be reduced from 30° to 15° by exciting phase sequence a, a+b, b,b+c, c etc. The technique of shifting excitation from one phase to another from a to b with an intermediate step of a+b is known as half step and is used to realize smaller steps continuous half stepping produces smoother shaft rotation.

The truth table for mode III operation in counter and clockwise directions are given in the table

Table 2.5: Counter ClockwiseRotation (CCW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	*	-	15°	AB°
-	*	-	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
*	-	*	75°	CA°
*	-	-	90°	A°
*	*	-	105°	AB°
-	*	-	120°	B°
-	*	*	135°	BC°
-	*	-	150°	C°
*	-	*	165°	CA°

Table 2.6: Clockwise Rotation (CW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	-	*	15°	AB°
-	-	*	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
-	*	-	75°	CA°
*	*	-	90°	A°
*	-	-	105°	AB°
*	-	*	120°	B°
-	-	-	135°	BC°
-	*	*	150°	C°
-	*	-	165°	CA°

2.4 MICRO STEPPING CONTROL OF STEPPING MOTOR

Stepping motor is a digital actuator which moves in steps of θs in response to input pulses. such incremental motion results in the following limitations of the stepper motor

Limited resolution

As θs is the smallest angle through which the stepper motor can move, this has an effect on position accuracy of incremental servo system employing stepper motors because the stepper motor cannot position the load to an accuracy finer than θs.

Mid frequency Resonance

A phenomenon in which the motor torque suddenly drops to a low value at certain pulse frequencies as in fig

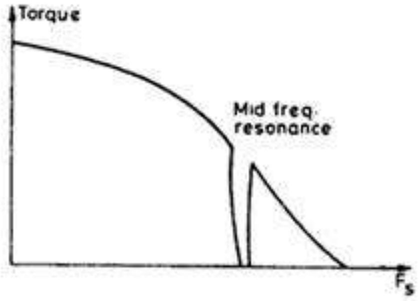


Fig 2.4 Mid frequency Resonance

A new principal known as micro stepping control has been developed with a view of overcoming the above limitation .It enables the stepping motor to move through a tiny micro step of size Δ θs << θs full step angle is response to input pulses.

2.5. MULTISTACK VARIABLE RELUCTANCE STEPPER MOTOR

These are used to obtain smaller step sizes, typically in the range of 2° to 15°. Although three stacks are common a multistack motor may employ as many as seven stacks. This type is also known as the cascade type. A cutaway view of a three stack motor is shown in fig. 2.6.

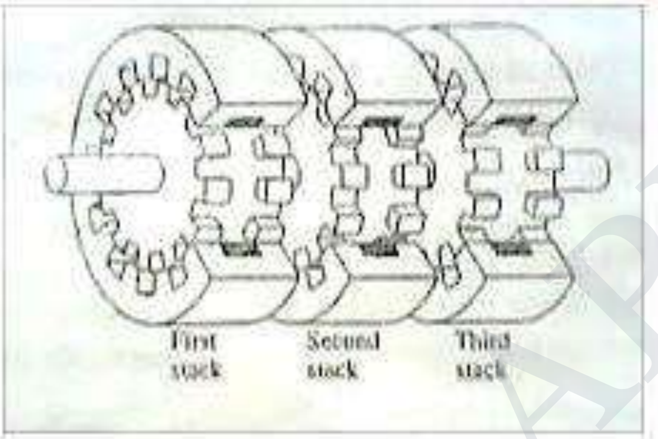


Fig. 2.6: Construction of multi-stack VR motor.

A multistack (or m-stack) variable reluctance stepper motor can be considered to be made up of ‘m‘ identical single stack variable reluctance motors with their rotors mounted on a single shaft. The stators and rotors have the same number of poles (or teeth) and therefore same pole (tooth) pitch. For a m0stack motor, the stator poles (or teeth) in all m stacks are aligned, but the rotor poles (teeth) are displaced by 1/m of the pole pitch angle from one another. All the stator pole windings in a given stack are exited simultaneously and, therefore the stator winding of each stack forms one phase. Thus the motor has the same number of phases as number of stacks.

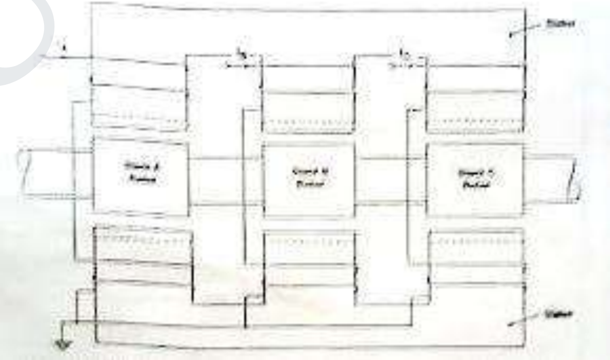


Fig. 2.7: Cross-section of a 3-stack, VR stepper motor parallel to the shaft.

Figure 2.7 shows the cross section of a three stack (3-phase) motor parallel to the shaft. In each stack, stator and rotors have 12 poles (teeth). For a 12 pole rotor, pole pitch is 30° and therefore, the rotor poles (teeth) are displaced from each other by 1/3rd of the pole pitch or 10°. The stator teeth in each stack are aligned. When the phase winding A is excited rotor teeth of stack A are aligned with the stator teeth as shown in fig. 2.8.

When phase A is de-energized and phase B is excited the rotor teeth of stack B are aligned with stator teeth. The new alignment is made by the rotor movement of 10° in the anticlockwise direction. Thus the motor moves one step (equal to ½ pole pitch) due to change of excitation from stack A to stack B

Next phase B is de-energized and phase C is excited. The rotor moves by another step 1/3rd of pole pitch in the anticlockwise direction. Another change of excitation from stack C to stack A will once more align the stator and rotor teeth in stack A. however during this process (A → B → C → A) the rotor has moved one rotor tooth pitch.

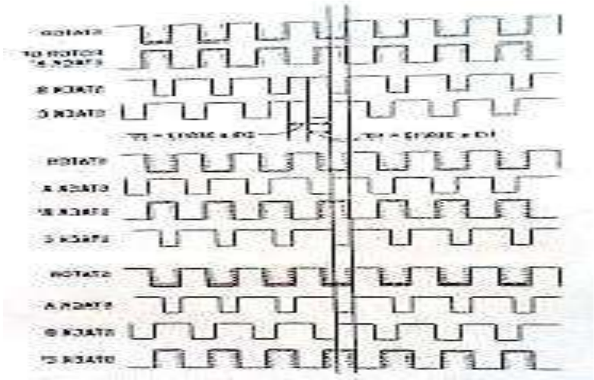


Fig. 2.8: Position of stator & rotor teeth of 3 stack VR motor

Let Nr be the number of rotor teeth and _m‘ the number of stacks or phases, then

Tooth pitch Tp= 360/Nr ……………… (2.1)

Step Angle α= 360°/mNr ………………. (2.2)

2.6. Hybrid stepper motor

Principle of operation

Most widely used hybrid motor is the two phase type as shown in fig2.11. This model has four poles and operates on one phase on excitation.

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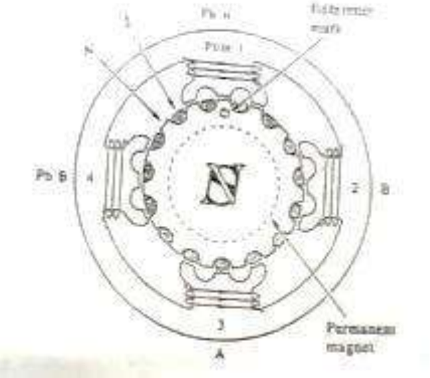


Fig2.9cross-section of a two phase hybrid motor

The coil in pole 1 and that in pole 3 are connected in series consisting of phase A, and pole 2 and 4 are for phase B. Fig 2.12 shows the proce3ss of rotor journey as the winding currents are switched in one phase ON excitation

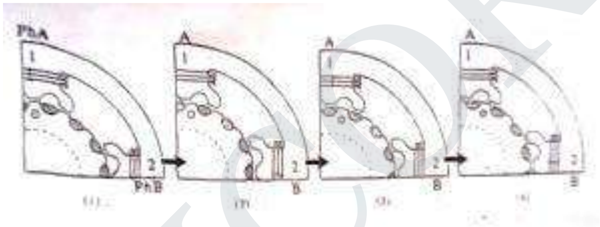


Fig2.10 one-phase on operation of a two-phase hybrid motor.

The poles of phase A are excited the teeth of pole 1 attract some of the rotors north poles, while the teeth of pole 3 align with rotor‘s south poles. Current is then switched to phase B, The rotor will travel a quarter tooth pitch so that tooth alignment takes place in 2 and 4.

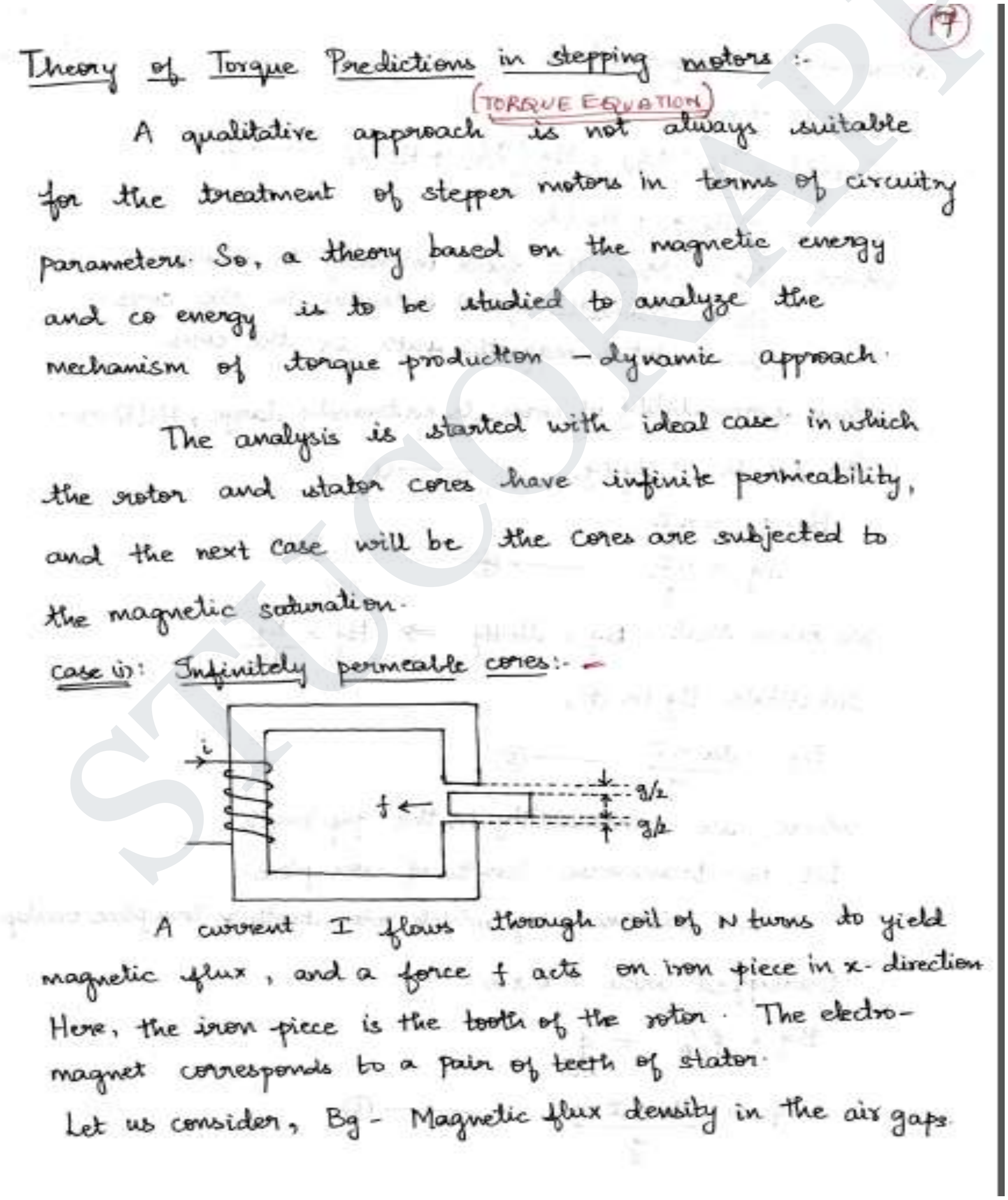
Next current is switched back to phase A but in opposite polarity to before, the rotor will make another quarter tooth journey. The tooth alignment occurs in opposite magnetic polarity to state 1. When current is switched to phase B in opposite polarity (4) Occurs as a result of quarter tooth pitch journey.

The structures of two phase motor considered in fig.2.11 will not produce force in a symmetrical manner with respect to the axis. The motor having 8 poles in the stator shown in fig2.13 considered as the structure in which torque is generated at a symmetrical position on the surface.

Fig2.11 Two-phase hybrid motor with 8 stator poles.

2.9. THEORY OF TORQUE PREDICTION

According to Faradays laws of electromagnetic induction



Theory of Torque Predictions in stepping motors :-

(TORQUE EQUATION)

A qualitative approach is not always suitable for the treatment of stepper motors in terms of circuitry parameters. So, a theory based on the magnetic energy and co energy is to be studied to analyze the mechanism of torque production - dynamic approach.

The analysis is started with ideal case in which the rotor and stator cores have infinite permeability, and the next case will be the cores are subjected to the magnetic saturation.

Case (i): Infinitely permeable cores:-

A current I flows through coil of N turns to yield magnetic flux, and a force f acts on iron piece in x- direction. Here, the iron piece is the tooth of the rotor. The electro-magnet corresponds to a pair of teeth of stator.

Let us consider, Bg - Magnetic flux density in the air gaps

According to ampere's law,

$$\oint H \cdot dl = nI \qquad \text{——} ①$$

$$\oint H \cdot dl = H_g\left(g/2\right) + H_g\left(g/2\right) + H_i(l) \qquad \text{——} ②$$

$$= H_g(g) + H_i(l)$$

where, H_g – Magnetic field intensity in airgap.

H_i – Magnetic field intensity in the cores.

l – total magnetic path in the cores.

when permeability of cores is extremely large, $H_i(l) = 0$.

So, $\oint H \cdot dl = H_g(g) \qquad \text{——} ③$

$$H_g \cdot g = nI$$

$$H_g = \frac{nI}{g} \qquad \text{——} ④$$

We know that, $B_g = \mu_0 H_g \Rightarrow H_g = \frac{B_g}{\mu_0}$

Substitute H_g in ④,

$$B_g = \frac{\mu_0 nI}{g} \qquad \text{——} ⑤$$

where, μ_0 - permeability in the gap length.

Let w - transverse length of iron piece.

x - distance by which rotor tooth & iron piece overlap

Overlapped area $= x \times w$.

$$B_g = \phi/A = \frac{\phi}{xw}$$

$$\phi = \frac{\mu_0 n I x w}{g} \qquad \text{——} ⑥$$

Flux linkages, $\psi = n\phi$ — ⑦

Substitute ⑥ in ⑦,

$$\psi = \frac{x w \mu_0 n^2 I}{g} \quad \text{—} ⑧$$

Let us assume that there is an incremental displacement Δx at time Δt,

$$\Delta\psi = \frac{w \mu_0 n^2 I \Delta x}{g} \quad \text{—} ⑨$$

$$\text{Emf, } e = -\frac{\Delta\psi}{\Delta t} = -\frac{w \mu_0 n^2 I}{g} \cdot \frac{\Delta x}{\Delta t} \quad \text{—} ⑩$$

$$\text{Workdone, } \Delta P_i = I|e|\Delta t$$

$$= \frac{w \mu_0 n^2 I^2}{g} \, \frac{\Delta x}{\cancel{\Delta t}} \cdot \cancel{\Delta t}$$

$$\Delta P_i = \frac{w \mu_0 n^2 I^2}{g} \Delta x \quad \text{—} ⑪$$

Coil resistance is zero,

$$\Delta P_i = \frac{B_g^2 \cdot g\, w\, \Delta x}{\mu_0} \quad \text{—} ⑫$$

Work done by the source is converted partly to mechanical work and the rest in increasing the magnetic field energy in the gaps.

$$\Delta W_m = \tfrac{1}{2} \Delta P_i$$

$$= \frac{1}{2} \frac{B_g^2}{\mu_0} \cdot g \cdot w \Delta x \quad \text{—} ⑬$$

ΔP_i is converted into magnetic field energy and other half of ΔP_i is converted into the mechanical work. Since the mechanical work is the force 'f' multiplied by the displacement Δx.

Comparing ⑬ & ⑭,

$$f = \frac{1}{2}\frac{B_g^2}{\mu_0} g w \qquad \text{— ⑮}$$

Substitute ⑮ to B_g,

$$f = \frac{1}{2}\frac{\mu_0^2 n^2 I^2}{g^2 \mu_0} g w$$

$$f = \frac{1}{2}\frac{w \mu_0 n^2 I^2}{g} \qquad \text{— ⑯}$$

Magnetic energy $W_m = fx$

$$W_m = \frac{1}{2}\frac{B_g^2}{\mu_0} g x w$$

$$W_m = \frac{1}{2}\frac{\mu_0 n^2 I^2}{g} x w \qquad \text{— ⑰}$$

Compare ⑮ & ⑰,

$$f = \left[\frac{\partial W_m}{\partial x}\right]_{I = \text{constant}}$$ (in rigorous form).

$$f = \left[\frac{d W_m}{d x}\right]_{I = \text{constant}}$$

$$f = -\left[\frac{\partial W_m}{\partial x}\right]_{\phi = \text{constant}}$$ (coil resistance is not zero)

21

Case (ii) – Constant permeabilities :-

In the infinitely permeable cores, the magnetic field appears only in the gaps. When cores are of finite permeability, the magnetic energy appears also in the cores and spaces other than the gaps.

$$\psi = LI \quad \text{——} ⑱$$

where ψ = flux linkages

L = coil inductance

The magetic energy,

$$W_m = \frac{1}{2} LI^2$$

$$\text{Emf}, \; e = -\frac{\Delta\psi}{\Delta t} = \frac{-\Delta(LI)}{\Delta t}$$

$$e = -I\frac{\Delta L}{\Delta t} \quad \text{——} ⑲$$

Work ΔP_i can be expressed as,

$$\Delta P_i = I|e|\Delta t$$

$$= I\left|-I\frac{\Delta L}{\Delta t}\right|\Delta t$$

$$\Delta P_i = I^2 \Delta L \quad \text{——} ⑳$$

Increase in the magnetic energy ΔW_m,

$$\Delta W_m = \frac{1}{2}\Delta P_i$$

$$\Delta W_m = \frac{1}{2} I^2 \Delta L \quad \text{——} ㉑$$

Mechanical work, $\Delta P_0 = f \Delta x$ —— ㉒

comparing ㉑ & ㉒,

$$f \Delta x = \frac{1}{2} I^2 \Delta L$$

$$f = \frac{1}{2} I^2 \frac{\Delta L}{\Delta x} \quad \text{——} \quad ㉓$$

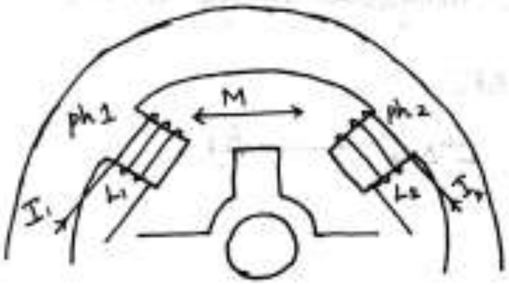
In the above procedure, it was assumed that the coil resistance was zero and the power supply was a current source.

<u>Effects of mutual induction</u>:-

Number of drive schemes for stepping motors are

1). One phase on drive.
2). Two phase on drive.
3). Three phase on drive.
4). Half step drive.

In a drive scheme, other than one phase on drive, it is desirable that the mutual inductance is minimum. When mutual inductance is not negligible, the torque in terms of linear theory is derived by the following procedure.



㉓ ④

mutual Induction,

$$e = -I\frac{\Delta L}{\Delta t}$$

$$e_1 = -I_1\frac{\Delta L_1}{\Delta t} - I_2\frac{\Delta M}{\Delta t}$$

$$e_2 = -I_2\frac{\Delta L_2}{\Delta t} - I_1\frac{\Delta M}{\Delta t}$$

where, e_1 = induced voltage of phase 1.

e_2 = induced voltage of phase 2

L_1 = Inductance of phase 1.

L_2 = Inductance of phase 2

M = mutual inductance between the two phases.

The work done by the two power supplies during Δt,

$$\Delta P_i = -(e_1 I_1 + e_2 I_2)\Delta t$$

$$= -\left[-I_1^2\frac{\Delta L_1}{\Delta t} - I_1 I_2\frac{\Delta M}{\Delta t} - I_2^2\frac{\Delta L_2}{\Delta t} - I_1 I_2\frac{\Delta M}{\Delta t}\right]$$

$$\Delta P_i = I_1^2\Delta L_1 + I_2^2\Delta L_2 + 2I_1 I_2\Delta M \quad — ㉔$$

The increment of magnetic energy,

$$\Delta W_m = \tfrac{1}{2}\Delta P_i$$

$$= \tfrac{1}{2}\left[I_1^2\Delta L_1 + I_2^2\Delta L_2\right] + I_1 I_2\Delta M \quad — ㉕$$

Mechanical output,

$$\Delta P_o = T\Delta\theta \quad — ㉖$$

$$T\Delta\theta = \tfrac{1}{2}(I_1^2\Delta L_1 + I_2^2\Delta L_2) + I_1 I_2\Delta M$$

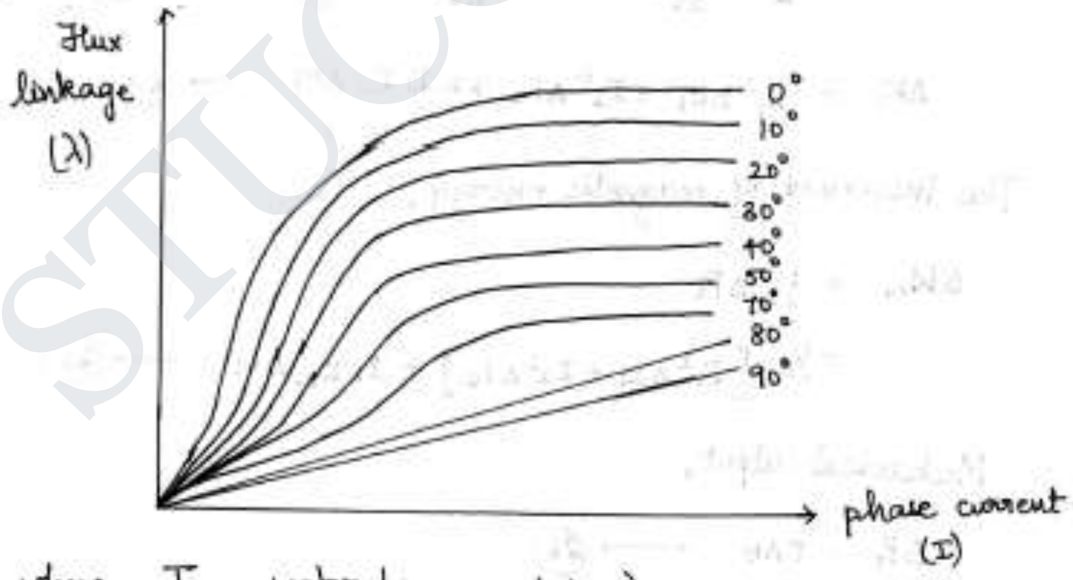
Torque is expressed as,

$$\boxed{T = \frac{1}{2} I_1^2 \frac{\partial L_1}{\partial \theta} + \frac{1}{2} I_2^2 \frac{\partial L_2}{\partial \theta} + I_1 I_2 \frac{\partial M}{\partial \theta}}$$

Linear and Non Linear Analysis :-

In linear analysis, it is assumed that the magnetic material in the motor has constant permeability (i.e.,) the machine with linear magnetic characteristics means that it is having constant magnetic permeability and no magnetic saturation. The flux density is proportional to the winding current.

But in practice, variable reluctance motors do operate with their magnetic material in saturation.



where, Tm – motor torque (N-m)

J – inertia of rotor (kg m²)

25 ⑤

ω - angular velocity of rotor.

D - damping coefficient.

T_f - frictional load torque

ϕ_s - step angle (radians)

f - stepping rate (steps/sec).

Frictional load torque,

$$T_f = K\theta$$

According to rotor dynamics,

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

Also, $\theta_s = \theta = \omega t$ = step angle

$$\omega = \frac{\theta_s}{t} = f\theta_s \quad \text{——} ②$$

where $f = \frac{1}{t}$

Substitute ② in ①,

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

where $\theta_s = \frac{360}{mN_r}$

$$(\because) \quad T_m = J\theta_s\frac{d}{dt}(f) + D\theta_s(f) + T_f.$$

→ If viscous friction constant is neglected, the equation will be a linear equation, the corresponding analysis is a linear analysis where linear acceleration is present.

→ The damping coefficient is also considered, the corresponding acceleration will be non linear and the equation will be non-linear and the equation will be non-linear.

a) Linear acceleration or linear analysis :-

If damping coefficient is neglected,

$D = 0$

Expression for motor torque becomes,

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

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

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

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

On integrating,

$$\omega = \left(\frac{T_m - T_f}{J}\right)t + \omega_1 \quad \text{———} \; ④$$

where ω_1 = integration constant (initial angular velocity of motor)

$$(\because)\ \omega = \theta_s f \quad ; \ \omega_1 = \theta_s f_1 \quad \text{———} \; ⑤$$

Substitute ⑤ in ④,

$$\left(\frac{T_m - T_f}{J}\right)t + \theta_s f_1 = \theta_s f$$

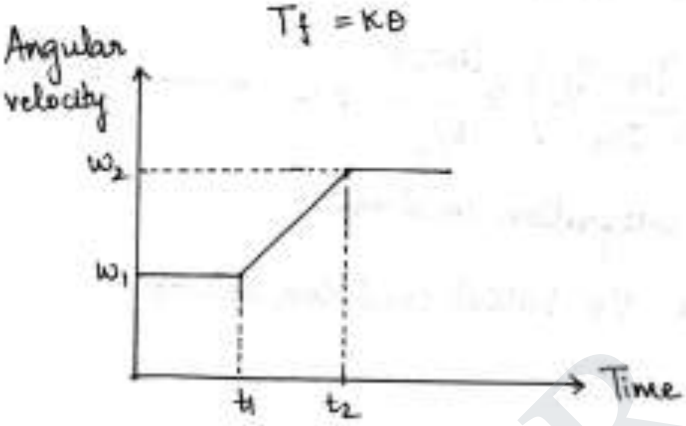
27

$\div$ by θ_s,

$$\left(\frac{T_m - T_f}{J\theta_s}\right)t + f_1 = f$$

$$(\therefore) \text{ Stepping rate, } f = \left(\frac{T_m - T_f}{J\theta_s}\right)t + f_1$$

$$T_f = K\theta$$



Linear acceleration from ω_1 to ω_2

(b) Non linear acceleration (exponential) :-

$$T_m = J\theta_s \frac{df}{dt} + D\theta_s f + T_f$$

$$(T_m - T_f) = J\theta_s \frac{df}{dt} + D\theta_s f$$

Dividing by $J\theta_s$

$$\frac{df}{dt} + \left(\frac{D}{J}\right)f = \frac{T_m - T_f}{J\theta_s}$$

The above equation is in the form,

$\frac{dy}{dx} + Py = Q$ which have the solution of

$$y e^{\int P dx} = \int Q e^{\int P dx} + c$$

Here, $y = f$; $x = t$; $P = \frac{D}{J}$ and $Q = \frac{T_m - T_f}{J\theta_s}$ = constant

$$f e^{\int D/J\, dt} = \int \left(\frac{T_m - T_f}{J\theta_s} \right) e^{\int (D/J) dt} + c$$

$$f e^{(D/J)t} = \left(\frac{T_m - T_f}{J\theta_s} \right) \int e^{(D/J)t} + c$$

$$f e^{(D/J)t} = \left(\frac{T_m - T_f}{J\theta_s} \right) \frac{e^{(D/J)t}}{D/J} + c \quad \text{——} ⑥$$

where c is the integration constant.

To find c, substitute the initial condition at t = 0.

$$f = f(0) = f_1$$

$$f_1 e^0 = \left(\frac{T_m - T_f}{J\theta_s} \right) \frac{e^0}{D/J} + c$$

$$f_1 = \left(\frac{T_m - T_f}{J\theta_s} \right) \left(\frac{J}{D} \right) + c$$

$$f_1 = \frac{T_m - T_f}{D\theta_s} + c$$

$$(\because) \quad c = f_1 - \left(\frac{T_m - T_f}{D\theta_s} \right)$$

$$f e^{(D/J)t} = \left(\frac{T_m - T_f}{J\theta_s} \right) \left(\frac{J}{D} e^{(D/J)t} \right) + \left[f_1 - \left(\frac{T_m - T_f}{D\theta_s} \right) \right] \text{——} ⑦$$

$$f e^{(D/J)t} = \left(\frac{T_m - T_f}{D\theta_s} \right) e^{(D/J)t} + \left[f_1 - \left(\frac{T_m - T_f}{D\theta_s} \right) \right]$$

29

Divide by $e^{(D/J)t}$,

$$f = \frac{T_m - T_f}{D\theta_s} + \left[f_1 - \left(\frac{T_m - T_f}{D\theta_s}\right)\right] e^{(-D/J)t}$$

Stepping frequency,

$$f = \frac{T_m - T_f}{D\theta_s} + \left[f_1 - \left(\frac{T_m - T_f}{D\theta_s}\right)\right] e^{(-D/J)t} \quad \text{---} ⑧$$

This is a non-linear exponential equation which gives rise to non-linear acceleration of the rotor of the machine.

Thus, torque production is assumed as linear one in some cases, the saturation of the magnetic material of the machine leads to non-linear operation which necessitates, the study of non linear acceleration of the rotor due to the torque production.

2.11. CHARACTERISTICS OF STEPPER MOTOR

Stepper motor characteristics are divided into two groups

- Static characteristics
- Dynamic characteristics

2.11.1. Static characteristics

It is divided into two characteristics.

(i)Torque Angle curve

(ii)Torque current curve

(i)Torque-Angle curve

Torque angle curve of a step motor is shown in fig.2.19. it is seen that the Torque increases almost sinusoid ally, with angle Θ from equilibrium.

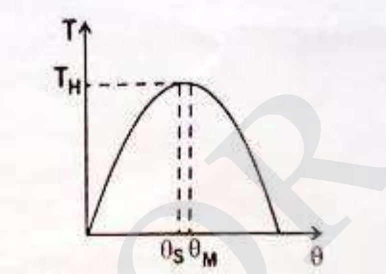


Fig. 2.19 Torque Angle

Holding Torque (T_H)

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

Detent torque (T_D):

It is the maximum load torque which the un-energized stepper motor can withstand slipping. Detent torque is due to magnetism, and is therefore available only in permanent magnet and hybrid stepper motor. It is about 5-10 % of holding torque.

Torque current curve

A typical torque curve for a stepper motor is shown in fig.2.19. It is seen the curve is initially linear but later on its slope progressively decreases as the magnetic circuit of the motor saturates.

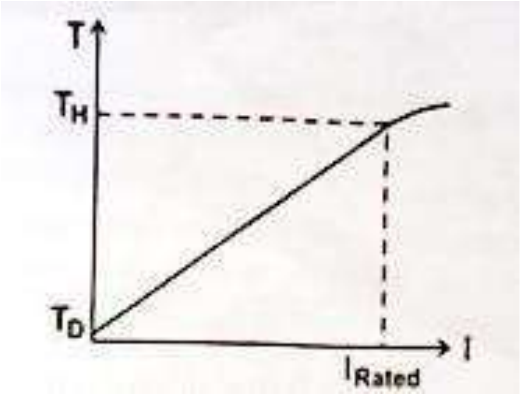


Fig.2.20 Torque-current Curve

Torque constant (Kt)

Torque constant of the stepper is defined as the initial slope of the torque-current (T-I) curve of the stepper motor. It is also known as torque sensitivity. Its units N-mA, kg-cm/A or OZ-in/A

2.11.2. Dynamic characteristics

A stepper motor is said to be operated in synchronism when there exist strictly one to one correspondence between number of pulses applied and the number of steps through which the motor has actually moved. There are two modes of operation.

Start-Stop mode

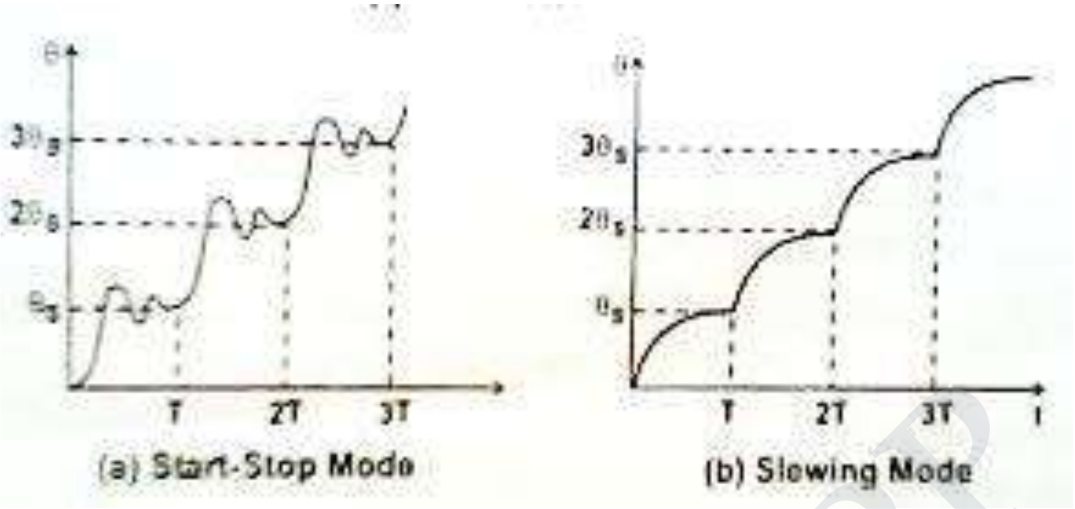
Also called as pull in curve or single stepping mode.

Slewing mode

In start –stop mode the stepper motor always operate in synchronism and the motor can be started and stopped without using synchronism. In slewing mode the motor will be in synchronism, but it cannot be started or stopped without losing synchronism. To operate the motor in slewing mode first the motor is to be started in start stop mode and then to slewing mode. Similarly to stop the motor operating in slewing mode, first the motor is to be brought to the start stop mode and then stop.

Start Stop mode

Start stop mode of operation of stepper motor is shown in fig.2.21 (a).In this second pulse is given to the stepper motor only after the rotor attained a steady or rest position due to first pulse. The region of start-stop mode of operation depends on the operation depends on the torque developed and the stepping rate or stepping frequency of stepper motor.



(a) Start-Stop Mode

(b) Slewing Mode

Fig. 2.21 Modes of operation

2.12. TORQUE-SPEED CHARACTERISTICS

Torque developed by the stepper motor and stepping rate characteristics for both modes of operation are shown in fig.2.22.the curve ABC represents the "pull in" characteristics and the curve ADE represents the "pull-out" characteristics.

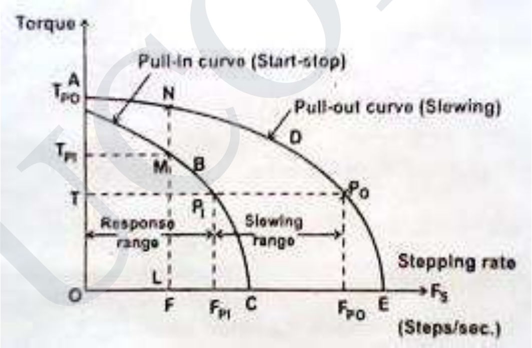


Fig. 2.22 Torque-Speed Characteristics

The area OABCO represents the region for start stop mode of operation. At any operating point in the region the motor can start and stop without losing synchronism. The area ABCEDA refers to the region for slewing mode of operation. At any operating point without losing synchronism to attain an operating point in the slewing mode at first the motor is to operate at a point in the start-stop mode and then stepping rate is increased to operate in slewing mode, similarly while switching off it is essential to operate the motor from slewing mode to start-stop mode before it is stopped.

Pull in torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the start-stop mode of operation without losing synchronism. LM represents the pull in torque (i.e)TPI corresponding to the stepping rate F (i.e.) OL.

Pull out torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the slewing mode without losing synchronism. LN represents the pull in torque (i.e.) TPO corresponding to F (i.e.) OL.

Pull in range

It is the maximum stepping rate at which the stepper motor can operate in start-stop mode developing a specific torque (without losing synchronism). PIT represents pull in range for a torque of T (i.e.) OP. This range is also known as response range of stepping rate for the given torque T.

Pull out range

It is the maximum stepping rate at which the stepper motor can operate in slewing mode developing a specified torque without losing synchronism. PIPO represents the pull out range for a torque of T. The range PIPO is known slewing range.

Pull in rate (FPI)

It is the maximum stepping rate at which the stepper motor will start or stop without losing synchronism against a given load torque T.

Pull out rate (FPO)

It is the maximum stepping rate at which the stepper motor will slew, without missing steps, against load torque T.

Synchronism

This term means one to one correspondence between the number of pulses applied to the stepper motor and the number of steps through which the motor has actually moved.

Mid frequency resonance

The phenomenon at which the motor torque drops to a low value at certain input pulse frequencies.

2.13 DRIVE SYSTEM AND CONTROL CIRCUITRY FOR STEPPER MOTOR

2.13.1 DRIVE SYSTEM

The stepper motor is a digital device that needs binary (digital) signals for its operation .Depending on the stator construction two or more phases have to be sequentially switched using a master clock pulse input. The clock frequency determines the stepping rate, and hence the speed of the motor. The control circuit generating the sequence is called a translator or logic sequencer.

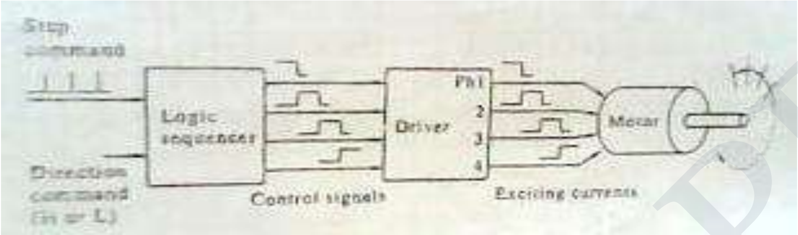


Fig. 2.23 Block Diagram of the drive system of a stepping motor.

The fig 2.23 shows the block diagram of a typical control circuit for a stepper motor. It consists of a logic sequencer, power driver and essential protective circuits for current and voltage limiting. This control circuit enables the stepper motor to be run at a desired speed in either direction. The power driver is essentially a current amplifier, since the sequence generator can supply only logic but not any power. The controller structure for VR or hybrid types of stepper motor

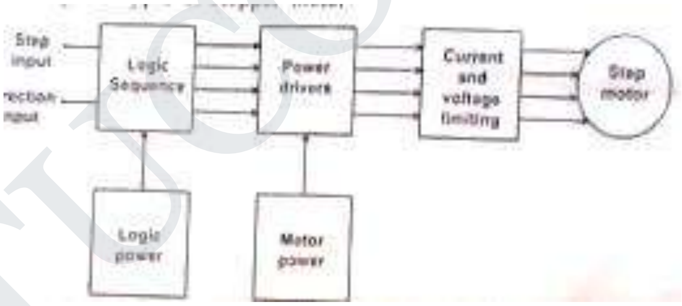


Fig. 2.24 Block diagram of a typical step motor control

2.13.2 LOGIC SEQUENCER

The logic sequencer is a logic circuit which control the excitation of the winding sequentially, responding to step command pulses. A logic sequencer is usually composed of a shifter register and logic gates such as NANDs, NORs etc. But one can assemble a logic sequencer for a particular purpose by a proper combination of JK flip flop, IC chips and logic gate chips.

Two simple types of sequencer build with only two JK-FFs are shown in fig 2.39 for unidirectional case. Truth tables for logic sequencer also given for both the directions.

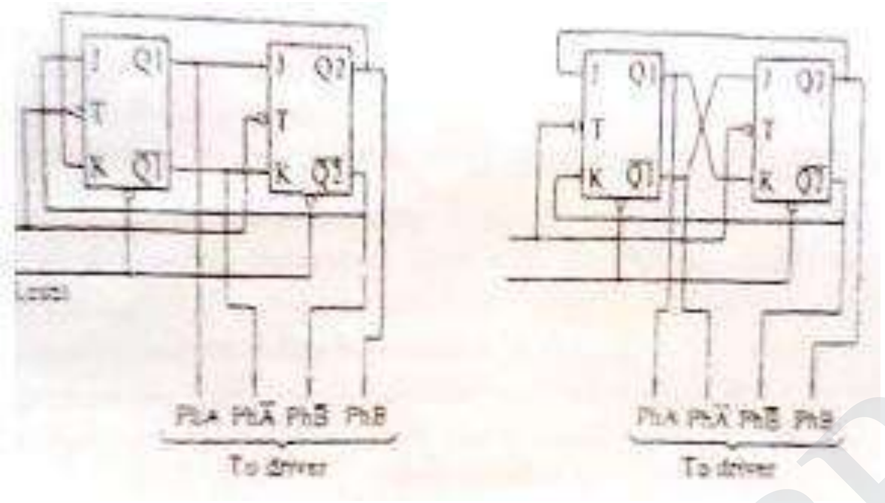


TABLE 2.7 Logic Sequencer

	R	1	2	3	4	5	6	….
Ph A,Q1	0	1	1	0	0	1	1	….
Ph B,Q2	0	0	1	1	0	0	1	….
Ph A,Q1	1	0	0	1	1	0	0	….
Ph B,Q2	1	1	0	0	1	1	0	…

	R	1	2	3	4	5	6	….
Ph A,Q1	0	0	1	1	0	0	1	….
Ph B,Q2	0	1	1	0	0	1	1	….
Ph A,Q1	1	1	0	0	1	1	0	….
Ph B,Q2	1	0	0	1	1	0	0	….

Fig.2.25 A unidirectional logic sequencer for two phase on operation of a two phase hybrid motor

The corresponding between the output terminals of the sequencer and the phase windings to be controlled is as follows.

Q1----- Ph A

$\overline{Q1}$----- Ph $\overline{A}$

Q2----- Ph B

$\overline{Q2}$----- $\overline{B}$

If Q1 is on the H level the winding Ph A is excited and if Q1is on L level, Ph A is not excited.

To reserve the rotational direction, the connection of the sequencer must be interchanged. The direction switching circuits shown in fig 2.40 may be used for this purpose. The essential functions being in the combination of three NAND gates or two AND gates and a NOR gate.

2.13.3. Power Driver Circuit

The number of logic signals discussed above is equal to the number of phases and the power circuitry is identical for all phases. Fig. 2.26(a) shows the simplest possible circuit of one phase consisting of a Darlington pair current amplifier and associated protection circuits. The switching waveform shown in fig. 2.26(c) is the typical R-L response with an exponential rise followed by decay at the end of the pulses.

In view of the inductive switching operation, certain protective elements are introduced in the driver circuit. These are the inverter gate 7408, the forward biased diode D1 and the freewheeling diode D. The inverter IC provides some sort of isolation between the logic circuit and the power driver.

There are some problems with this simple power circuit. They can be understood by considering each phase winding as a R-L circuit shown in fig. 2.26(b) subject to repetitive switching. On application of a positive step voltage, the current rises exponentially as

$$i(t)=I(1-e^{-t/}) \qquad \dots\dots(2.29)$$

Where I=V/R – rated current and

Ʈ=L/R winding time constant.

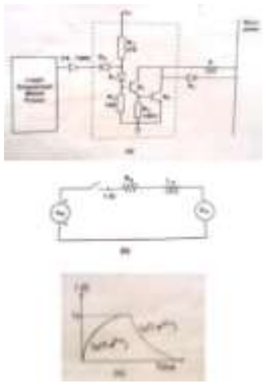


Fig. 2.26 Power Driver Stage of Stepper Motor Controller

In practice, the time constant Ƭ limits the rise and fall of current in the winding. At low stepping rate the current rises to the rated value in each ON interval and falls to zero value in each OFF interval. However as the switching rate increases, the current is not able to rise to the steady state, nor fall down to zero value within the on/off time intervals set by the pulse waveform. This in effect, smoothens the winding current reducing the swing as shown in fig. 2.45. As a result the torque developed by the motor gets reduced considerably and for higher frequencies, the motor just vibrates or oscillates within one step of the current mechanical position.

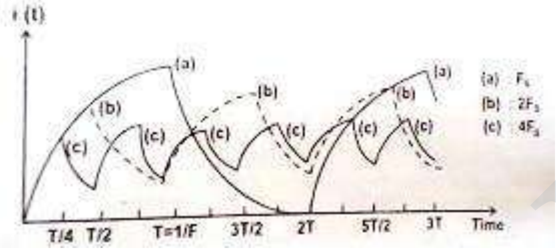


Fig. 2.27 Effect of increasing Stepping Rate on Current Swing

In order to overcome these problems and to make improvement of current build up several methods of drive circuits have been developed.

For example when a transistor is turned on to9 excite a phase, the power supply must overcome effect of winding inductances has tendency to oppose the current built up. As switching frequency increases the position that the buildup time takes up within the switching cycle becomes large and it results in decreased torque and slow response.

2.13.4 Improvement of current buildup/special driver circuit

(a) Resistance drive (L/R drive)

Here the initial slope of the current waveform is made higher by adding external resistance in each winding and applying a higher voltage proportionally. While this increases the rate of rise of the current, the maximum value remains unchanged as shown in fig.

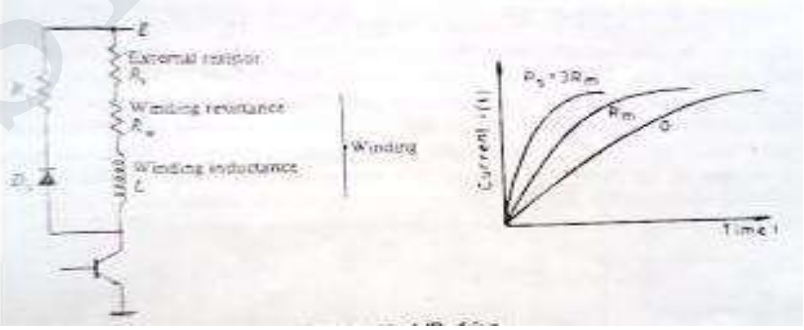


Fig. 2.28 L/R drive

The circuit time constant is now reduced and the motor is able to develop normal torque even at high frequencies. The disadvantage of this method is

Flow of current through external resistance causes I^2R losses and heating. This denotes wastage of power as far as the motor is concerned.

In order to reach the same steady state current I_R as before, the voltage required

To be applied is much higher than before. Hence this approach is suitable for small instrument stepper motor with current ratings around 100 mA, and heating is not a major problem.

(b) Dual voltage driver (or) Bi-level driver

To reduce the power dissipation in the driver and increase the performance of a stepping motor, a dual-voltage driver is used. The scheme for one phase is shown in fig. 2.29.

When a step command pulse is given to the sequencer, a high level signal will be put out from one of the output terminal to excite a phase winding. On this signal both T 1 and T 2 are turned on, and the higher voltage E_H will be applied to the winding. The diode D_1 is now reverse biased to isolate the lower voltage supply. The current build up quickly due to the higher voltage E_H. The time constant of the monostable multivibrator is selected so that transistor T 1 is turned off when the winding current exceeds the rated current by a little. After the higher

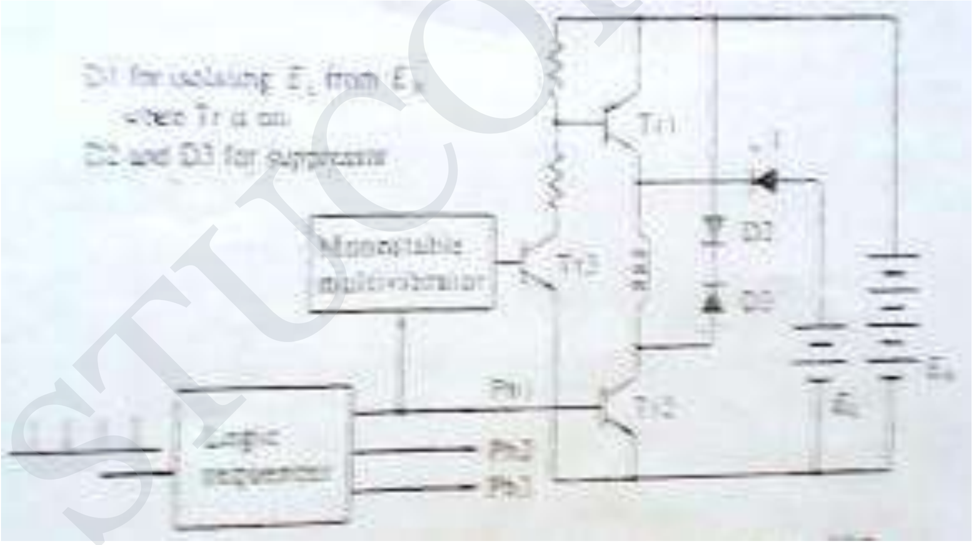


Fig. 2.29 Improvement of current buildup by dual voltage drive

Voltage source is cut off the diode is forward biased and the winding current is supplied from the lower voltage supply. A typical current wave form is shown in fig.

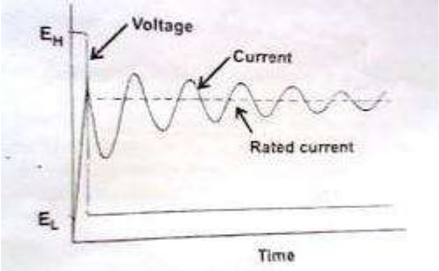


Fig. 2.30 Voltage and current wave form in dual voltage driver

When the dual voltage method is employed for the two phase on drive of a two phase hybrid motor, the circuit scheme will de such as that shown in fig. Two transistor T 1 r & T 2 and two diodes $D_1$and D_2 are used for switching the higher voltage. In dual voltage scheme as the stepping rate is increased, the high voltage is turned on for a greater percentage of time

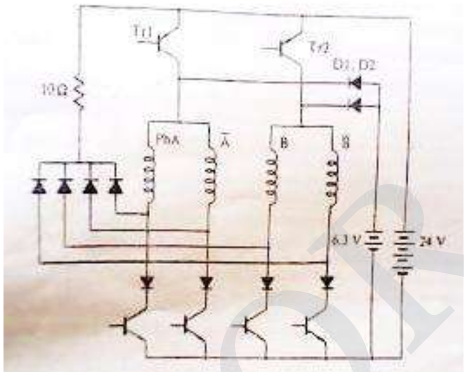


Fig. 2.31 A dual-voltage driver for the two-phase-on drive of a two phase hybrid motor

This drive is good and energy efficient. However it is more complex as it requires two regulated power supplies EH& EL end two power transistor switches Tr1 & Tr2 and complex switching logic. Hence it is not very popular.

(c)Chopper drive

Here a higher voltage 5 to 10 times the related value is applied to the phase winding as shown in fig. and the current is allowed to raise very fast. As soon as the current reaches about 2 to 5% above the rated current, the voltage is cut off, allowing the current to decrease exponentially. Again as the current reaches some 2 to 5% below the rated value, the voltage is applied again. The process is repeated some 5-6 times within the ON period before the phase is switched off. During this period the current oscillates about the rated value as shown in fig. A minor modification is to chop the applied dc voltage at a high frequency of around 1khz, with the desired duty cycle so as to obtain the average on-state current equal to the rated value.

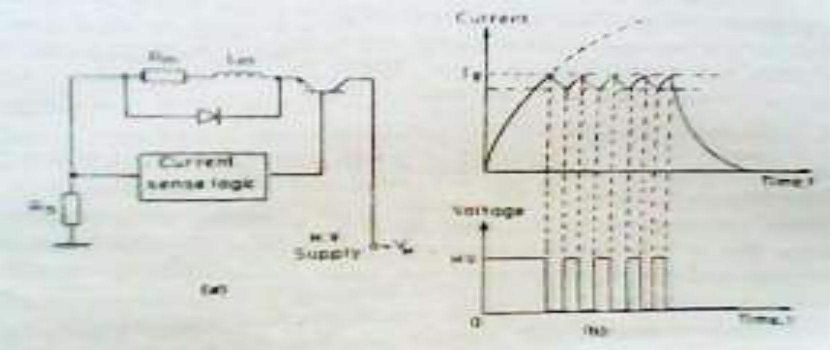


Fig. 2.32 Chopper drive

The chopper drive is particularly suitable for high torque stepper motors. It is ener4gy efficient like the bi-level drive but the control circuit is simpler.

(d) Problems with driver circuits

A winding on a stepping motor is inductive and appears as a combination of inductance and resistance in series. In addition, as a motor revolves a counter emf is produced in the winding. The equivalent circuit to a winding is hence, such as that shown for designing a power driver one must take into account necessary factors and behavior of this kind of circuit. Firstly the worst case3 conditions of the stepping motor, power transistors, and supply voltage must be considered. The motor parameters vary due to manufacturing tolerance and operating conditions. Since stepping motors are designed to deliver the highest power from the smallest size, the case temperature can be as high as about 100°c and the winding resistance therefore increases by 20 to 25 per cent.

Suppressor circuits

These circuits are needed to ensure fast decay of current through the winding when it is turned off. When the transistor in the above fig is turned off a high voltage builds up to Ldi/dt and this voltage may damage the transistor. There are several methods of suppressing this spike voltage and protecting the transistor as shown in the following.

(a) Diode suppressor

If a diode is put in parallel with the winding in the polarity as shown in fig. a circulating current will flow after the transistor is turned off, and the current will decay with time. In this scheme, no big change in current appears at turn off, and the collector potential is the supply potential E plus the forward potential of the diode. This method is very simple but a drawback is that the circulating current lasts for a considerable length of time and it produces a braking torque.

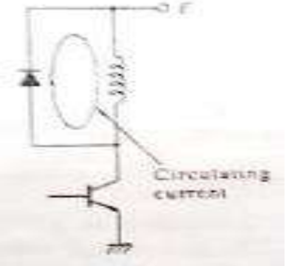


Fig. 2.33 Diode suppressor

(b)Diode-Resistor suppressor

A resistor is connected in series with the diode as shown in fig to damp quickly the circulating current. The voltage VCE applied to the collector at turn-off in this scheme is

VCE=E+IRS+VD

Where E= supply potential
I= Current before turning off

Rs-resistance of suppressor resistor

VD-forward potential of diode

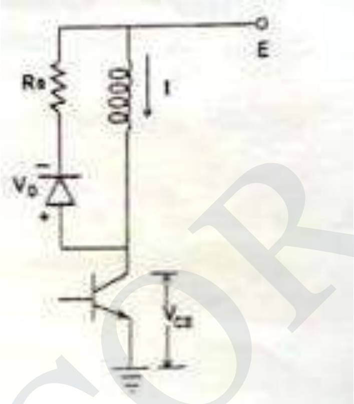


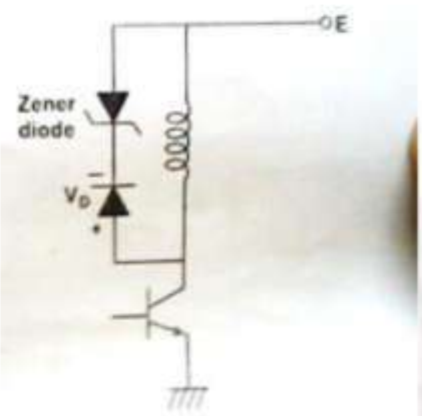
Fig. 2.34 Diode-resistor suppressor

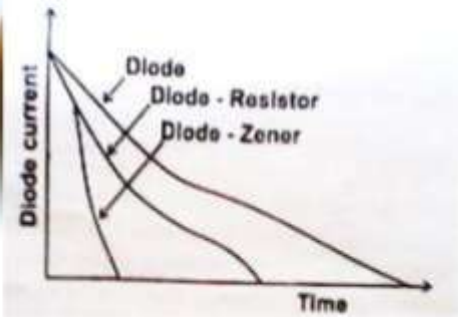
A high resistance RS is required to achieve a quick current decay, but this also results in a higher collector potential VCE, thus a transistor with a high maximum voltage rating is necessary.

(a) Zener diode suppressor

In this zener diode are often used to connect in series with the ordinary diode as shown in fig. Compared with preceding two cases zener diode which provides negative bias causes the current to decay more quickly after turn off. In addition to this, it is a merit of this method that the potential applied to the collector is the supply potential plus the zener potential, independent of the current. This makes the determination of the rating of the maximum collector potential easy. However zeners are signal diodes, rather than power diodes. Their power dissipation is limited to 5w. Consequently, this suppressor can be used for very small instrument stepper motors of typical size 8 to 11.

Comparison of effects of various suppressor schemes of various suppressor schemes





d)Condenser suppressor

This scheme is often employed for bifilar-wound hybrid motor. An explanation is given for the given for the circuit shown in fig:

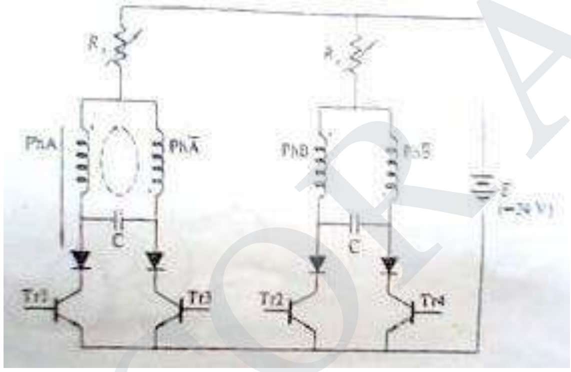


Fig. 2.37 Condenser suppressor

A condenser is put between ph A and ph A∟ and between ph B and ph B□. These condensers serve two fold purposes.

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

Let us see the situation just after the Tr 1 is turned off in the one phase on mode. Either Tr 2 or Tr 4 will turn on, but Tr 3 will still be in the turned off state. Since the winding of ph A & ph A| are wound in the bifilar fashion, a transient current will circulate in loop. If Tr 3 is turned on when the transient current becomes zero and the charge stored in the condenser becomes maximum, a positive current can easily flow through phase A winding. By this resonance mechanism, currents are used efficiently in this scheme. This feature remains in the two phase on mode too. The condenser suppressor is suited to drives in which stepping rate is limited in a narrow range.

2 .Another utility of condensers is as an electrical damper, a method of damping rotor oscillations is to provide a mechanism to convert kinetic energy to joule heating. If a rotor

having a permanent magnet oscillates, an alternating emf is generated in the winding. However if a current path is not provided or a high resistance is connected, no current will be caused by this emf. When the condenser is connected between phases an oscillatory current will flow in the closed loop and joule heat is generated in the windings, which means that the condenser works as an electrical damper.

2.14 APPLICATION OF STEPPER MOTOR:

The main application of stepper motor may be divided into the following groups.

1. Instrumentation applications.
2. Computer peripherals & Office equipment's.
3. Numerical control of machine tools and robotics.
4. Applications in semiconductor technology.
5. Space vehicles and satellites.
6. Electro medical and
7. Miscellaneous applications.

1. Instrumentation application:

This involve low torque applications such as

Quartz watches.

Synchronized clocks.

Camera shutter operations.

2. Stepper motor application in computer peripherals:

This involve medium torque, high performance and high volume application such as
Dot matrix and line printers.

Graph plotters.

Floppy disk drives

Digital X-Y plotters.

Magnetic tape drives.

Paper tape drives.

3. Application is office equipment:

Electronic typewriters.

Copiers

Facsimile machines.

4. Machine tool applications:

This involve high torque application such as

Numerical control system for milling machine

X-Y tables and index table.

Home use and industrial sewing machines.

5. Application in semiconductor technology:

Stepper motors used in high vacuum.

Goniometer-An instrument used to determine crystalline structure.

Electron beam micro fabricator.

6. Stepper motor used in space vehicles and satellites.

7. Robotics.

8. Electro medical applications:

This involve high torque applications such as

X-ray machines.

Radiation therapy units.

Ultra sound scanner.

9. Miscellaneous applications:

Nuclear reactors.

Heavy industry applications.

Automatic focusing mechanism in camera

Constructional features – Rotary and Linear SRM - Principle of operation – Torque production – Steady state performance prediction- Analytical method -Power Converters and their controllers – Methods of Rotor position sensing – Sensor less operation – Characteristics and Closed loop control – Applications.

3.1 INTRODUCTION

Switched reluctance motor (SRM) is electromagnetic and electrodynamics equipment which converts the electrical energy into mechanical energy. The electromagnetic torque is produced on variable reluctance principle. SRM makes use of

- Power semiconductor switching circuitry
- Rotor position sensor.

SRM is singly excited and doubly salient electrical motor. This means that it has salient poles on both the rotor and the stator but the only one member carries winding. The rotor has no winding, magnets and cage winding but it is build from a stack of salient pole laminations.

- construction is simple and robust
- It requires less maintenance
- Its overall efficiency is better
- It is flexible control driving motor as motoring mode generating mode of operations of the machine can be easily achieved,

In the light of above it is a competitive motor variable speed dc motor and variable speed 3 – phase cage induction motor.

3.2 CONSTRUCTION AND OPERATION OF SRM

3.2.1 Construction of SRM

Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure 3.1

The stator is made up of silicon steel stampings with inward projected poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8). All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf‘s are additive and they are called phase windings. Individual coil or a group of coils constitute phase windings. Each of the phase windings are connected to the terminal of the motor. These terminals are suitably connected to the output terminals of a power semiconductor switching circuitry, whose input is a d.c. supply.

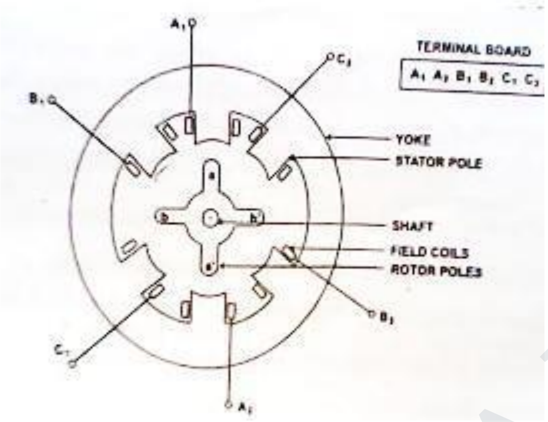


Fig 3.1 Cross sectional view of SRM

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

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

3.2.2 Block diagram of SRM

Fig. 3.2 shows the block diagram of SRM. Dc supply is given to the power semiconductor switching circuitry which is connected to various phase windings of SRM. Rotor position sensor which is mounted on the shaft of SRM, provides signals to the controller about the position of the rotor with reference to reference axis. Controller collects this information and also the reference speed signal and suitably turns ON and OFF the concerned power semiconductor device to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.

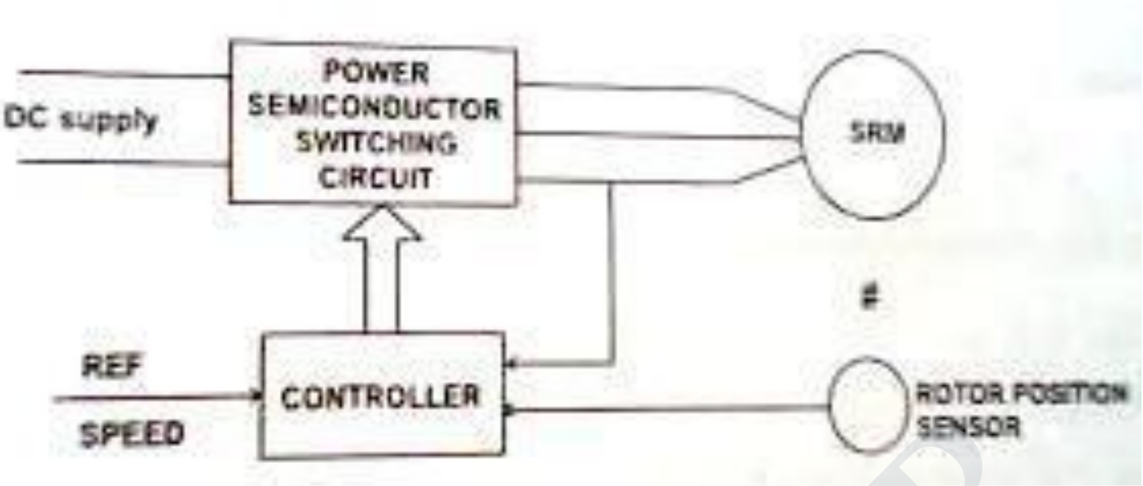


Fig. 3.2 Block Diagram of SRM

3.2.3. Principle of operation

Fig. 3.3 represents the physical location of the axis stator poles and rotor poles of a 6/4 SRM.

To start with stator pole axis AA‘ and rotor pole axis aa‘ are in alignment as shown in fig. 3.3(a). They are in the minimum reluctance position so far as phase windings is concerned. Then $dL_a/d\theta=0$. At this position inductance of B windings is neither maximum nor minimum. There exists $dL_b/d\theta$ and $dL_c/d\theta$.

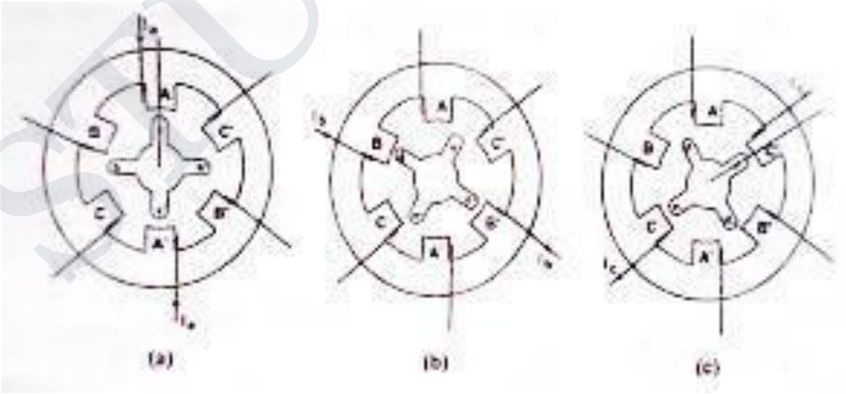


Fig. 3.3 Physical location of the axis of stator and rotor poles of 6/4 SRM

Now if B phase is energized then the rotor develops a torque because of variable reluctance and existences of variation in inductance. The torque developed is equal to $(1/2)i_{B}2(dL_{B}/d\theta)$. This direction is such that BB‘ and bb‘ try to get aligned. If this torque is more than the opposing load torque and frictional torque the rotor starts rotating. When the shaft occupies the position such that BB‘ and bb‘ are in alignment (i.e.,) θ=30°, no torque is developed as in this position $dL_B/d\theta=0$. [Vide fig. 3.3(b)]

Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as $(dL_C/d\theta)$ exists. The rotor continues to rotate. When the rotor rotates further 30°, the torque developed due to winding C is zero [vide fig. 3.3(c)] Then the phase winding C is switched off and phase winding A is energized. Then rotor experiences a torque and rotates further step 30°. This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor.

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

When the load torque is increased, the speed of the motor tends to fall, so that the power balance is maintained. If the speed is to be develop at the same value, the develop torque is to be increased by increasing the current. Thus more power is drawn from the mains. Vice-versa takes place when the load is reduced. Thus electrical to mechanical power conversion takes place.

3.3. POWER SEMICONDUCTOR SWITCHING CIRCUITS FOR SRM (POWER CONTROLLERS)

The selection of controller (converter) depends upon the application. One of the main aspects of the research in SRM drives has been the converter design. The main objectives of the design of the converter are performance of the drive and cost of the drive. The power semiconductor switching circuits used are

1. Two power semiconductor switching devices per phase and two diodes.
2. (n+1) power semiconductor switching devices (n+1) diodes.
3. Phase winding using bifilar wires.

4. Split-link circuit used with even-phase number.
5. C-dump circuit.

3.3.1 Two Power Semiconductor Switching Devices per phase and two diodes

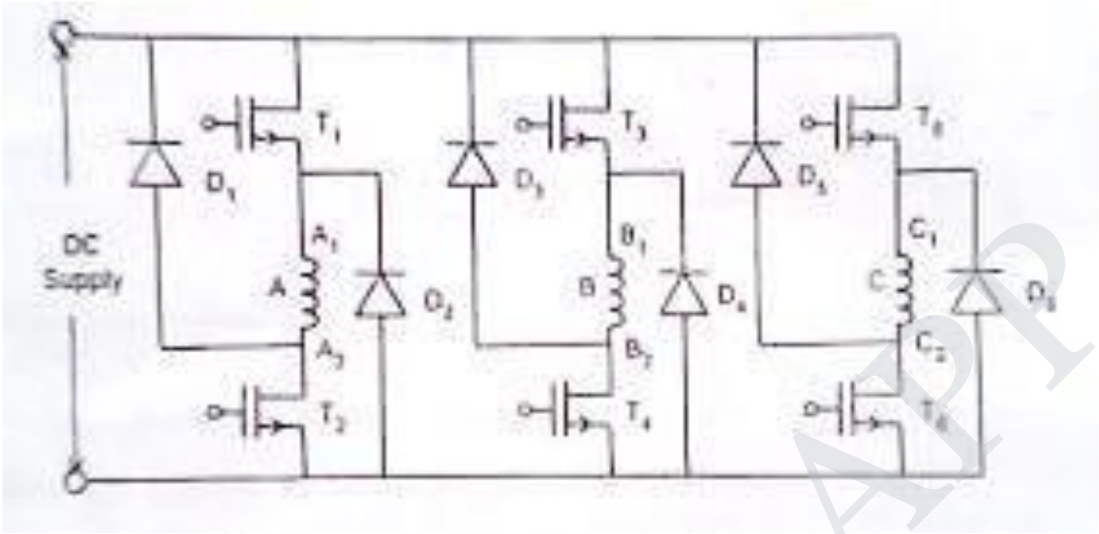


Fig. 3.4 Two Power Semiconductor switching devices and two diodes.

As shown in fig 3.4 phase winding A is connected to the dc supply through power semiconductor devices T_1 and T_2. Depending upon the rotor position, when the phase winding A is to be energized the devices T_1 and T_2 are turned ON. When the phase winding is to be disconnected from the supply (this instant is also dependent on the position of the shaft) the devices T_1 and T_2 are turned off .The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D_1 and D_2 to the supply. Thus the stored energy is fed back to the mains.

Similarly phase winding B & C are also switched on to the supply and switched off from the supply in a cyclic manner. This circuit requires 2 power switching devices and 2 diodes for each phase winding. For high speed operation it is required to see that the stored energy can be fed back to the mains within the available period.

Usually the upper devices T_1, T_3 and T_5 are turned on and off from the signals obtained from the rotor position sensor .The duration of conduction or angle of conduction θ can be controlled by using suitable control circuitry .The lower devices T_2, T_4, T_6 are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical AND ing of the rotor position sensor and chopping frequency .As a result it is possible to vary the effective phase current from a very low value to a high value .For varying the following methods are available.

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

Merits

- Control of each phase is completely independent of the other phase.
- The converter is able to free wheel during the chopping period at low speeds which helps to reduce the reduce the switching frequency and thus the switching losses of the converter.
- The energy from the off going phase is feedback to the source, which results in utilization of energy

Demerits

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

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

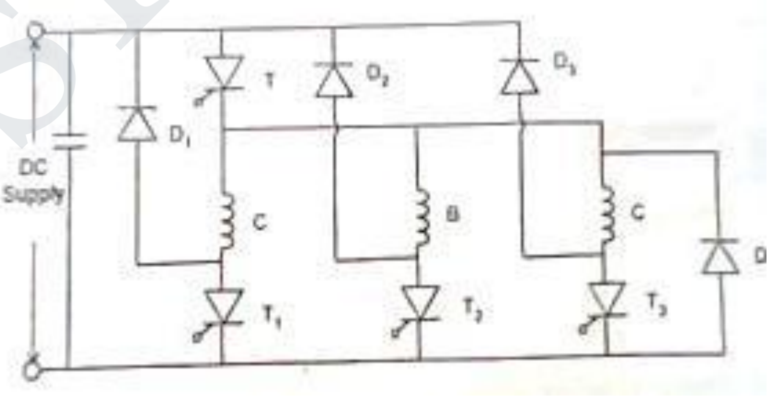


Fig. 3.5 (n+1) power switching devices and (n+1) diodes

This circuit makes use of less number of power switching devices and diodes as shown in fig 3.5. When the (SCRs) switching devices T and T_1 are turned on phase winding A is energized from the dc supply. When these devices are turned off the stored energy in the phase winding is fed back to the mains through diodes D and D1. When devices T and T_2 are turned on the phase winding B is energized .When they are turned off ,the stored energy in B phase winding C is switched on and off from the mains. The cycle gets repeated.

This circuit makes use of (n+1) power switching devices and (n+1) diodes where n is equal to the number of phases.

Merits

- The converter uses low number of switching devices, which reduces the cost of the converter.
- The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses.
- Voltage rating of all the switching devices and the diodes are V_{dc}, which is relatively low.
- The energy for the off going phase is transferred back into the source, which results in useful utilization of the energy and also improves the efficiency.

Demerits

- Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.
- At higher speeds of the off going phase cannot be de-energized fast enough because the common switch ―T‖ keeps turnings on intermediately, disabling forced demagnetization.
- The common switch conducts for all the phases and thus has higher switching stress.

3.3.3Phase winding using bifilar wires

Each phase winding has two exactly similar phase windings as shown in fig 3.6.For this bifilar wires are used .Each phase consists of two identical windings and are magnetically coupled when one of them are excited.

In stepper motor, the purpose of bifilar winding is for bipolar excitation with a reduced number of switching elements.

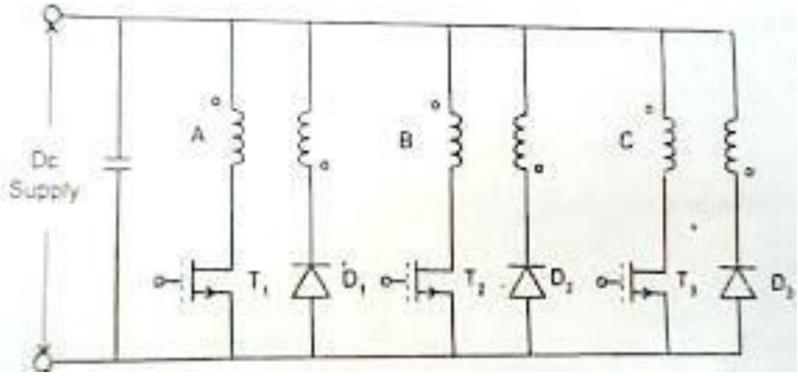


Fig 3.6 Phase winding using bifilar wires

When T_1 is turned on the dc current passes through the phase winding A. when the devices T_1 is turned off the stored energy in the magnetic field is fed back to the dc source through the winding A‘ and D_1 to the supply.

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

Merits

- The converter uses lower number of switching devices thus reducing the cost on the converter.
- The converter allows fast demagnetization of phases during commutation.

Demerits

- Bifilar winding suffers from double number of connections.
- A poor utilization of copper.
- Freewheeling is not possible during chopping as the phases have $-V_{dc}$. this causes of higher ripples in current and torque during chopping.
- The imperfection in the coupling between the two winding causes voltage spikes during turn off.
- The copper loss associated with the auxiliary winding is unacceptable high for many applications.

3.3.4Split – link circuit used with even phase number

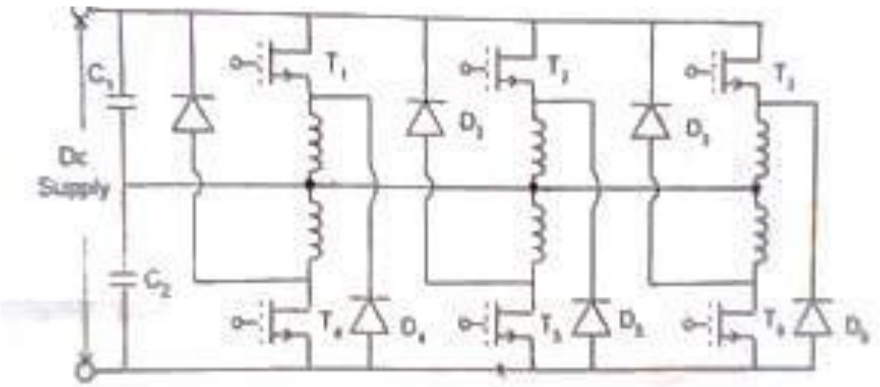


Fig. 3.7 split link circuit used with even phase number

The circuit shown in fig.3.7 is used in a range of highly efficient drives (from 4-80kw).

The main power supply is split into two halves using split capacitors. During conduction, energy is supplied to the phases by one half the power supply. During commutation period, the phases demagnetize into other half of the power supply.

When switch T1 is turned on, phase winding 1 is energized by capacitor c1. When switch T2 is turned off, the stored energy in the phase winding 1 is fed back to the capacitor c2 through diode D4.

When T4 is turned on by capacitor C2 and phase winding 4 is energized. When switch T4 is turned off, stored energy in the winding 4 is feedback to the capacitor C1 through diode D1. The similar operation takes place in the remaining winding also.

Merits

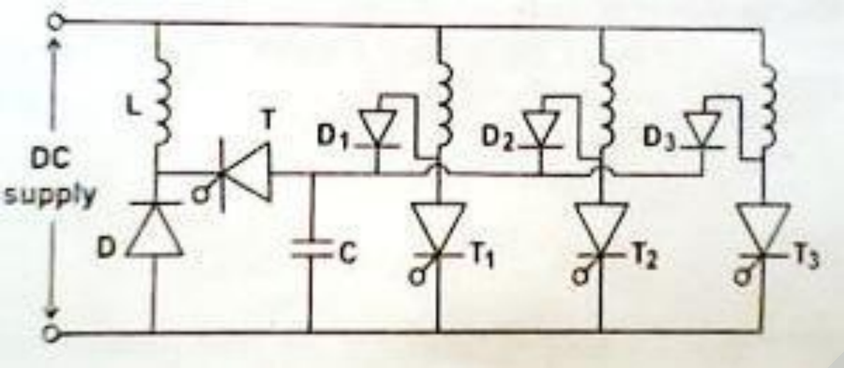
- It requires lower number of switching devices.
- Faster demagnetization of phases during commutation.

Demerits

- During chopping, freewheeling is not possible as the phaser have the voltage Vdc/2. This causes higher switching frequency and more losses.
- This is not feasible for low voltage application.
- The converter is fewer faults tolerant as fault in any phase will unbalance the other phase that is connected to it.

3.3.5 C-Dump circuit

In the C dump circuit shown in fig. 3.8. the device count is reduced to _n‘ plus one additional devices to bleed the stored energy from the dump capacitor C back to supply via the step down chopper circuit. The mean capacitor voltage is maintained well above the supply to permit rapid defluxing after commutation.



A control failure in the energy-recovery circuit would result in the rapid build-up of charge on the capacitor and if protective measures were not taken the entire converter could fail from over voltage.

Demerits

- Dump capacitor voltage is maintained ―2 Vdc‖ to allow fast demagnetization. But use of a capacitor and an inductor in the dump circuit and also the voltage rating of other devices is twice the bus voltage
- Monitoring of the dump capacitor voltage ‗C' and control of dump switch T makes the converter very complicated and also the converter does not allow freewheeling.

TORQUE PRODUCTION IN SWITCHED RELUCTANCE MOTORS :

⑮

→ Torque is Produced due to Variable reluctance Principle.

The flux linkage (λ) due to excitation of winding :

$$\lambda = Li \longrightarrow ①$$

According to Faraday's law of electromagnetic induction, emf (e) due to change in flux linkage,

$$e = (-)\frac{d\lambda}{dt} \longrightarrow ②$$

Substituting λ from eqn ① in ②,

$$② \Rightarrow \quad e = (-)\frac{\partial(Li)}{\partial t} = -L\frac{\partial i}{\partial t} - i\frac{\partial L}{\partial t}$$

Multiply (x) & Divide (÷) by $\partial\theta$ on the second term,

$$e = (-)L\frac{\partial i}{\partial t} - i\frac{\partial L}{\partial \theta} \times \left(\frac{\partial\theta}{\partial t}\right)$$

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

$$\left[\because \theta = \omega t, \quad \therefore \omega = \frac{\partial\theta}{\partial t}\right]$$

$$e = (-)\left[L\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial \theta}(\omega)\right] \longrightarrow ③$$

Considering only magnitude,

$$\therefore e = L\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial \theta}(\omega) \longrightarrow ④$$

Energy stored in the magnetic field,

$$W_e = \frac{1}{2} L i^2 \rightarrow ⑤$$

Mechanical Power developed = Power input to motor (–) Power due to variation in stored energy

Power input to the motor $= e\,i \rightarrow ⑥$

$$= \left[L\frac{\partial i}{\partial t} + i(\omega)\frac{\partial L}{\partial \theta}\right] i$$

$$= Li\frac{\partial i}{\partial t} + i^2\omega\frac{\partial L}{\partial \theta} \rightarrow ⑦$$

$$\left.\begin{array}{l}\text{Power due to variation}\\ \text{in stored energy}\end{array}\right\} = \frac{dW_e}{dt}$$

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

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

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

$$= Li\frac{\partial i}{\partial t} + \frac{i^2}{2}\frac{\partial L}{\partial t}$$

$$= Li\frac{\partial i}{\partial t} + \frac{i^2}{2}\frac{\partial L}{\partial \theta}\left(\frac{\partial \theta}{\partial t}\right)$$

$$= Li\frac{\partial i}{\partial t} + \frac{i^2}{2}(\omega)\frac{\partial L}{\partial \theta} \longrightarrow$$ ⑧

Subtracting ⑧ from ⑦,

~~⑧~~ ⑦-⑧ ⇒

Mechanical Power developed $= P_m = \cancel{Li\frac{\partial i}{\partial t}} + i^2\omega\frac{\partial L}{\partial \theta}$

$$- \cancel{Li\frac{\partial i}{\partial t}} - \frac{i^2}{2}(\omega)\frac{\partial L}{\partial \theta}$$

$$\therefore P_m = \frac{1}{2}\left[i^2\omega\frac{\partial L}{\partial \theta}\right] \longrightarrow$$ ⑨

In general,

$$P_m = \frac{2\pi N T}{60} = \left[\frac{2\pi N}{60}\right]T = \omega T$$

$$\therefore P_m = \omega T \longrightarrow$$ ⑩

where,
ω → angular velocity,
T → Electromagnetic torque developed.

From ⑩ ⇒

$$T = \frac{P_m}{\omega} \longrightarrow$$ ⑪

Subtituting ⑨ in ⑪,

$$T = \frac{\frac{1}{2}\left(i^2\cancel{\omega}\frac{\partial L}{\partial \theta}\right)}{\cancel{\omega}}$$

$$\therefore \boxed{T = \frac{1}{2}\left[i^2\frac{\partial L}{\partial \theta}\right]} \longrightarrow$$ ⑫

Torque corresponds to motoring,

when $\frac{\partial L}{\partial \theta}$ is +ve.

Torque corresponds to generating

when $\frac{\partial L}{\partial \theta}$ is -ve.

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

* If there is magnetic saturation equation ⑫ is invalid & the torque should be derived as the derivative of co-energy or field stored energy.

x —— x —— x —— x —— x

3.8 TORQUE-SPEED CHARACTERISTICS

Torque developed (i.e.) average torque developed but SRM depends upon the current wave form of SRM phase winding. Current waveform depends upon the conduction period and chopping details. It also depends upon the speed.

Consider a case that conduction angle ϴ is constant and the chopper duty cycle is 1.(i.e.) it conducts continuously. For low speed operating condition, the current is assumed to be almost flat shaped. Therefore the developed torque is constant. For high speed operating condition, the current wave form gets changed and the average torque developed gets reduced.

Fig. 3.12(a) represents the speed torque characteristics of SRM for constant ϴ and duty cycle. It is constant at low speeds and slightly droops as speed increases. For various other constant value of ϴ , the family of curves for the same duty cycle is shown in fig.3.12.

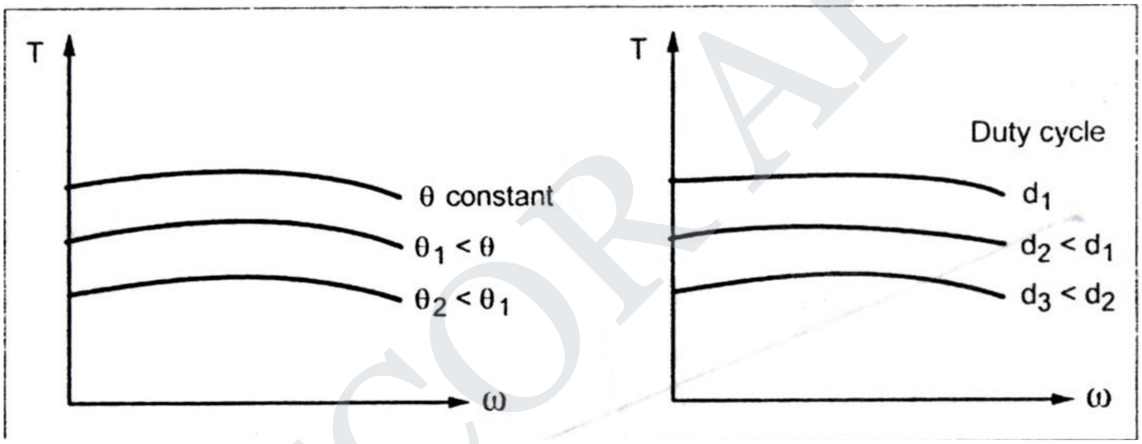


Fig. 3.12 Torque speed characteristics at constant conduction angle θ and duty cycle

Torque speed characteristics for fixed ϴ and for various duty cycles are shown in fig. 3.12. ϴ and duty cycle are varied by suitably operating the semiconductor devices.

3.8.1 Torque Speed Capability Curve

Maximum torque developed in a motor and the maximum power that can be transferred are usually restricted by the mechanical subsystem design parameters.

For given conduction angle the torque can be varied by varying the duty cycle of the chopper. However the maximum torque developed is restricted to definite value based on mechanical consideration.

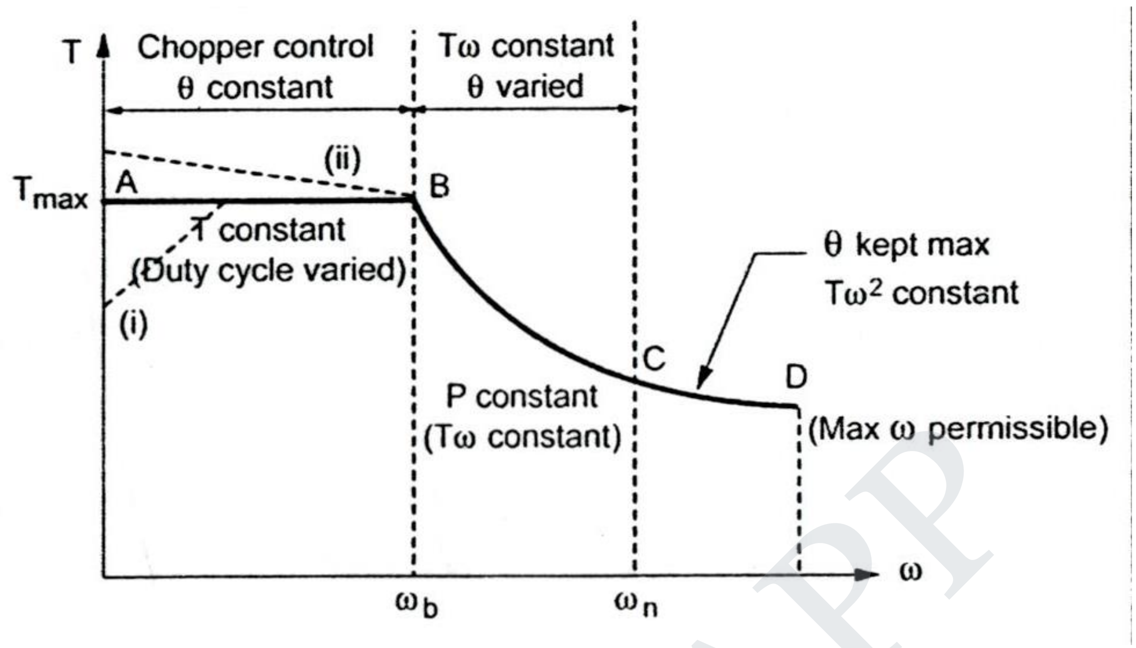


Fig. 3.13 Torque speed characteristic of switched reluctance motor

At very low speeds, the torque / speed capability curve may deviate from the clock torque characteristics. If the chopping frequency is limited or if the bandwidth of the current regulator is limited, it is difficult to limit the current without the help of self emf of the motor and the current reference may have to be reduced.

If very low windage and core loss permit the chopper losses to be increased, so that with higher current a higher torque is obtained. Under intermittent condition of course very much higher torque can be obtained in any part of the speed range up to ω b.

The motor current limits the torque below base speed. The corner point‘or base speed _ω b‘is the highest speed at which maximum current can be supplied at rated voltage with fixed firing angles. If these angles are still kept fixed, the maximum torque at rated voltage decreases with speed squared. But if the conduction angle is increased,(i.e.)Ɵ on is decreased, there is a considerable speed range over which maximum current can be still be forced into the motor. This maintains the torque at a higher level to maintain constant power characteristic. But the core losses and windage losses increases with the speed. Thus the curve BC represents the maximum permissible torque at each speed without exceeding the maximum permissible power transferred. This region is obtained by varying Ɵ D to its maximum value Ɵ D max. Ɵ D is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power; maximum permissible conduction angle

ƟD max and duty cycle of the chopper is unity.

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

3.9 DISTINCTION BETWEEN SWITCHED RELUCTANCE MOTOR AND THE VARIABLE RELUCTANCE STEPPER MOTOR

The conduction angle for phase currents is controlled and synchronized with the rotor position, usually by means of a shaft position sensor.

Thus SR motor is exactly like a brushless dc motor. But the stepper motor is usually fed with a square-wave of phase current without rotor position feedback.

SR motor is designed for efficient power conversion at high speeds comparable with those of the PM brushless dc motor. The stepper motor is usually designed as a torque motor with a limited speed range.SR motor is more than a high-speed stepper motor. Its performance and low manufacturing cost make it a competitive motor to PM brushless dc system.

3.9.1 Merits of SRM

1. Construction is simple and robust, as there is no brush.
2. Rotor carries no windings, no slip rings and brush-less maintenance.
3. No permanent magnet, neither in the stator nor in the rotor.
4. Ventilating system is simpler as losses takes place mostly in stator.
5. Power semiconductor switching circuitry is simpler.
6. No shoot-through fault is likely to happen in power semiconductor circuits.
7. Torque developed does not depend upon the polarity of the current in the phase winding.
8. The operation of the machine can be easily changed from motoring mode to generating mode by varying the region of conduction.
9. It is impossible to have very high speeds.
10. Depending upon the requirement, the desired torque speed characteristics can be tailor made.
11. It is a self-starting machine.
12. Starting torque can be very high without excessive inrush currents.

3.9.2 Demerits of SRM

1. Stator phase winding should be capable of carrying the magnetizing current also, for setting up the flux in the air gap.
2. For high speed operations, the developed torque has undesirable ripples. As a result it develops undesirable acoustic losses (noise).
3. For high speeds, current waveform also has undesirable harmonics. To suppress this effect large size capacitor is to be connected.
4. The air gap at the aligned axis should be very small while the air gap at the inter-polar axis should be very large. It is difficult to achieve. No standardized practice is available.
5. The size of the motor is comparable with the size of variable speed induction motor drive.
6. Number of power wires between power semiconductor circuitry and the motor and the number of control cables from one controller to the power semiconductor circuitry are more and all to be properly connected.
7. It requires a position sensor.

3.9.3 Application of SRM

1. Washing machines
2. Vacuum cleaners
3. Fans
4. Future automobile applications
5. Robotic control applications

3.10 SHAFT POSITION SENSING

- Commutation requirement of the SR motor is very similar to that of a PM brushless motor.
- The shaft position sensor and decoding logic are very similar and in some cases it is theoretically possible to use the same shaft position sensor and the same integrated circuit to decode the position signals and control PWM as well.
- The shaft position sensors have the disadvantage of the associated cost, space requirement and possible extra source of failure. Reliable methods are well established. In position sensors or speed sensors, resolvers or optical encoders may be used to perform all the functions of providing commutation signals, speed feedback and position feedback.
- Operation without position sensor is possible. But to have good starting and running performance with a wide range of load torque and inertias, sensor is necessary.

- When the SR motor is operated in the _open-loop‘ mode like a stepper motor in the slewing range, the speed is fixed by the reference frequency in the controller as long as the motor maintains _step integrity‘. (i.e) stay in synchronism. Therefore like an ac synchronous motor, the switched reluctance motor has truly constant speed characteristics.

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

(b) To ensure reliable starting.

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

3.11 MICROPROCESSOR OR COMPUTER BASED CONTROL OF SRM DRIVE

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

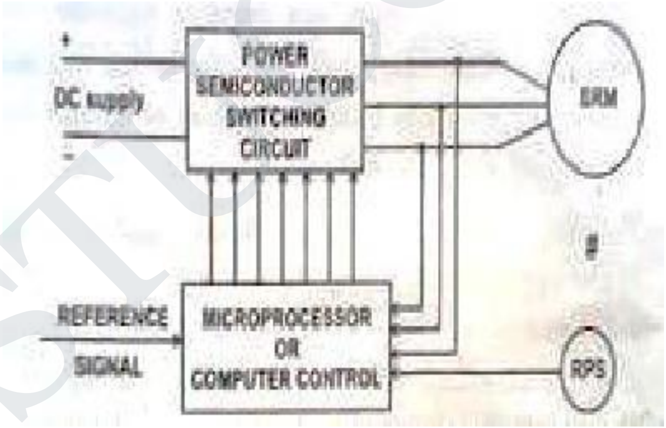


Fig. 3.14 Microprocessor or computer based control of SRM

Fig. shows the block diagram of microprocessor based control of SRM drive. This control system consists of power semiconductor switching circuit, SRM with rotor position sensor and microprocessor system. In this system microprocessor acts as a controller for the switched reluctance motor and generate control pulses to the power semiconductor switching circuits.

The input DC supply is fed to the power semiconductor switching circuits. Different types of power semiconductor switching circuits are used for different application. Normally the circuits are inverter circuit configuration. The power semiconductor devices are turned on and off by controller circuit. Here the controller circuit is microprocessor or computer based control system.

In the SRM drive shown in fig. 3.14, the rotor position sensor gives the information about the rotor with respect to the reference axis to the microprocessor or computer control. The controller also receives the status of current, flow through the phase winding and reference signal.

The microprocessor or computer compares the signals obtained from the RPS and reference and generate square pulses to the power semiconductor devices. This signal is fed to the inverter circuit. The phase winding of the SRM is energized depending upon the turning on and off of the power semiconductor switching circuit.

The microprocessor or computer controller can perform the following functions.

a) Control the feedback loops.
b) PWM or square wave signal generation to inverters.
c) Optimal and adaptive control.
d) Signal monitoring and warning.
e) General sequencing control.
f) Protection and fault overriding control.
g) Data acquisition.

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

Permanent Magnet materials – Minor hysteresis loop and recoil line-Magnetic Characteristics – Permeance coefficient -Principle of operation – Types – Magnetic circuit analysis – EMF and torque equations –Commutation - Power Converter Circuits and their controllers – Motor characteristics and control– Applications

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 FEATURES 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

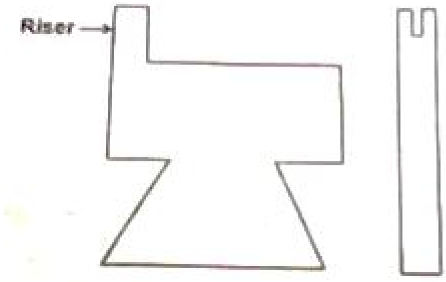


Fig 4.2 Commutator Segment

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.

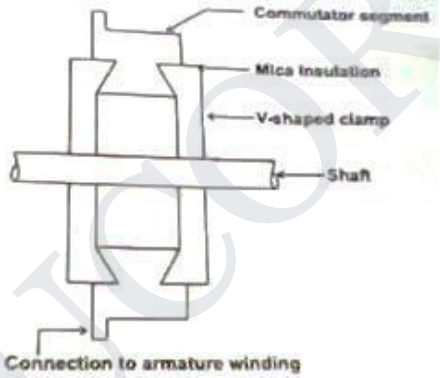


Fig 4.3 connection of commutator segments to shaft

4.2.6 Mechanical Commutator and Brushes Arrangement

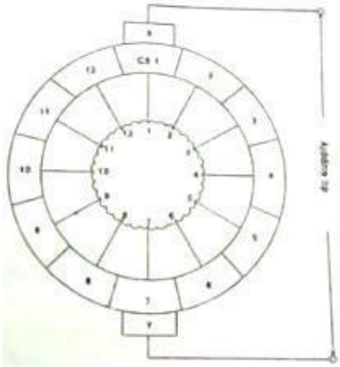


Fig 4.4 Mechanical Commutator and Brushes Arrangement

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.

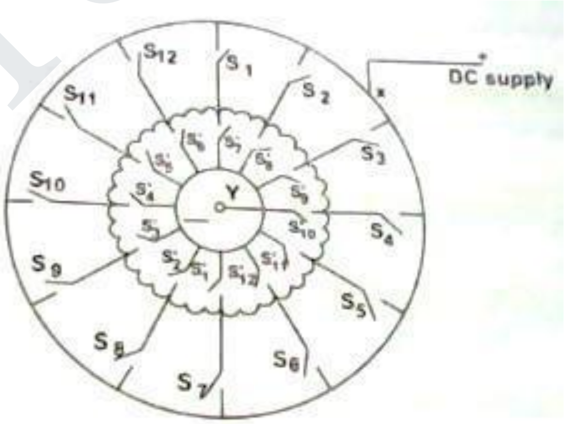


Fig 4.5 Electronic Commutator

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.

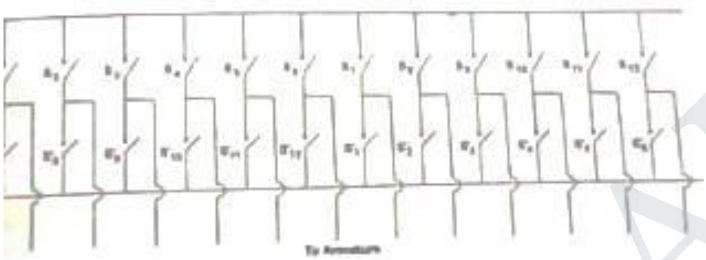


Fig 4.6 switching circuit of electronics commutator

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.

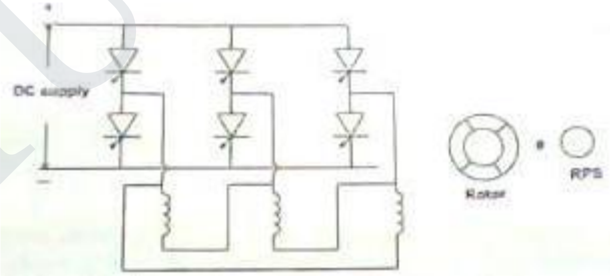


Fig 4.7 Delta Connected Stator Armature Winding

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.

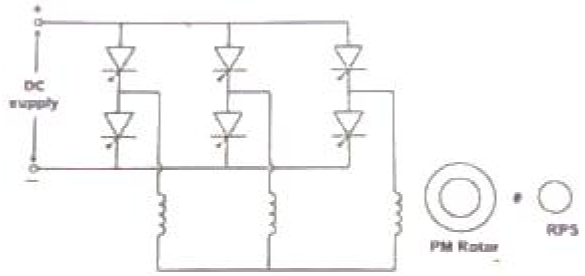


Fig 4.8 Star Connected Armature Winding

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 B – H LOOP AND DEMAGNETIZATION CHARACTERISTICS

4.3.1 Permanent Magnets Material

NdFeB – Neodymium – iron – boron has the highest energy product of all commercially available magnets at room temperature. It has high remanence and coercivity in the motor frame size for the same output compared with motors using ferrite magnets. But it is costlier. But both of the above stated magnets are sensitive to temperature and care should be taken for working temperature above 100˚.For very high temperature applications, alnico or rare earth cobalt magnets must be used.

4.3.2 B – H Loop

It is used for understanding characteristics hysteresis loop as shown.

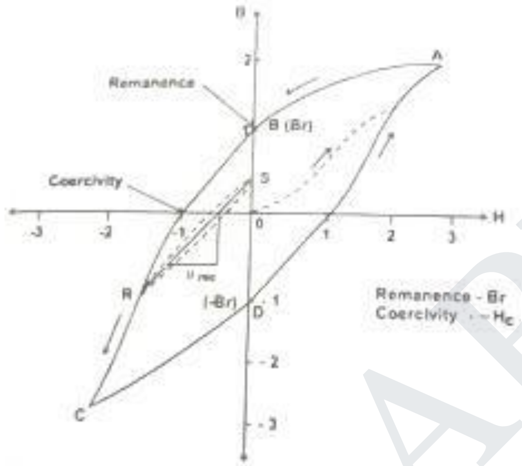


Fig 4.9 BH Hysteresis loop of hard permanent magnet material

X – axis – Magnetizing force or field intensity H.

Y – axis – Magnetic flux density B in the material.

- An un-magnetized sample has B = 0 and H = 0 and therefore starts out at the origin.

Curve OA

- If it is subjected to a magnetic field, magnetic fixture (an electromagnetic with shaped pole pieces to focus flux into the magnet), then B and H in the magnet follow the curve OA as the external ampere – turns are increased.

Curve AB

- If the external ampere – turns are switched off, the magnet relaxes along AB. The operating point (H, B) depends on the shape of the magnet and permanence of the surrounding magnetic circuit.If the magnet is surrounded by a highly permeable magnetic circuit, that is if it is keepered then its poles are effectively shorted together so that H = 0 and then the flux density is the value at point remanence Br.

Pemanence: Maximum flux density that can be retained by the magnet at a specified temperature after being magnetized to saturation.

Curve BC

- External ampere turns applied in the opposite direction cause the magnets operating point to follow the curve from B through the second quadrant to C.

Curve CD

- If the ampere – turns are switched off at c the magnet relaxes along CD.

It is now magnetized in the opposite direction and the maximum flux density it can retain when keepered is – Br.

- To bring B to zero from negative remanence point D, the field +Hc must be applied.
- The entire loop is usually symmetrical and be measured using instruments such as hysteresis graph.

4.3.3 Soft PM

- Soft PM materials have Knee in the second quadrant such as Alnico.
- Alnico magnets have very high remanence and excellent mechanical and thermal properties. But they are limited in the demagnetizing field they can withstand.
- These soft PM are hard when compared with lamination steels the hysteresis loop of typical non oriented electrical steel is very narrow when compared with Alnico.

4.3.4 Demagnetization curve

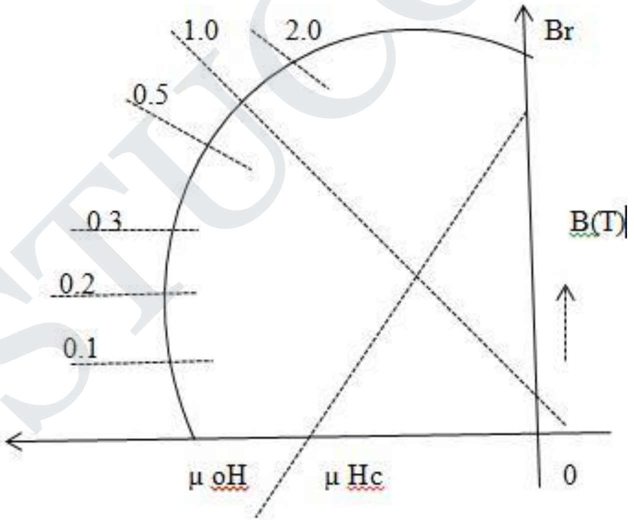


Fig 4.10 Demagnetization curve

In the absence of externally applied ampere – turn, the magnets operating point is at the intersection of the demagnetization curve and the load line.

- The slope of the load line is the product of μ_0 and the permeance co efficient of the external circuit.

In a permanent magnet, the relationship between B and H is

$$B = \mu_0 H + J$$

$\mu_0 H$ – flux density that would exist if the magnet were removed and the magnetizing force remain at the value H.

J – contribution of the magnet to the flux - density within its own volume.

- If the demagnetization curve is a straight line, and therefore its relative slope and there by the μ_{rec} is unity, Then J is constant.

J – Magnetization of the magnet, unit T tesla

- Hard magnets have $\mu_{rec} >= 1$,J decreases as the –Hc increases.
- The magnet can recover or recoil back to its original flux density as long as the magnetization is constant.
- The coercive force required to permanently demagnetize the magnet is called the intrinsic coercivity and it is Hci.

4.4 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 Pm =ωT and the various losses in the motor and in the electronic switching circuitry.

4.5 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.

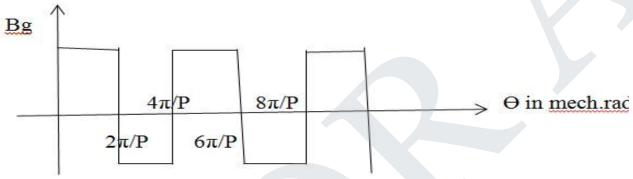


Fig 4.11 Air gap flux density distribution in 180Ʈ BLPM SQW motor.

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

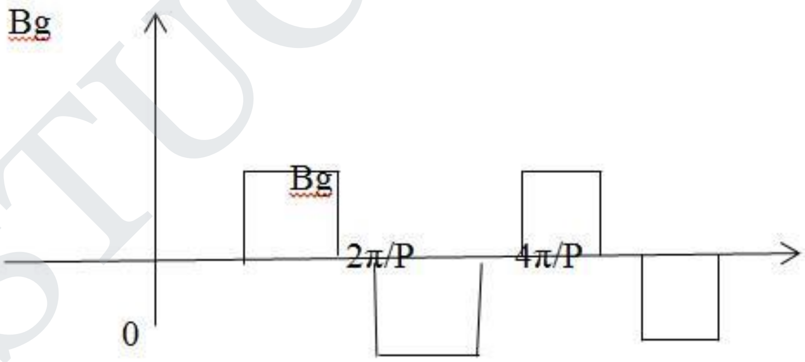


Fig 4.12 Air gap flux density distribution in 120Ʈ BLPM SQW motor

(b)BLPM Sine wave DC Motor

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

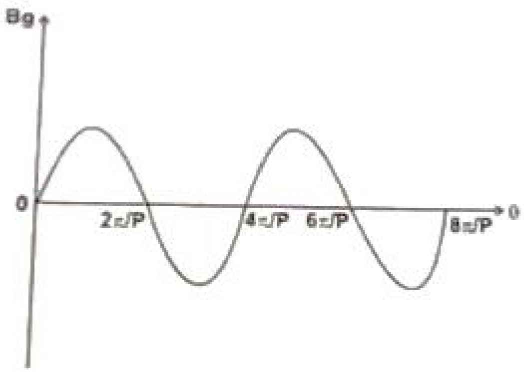


Fig 4.13 Flux density distribution of BLPM DC sine wave motor

4.6 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 $\Theta = 0$ .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 ($180^{ʊ}$ 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 $\omega_{mt}=0$,the centre of N-pole magnet is aligned with x-axis.

At $\omega_{mt}=0$,x-axis is along PM axis.

Therefore flux enclosed by the coli is

Φ_{max}=B x 2πr/p x l ………………...(4.1)

=flux/pole

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

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

$=B_g rl[\pi]$

At ω_{mt}=0,the flux linkage of the coil is

Λ_{max}= (B_g x 2πr/p x l)T_c ωb-T ……………………….(4.2)

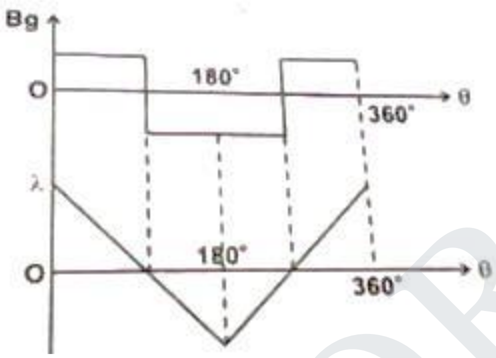


Fig 4.14 Magnetic Flux Density around the Air gap

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

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 $B_grlTc\pi/p$ 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

$\Delta\lambda/\Delta t$ =Final flux linkage – Initial flux linkage/time.

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

$$=-(2B_grlTc\omega_m) \quad \text{..................................(4.3)}$$

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

$$e_c=2B_grlTc\omega_m \quad \text{..................................(4.4)}$$

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

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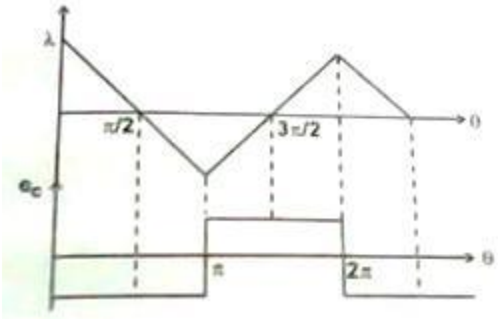


Fig 4.16 Emf waveform of coil 1

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

$e_c = 2B_g rlTc\omega_m$ 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 $30^{\text{Ʊ}}$(i.e.) slot angle ϒ .

The magnitude of emf induced in the coil a1A1

$e_{c2} = B_g rlTc\omega_m$ volts …………………………….(4.6)

The magnitude of emf induced in the coil a2A2

$e_{c2} = B_g rlTc\omega_m$ volts …………………………...(4.7)

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

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

$e_{c1} + e_{c2} = 2B_g rlTc\omega$ ………………………………..(4.8)

$e_{ph} = n_c\,[2B_g rlTc\omega_m\,]$ ……………………………….(4.9)

$e_{ph} = 2B_g rlTph\omega_m$ 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

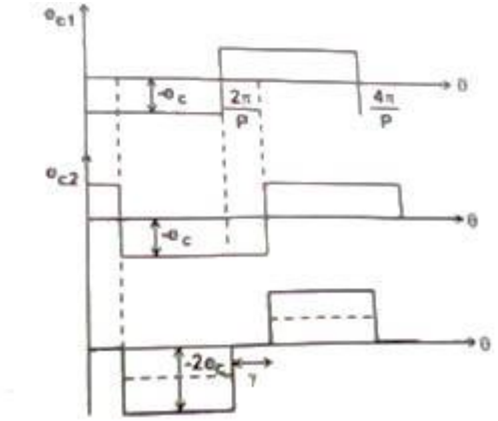


Fig 4.17 Emf waveform of phase A

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.

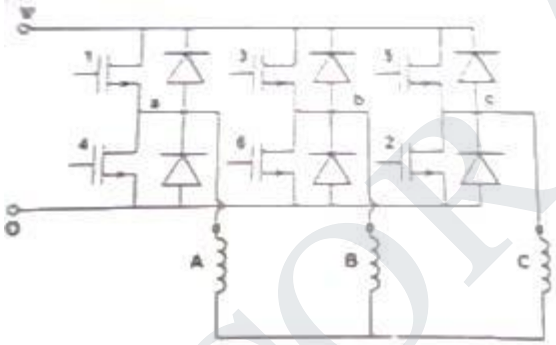


Fig.4.18 converter of brushless dc motor with star connected phase winding.

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.

4.7 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 .

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

If V_{dd} is neglected

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

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

$$I = \frac{V-E}{R} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.12)$$

(a) Starting condition

Speed is zero $\omega_m = 0$

Supply voltage is V

Since ω_m=0; e_{ph} = 0

$$\text{Starting current } I_{stg} = \frac{-}{2\mathrm{Rph}} = \frac{V}{2\mathrm{Rph}} = \frac{V}{R} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.13)$$

$R = 2\, R_{ph}$ 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

$$V = 2\, e_{pho} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.14)$$

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

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

$$V = k_e\, \omega_{mo}$$

No load current I_o=0

(c) ON load condition:

$V = 2\,\mathrm{eph} + 2\, I\, \mathrm{Rph}$

$= 4\, \mathrm{Bg}\, r\, l\, \omega\mathrm{m}\, \mathrm{tph} + 2\, I\, \mathrm{Rph}$

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

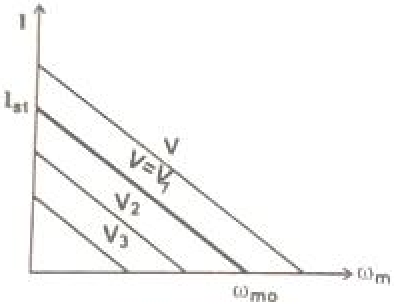


Fig.4.19 I Vs. ωm Curve

4.8 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

$T = K_tI$ …………………………..(4.34)

$= 4 B_gr lT_{ph} I$

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

$I/(T_{stg}) =(K_tI)/(K_tI_{stg})$

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

$T/ T_{stg}=2I R_{ph}/V$ ………………….. (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)

4.9 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

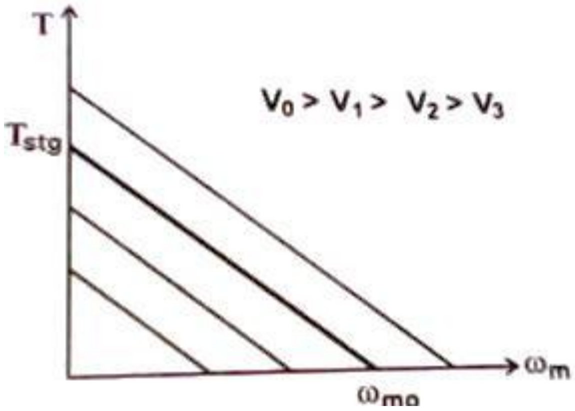


Fig 4.20 T-ω_m curve for various supply voltages Permissible region of operation in T-ω_m plane

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}.

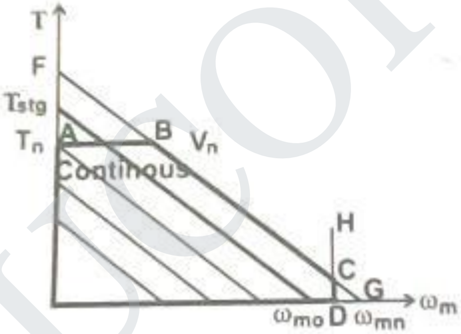


Fig. 4.21 Torque-speed characteristics

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.

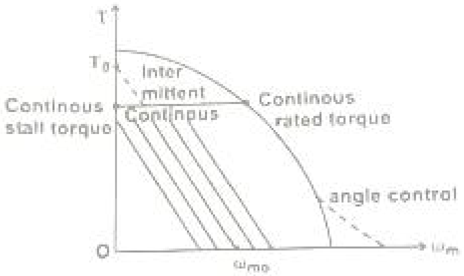


Fig.4.22 Torque speed characteristics of ideal brushless DC motor

- 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.

4.10 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.

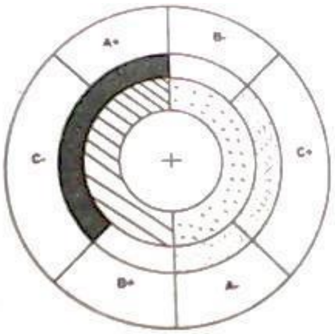


Fig.4.23 BLDC motor with 180° magnet arc and 120° square wave phase currents

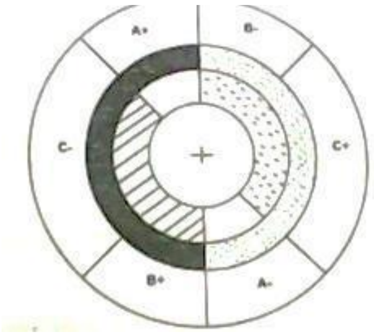


Fig.4.24 BLDC motor with 120° magnet arcs and 180° square wave phase currents

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

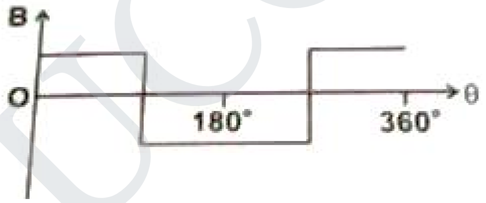


Fig.4.25 Flux density around air gap

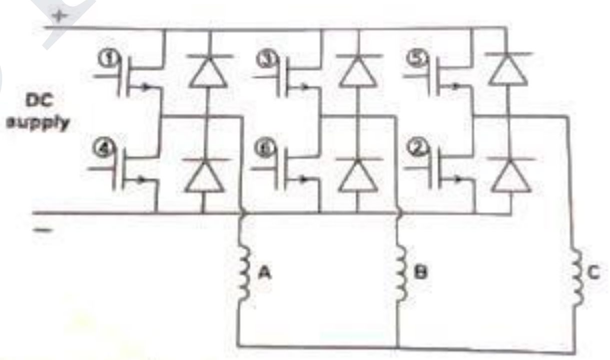


Fig.4.26 Converter of brushless DC motor for star connected phase winding

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

- 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

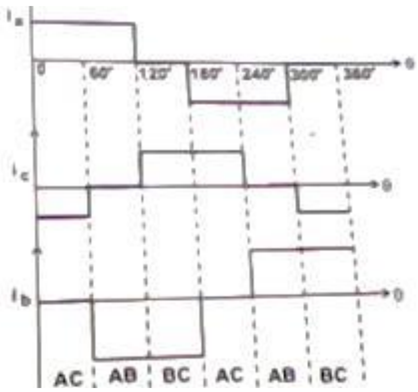


Fig. 4.27 phase current waveforms of BLDC motor with 180º pole arc.

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 has a stepped wave form as shown in fig.4.28 that reflects the slotting.

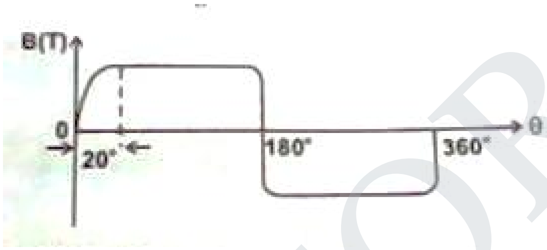
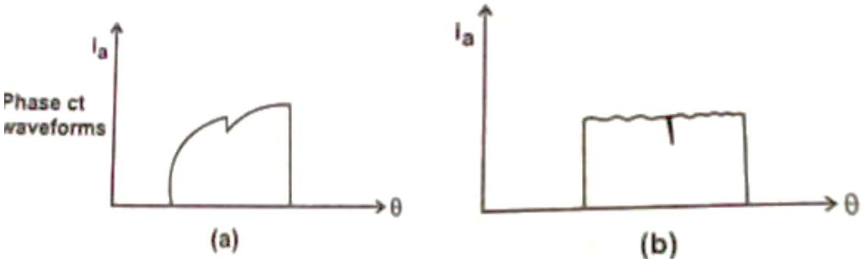


Fig 4.28 Air Gap Flux Density on Open Circuit

To some extent these effects cancel each other so that s those 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 60° and then jumps to a position 60° ahead.

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

Table 4.2 120° Magnet Delta Winding, 180° 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

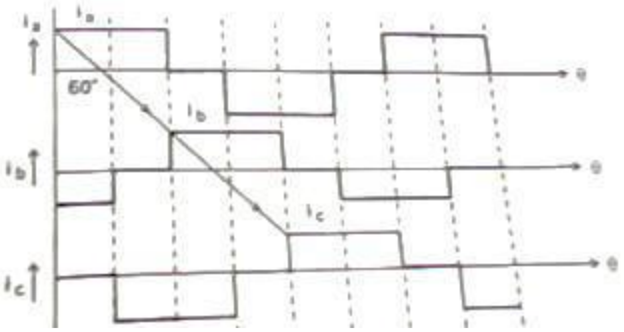


Fig.4.30 phase currents wave forms of BLDC motor with120º pole arc

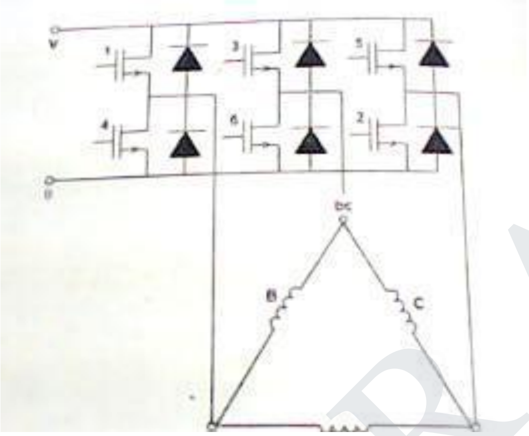


Fig 4.31 converter of brushless dc motor for delta connected phase winding

- 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 opposite 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.

4.11 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)

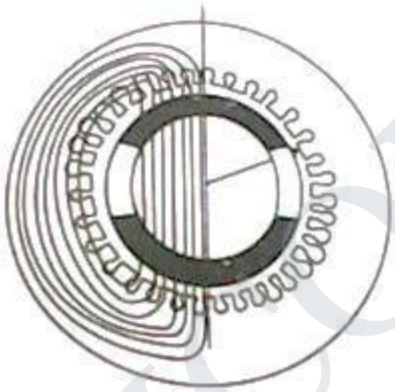


Fig 4.32 magnetic circuit analysis of BLDC motor

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.

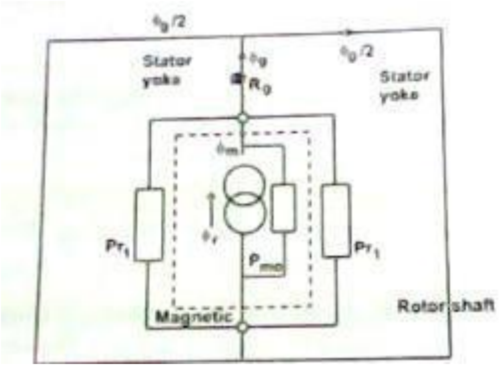


Fig .4.33 magnetic equivalent circuit.

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}.

$\upsilon r = BrAm$ …….(4.43)

$Pmo = \mu 0 \mu recAm/lm$ …….(4.44)

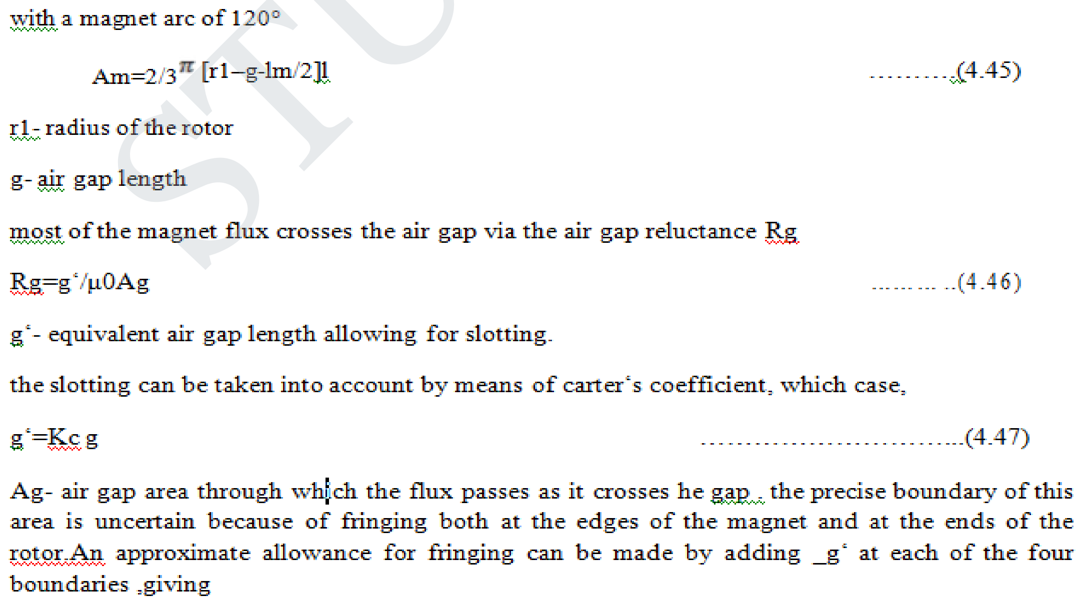
where Am – pole area the magnet

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°

$Am=2/3^{\pi}\,[r1-g-lm/2]l$ ……….(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

$Rg=g'/\mu 0Ag$ ……… ..(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,

$g'=Kc\,g$ …………………………...(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

$$Ag=[2/3\quad(r1-g/2)+2g](l+2g) \qquad \text{…..(4.48)}$$

- 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

$$pm=pmo+prl$$

$$pm=pmo(1+prl)$$

prl-normalized rotor leakage permeance

4.12 A controller for BLPM SQW DC Motor

4.12.1 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.

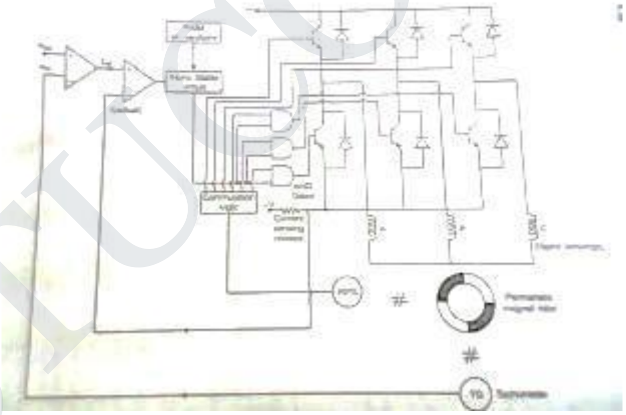


Fig 4.34 structure of controller for brushless PM DC Motor

4.12.2 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.

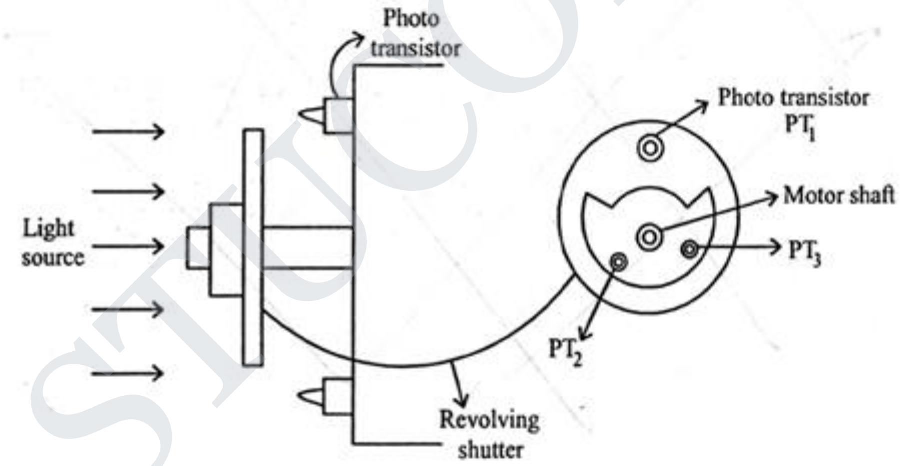


Fig 4.35 Optical position sensor

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.

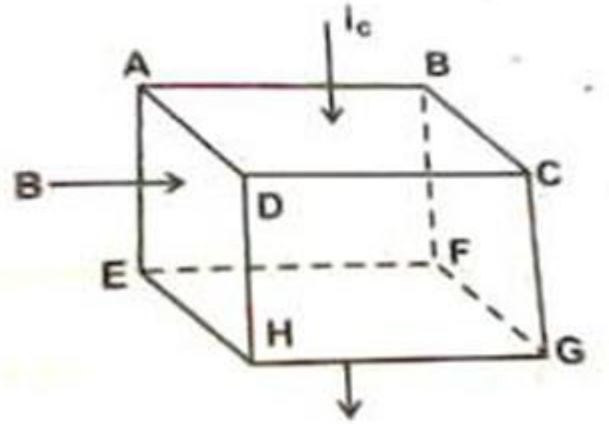


Fig 4.36 Hall Effect

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

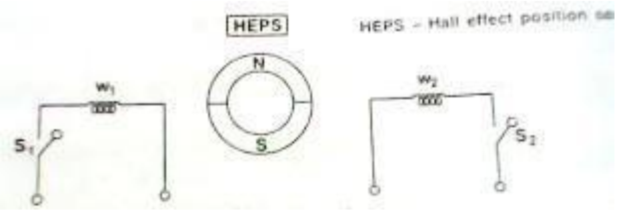
B- Flux density in tesla

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.

4.12.3 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.



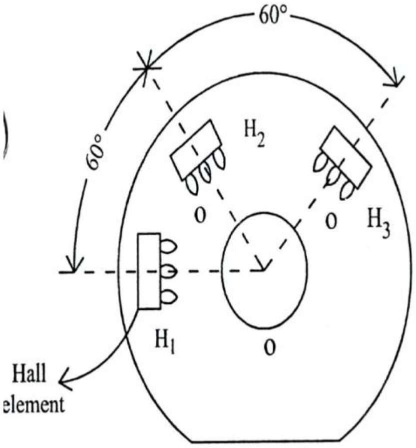


Fig 4.37 2 pole BLPM motor

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.

4.13 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.

4.13.1 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.

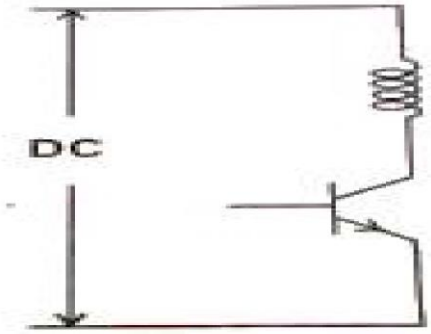


Fig. 4.38 one phase one pulse BLPM motor.

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

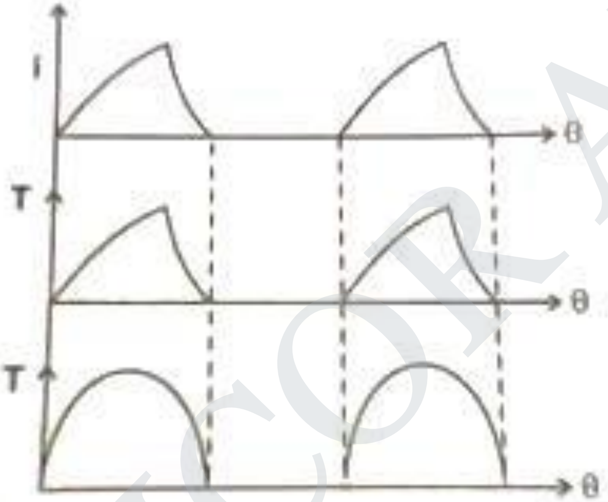


Fig.4.39 Current and torque waveform

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%.

4.13.2 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.

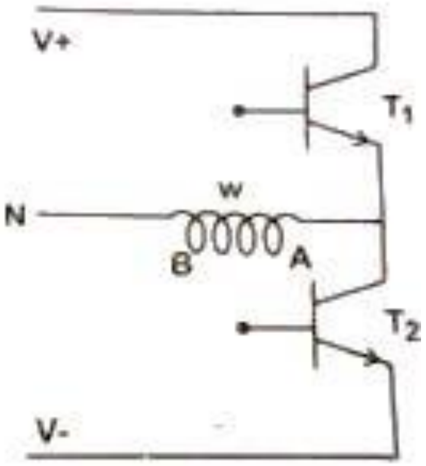


Fig. 4.40 One phase two pulse BLPM motor

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.

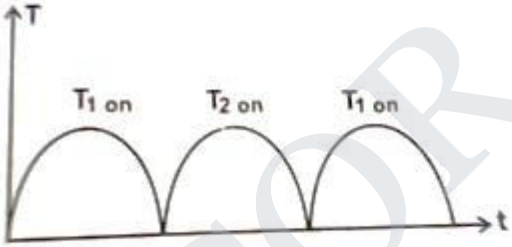


Fig. 4.41 Torque waveform

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.

4.13.3 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.

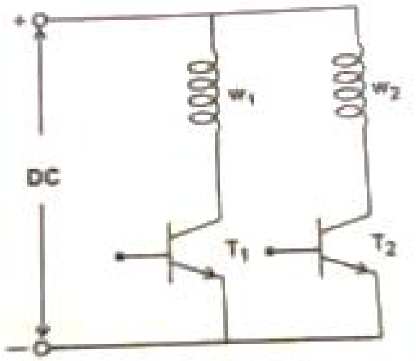


Fig. 4.42 two phase winding and two pulse motor

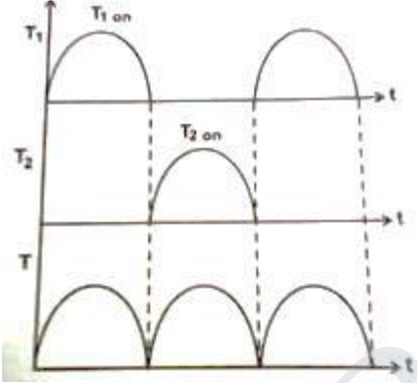


Fig. 4.43 torque waveform

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.

4.13.4 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

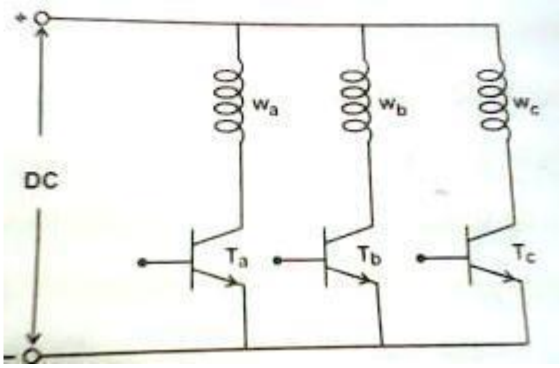


Fig. 4.44 3 phase, 3 pulse BLPM motor.

4.13.5 Three phase six pulse BLPM motor

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

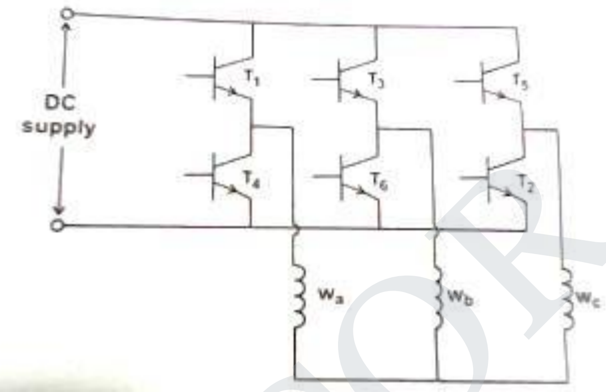


Fig. 4.45 3-phase six pulse BLPM motor.

Principle of operation – Ideal PMSM – EMF and Torque equations – Armature MMF – Synchronous Reactance – Sine wave motor with practical windings - Phasor diagram – Torque/speed characteristics - Power controllers - Converter Volt-ampere requirements– Applications.

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.

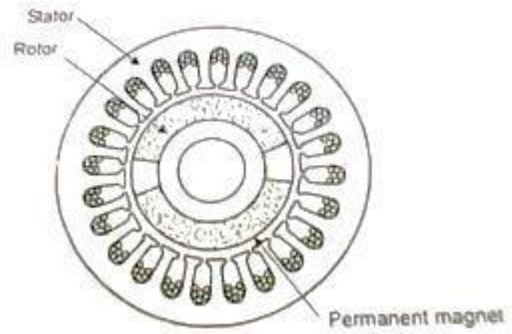


Fig. 5.1 structure of the stator and rotor

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

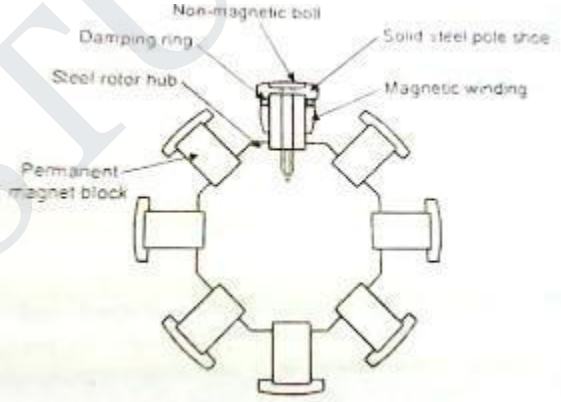


Fig. 5.2 PMSM rotor

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

Flux density can be expressed as B= □B□sinθ or B□ cospθ or B□sin(pθ +α)orB□ cos (ρθ+α),2p=p,(i.e)p-no of pole pairs depending upon the position of the reference axis as shown in fig5.3

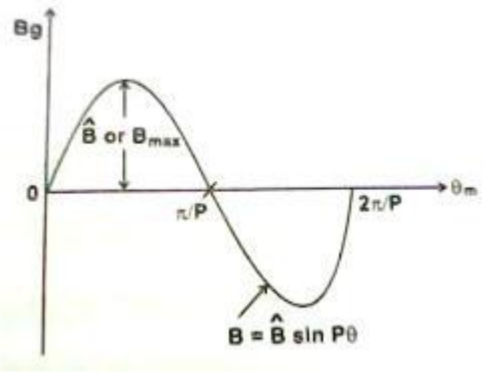
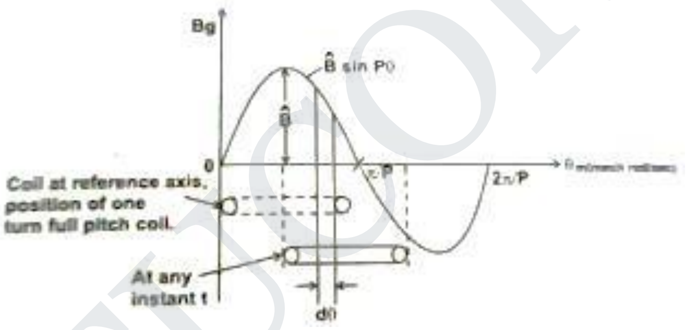


Fig 5.3 flux density distribution

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.



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

Flux density at the strip B= B□sin pθ
Incremental flux in the strip dθ = B X area swept by the conductor
dθ = B□ sin pθ X lr dθ
B lr dθ weber
Where
L – Length of the armature in m
r – Radians of the armature
d θ = B□ sin pθ X lr dθ
= B□ lr sin pθ X dθ
Flux enclosed by the coil after lapes of t sec is

$$\phi = \qquad \text{lr} \sin P\,\theta\, d\,\theta \qquad \text{……..(5.1)}$$

$\phi = (2\, B\square\, lr/p) \cos p\theta\, \omega_{mt}$

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
$= - d\phi\ /dt\ ((2\, B\square\, lr/p)$
$\cos p\theta\ \omega_{mt}) = (2\, B\square$
$lr/p)\ p\ \omega_m \sin p\ \omega_{mt}$

$e = 2\, B\square\, lr\, \omega_m \sin p\, \omega_{mt}$ ……..(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.

$e_{ph} \quad = lr\, \omega_m \sin p\, \omega_{mt})T_{ph}$ ……..(5.3)
$lr\, \omega_m\, T_{ph} \sin p\, \omega_{mt}$
$= \breve{E}_{ph} \sin \omega_{et}$

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

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

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

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

$\omega_m = \omega_e/\rho$

ϕ_m – sinusoidal distributedflux / pole

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

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

Average value of flux density for sinewave $=2/\pi$

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

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

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

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

π elec rad

π/ρ mech. Rad

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

[m π *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

$= \frac{2}{n_s}\pi\frac{\rho}{s}$; n = 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

$$\mathbf{E_{ph} = 4.44\, f T_{ph} \phi_m K_{w1}} \text{ volts.} \qquad \text{……..(5.9)}$$

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.

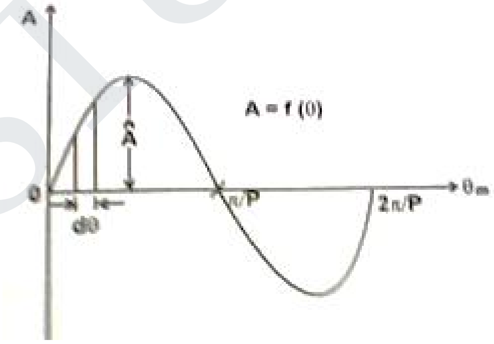


Fig. 5.5 Ampere conductor density distribution

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

Where A = ampere conductor density

= ampere conductor/degree

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

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

$$= A^{\wedge} \sin P\theta \, d \, \theta$$

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

$$= - A^{\wedge} \left[\frac{\cos P}{P} \theta\right]$$

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

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

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

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

$A^{\wedge} = \frac{i\,Tph}{2}$ ……..(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 θ

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

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

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

$$B = B^{\wedge} \cos \qquad - \qquad \text{……..(5.14)}$$

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

Flux density at the strip B =$B^{\wedge}$ cos(pϴ-α)

Ampere conductors in the strip =Adϴ

=A sinPϴ dϴ

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

dF=$B^{\wedge}$ cos(Pϴ-α)1.$A^{\wedge}B^{\wedge}$1.$A^{\wedge}$sin Pϴ.dϴ

dF=$A^{\wedge}B^{\wedge}$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 = $\int_0^{\pi/p} dT$

$$T=\int_0^{\pi} A\,B\ rl \sin P\,\theta \cos(P\,\theta - \alpha)\,d\,\theta \qquad \text{……..(5.16)}$$

$$= A\ B\ rl/2 \int_0^{\pi} /p\,(\sin P\,\theta + P\,\theta\_\alpha + \sin\alpha)\,d\,\theta$$

$$= A\ B\ rl/2\left[\_\frac{\cos(}{2p}\ 2P\theta\_\alpha) + \theta \sin\alpha\right]$$

$$=A\ B\ rl/2\ - \left[\frac{\cos\alpha}{}\ \frac{\cos\alpha}{}\ \frac{\pi}{}\sin\alpha\right]$$

$$T=A\ B\ rl/2. - \qquad \text{N-m} \qquad \text{……..(5.17)}$$

The total torque experienced by all the armature conductors

=2P x torque/pole

=2P x – ——

T= π A B rl sin α N-m… …..(5.18)

$\frac{\pi}{P} \times \frac{ABrl}{2} \sin\alpha$

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

$i_a = Im\cos\omega t\ (i.\ \ \bar{}\ I\cos\omega t$ ……..(5.20)

$I_{b=}\ Im\cos\left(\omega t - \frac{2\pi}{3}\right) = \sqrt{2}I\cos\left(\omega t - 2\pi/3\right)$ ……..(5.21)

i_c=cos Im $\left(\omega t + \frac{2\pi}{3}\right) = \sqrt{2}I\cos\left(\omega t - 4\pi/3\right)$ ……..(5.22)

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.

= cos P θ ……..(5.23)

$f_a \quad F_m$

$f_b = F_m \cos [P\,\theta - 2\pi/3]$ ……..(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

  $= \frac{\sin\sigma/}{} 2$; 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.

  $= 4/\pi.3/2\,\sqrt{2}$ Iph Kw1 Tph ……..(5.27)

- 4.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 = $\frac{\frac{4}{}3/2.\sqrt{2}}{}$ Iph Kw1 Tph

Electromagnetic torque developed in a practical BLPL SNW motor

=π A B rl sin β ……..(5.28)

=π $\frac{}{\_}$ B r l sin β

$$\left[3\sqrt{\frac{2}{\pi}}\,Iph\;Kw1\;Tph\right]$$

$$= 3(\sqrt{2}\text{Kw1 Tph B rl})\,Iph\;sin\beta$$

$$=3\,\frac{Eph}{\omega m}\;Iph\sin\beta \qquad \text{……..(5.29)}$$

$$i_a\,T_{ph} = I_{max}\cos\omega t\,\cos\theta \qquad \text{……..(5.30)}$$

$$i_b\,T_{ph} = I_{max}\cos\left(\omega t-\frac{2\pi}{3}\right)\cos\left(\theta-\frac{2\pi}{3}\right) \qquad \text{……..(5.31)}$$

$$i_c\,T_{ph} = I_{max}\cos\left(\omega t-\frac{4\pi}{3}\right)\cos\left(\theta-\frac{4\pi}{3}\right) \qquad \text{……..(5.32)}$$

$$i\;\;T_{ph} = i_a\,T_{ph}+i_b\,T_{ph}+i_c\,T_{ph} \qquad \text{……..(5.33)}$$

$$= I_{max}\left(\frac{\cos(\omega t+\theta)+\cos(\omega t-\theta)}{2}\right)+I_{max}\left(\frac{\cos(\omega t+\theta-4\pi/3)+\cos(\omega t-\theta)}{2}\right)+$$
$$I_{max}\left(\frac{\cos(\omega t+\theta-8\pi/3)+\cos(\omega t-\theta)}{2}\right)$$

$$=\frac{1}{2}I_{max}.3\cos(\omega t-\theta)+\frac{}{2}I_{max}[\cos(\omega t+\theta)\cos 240+\sin(\omega t+\theta)sin240+\cos(wt+\theta)\cos 480+\sin(wt+\theta)sin480]$$

$$=\frac{3}{2}I_{max}\cos(\omega t-\theta)+\frac{1}{2}I_{max}[\cos(\omega t+\theta)-\cos(\omega t+\theta)-0.866\sin(\omega t+\theta)-0.5\cos(\omega t+\theta)+0.866\sin(\omega t+\theta)]$$

$$=\frac{3}{2}I_{\max T_{ph}}\cos(\omega t-\theta) \qquad \text{……..(5.34)}$$

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 $\acute{\omega}_m$ 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 = $3E_{ph}I_{ph}\sin\beta/\acute{\omega}_m$N-m

Where ώm-angular velocity in rad/sec.

$\acute{\omega}m=2\pi Ns/60$ where N_S is in rpm

$T=60/2\pi Ns\ (3E_{ph}I_{ph}\sin\beta)$

$=3E_{ph}I_{ph}\sin\beta$ syn.watts.

1 syn.watt=$60/2\pi Ns$ N-m

It is a machine dependent conversion factor

.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. Therefore 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
   $E_f=4.44\upsilon_{mf}K_{w1}T_{ph}=|E_f|$
   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 $\upsilon\infty I_a$

|

$|E_a| = |I_a X_a|$ where $X_a = 4.44fKK_{w1}T_{ph}$

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.

$|E_{al}| = 4.44 f \emptyset_{al} K_1 T_{ph}$

$\emptyset_{al}$ 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 $X_{al} = 4.44 f K_{al} K_{w1} T_{ph}$ 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.

$\dot{V} + \dot{E}f - j\,\dot{I}a\, Xa - j\,\dot{I}a\, Xal = \dot{I}a\, Ra$

$\dot{V} + \dot{E}f - j\,\dot{I}a\, (Xa + Xal) = \dot{I}a\, Ra$

$\dot{V} + \dot{E}f - j\,\dot{I}a\, Xs = \dot{I}a\, Ra$ ……..(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

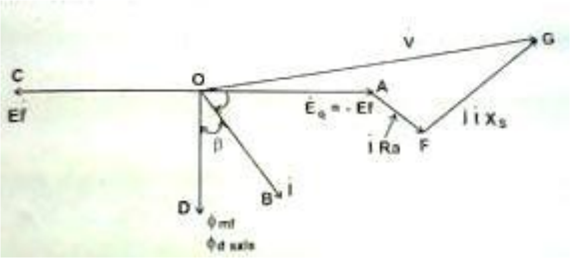


Fig 5.7 phasor diagram of BLPM sine wave motor

ϕ_{mf} be the mutual flux set up by the permanent magnet,but linked by the armature winding.

Ef lags behind =

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 Ra+O ……..(5.37)

3Eq I – electromagnetic power transferred as mechanical power.

3 Ra – 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 =60/2 Ns × 3Eq I sin β

= P/

= 3Eq Isin β/ ……..(5.40)

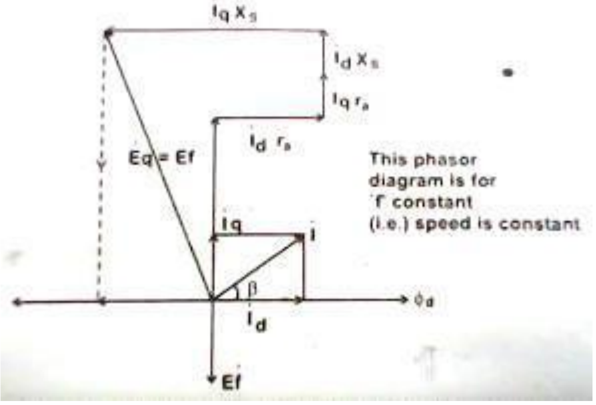


Fig 5.8 Phasor Diagram of BLPM sine wave motor with ϕ d or ϕ mf as reference axis

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 - Iq Xs)+j (Eq+ Iq r + Id Xs)) ((Id-j IQ))) (i.e) power input $= \mathrm{Re}(3(\ _d\, ra - Id\,Iq\,Xs) + (-j\,Id\,Iq\,ra + j\ \ I_q^2\,Xs)\ + j(Eq\,Id + Iq\,Id\,ra + I_d^2 Xs) + (Eq\,Iq + \ _q\, ra + Id\,Iq\,Xs))$

$= 3(I_a^2\, ra - Id\ Iq\ Xs) + 3\ (Eq\ Iq + I^2{}_q ra + Id\ Iq\ Xs)$

$= 3\ Eq\,Iq + 3(I_a^2 + I_q^2)r_a$

$= 3\ Eq\ Iq + 3\,I\,2\,r_a$ ……(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)

$$\frac{p}{\omega m} = 3[I_d^2 r_a\ \ I_d I_q X_s] + 3[E_q I_q\ +\ \ \ + I_d I_q X_s]$$

$$= 3[I_d^2 r_a\ \ I_d I_q (X_d + X_q)] + 3[E_q I_q + I_q^2 r_a + I_d I_q (X_d + X_q)]$$

Power input $= R_e\ 3[(I_d r_a - I_q X_s) + j(E_q + I_d X_s + I_q r_a)(I_d - jI_q)]$

$$= R_e\ 3[((I_d r_a - I_q(X_d + X_q)) + j(E_q + I_d(X_d + X_q) + I_q r_a)(I_d - jI_q)]$$

$$= R_e\ 3\ \ \ \ - I_q\ \ \ +\ \ \ \ + E_q I_q + I_d I_q\ \ \ +\ \ \ +$$

$$= 3\ \ E_q I_q + 3I^2 R_a$$

Torque developed for a salient pole machine is given by

$$T = \frac{3p}{}[E_q I_q\ \ \ (X_d - X_q) I_d I_q] N -$$

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 d_c commutator motor.

In the phasor diagram shown in fig. 5.10.

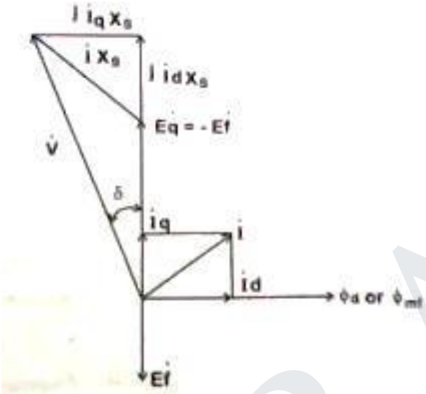


Fig 5.9 Phasor Diagram neglecting the effect of resistance

Neglecting the effect of resistance, the basic voltage equation of BLPMSNW motor

(i.e.,) $\dot{V} = \dot{E}_q + jX_s$

As the effect of resistance is neglected

$$\frac{\dot{V}}{jX_s} = \frac{\dot{E}_q}{jX_s} + \dot{I} \qquad \text{……..(5.44)}$$

$$\dot{I} = \frac{\dot{V} - \dot{E}_q}{jX_s} \qquad \text{……..(5.45)}$$

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

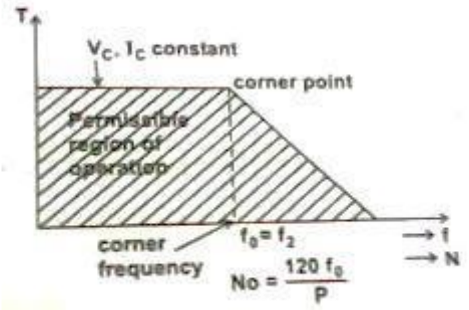


Fig 5.10 torque-speed characteristics of BLPM sine wave (SNW) motor.

For a given V_c and I_c (i.e) maximum permissible voltage and maximum permissible current, maximum torque remains constant from a low frequency to f_c (i.e) corner frequency.

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.

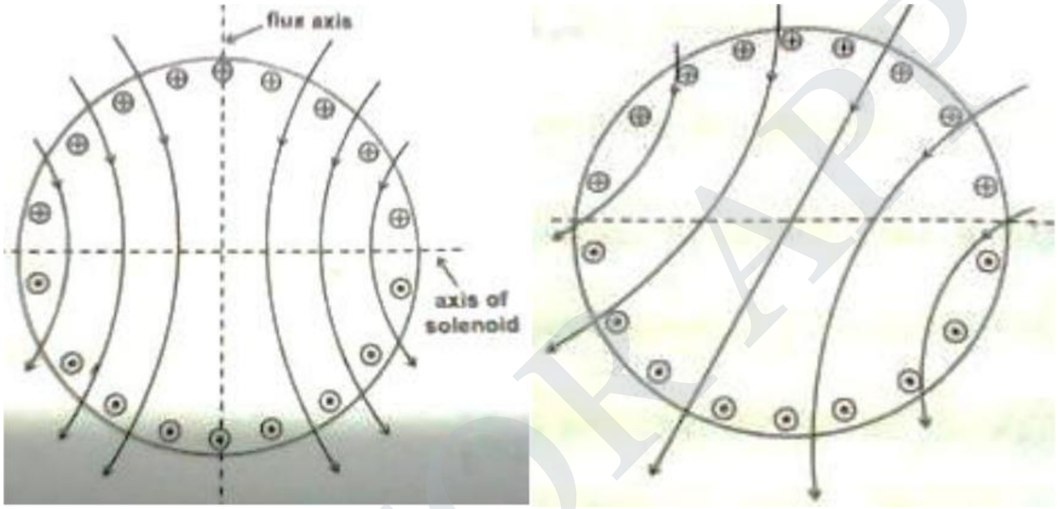
In such a case the reactive current is limited only by the synchronous reactance. As the speed increase further, it approaches the short circuit current $\frac{E_q}{X_S}$ which is many times larger than the normal current rating of the motor winding or the converter. This current may be sufficient to 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.



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

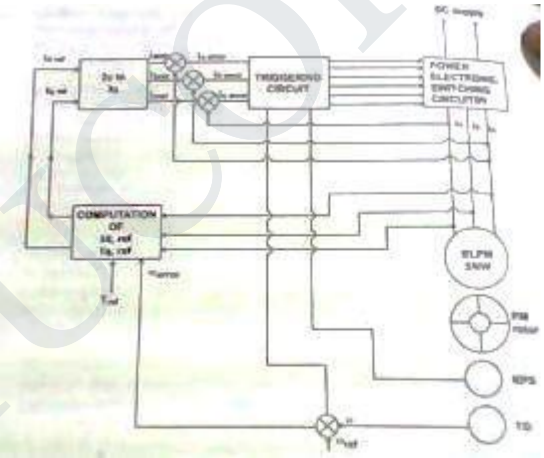
BLPM SNW motor is usually employed for variable speed applications. For this we keep V/f constant and vary V and f to get the desired speed and torque.

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.

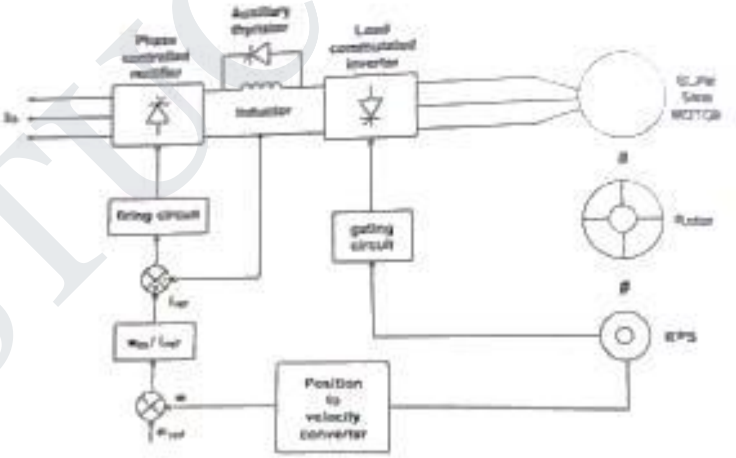


Fig 5.14 Schematic diagram of self-control

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

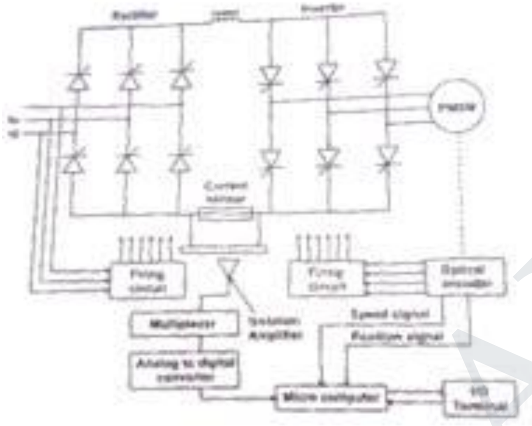


Fig.5.15 Microprocessor Based Control of PMSM

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 inverter 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 inverter 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.

Constructional features – Types – Axial and Radial flux motors – Operating principles – Variable Reluctance Motors – Voltage and Torque Equations - Phasor diagram - performance characteristics – Applications.

1.1 CONSTRUCTION OF SYNCHRONOUS RELUCTANCE MOTOR

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

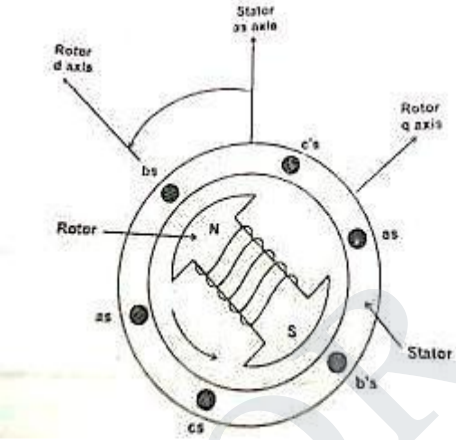


Fig 1.1 Idealized Three Phase Four Pole Synchronous Machine (Salient Pole)

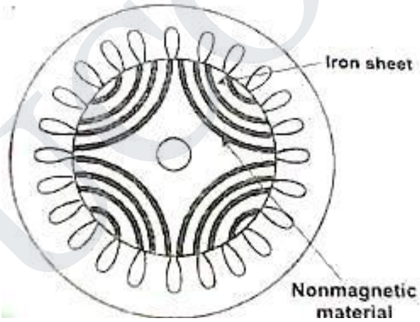


Fig 1.2 Cross Section of Synchronous Reluctance Motor

The rotor of the modern reluctance machine is designed with iron laminations in the axial direction separated by non-magnetic material. The performance of the reluctance motor may approach that of induction machine. With high saliency ratio a power factor oh 0.8 can be reached. The efficiency of a reluctance machine may be higher than an induction motor because there is no rotor copper loss. Because of inherent simplicity, robustness of construction and low cost.

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

Synchronous reluctance motor is designed for high power applications. It can broadly be classified into

Axially laminated and

Radially laminated.

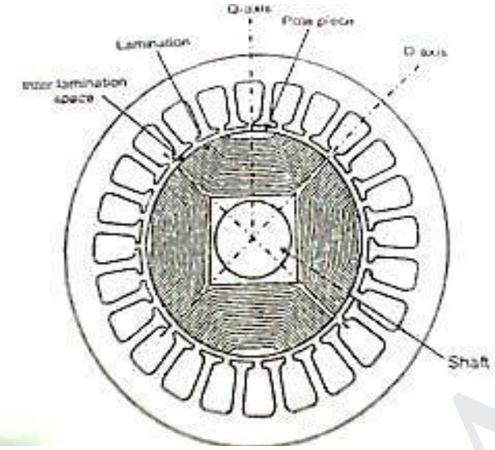


Fig.1.3 cross section of axially laminated

Reluctance motors can deliver very high power density at low cost, making them ideal for many applications. Disadvantages are high torque ripple (the difference between maximum and minimum torque during one revolution) when operated at low speed, and noise caused by torque ripple. Until the early twenty-first century their use was limited by the complexity of designing and controlling them. These challenges are being overcome by advances in the theory, by the use of sophisticated computer design tools, and by the use of low-cost embedded systems for control, typically based on microcontrollers using control algorithms and real-time computing to tailor drive waveforms according to rotor position and current or voltage feedback. Before the development of large-scale integrated circuits the control electronics would have been prohibitively costly.

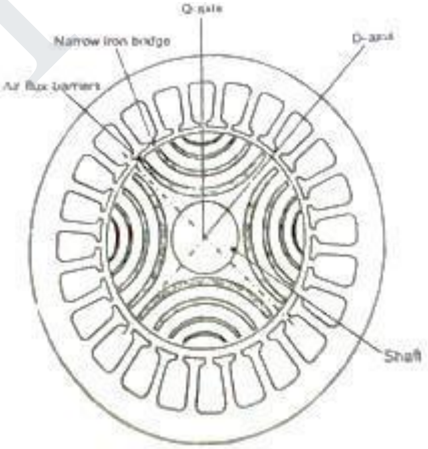


Fig 1.4 cross section of radially laminated

The stator consists of multiple projecting (salient) electromagnet poles, similar to a wound field brushed DC motor. The rotor consists of soft magnetic material, such as laminated silicon steel, which has multiple projections acting as salient magnetic poles through magnetic reluctance. The number of rotor poles is typically less than the number of stator poles, which minimizes torque ripple and prevents the poles from all aligning simultaneously—a position which cannot generate torque.

When a rotor pole is equidistant from the two adjacent stator poles, the rotor pole is said to be in the "fully unaligned position". This is the position of maximum magnetic reluctance for the rotor pole. In the "aligned position", two (or more) rotor poles are fully aligned with two (or more) stator poles, (which mean the rotor poles completely face the stator poles) and is a position of minimum reluctance.

When a stator pole is energized, the rotor torque is in the direction that will reduce reluctance. Thus the nearest rotor pole is pulled from the unaligned position into alignment with the stator field (a position of less reluctance). (This is the same effect used by a solenoid, or when picking up ferromagnetic metal with a magnet.) In order to sustain rotation, the stator field must rotate in advance of the rotor poles, thus constantly "pulling" the rotor along. Some motor variants will run on 3-phase AC power (see the synchronous reluctance variant below). Most modern designs are of the switched reluctance type, because electronic commutation gives significant control advantages for motor starting, speed control, and smooth operation (low torque ripple).

Dual-rotor layouts provide more torque at lower price per volume or per mass. The inductance of each phase winding in the motor will vary with position, because the reluctance also varies with position. This presents a control systems challenge.

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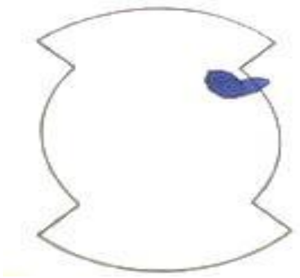


Fig.1.5 Salient rotor

Salient rotor design is as shown. The low $L_{d.}$ /$L_q$ratios are largely the result of circulating flux in the pole faces of the rotor. However the ruggedness and simplicity of the rotor structure has encouraged for high speed applications.

1.2.2 Radially Laminated Rotor (Flux Barrier)

Another approach is to use laminations with flux barriers punched into the steel for a 4 pole machine. The flux barriers and the central hole of the lamination required for the shaft weaken the rotor structurally and thus make this approach a poor choice for high speed design.

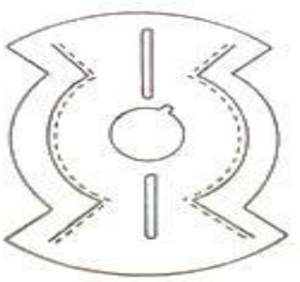


Fig.1.6 Radially Laminated Rotor

1.2.3 Axially Laminated Rotor

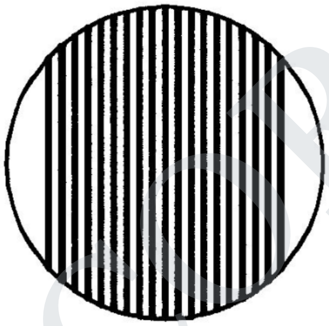


Fig.1.7 Axially Laminated Rotor

Two pole phase axially laminated rotor with a $L_{d.}$ /$L_q$ratio of 20, the maximum efficiency is 94% has been reported in the literature. It is observed that torque ripple and iron losses are more axially laminated rotor than radially laminated rotor.

Another rotor design as shown in fig. The rotor consists of alternating layers of ferromagnetic and non-magnetic steel. If choose the thickness of the steel such that the pitch of the ferromagnetic rotor segments matched the slot pitch of the stator.

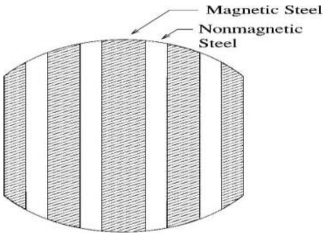


Fig 1.8 New rotor design

The ferromagnetic rotor segments always see a stator tooth pitch regardless of the angle of rotation of the rotor. This is done to maximize flux variations and hence iron losses in the rotor.

Special rotor laminations make it possible to produce the same number of reluctance path as there are magnetic poles in the stator. Synchronous speed is achieved as the poles lock in step with magnetic poles of the rotating stator field and cause the stator to run at the same speed as the rotating fields. The rotor is pressures with end rings similar to induction motor .Stator winding are similar to squirrel cage induction motor.

S.No	**Axial air gap motors**	**Radial air gap motors**
1.	Low speed applications	High speed applications
2.	Lamination is axial	Lamination is radial
3.	Less mechanical strength	More mechanical strength
4.	The axially laminated rotor in general gives the best performance. But the mass production difficulties with folding and assembling the laminations make its adoption by industry unlikely.	The radially laminated rotor has the best potential for economic production.

1.3 ROTOR CONSTRUCTION

Explosion bonding technique as shown in fig. Other joining techniques such as brazing roll bonding, or diffusion bonding may also appropriate for rotor construction.

First sheets of ferromagnetic and non-ferromagnetic steel are bonded. The bonded sheets are then cut into rectangular blocks h\which are machined into the desired rotor. The rotor shaft can also be machined out of the same block as the rotor.

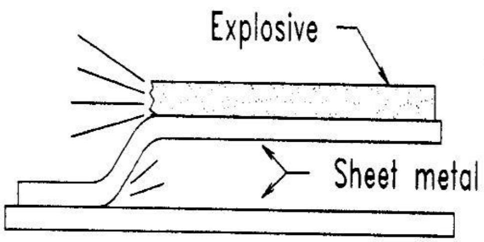


Fig 1.9 Explosion bonding

The rotor joining technique known as explosion bonding. Explosion bonding uses explosive energy to force two or more metal sheets together at high pressures. Conventionally the high pressure causes several atomic layers on the surface of each sheet to behave as a fluid. The angle of collision between the two metals forces this fluid to jet outward. Effectively cleaning the metal surface, these ultra clean surfaces along with the high pressure forcing the metal plates together provide the necessary condition for solid phase welding.

Experimental tests on a stainless steel/mild steel bond indicate that the tensile and fatigue strengths of the bond are greater than those of either of the component materials due to the shock hardening which occurs during the process. The bond was also subjected to 10 cycles of temperature variation from 20° C - 70°C, with no significant reduction in tensile strength.

1.4 WORKING OF SYNCHRONOUS RELUCTANCE MOTOR

In order to understand the working of synchronous reluctance motor, when a piece of magnetic material is located in a magnetic field, a force acts on the material tending to bring it into the desert portion of the field. The force tends to align the specimen of the material in such a way that the reluctance of the magnetic path that passes through the material will be minimum.

When supply is given to the stator winding, the revolving magnetic field will exert reluctance torque on the unsymmetrical rotor tending to align the salient pole axis of the rotor with the axis of the revolving magnetic field, because in this position, the reluctance of the magnetic path would be minimum. If the reluctance torque is sufficient to start the motor and its load, the rotor will pull into step with the revolving field and continue to run at the speed of the revolving field. Actually the motor starts as an induction motor and after it has reached its maximum speed as an induction motor, the reluctance torque pulls its rotor into step with the revolving field, motor now runs as synchronous motor by virtue of its saliency.

Reluctance motors have approximately one third the HP rating they would have as induction motors with cylindrical rotors. Although the ratio may be increased to 9one half by proper design of the field windings, power factor and efficiency are poorer than for the equivalent induction motor. Reluctance motors are subject to cogging, since the locked rotor torque varies with the rotor position, but the effect may be minimized by skewing the rotor bars and by not having the number of poles.

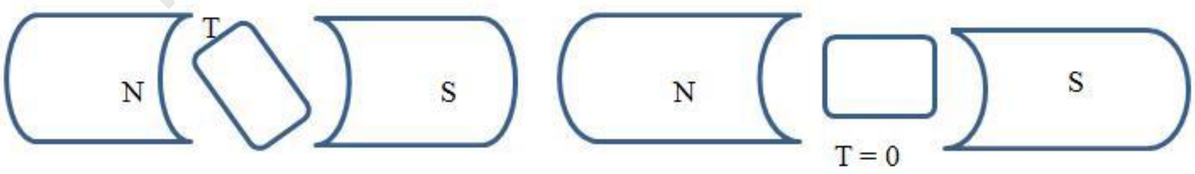
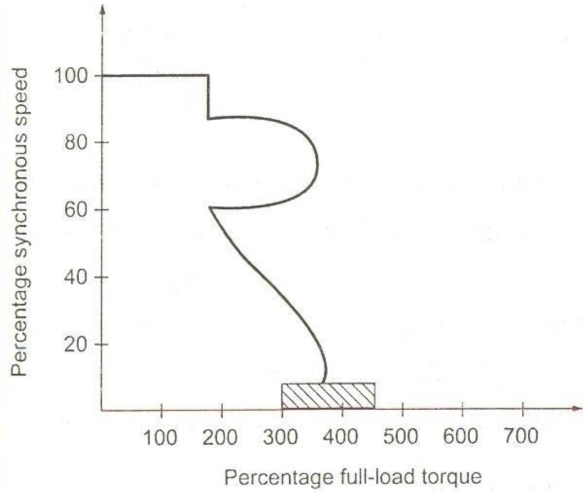
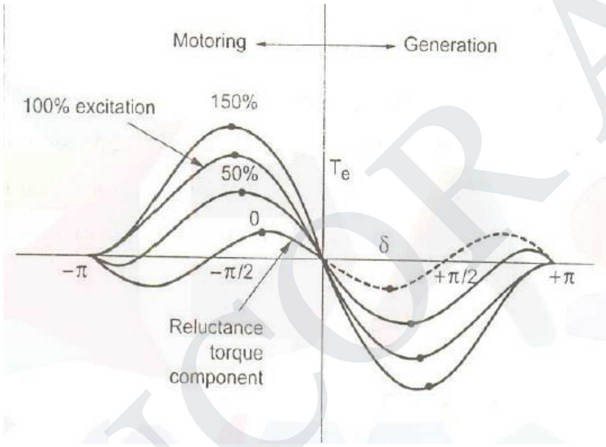


Fig1.10 Rotor Position due to Revolving Magnetic Field

1.6 PERFORMANCE CHARACTERISTICS

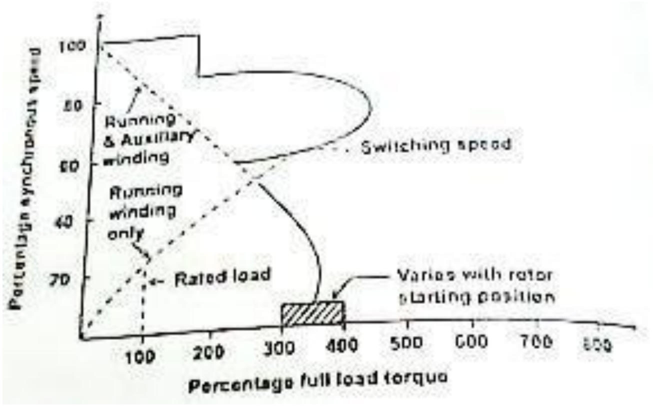


Torque – angle characteristics



The torque speed characteristic of synchronous reluctance motor is shown in fig. The motor starts at anywhere from 300 to 400 percent of its full load torque (depending on the rotor position of the unsymmetrical rotor with respect to the field winding) as a two phase motor. As a result of the magnetic rotating field created by a starting and running winding displaced 90° in both space and time.

At about ¾th of the synchronous speed a centrifugal switch opens the starting winding and the motor continues to develop a single phase torque produced by its running winding only. As it approaches synchronous speed, the reluctance torque is sufficient to pull the rotor into synchronism with the pulsating single phase field. The motor operates at constant speed up to a little over 20% of its full load torque. If it is loaded beyond the value of pull out torque, it will continue to operate as a single phase induction motor up to 500% of its rated speed.



1.7 PHASOR DIAGRAM OF SYNCHRONOUS RELUCTANCE MOTOR

The synchronous reluctance machine is considered as a balanced three phase circuit, it is sufficient to draw the phasor diagram for only one phase. The basic voltage equation neglecting the effect of resistance is

$$V = E - j\, I_{sd} X_{sd} - j\, I_{sq}\, X_{sq} \quad \ldots\ldots\ldots\ldots(1.1)$$

Where

V - Supply Voltage

I_s - stator current

E - excitation emf

δ - load angle

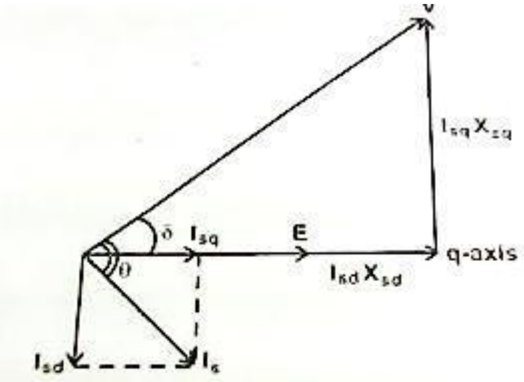
Φ - phase angle

X_{sd} and X_{sq} - synchronous reactance of direct and quadrature axis

I_{sd} and I_{sq} - direct and quadrature axis current

$I = I_{sd} + I_{sq} \ldots\ldots\ldots\ldots\ldots(1.2)$

I_{sd} is in phase quadrature with E and I_{sq} is in phase with E.



$V = E - j\, I_{sd}X_{sd} - j\, I_{sq}\, X_{sq}$

From phasor diagram

$V \cos 8 = E + Isd + X_{sd}$ ………………(1.3)

$I_{sd} = \frac{V cos - E}{Xsd}$

$I_{sq}X_{sq} = V \sin 8$

$Isq = \frac{V\, sin}{Xsq}$ ………………..(1.4)

Is cos ϕ = Isq cos8 - Isd sin8 ……………(1.5)

Where

X_{sd} and X_{sq} are synchronous reactance of d and q axis.

Sub (3) and (4) in Eqn (5)

$Is \cos \phi = \frac{E}{Xsd} sin + 2 \frac{Xsd - Xsq}{2\, Xsd\, Xsq}$…………………(1.6)

P = 3 Vis cos ϕ …………………(1.7)

Sub equ (6) in equ (7)

$Pm = 3 [\frac{VE}{Xsd} \sin + V^2 \frac{(Xsd - Xsq)}{2\, Xsd\, Xsq} \sin 2\, 8]$

$Pm = T\, \omega_S$

$T = Pm/\omega_S$

Sub E = 0

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

Equation (1.9) is the **torque equation of synchronous reluctance motor**.

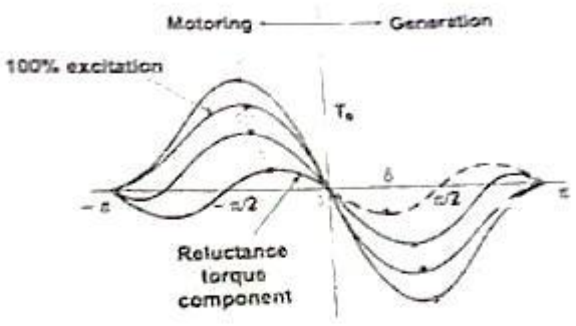


Fig 1.13 Torque Angle Characteristics of Salient Pole Machine

Plotting the equation (9) as shown in fig indicates that the stability limit is reached at $\delta = \pm\ \pi\ /4$

And by increasing g load angle torque also increases.

$$V^2 \left[\frac{Xsd}{2\,XsdXsq} - Xsq\right] \sin 2\,\delta = \text{reluctance Power}$$

In synchronous reluctance motor, the excitation emf(E) is zero.

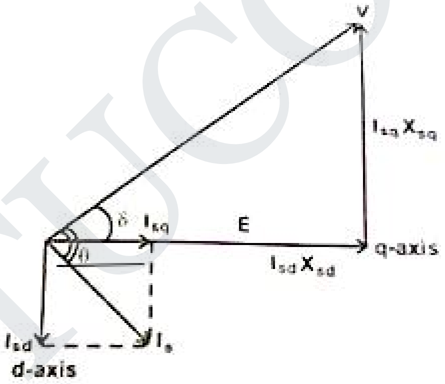


Fig 1.14 Phasor Diagram of Synchronous Reluctance Motor with E=0

1.8 ADVANTAGES AND DISADVANTAGES OF SYNCHRONOUS RELUCTANCE MOTOR

ADVANTAGES

- There is no concern with demagnetization; hence synchronous reluctance machines are inherently more reliable than PM machines.
- There need not be any exciting field as torque is zero, thus eliminating electromagnetic spinning losses.
- Synchronous reluctance machine rotors can be constructed entirely from high strength, low cost materials.

DISADVANTAGES

- High cost than induction Motor.
- Need Speed synchronization to invertor output frequency by using rotor position sensor and sensor less control.
- Compared to induction motor it is slightly heavier and has low power factor.
- By increasing the saliency ratio L_{ds}/L_{qs}, the power factor can be improved.

1.9 APPLICATIONS OF SYNCHRONOUS RELUCTANCE MOTOR

- Metering Pumps.
- Auxiliary time Mechanism.
- Wrapping and folding Machines.
- Proportioning Devices on Pumps or conveyors.
- Synthetic fibre manufacturing equipment.
- Processing continuous sheet or film material.