UNIT IV

PERMANENT MAGNET BRUSHLESS D.C. MOTORS
4.1 INTRODUCTION

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

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

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

4.2 CONSTRUCTIONAL FEATURESB OF BLPM MOTORS

4.2.1 Construction

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

Fig 4.1 Arrangement of permanent magnet in the rotor

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

4.2.2 Merits and Demerits

Merits

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

Demerits

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

4.2.3 Comparison of brushless dc motor relative to induction motor drives

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

4.2.4 Commutator and brushes arrangement

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

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

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

4.2.5 Construction of Mechanical Commutator
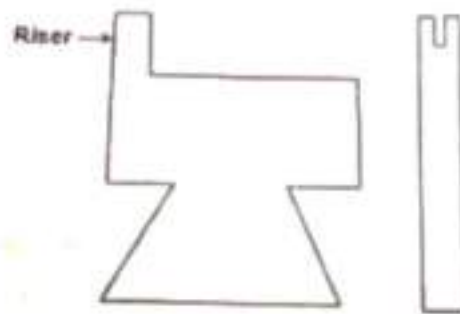
Commutator Segment

Fig 4.2 Commutator Segment

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

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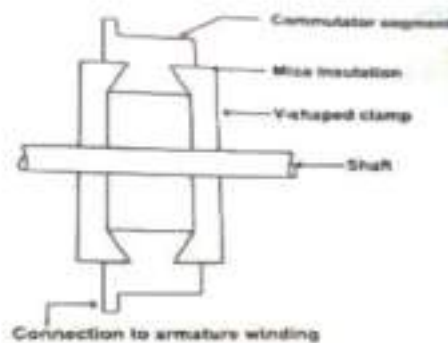

Fig 4.3 connection of commutator segments to shaft

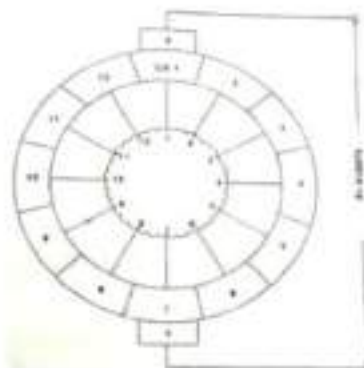### 4.2.6 Mechanical Commutator and Brushes Arrangement

Fig 4.4 Mechanical Commutator and Brushes Arrangement

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

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

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

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

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

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

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

4.2.7 Electronic commutator

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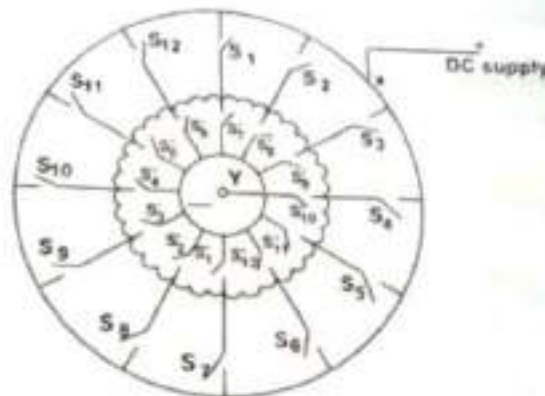

Fig 4.5 Electronic Commutator

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

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

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

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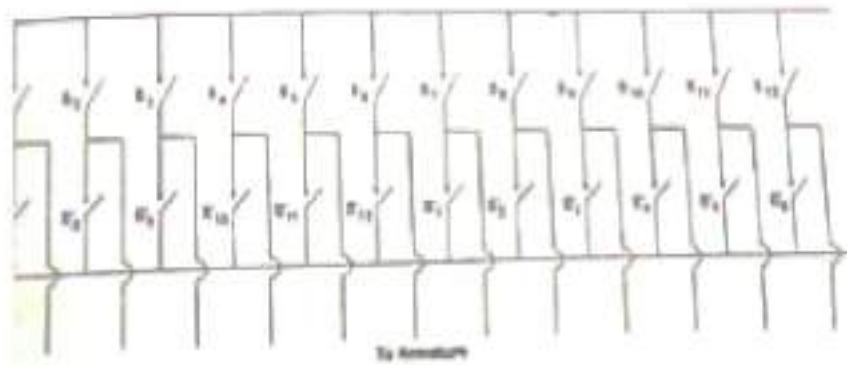

Fig 4.6 switching circuit of electronics commutator

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

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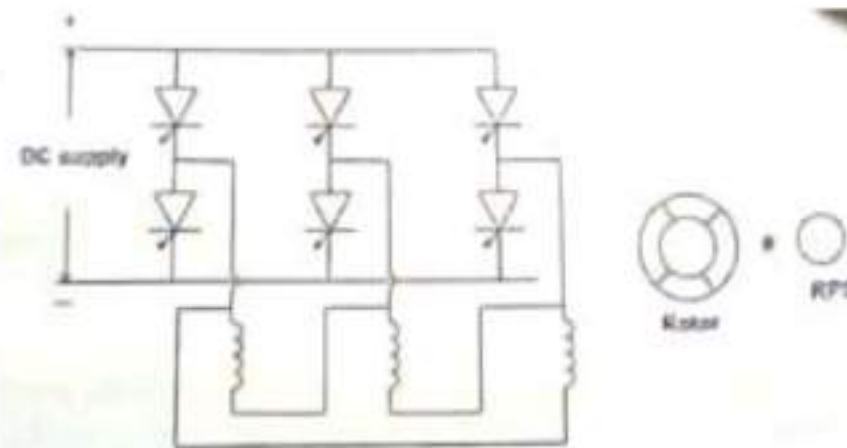

Fig 4.7 Delta Connected Stator Armature Winding

For normal electronic commutator, usually six switching devices are employed. Then the winding should have three tapping's. Therefore the winding can be connected either in star or in delta.
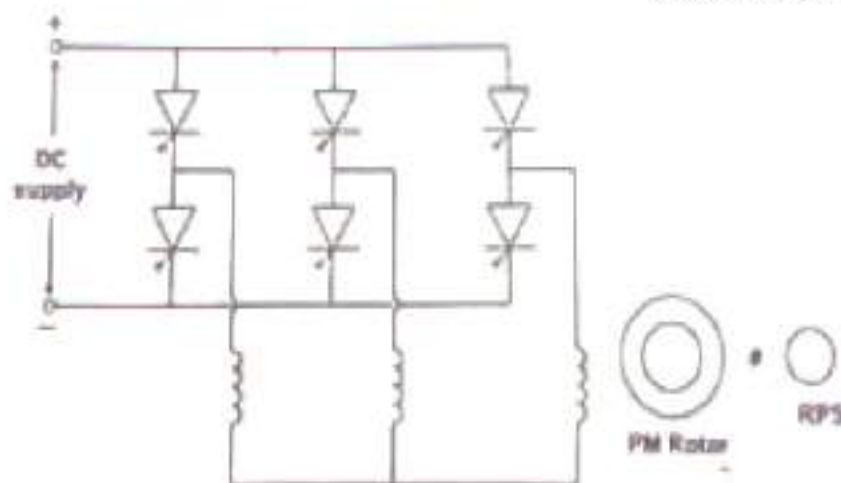
Fig 4.8 Star Connected Armature Winding

4.2.8 Comparison between mechanical Commutator and brushes and Electronic Commutator

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

4.3 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

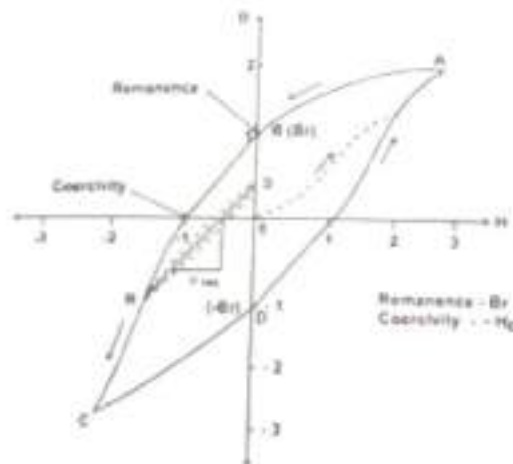It is used for understanding characteristics hysteresis loop as shown.

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.
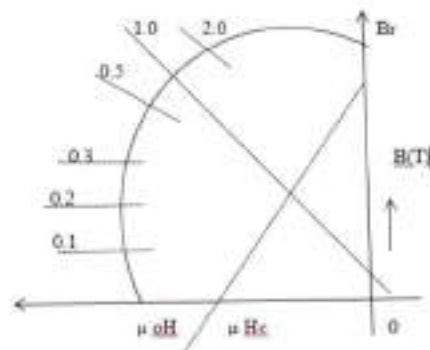
4.3.4 Demagnetization curve

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

$$B = \mu_0 H + J$$

μ_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 $\frac{2\pi NT}{60}$ = 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: $180\Box$ pole arc.

$120\Box$ pole arc.

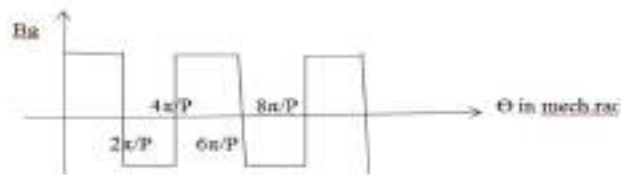Air gap flux density distribution in $180\Box$ BLPM SQW motor as shown in fig.

Fig 4.11 Air gap flux density distribution in $180\Box$ BLPM SQW motor.

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

Fig 4.12 Air gap flux density distribution in $120\Box$ BLPM SQW motor

(b)BLPM Sine wave DC Motor

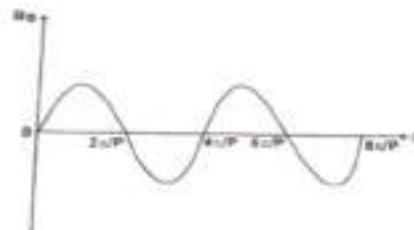Air gap density distribution of BLPM dc sine wave motor as shown in fig.

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/m².

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

'r' be the radius of the airgap in m.

'l' be the length of the armature in m.

'T_c' be the number of turns per coil.

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

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

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

Let at $\omega_{mt}=0$,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

$$\Phi_{max} = B \times 2\pi r/p \times l \qquad \dots\dots\dots\dots\dots(4.1)$$

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

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

$$= B_g rl[\theta]_0^\pi$$

$$= B_g rl[\pi]$$

At $\omega_{mt}=0$,the flux linkage of the coil is

$$\Lambda_{max} = (B_g \times 2\pi r/p \times l)T_c \ \omega b\text{-T} \qquad \dots\dots\dots\dots\dots(4.2)$$
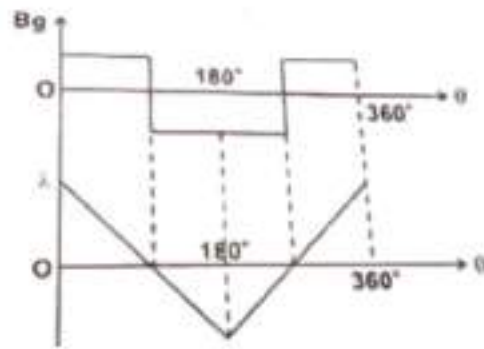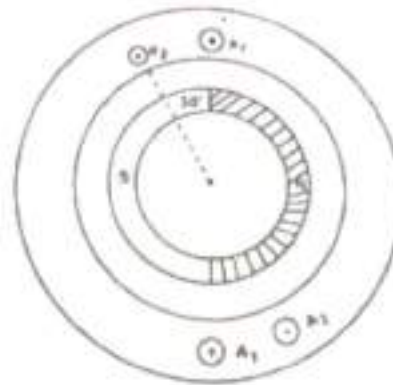
Fig 4.14 Magnetic Flux Density around the Air gap.

Fig 4.15 Motor Showing two Coils of One Phase.

Let the rotor rotating in ccw direction and when $\omega_m t = \pi/2$, 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 $B_g r l T c \pi/p$ at $\omega_m t = 0$ (i.e) t = 0 to θ at $t = \pi/p\omega_m$.

Change of flux linkage of the coil (i.e) $\Delta\lambda$ is

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

$$= 0 - (2B_g r l T c \pi/p)/ (\pi/p\omega_m)$$

$$= -(2B_g r l T c \omega_m) \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots(4.3)$$

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

$$e_c = 2B_g r l T c \omega_m \qquad \dots\dots\dots\dots\dots\dots\dots\dots(4.4)$$

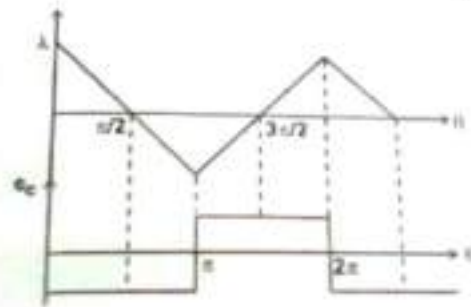Distribution of e_c with respect to t is shown in fig 4.16

Fig 4.16 Emf waveform of coil 1

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

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

Consider two coils a1A1 and a2A2 as shown in fig 5.15.Coil a2A2 is adjacent to a1A1 is displaced from a1A1 by an angle $30^\square$ (i.e.) slot angle Υ.

The magnitude of emf induced in the coil a1A1

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

The magnitude of emf induced in the coil a2A2

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

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

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

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

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

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

$e_{ph} = 2B_g rl T ph\omega_m$ volts ....(4.10)

e_{ph} = resultant emf when all n_c coils are connected in series.
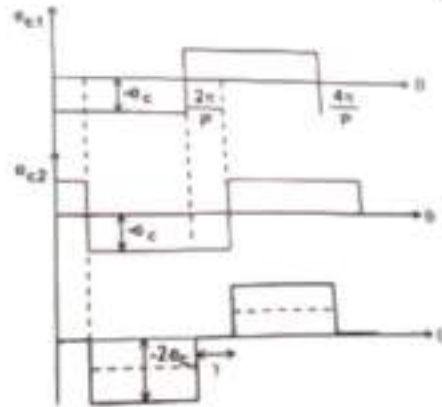
The waveforms are as shown in fig 4.17

Fig 4.17 Emf waveform of phase a

The waveform of e_{ph} is stepped and its amplitude is $2B_grlTph\omega_m$ volts.

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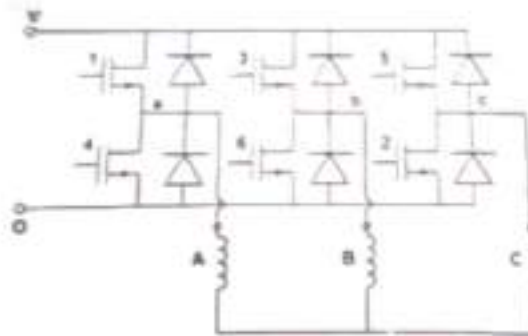

Fig.4.18 converter of brushless dc motor with star connected phase winding.

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 .

$$V = 2 e_{ph} + 2IR_{ph} + 2V_{dd} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.11)$$

If V_{dd} is neglected

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

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

$$I = \frac{V - E}{R} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.12)$$

(a) Starting condition

Speed is zero $\omega_m = 0$

Supply voltage is V

Since $\omega_m = 0$; $e_{ph} = 0$

$$\text{Starting current } I_{stg} = \frac{V - 0}{2 R_{ph}} = \frac{V}{2 R_{ph}} = \frac{V}{R} \quad \dots\dots\dots\dots\dots\dots\dots(4.13)$$

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

This current is also known as starting current.

(b) NO load condition

Current is very very small

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

$2 I R_{ph}$ − negligible

$$V = 2 e_{pho} \quad \dots\dots\dots\dots\dots\dots\dots\dots(4.14)$$

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

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

$$V = k_e \omega_{mo} \quad \dots\dots\dots\dots\dots\dots\dots(4.15)$$

$$\text{No load speed, } \omega_{mo} \cong \frac{V}{4 B_g r l T_{ph}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots(4.16)$$

$$= \frac{V}{k_e} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.17)$$

No load current $I_o = 0$

(c) ON load condition:

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

$$= 4 B_g r l \omega_m t_{ph} + 2 I R_{ph} \quad \dots\dots\dots\dots\dots\dots(4.18)$$

On load current

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

$$= \frac{V - ke\,\omega}{2\,Rph} \quad \dots\dots\dots\dots\dots\dots(4.20)$$

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

I vs ωm curve is shown in fig 4.19
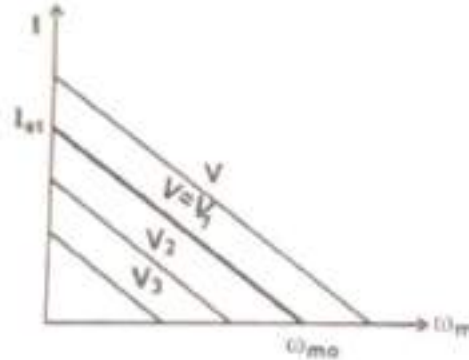
Fig.4.19 I Vs. ωm Curve

4.8 TORQUE EQUATION OF BLPM SQUARE WAVE MOTOR

Power input = VI

$$= [\,2\,eph + 2\,I\,Rph + 2\,Vdd\,]\,I \quad \dots\dots\dots\dots\dots\dots(4.22)$$

$$VI = [\,2\,eph + 2\,I\,Rph + 2\,Vdd\,]\,I \quad \dots\dots\dots\dots\dots\dots(4.23)$$

VI = electrical power input

2 eph I = power converted as mechanical

$2\,I^2\,Rph$ = power loss in the armature winding

2 Vdd I = power loss in the device

$$\text{Mechanical power developed} = 2\,eph\,I \quad \dots\dots\dots\dots\dots\dots(4.24)$$

eph= 2(2BgrlTphωm)I

$$eph = 4BgrlTph\omega m \quad \dots\dots\dots\dots\dots(4.25)$$

$$\text{Mechanical power} = (2\pi N/60)T \quad \dots\dots\dots\dots\dots\dots(4.26)$$

$$= \omega m\,T \quad \dots\dots\dots\dots\dots\dots(4.27)$$

Where N=Speed in rpm

T=Torque in N-m

ωm=Speed in rad/sec

$$\text{Therefore } T = 4BgrlTphI \quad \dots\dots\dots\dots\dots\dots(4.28)$$

$$= KtT \quad \dots\dots\dots\dots\dots\dots(4.29)$$

$$\text{Where } Kt = 4BgrlTph = Ke \quad \dots\dots\dots\dots\dots\dots(4.30)$$

(a) Case1: Starting Torque

ωm=0

$$Istg = (V/2Rph) \quad \dots\dots\dots\dots\dots\dots(4.31)$$

$$Tstg = 4BgrlTph(V/2Rph) \quad \dots\dots\dots\dots\dots\dots(4.32)$$

$$Tstg = Kt(V/2Rph) \quad \dots\dots\dots\dots\dots\dots(4.33)$$

Starting torque or stalling torque depends upon V.

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

(b) Case 2: On load condition

$$T = K_t I \qquad \dots\dots\dots(4.34)$$

$$= 4 \, B_g r \, lT_{ph} \, I$$

$$I = (V - 2e_{ph})/(2R_{ph}) \qquad \dots\dots\dots(4.35)$$

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

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

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

$$\omega_m = (V - 2I \, R_{ph})/ \, K_e \qquad \dots\dots\dots(4.37)$$

$$\omega_{m0} = V/ \, K_e \qquad \dots\dots\dots(4.38)$$

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

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

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

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

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

$$T/ \, T_{stg} = 2I \, R_{ph}/V \qquad \dots\dots\dots(4.40)$$

Substituding eqn. 5.40 in eqn. 5.39

$$\omega_m / \, \omega_{m0} = 1 - (\, T/ \, T_{stg}) \qquad \dots\dots\dots(4.41)$$

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

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
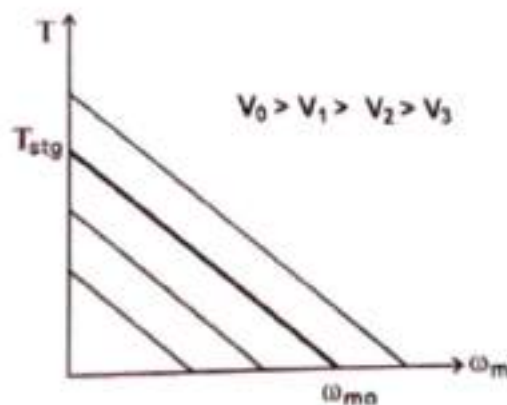
Fig 4.20 T-ω_m curve for various supply voltages

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 $K_t I_n$.
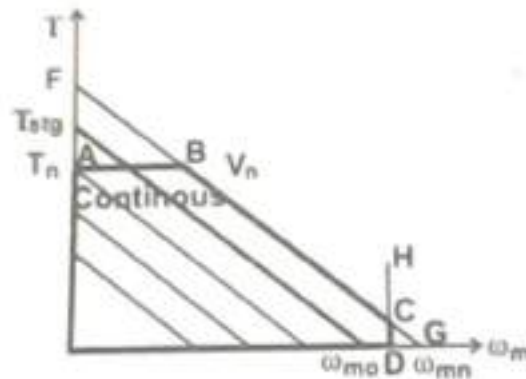2. The maximum permissible supply voltage = V_n.
3. The speed should not exceed ω_{mn}.

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.
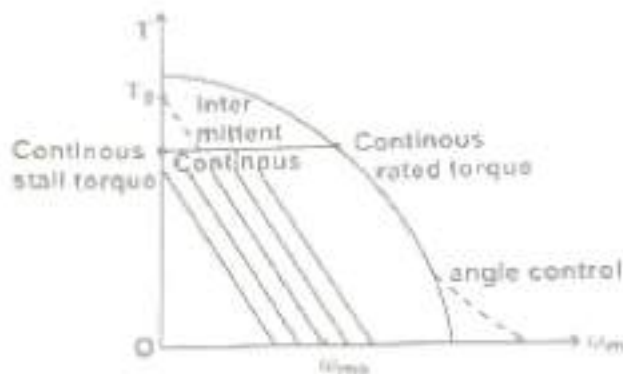
Fig.4.22 Torque speed characteristics of ideal brushless DC motor

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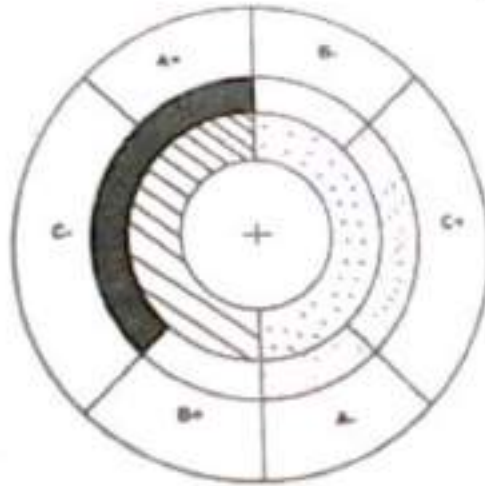
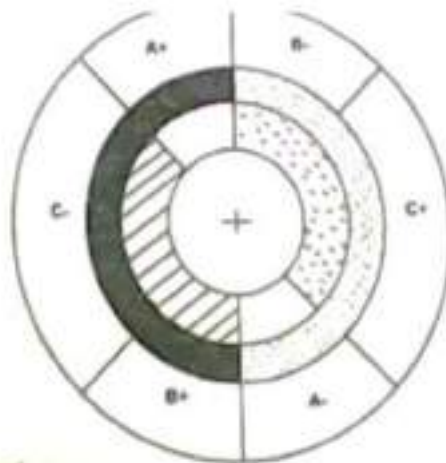Fig.4.23 BLDC motor with 180° magnet arc and 120° square wave phase currents

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
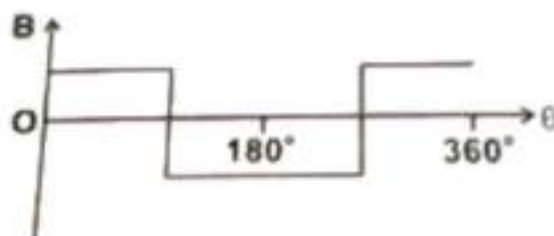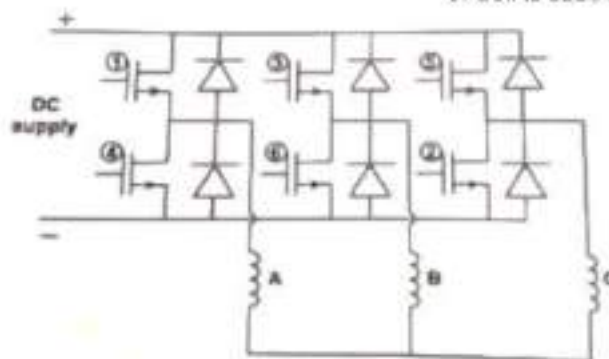

Fig.4.25 Flux density around air gap

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 60° 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 60°, then the torque will be unaffected and will continue constant for a further 60°. After 120°, positive current must be commutated from A to C.

Commutation tables for three-phase brushless dc motors.

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

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

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

❖ The production of smooth, ripple free torque depends on the fact the magnet pole arc exceeds the mmf arc by 60°.

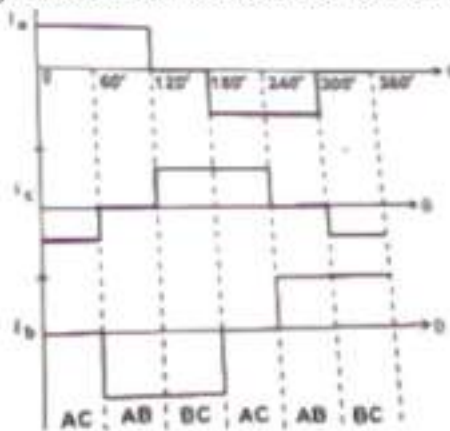❖ Here only 2/3 of the magnet and 2/3 of the stator conductors are active at any instant

Fig. 4.27 phase current waveforms of BLDC motor with 180° 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 180° magnet arcs there is a transition section of the order of 10-20° in width. This is due to fringing effect. Likewise on the stator side, the mmf distribution is not rectangular but have a stepped wave form as shown in fig.4.28 that reflects the slotting.
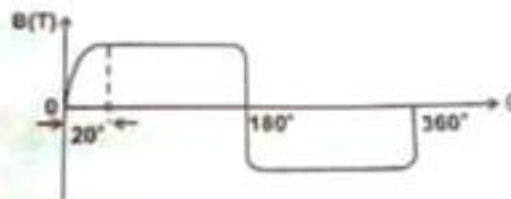

Fig 4.28 Air Gap Flux Density on Open Circuit

To some extent these effects cancel each other so that s that satisfactory results are obtained with a magnet arc as short as 150°, 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 60° 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)
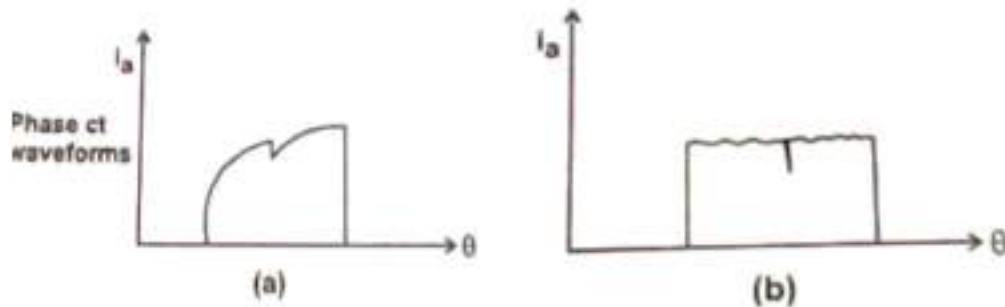
(a) High speed, full voltage. Note the dip caused by commutation of other 2 phases,
(b) Low speed with current controlled by chopping.

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.

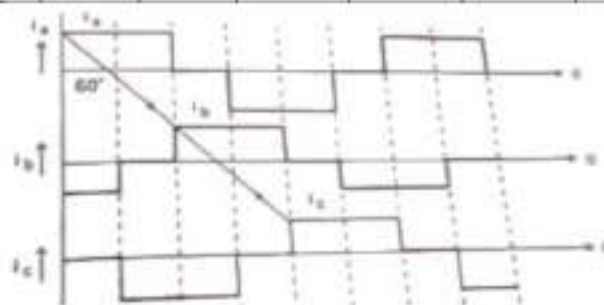| Rotor Position	A	B	C	ab u (1)	ab L (4)	bc u (3)	bc L (6)	ca u (5)	ca L (2)
0 – 60	+1	+1	-1	0	0	1	0	0	1
60 – 120	+1	-1	-1	1	0	0	0	0	1
120 – 180	+1	-1	+1	1	0	0	1	0	0
180 – 240	-1	-1	+1	0	0	0	1	1	0
240 – 300	-1	+1	+1	0	1	0	0	1	0
300 - 360	-1	+1	1	0	1	1	0	0	0

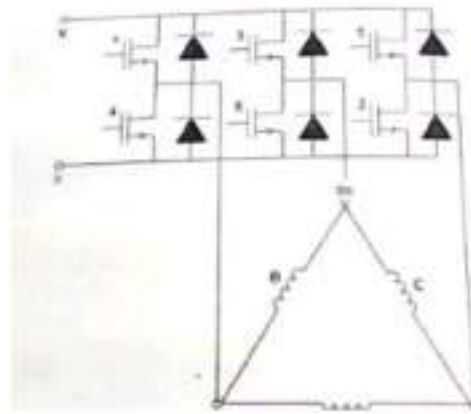Fig.4.30 phase currents wave forms of BLDC motor with120° pole arc

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

❖ C phase belt remains covered by the magnet poles. While the coverage of A phase belt increases thereby decreasing that of B phase belt.

❖ Since all the conductors are varying same current the increasing torque contribution of phase A is balancing by the decreasing contribution of phase B. Therefore, the total torque remains constant.

❖ Similarly there is a linear increase in the back emf of A and equal and oppoaite decrease in the back emf in phase B, Therefore the back emf at the terminals remains constant.

❖ Line current divides equally between two paths
One-phase C Second-phase A & B series.

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

When compared with 180° pole arc machine.

❖ For the same ampere-conductors per slot and for the same peak flux density, the 120° pole arc machine has 1.5 times copper losses, but produces the same torque.

❖ Also the ampere-conductors per slot would have to be reduced because the duty cycle is 1.0 instead of 2/3.

Merits

❖ For the same magnet flux density the total flux is only 2/3 of that of 180° pole arc motor, so that only 2/3 of the stator yoke thickness is required. If the stator outside diameter is kept the same, the slots can be made deeper so that the loss of ampere conductors can be at least partially covered .consequently the efficiency of the motor may not be very much less than that of 180° pole arc machine.

❖ In this machine also, the effects of fringing flux, slotting and communication overlap combine to produce torque ripple.

❖ Only emf and torque are discussed. The concept of hanging flux-linkage and energy balance can also be used to analyze the operation.

4.11 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)
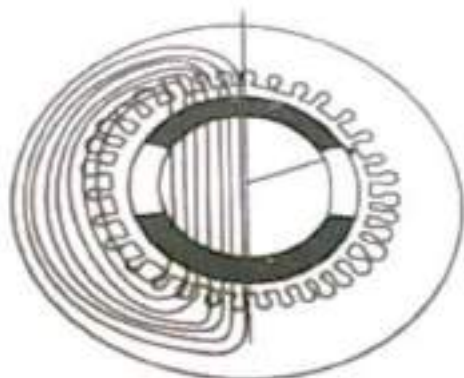
(a) Motor cross section and flux pattern   (b)magnet demagnetization curve

Fig 4.32 magnetic circuit analysis of BLDC motor

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

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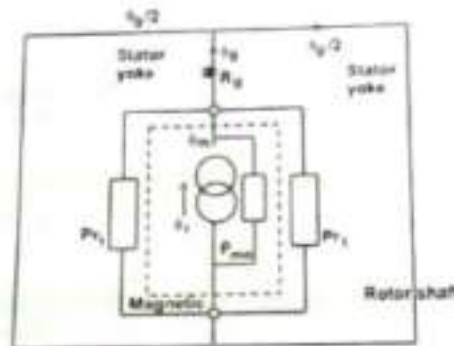

Fig .4.33 magnetic equivalent circuit.

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

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

$\varphi r = BrAm$ ....(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°

$$Am=2/3\pi[r1-g-lm/2]l \qquad\qquad \dots\dots\dots(4.45)$$

r1- radius of the rotor

g- air gap length

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

$$Rg=g'/\mu0Ag \qquad\qquad \dots\dots\dots(4.46)$$

g'- equivalent air gap length allowing for slotting.

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

$$g'=Kc\ g \qquad\qquad \dots\dots\dots(4.47)$$

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

$$Ag=[2/3\ \pi(r1-g/2)+2g](l+2g) \qquad\qquad \dots(4.48)$$

❖ the remaining permeance in the magnetic circuit I the rotor leakage permeance prl, 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

$$pm=pmo+prl \qquad\qquad \dots\dots\dots(4.49(a))$$

$$pm=pmo(1+prl) \qquad\qquad \dots\dots(4.49(b))$$

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.
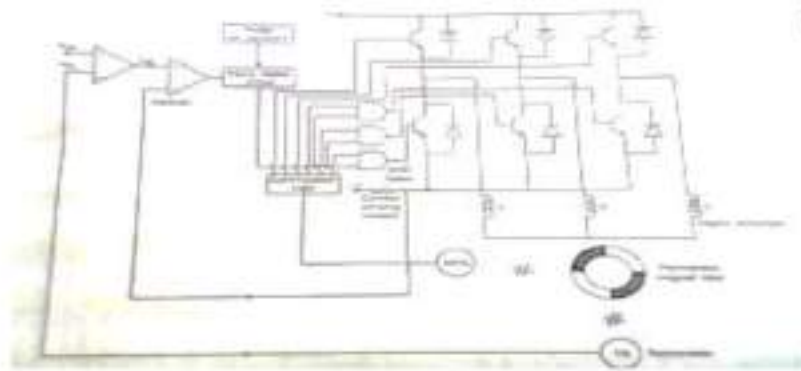
Fig 4.34 structure of controller for brushless PM DC Motor

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.
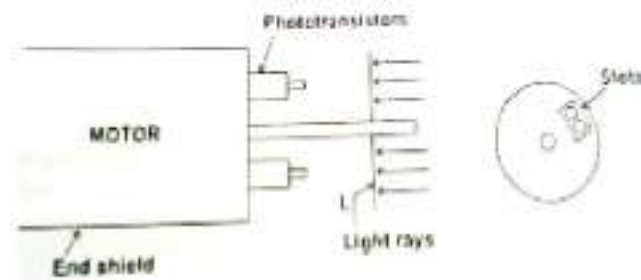
Fig 4.35 Optical position sensor

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.
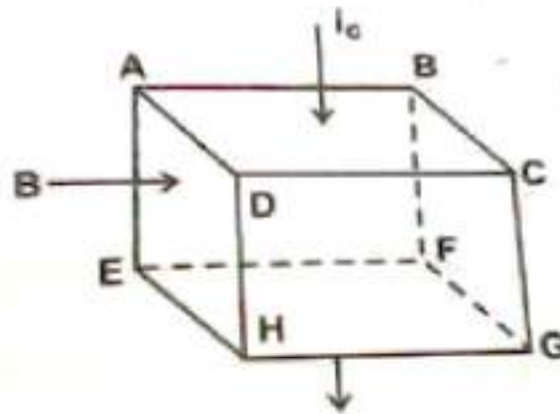
Fig 4.36 Hall Effect

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.
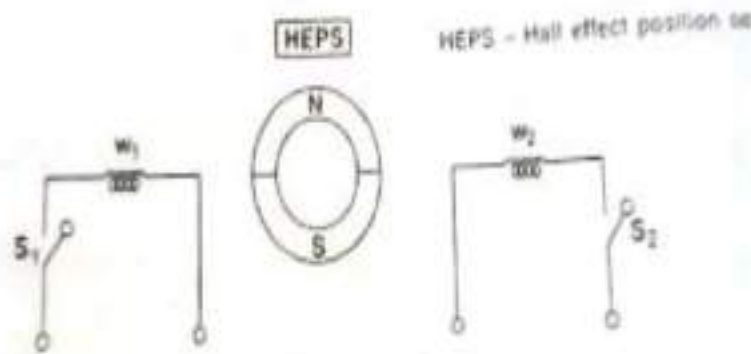
Fig 4.37 2 pole BLPM motor

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.
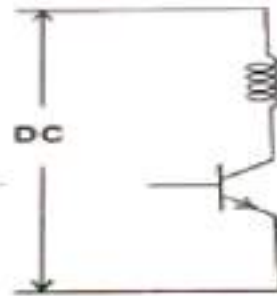

Fig. 4.38 one phase one pulse BLPM motor.

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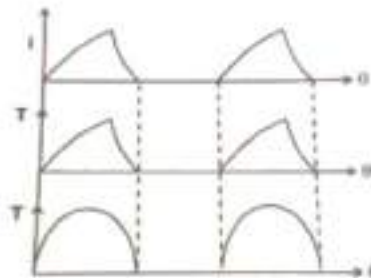
Fig.4.39 Current and torque waveform

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.
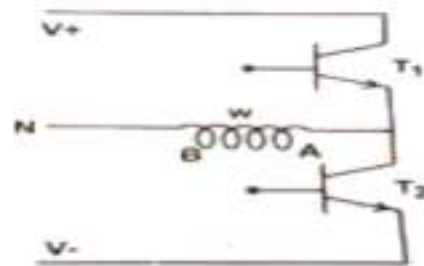
Fig. 4.40 One phase two pulse BLPM motor

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.
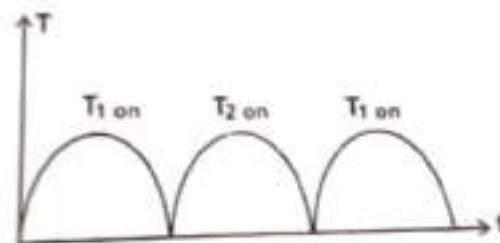

Fig. 4.41 Torque waveform

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.
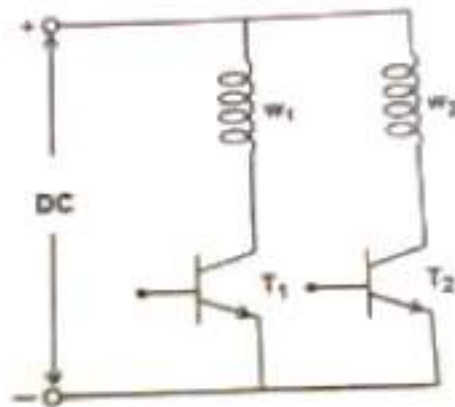
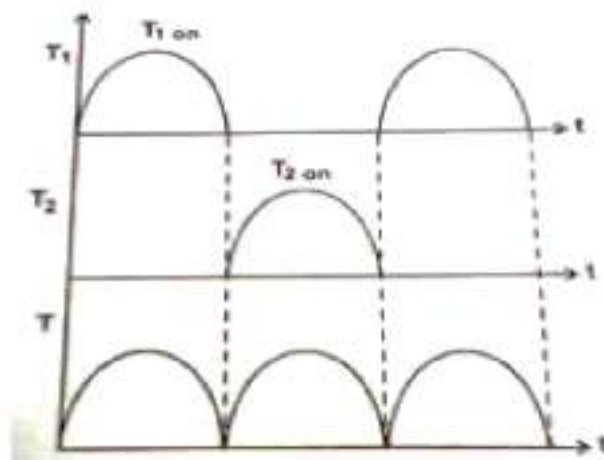Fig. 4.42 two phase winding and two pulse motor

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.
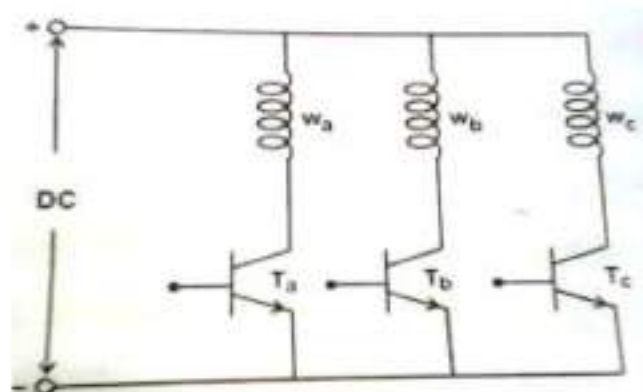
Fig. 4.44 3 phase, 3 pulse BLPM motor.

4.13.5 Three phase six pulse BLPM motor
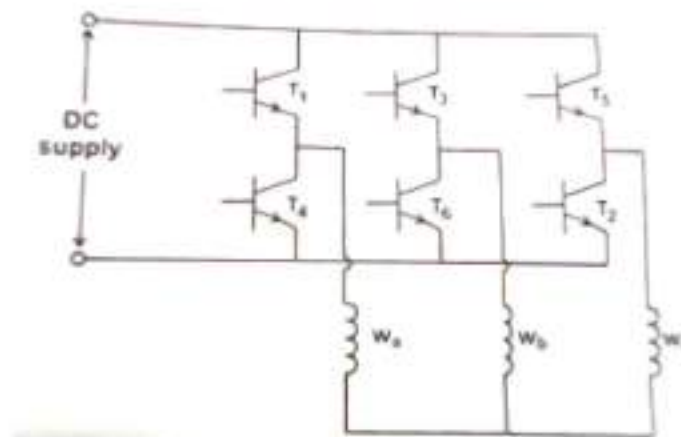
Most commonly used. It has 3 phase windings and six witching devices as shown in fig. 4.45.

Fig. 4.45 3-phase six pulse BLPM motor.