RAPPELLE
OBJECTIFS
Présenter aux étudiants la construction, le principe de fonctionnement et les performances des machines électriques spéciales comme une extension à l'étude des machines électriques de base.
Transmettre des connaissances sur:

I. Construction, principe de fonctionnement et performances des moteurs à réluctance synchrones.
II. Construction, principe de fonctionnement, contrôle et performances des moteurs pas à pas.
III. Construction, principe de fonctionnement, contrôle et performances des moteurs à réluctance commutée.
IV. Construction, principe de fonctionnement, contrôle et performances des moteurs CC sans balais à aimant permanent.
V. Construction, principe de fonctionnement et performances des moteurs synchrones à aimants permanents.

TEXT BOOKS:

REFERENCES:
- chap12 M.G. Say_ _ _ Alternating Current Machines, 1983
- Chapter 8 ELECTROMAGNETIC AND ELECTROMECHANICAL MACHINES, Third Edition, Leander W. Matsch, Late, J. Derald Morgan, 1986
- Chapter 11 &12 Electrical Machines, S. K. Sahdev, 2017

Merci de me visiter sur le site :
Bienvenue à notre site Web!

{Voici Un accès à des ressources numériques (disons informations pédagogiques et educatives supplémentaires : Cours, exercices, Tp, vidéos, quizz, liens ...), en ligne et gratuitement, pour compléter et approfondir ses connaissances, sans inscription et sans obtenir de diplôme.}

HEMSAS Kamel Eddine

http://hemsas-kamel-eddine.e-monsite.com/
1. Introduction aux machines spéciales
2. ** Moteurs monophasés
   ** Moteurs linéaires
   ** Moteurs pas à pas

**Contenu partie 2**

<table>
<thead>
<tr>
<th>Titre</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAP 3 MOTEURS SYNCHRONES À RELUCTANCES</td>
<td>3 -19</td>
</tr>
<tr>
<td>CHAP 4 MOTEURS À COURANT CONTINU À AIMANTS PERMANENTS</td>
<td>21 - 56</td>
</tr>
<tr>
<td>CHAP 5 MOTEURS SYNCHRONES À AIMANTS PERMANENTS</td>
<td>58 - 84</td>
</tr>
</tbody>
</table>

Banque de diverses questions en français 86 - 90
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)](image1)

![Fig 1.2 Cross Section of Synchronous Reluctance Motor.](image2)

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.

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.

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.

Applications
- Some washing machine designs.
- Control rod drive mechanisms of nuclear reactors.
- The *Dyson Digital Motor* used in some products produced by the Dyson company.

1.2 ROTOR DESIGN

1.2.1 Salient rotor (Segmental)

Salient rotor shape such that the quadrature air gap is much larger than the direct air gap. This yields reactively small $L_d/L_q$ ratios in the range of 2.3.

![Fig. 1.5 Salient rotor](image)

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](image)
1.2.3 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. 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.

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 which are machined into the desired rotor. The rotor shaft can also be machined out of the same block as the rotor.

![Explosion bonding](image)

**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 one 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](image)

**1.5 PRIMARY DESIGN CONSIDERATIONS**

- High output power capability.
- Ability of the rotor to withstand high speeds.
- Negligible zero torque spinning losses.
- High reliability.
- High efficiency.
- Low cost.

(a) **Power factor:**

The maximum achievable power factor \( \text{PF}_{\text{max}} \) of a synchronous reluctance machine given as

\[
\text{PF}_{\text{max}} = \frac{L_d}{L_q} - \frac{1}{L_d/L_q + 1}
\]

Higher \( L_d/L_q \) ratio yield higher power factors, which corresponds to reduced \( I^2R \) losses and reduced volt ampere ratings of the inverter driving the machine.

(b) **Copper loss and core loss:**

Copper loss = \( 3 I^2R_s \)

\[
= 3V^2R_s/(R_s^2 + \omega^2L_dL_q)^2 \{ R_s^2 + R_s \omega(L_d-L_q) \sin 2\theta \} + \omega^2 [L_d^2 + L_q^2/2 - L_q^2 - L_d^2/2 \cos 2\theta ]
\]

Where

- \( R_s \) – Stator resistance
- \( L_d, L_q \) - direct and quadrature inductance
- \( \theta \) - Torque Angle

Core loss \( P_{\text{core}} (R) = \frac{400}{k \pi} \int_0^2 (v^2)dv \)

The core losses are calculated corresponding to the fundamental component of flux density in the stator iron core. There will also be significant core losses in the stator and rotor due to the winding and slot harmonics. The losses are difficult to estimate reliably.
1.6 TORQUE – SPEED 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.

Application Characteristics:

- Comparable power density but better efficiency than induction motor.
- Slightly lower power factor than induction motor.
- Slightly small field weakening range than induction motor.
- High cost than induction motor but lower than any type of PM motors.
- Need speed synchronization to inverter out frequency by rotor position sensor sensor less control.
- Sensor less control is much easier due to motor saliency.
- By adding squirrel cage induction motor to synchronous reluctance motor one obtains line starting reluctance moors.
- Line started reluctance motors can be parallel with open loop control if the load does not change suddenly.
- Other combinations are possible such as adding PM for improved performance.
Rotor design for best manufacturability is still being optimized especially for high speed applications.

1.7 Phaser 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

\[ V = E - j IsdXsd - j Isq \ldots \ldots (1.1) \]

Where

- \( V \) is the Supply Voltage
- \( Is \) is the stator current
- \( E \) is the excitation emf
- \( \theta \) is the load angle
- \( \phi \) is the phase angle
- \( Xsd \) and \( Xsq \) are the synchronous reactance of direct and quadrature axis
- \( Isd \) and \( Isq \) are the direct and quadrature axis current

\[ I = Isd + Isq \ldots \ldots (1.2) \]

\( Isd \) is in phase quadrature with \( E \) and \( Isq \) is in phase with \( E \).
\[ V = E - j \text{Isd}X_{sd} - j \text{Isq}X_{sq} \]

From phasor diagram

\[ V \cos \theta = E + \text{Isd} + X_{sd} \] ……………(1.3)

\[ \text{Isd} = \frac{V \cos \theta - E}{X_{sd}} \]

\[ \text{Isq}X_{sq} = V \sin \theta \]

\[ \text{Isq} = \frac{V \sin \theta}{X_{sq}} \] ……………(1.4)

\[ \text{Is} \cos = \text{Isq} \cos \theta - \text{Isd} \sin \] ……………(1.5)

Where

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

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

\[ \text{Is} \cos \phi = \frac{E \sin \theta}{X_{sd}} + 2 \frac{X_{sd} - X_{sq}}{2 X_{sd} X_{sq}} \] ……………(1.6)

\[ P = 3 \text{Vis} \cos \phi \] ……………(1.7)

Sub equ (6) in equ (7)

\[ P_m = 3 \left[ \frac{VE}{X_{sd}} \sin \theta + V^2 \frac{(X_{sd} - X_{sq}) \sin 2 \theta}{2 X_{sd} X_{sq}} \right] \]

\[ P_m = T \omega_s \]

\[ T = \frac{P_m}{\omega_s} \]

\[ = \frac{3}{w_s} \left[ \frac{VE}{X_{sd}} \sin \theta + \frac{v^2(X_{sd} - X_{sq})}{2 X_{sd} X_{sq}} \sin 2 \theta \right] \] ……………(1.8)

Sub \( E = 0 \)

\[ T = \frac{3}{w_s} \sqrt{\frac{X_{sd} - X_{sq}}{2X_{sd} X_{sq}}} \sin 2 \theta \] ……………(1.9)

Equation (9) is the torque equation of synchronous reluctance motor.
Plotting the equation (9) as shown in fig indicates that the stability limit is reached at \( \delta = \pm \pi /4 \).

And by increasing the load angle torque also increases.

\[
V^2 \left[ \frac{X_{sd} - X_{sq}}{2 X_{sd} X_{sq}} \right] \sin 2 \delta = \text{reluctance Power}
\]

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

- 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.

1.10 VERNIER MOTORS

A Vernier motor is an unexcited (or reluctance Type) inductor synchronous motor. It is also named because it operates on the principle of a vernier. The peculiar feature of this kind of motor is that a small displacement of the rotor produces a large displacement of the axes of maximum and minimum permeance. When a rotating magnetic field is introduced in the air gap of the machine, rotor will rotate slowly and at a definite fraction of the speed of the rotating field.

This rotating field can be produced either by feeding poly phase current to the stator winding or by exciting the stator coil groups in sequence. AS the rotor speed steps down from the speed of the rotating field, the motor torque steps up. A vernier motor works as an electric gearing. This kind of motor is attractive in applications which require low speed and high torque and where mechanical gearing is undesirable.
1.10.1 Principle of operation

The stator of a vernier motor has slots and a distributed winding just like the stator of an ordinary poly phase induction motor. The rotor is a slotted iron core without winding. A 2–pole machine with 12 stator slots and 10 rotor slots.

The stator and rotor teeth are facing each other in the vertical axis. The stator teeth are facing rotor slots in the horizontal axis. At this position therefore, the maximum permeance is along the vertical axis and the minimum permeance is along the horizontal axis. When then rotor is rotated one half of its slot pitch, the rotor slots will face stator teeth in the vertical axis. The rotor and stator teeth will face each other in the horizontal axis. The axis of maximum permeance is now horizontal and the axis of minimum permeance is now vertical. Thus the rotor movement of one–half rotor slot pitch results in a 90 degree displacement of the permeance axes.

Suppose that a magnetic field is rotating in the machine. Whenever the rotating field rotates 90 degrees, the rotor will rotate one half of its slot pitch. When the rotating field completes one revolution, the rotor will rotate through an angle corresponding to two rotor slot pitches.

1.10.2 Air–Gap permeance Distribution

The fluxes in the air gap are assumed all in the radial direction. The permeance of air space between stator and rotor at any location is inversely proportional to the radial length of air space at that location. The stator and rotor slot depth are much larger in comparison with air gap length, the permeance of airspace can be considered as zero, where stator tooth surface is facing rotor tooth surface. The width of rectangular blocks is the widths of overlap between the stator and the rotor teeth. These widths of overlap vary linearly from a maximum and back to a minimum. The area of overlap is reduced a constant amount for each successive stator tooth until a minimum is reached.

The permeance distribution curve is not convenient to use because it cannot be represented by simple mathematical function. When the rotor rotates, this permanence wave rotates at a much faster speed. Five times the rotor speed for the machine. The axes at which maximum and minimum permeance occur are the direct and quadrature axes respectively of the vernier motor.
1.10.3 Design of Vernier Motor

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

\[ N_1 = N_2 \pm P \]

Where

- \( N_1 \) – Number of Stator Slots
- \( N_2 \) – Number of Rotor Slots
- \( P \) – Number of poles of the rotating magnetic field.

When the rotor rotates through an angle corresponding to one rotor slot pitch, the permeance wave rotates through an angle corresponding to one pole pitch. The pole pitch of the permeance wave is the same as the pole pitch of the stator mmf wave, because they have the same number of poles. Also in a reluctance machine, the speed of the permeance wave is the speed of rotating mmf.

Therefore,

\[
\frac{\text{Motor speed}}{\text{rotating field speed}} = \frac{\text{Rotor Slot Pitch}}{\text{MMF pole pitch}} = \frac{P}{N_2}
\]

or

\[
\text{Rotor Speed} = \frac{120 f}{N_2} \text{ rpm}
\]

And

\[
\text{Electric gear ratio} = \frac{N_2}{\pm(N_2-N_1)}
\]
The rotor speed is independent of the number of poles of the machine when the speed of rotating magnetic field is reduced by increasing the number of poles of the machine. It cannot be expected that the speed of the rotor be reduced proportionately because when \( P \) is increased the difference between \( N_2 \) and \( N_1 \) should also be increased, and the electric gear ratio is reduced in the inverse proportion. Thus the rotor speed is not affected by the number of poles but depends on the number of rotor slots.

The main step in design is to calculate the direct and quadrature axes reactance’s \( X_d \) and \( X_q \).

\[
X_d = X_1 + X_{ad}
\]

\[
X_q = X_1 + X_{aq}
\]

Where \( X_1 \) is the stator leakage reactance and \( X_{ad} \) and \( X_{aq} \) are the direct and quadrature axes reactance of armature reaction. \( X_{ad} \) is the ratio of the fundamental component of reactive armature voltage, produced by the mutual flux due to the fundamental direct axis component of armature current, Similarly \( X_{aq} \) is the ratio of the fundamental component of reactive armature voltage produced by the mutual flux due to the fundamental quadrature axis component of the armature current, to its component under steady state conditions and at rated frequency.
### Glossary Chap.3

1. **Synchronous reluctance motor** -- It is similar to the salient pole synchronous machine except that the rotor does not have any field winding.

2. **Reluctance torque** -- The tendency of the salient poles to align themselves in the minimum reluctance position.

3. **Vernier Motor** -- It is an excited reluctance type synchronous motor. The peculiar feature of this motor is that a small displacement of the rotor produces a large displacement of the axis of maximum and minimum permeance.

4. **Flux Barrier** -- It is another approach is to use laminations. The lamination required for the shaft weaken the rotor. It is used for low speed design.

5. **Axial air gap motor** -- It is another approach is to use laminations. The torque ripple and iron losses are more in axially laminated rotor than dially laminated.

6. **Explosion bonding** -- First sheets of ferromagnetic and nonmagnetic steel are bonded. The bonded sheets are then cut into rectangular blocks which are the machined into the desired rotor.

7. **Salient rotor** -- Salient rotor shape such that the quadrature air gap is much larger than the direct air gap. It is used for high speed application.

8. **Torque** Twisting or turning moment of force.

9. **Demagnetize** To disrupt the regular pattern of aligned magnetic domains, which eliminates a material's attraction.

10. **Magnetic Field** A force of attraction that surrounds magnets and current-carrying conductors.

11. **Magnetic Induction** The use of magnets to cause voltage in a conductor. Magnetic induction occurs whenever a conductor passes through magnetic lines of flux.

12. **Reluctance** A material's resistance to becoming magnetized.

13. **Residual Magnetism** The attractive force that exists in an object or substance after it has been removed from a magnetic field.

14. **Pole** One of two ends of the axis of a sphere. Poles also refer to the opposite ends of a magnet.

15. **Rotational Axis** The center line on which a ball or sphere turns or
rotates. The earth has a rotational axis.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16. Saturation</td>
<td>A magnetic state in which the attractive strength of a magnet has reached its peak.</td>
</tr>
<tr>
<td>17. Magnetized</td>
<td>To be made magnetic or made to attract other metals.</td>
</tr>
<tr>
<td>18. Conductor</td>
<td>A material or element that allows free movement of electrons and therefore allows easy flow of electricity. Most conductors are metals.</td>
</tr>
</tbody>
</table>
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).

![Arrangement of permanent magnet in the rotor](image)

**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 have 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 (i.e.) 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 7 and brush Y. There are two armature parallel paths between tapping’s 1 and 7. The current passing through the armature winding acts 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) \[2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8\]
(ii) \[2 \rightarrow 1 \rightarrow 12 \rightarrow 11 \rightarrow 10 \rightarrow 9 \rightarrow 8\]

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. Therefore, 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](image)

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 paths.

(i) \[1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7\]
(ii) \[1 \rightarrow 12 \rightarrow 11 \rightarrow 10 \rightarrow 9 \rightarrow 8 \rightarrow 7\]
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.
### 4.2.8 Comparison between mechanical Commutator and brushes and Electronic Commutator

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

![Fig 4.8 Star Connected Armature Winding](image-url)
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

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 $\mu_0$ and the permeance coefficient of the external circuit.

In a permanent magnet, the relationship between B and H is
\[ B = \mu_0 H + J \]

\( \mu_0 \) – 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 \( \mu_{\text{rec}} \) is unity, Then J is constant.

J – Magnetization of the magnet, unit T tesla

- Hard magnets have \( \mu_{\text{rec}} \geq 1 \), J decreases as the –\( H_c \) 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 \( H_c \).

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 \( \frac{2\pi NT}{60} = P_m = \omega T \) 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° pole arc.

120° pole arc.

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

![Fig 4.11 Air gap flux density distribution in 180° BLPM SQW motor.](image1)

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

![Fig 4.12 Air gap flux density distribution in 120° BLPM SQW motor](image2)

(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](image3)
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 Θ = 0. The stator has 12 slots and a three phasing winding. Thus there are two slots per pole per phase.

Consider a BLPM SQW DC MOTOR

Let ‘p’ be the number of poles (PM)
‘\(B_g\)’ be the flux density in the air gap in wb/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.
‘\(\omega_m\)’ be the uniform angular velocity of the rotor in mechanical rad/sec.
\(\omega_m = 2\pi N / 60\) where N is the speed in rpm.

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

Let at \(\omega_m t = 0\), the centre of N-pole magnet is aligned with x-axis.
At \(\omega_m t = 0\), x-axis is along PM axis.

Therefore flux enclosed by the coli is
\[
\Phi_{\text{max}} = B \times 2\pi r / p \times l 
\]
\[
\text{flux/pole}
\]
\[
\Phi_{\text{max}} = rl[0^\pi] B(\theta) d\theta
\]
\[
= B_g rl[0^\pi]
\]
\[
= B_g r l[\pi]
\]
At \(\omega_m t = 0\), the flux linkage of the coil is
\[
\Lambda_{\text{max}} = (B_g \times 2\pi r / p \times l) T_c \omega b - T
\]

\[
\text{...............(4.1)}
\]
\[
\text{...............(4.2)}
\]
Let the rotor rotating in ccw direction and when $\omega_{mt}=\pi/2$, the flux enclosed by the coil $\Phi$, Therefore $\lambda=0$.

The flux linkages of the coil vary with $\theta$ 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 $\omega_{mt}=0$ (i.e) $t=0$ to $\theta$ at $t=\pi/p \omega_m$.

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

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

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

$$= -(2B_g r l T c \omega_m) \quad \text{...............................................(4.3)}$$

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

$$e_c = 2B_g r l T c \omega_m \quad \text{...............................................(4.4)}$$

Distribution of $e_c$ with respect to $t$ is shown in fig 4.16
It is seen that the emf waveform is rectangular and it toggles between $+e_c$ to $-e_c$. The period of the wave is $2\pi/p\omega_m$ sec and the magnitude of $e_c$ is

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

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 $30^\circ$ (i.e.) slot angle $\Upsilon$.

The magnitude of emf induced in the coil $a1A1$

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

The magnitude of emf induced in the coil $a2A2$

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

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

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

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

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.

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

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

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

The waveforms are as shown in fig 4.17.
The waveform of $e_{ph}$ is stepped and its amplitude is $2Bg_rT_p\omega_m$ volts.

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

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 $= 2$ $e_{ph}$.
- Amplitude of back emf generated in Y connected armature winding $E = 2$ $e_{ph}$.

**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 $\lambda$ 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.
\[ V = 2 \ e_{ph} + 2I_R + 2V_{dd} \]  ...................(4.11)

If \( V_{dd} \) is neglected

\[ V = 2 \ e_{ph} + 2 \ I_R \]  

\[ I = \frac{V-2 \ e_{ph}}{2I_R} \]  

\[ I = \frac{V-E}{R} \]  .......................(4.12)

(a) Starting condition

Speed is zero \( \omega_m = 0 \)
Supply voltage is \( V \)
Since \( \omega_m = 0; e_{ph} = 0 \)

Starting current \( I_{stg} = \frac{V-0}{2R_{ph}} = \frac{V}{2R_{ph}} \)  ....................(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 \( V = 2 \ e_{ph} + 2 \ I_R \)  
\( 2I_R \) – negligible

\[ V = 2 \ e_{ph_{0}} \]  .............................(4.14)

\[ = 2 \ [2B_\gamma r l \ \omega_{mo T_{ph}}] \]

\[ = 4 \ [B_\gamma r l \ \omega_{mo T_{ph}}] \]

\[ V = k_e \ \omega_{mo} \]  .........................(4.15)

No load speed, \( \omega_{mo} = \frac{V}{4B_\gamma r l T_{ph}} \)  ....................(4.16)

\[ = \frac{V}{k_e} \]  .......................(4.17)

No load current \( I_0 = 0 \)

(c) ON load condition:

\( V = 2 \ e_{ph} + 2 \ I_R \)

\[ = 4B_\gamma r l \omega_{om tph} + 2 \ I_R \]  ..........................(4.18)

On load current
\[ I = \frac{V - 2 \text{eph}}{2Rph} = \frac{V - 4 Bgrl \omega m \text{tph}}{2Rph} \] 
\[ = \frac{V - ke \omega m}{2Rph} \] 
\[ I = \frac{V - ke \omega m}{2Rph} \] 
\[ (4.19) \]
\[ (4.20) \]
\[ (4.21) \]

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
\[ VI = \left[ 2 \text{eph} + 2 I Rph + 2 Vdd \right] I \]
\[ (4.22) \]
\[ (4.23) \]

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(2BgrlTphom)I
\[ (4.25) \]
Mechanical power = \( 2\pi N/60 \)T
\[ (4.26) \]
\[ (4.27) \]
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
\[ I_{stg} = (V/2Rph) \]
\[ (4.31) \]
Tstg=4BgrlTph(V/2Rph)
\[ (4.32) \]
Tstg=Kt(V/2Rph)
\[ (4.33) \]
Starting torque or stalling torque depends upon V.
To vary the starting torque the supply voltage is to be varied.

(b) Case 2: On load condition

\[
T = K_t I \quad \ldots \quad (4.34)
\]

\[
= 4 B_g r l T_{ph} I
\]

\[
I = (V - 2e_{ph})/(2R_{ph}) \quad \ldots \quad (4.35)
\]

\[
2e_{ph} = V - 2I R_{ph}
\]

\[
4 B_g r l T_{ph} \omega_m = V - 2I R_{ph} \quad \ldots \quad (4.36)
\]

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

\[
\omega_m = (V - 2I R_{ph})/K_e \quad \ldots \quad (4.37)
\]

\[
\omega_{m0} = V/K_e \quad \ldots \quad (4.38)
\]

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

\[
= (V - 2I R_{ph})/V \quad \ldots \quad (4.39)
\]

\[
I/(T_{stg}) = (K_t I)/(K_t I_{stg})
\]

\[
= I.(2R_{ph}/V)
\]

\[
T/T_{stg} = 2I R_{ph}/V \quad \ldots \quad (4.40)
\]

Substituting eqn. 5.40 in eqn. 5.39

\[
\omega_m/\omega_{m0} = 1 - \left( T/T_{stg} \right) \quad \ldots \quad (4.41)
\]

\[
\omega_m/\omega_{m0} = 1 - (1 - I_{stg}) \quad \ldots \quad (4.42)
\]

4.9 TORQUE- SPEED CHARACTERISTICS 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-\(\omega_m\) curve for various supply voltages
Permissible region of operation in $T$-$\omega_m$ 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 $\omega_{mn}$.

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 $T$-$\omega_m$ characteristics corresponding to the maximum permissible $V_n$. B and C are points in Fig. B is the point of intersection between AB and FG.

**Line DH**

It represents constant maximum permissible speed line (i.e) $\omega_{mn}$ 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.
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 are shown in fig. 4.23 and 4.24.
In Fig. 4.26 the rotor magnet poles are shaded to distinguish north and south. The phase belts are shaded us complete 60\(^\circ\) 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
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 shading, positive torque is produced. Where mmf and flux shading are unlike, negative torque is produced. Where one 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**

<table>
<thead>
<tr>
<th>Rotor Position</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>au(1)</th>
<th>aL(4)</th>
<th>bu(3)</th>
<th>bL(6)</th>
<th>cu(5)</th>
<th>cL(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 60</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>60 – 120</td>
<td>+1</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>120 – 180</td>
<td>0</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>180 – 240</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>240 – 300</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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 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.

<table>
<thead>
<tr>
<th>Rotor Position</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>ab u (1)</th>
<th>ab L (4)</th>
<th>bc u (3)</th>
<th>bc L (6)</th>
<th>ca u (5)</th>
<th>ca L (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 60</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>60 – 120</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>120 – 180</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>180 – 240</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>240 – 300</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>300 - 360</td>
<td>-1</td>
<td>+1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

(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 $p_{mo}$.

$$\varphi_r = BrAm \quad \ldots \ldots (4.43)$$

$$P_{mo} = \mu_0 \mu_{rec} Am/Im \quad \ldots \ldots (4.44)$$

where Am – pole area the magnet

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

Br- remanent flux density

$\mu_{rec}$- 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°

\[ Am = \frac{2}{3} \pi r_1 (g - \frac{lm}{2}) \]  

r1- radius of the rotor

g- air gap length

most of the magnet flux crosses the air gap via the air gap reluctance \( R_g \)

\[ R_g = \frac{g'}{\mu_0 A_g} \]  

\( g' \)- equivalent air gap length allowing for slotting.

the slotting can be taken into account by means of carters’s coefficient, which case,

\[ g' = K_c g \]  

\( K_c \)- carter’s coefficient, which case,

\( A_g \)- air gap area through which the flux passes as it crosses the gap. The precise boundary of this area is uncertain because of fringing both at the edges of the magnet and at the ends of the rotor. An approximate allowance for fringing can be made by adding ‘g’ at each of the four boundaries, giving

\[ A_g = \frac{2}{3} \pi (r_1 - \frac{g}{2}) + 2g (l + 2g) \]  

the remaining permeance in the magnetic circuit I the rotor leakage permeance \( \rho_{rl} \), 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

\[ \rho_m = \rho_{mo} + \rho_{rl} \]  

\[ \rho_m = \rho_{mo} (1 + \rho_{rl}) \]  

\( \rho_{rl} \)- 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 tacho-generator is coupled to the shaft to get feedback signal.
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.
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.

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

$$V_H = R_H (i_c / d) \text{ volts}$$

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](image)

When $w_1$ carries a current on closing S1 it set up a North Pole flux in the air gap. Similarly when $s_2$ is closed $w_2$ is energized and sets up a North Pole flux. $w_1$ and $w_2$ 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 $w_1$ sets up North Pole flux. The rotor experiences a torque and South Pole of the rotor tends to align with the axis of $w_1$. 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 $w_2$ sets up N pole flux in the air gap, the rotor rotates in clockwise direction. So that the s pole gets aligned with $w_2$ 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 fig 4.38.

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.](image)

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

![Fig.4.39 Current and torque waveform](image)

**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.
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.

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.
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. 4.44 3 phase, 3 pulse BLPM motor.

Fig. 4.45 3-phase six pulse BLPM motor.
### Glossary Chap.4

1. **Brushless PM D.C.Motor** -- It is similar to salient pole D.C.Motor except that there is no field winding on rotor and is provided by PM. It reduces losses. Complexity in construction is reduced.

2. **Magnetic Remanence** -- The magnetic flux density which persists in magnetic materials even though the magnetizing forces are completely removed.

3. **Coercivity Forces** -- The demagnetizing force which is necessary to neutralize completely the magnetism in an electromagnet after the magnetizing force becomes zero.

4. **Position Sensors** -- The position sensors detect the position of rotating magnets and send logic codes to commutation decoder.

5. **Energy Product** -- The absolute value of product of flux density and field intensity at each point along the demagnetization curve is called energy product.

6. **Electronic Commutator** -- It is to transfer the current to the armature. Power semiconductors are used as switching devices. Armature has three tappings, which can be connected either in star or in delta.

7. **Commutator** -- A commutator is a rotary electrical switch in certain types of electric motors or electrical generators.

8. **Friction** -- A force that resists motion between two objects that are in contact with each other. Smoother surfaces exhibit less friction, while rougher surfaces exhibit more friction.

9. **Magnet** -- A device or object that attracts iron and produces a magnetic field.

10. **Magnitude** -- The measurement of the amount of an applied force.

11. **Rotary Speed** -- A measure of circular motion found by counting the number of revolutions that occur in a specific amount of time.
13. Atmospheric Hazard -- A confined space hazard that is present in the environment. Atmospheric hazards are categorized as flammable, toxic, irritant, and asphyxiating.

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

15. Permeance, In general, is the degree to which a material admits a flow of matter or energy.
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 120°.

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](image)

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](image)
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 Lundell**
  The permanent magnets are generally disc shaped and magnetized axially. Long soft iron extensions emanate axially from periphery of the discs like claws or Lundell 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 \( B = B \sin \theta \) or \( B \cos \theta \) or \( B \sin(p\theta + \alpha) \) or \( B \cos(p\theta + \alpha) \), depending upon the position of the reference axis as shown in fig6.3.

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 \( \omega_m \) 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 \( d\theta \) mech.radians at a position \( \theta \) from the reference.

Flux density at the strip \( B = B \sin p\theta \)
Incremental flux in the strip \( d\theta = B X \) area swept by the conductor
\( d\theta = B \sin p\theta X lr \ d\theta \)
\( B \ lr \ d\theta \) weber
Where
\( L \) – Length of the armature in m
\( r \) – Radians of the armature
\( d\theta = B \sin p\theta X lr \ d\theta \)
\( = B \ lr \ sin p\theta X \ d\theta \)
Flux enclosed by the coil after lapses of \( t \) sec is
5.3.2. EMF Equation of an ideal BLPM sine wave motor

As per Faraday's law of electromagnetic induction, emf induction in the single turn coil.

\[ e = -N \frac{d \phi}{dt} \]

- \( d\phi /dt \) as \( N=1 \)

\[ = - d\phi /dt \ (2 \frac{B \ l r}{p} \cos p\theta \ \omega_{mt}) \]

\[ = (2 \frac{B \ l r}{p}) p \omega_m \sin p \omega_{mt} \]

\[ e = 2 \frac{B \ l r}{p} \omega_m \sin p \omega_{mt} \] .......(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.

\[ e_{ph} = (2 \frac{B \ l r}{p} \omega_m \sin p \omega_{mt})T_{ph} \] .......(5.3)

\[ = 2 \frac{B \ l r}{p} \omega_m T_{ph} \sin p \omega_{mt} \]

\[ = \bar{E}_{ph} \sin p \omega_{mt} \quad \text{where} \quad p \omega_{mt} = \omega_e \quad \text{angular frequency in rad/sec} \]

\[ = \bar{E}_{ph} \sin \omega_e t \]

\[ \bar{E}_{ph} = 2 \frac{B \ l r}{p} \omega_m T_{ph} \omega_m \] .......(5.4)

\( \bar{E}_{ph} \) = rms value of the phase emf

\[ = \bar{E}_{ph} / \sqrt{2} \]

\[ = \sqrt{2} \frac{B \ l r}{p} \omega_m T_{ph} \omega_m \]

\( \omega_m = \omega_e / \rho \)

\( \phi_m \) - sinusoidal distributed flux / pole

\[ \phi = \frac{B_{av} \tau}{l} \] .......(5.5)

\[ = B_{av} X (2\pi r / 2p) X l \]
Average value of flux density for sinewave = \( \frac{2}{\pi} \)

\[ \phi_m = \left( \frac{2}{\pi} \right) B \cdot X \left( \frac{\pi r}{P} \right) \cdot l \]

\[ \phi_m = \left( \frac{2}{\pi} \right) B \cdot r \cdot l / P \]

\[ B \cdot r \cdot l = \left( \frac{P \phi_m}{2} \right) \]

\[ \ldots \ldots (5.6) \]

\[ E_{ph} = \sqrt{2} B \cdot I_r \omega_m T_{ph} \text{ volt} \]

Sub equ

\[ E_{ph} = \sqrt{2} \left( \frac{P \phi_m}{2} \right) \omega_m T_{ph} \]

\[ = \sqrt{2} \left( \frac{P \phi_m}{2} \right) \left( \frac{\omega}{p} \right) T_{ph} \]

\[ = \sqrt{2} \left( \frac{P \phi_m}{2} \right) \left( \frac{2\pi f}{p} \right) T_{ph} \]

\[ E_{ph} = 4.44 f \phi_m T_{ph} \text{ Volt} \]

\[ \ldots \ldots (5.7) \]

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 chored 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.

\[ K_{w1} = K_{s1} K_{p1} K_{b1} \]

\[ \ldots \ldots (5.8) \]

\( K_{s1} = \) slew factor

\[ K_{s1} = \frac{\sin \sigma/2}{(\sigma/2)} \]

\[ K_{s1} = 1 \text{ (slightly less than 1)} \]

\( \sigma \) – Skew angle in elec. Radians.

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

\[ = \sin m\pi/2 \text{ or } \cos \rho/2 \]

Where \( m = \) coil span/pole pitch
\[ \pi (1 - m) = \rho \]

[Coil span = \( \tau \)

\[ = \pi \text{ elec rad} \]

\[ = \pi / \rho \text{ mech. Rad} \]

\[ K_{p1} = \sin \frac{m\pi}{2} \text{ or } \cos \frac{\rho}{2} \]

[m\pi \text{ is elec rad } \frac{m\pi}{p} \text{ mech. Rad. }]

\( K_{b1} \) = Distribution factor or width factor

\[ K_{b1} = \frac{\sin \frac{v}{q}}{q \sin \frac{\phi}{2}} \]

Where \( v = \) slot angle in elec. Radians

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

\[ q = \text{ slots/pole/phase for 60° phase spread} \]

\[ = \text{ slots/pair of poles/phase} \]

\( K_{b1} < 1; K_{p1} < 1; K_{s1} < 1 \)

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

Thus rms value of the per phase emf is

\[ E_{ph} = 4.44 f \phi_m T_{ph} K_{w1} \text{ volts.} \]

\[ \therefore (5.9) \]

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

\[ A = A^\wedge \sin p \Theta \]

Where \( A = \) ampere conductor density

\[ = \text{ampere conductor/degree} \]

Consider a strip of \( d \theta \) at an angle \( \theta \) from the reference axis.

Ampere conductor in the strip \( d \theta = A \, d \theta \)

\[ = A^\wedge \sin P \, \theta \, d \theta \quad \ldots\ldots (5.10) \]

Ampere conductor per pole =

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

\[ = - \frac{A^\wedge}{P} [\cos \pi - \cos 0] \]

\[ = \frac{2A^\wedge}{P} \]

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 \( \theta \) sine distributed.

Total ampere conductors [sine distributed] = \( 2i \, T_{ph} \)

Sine distributed ampere conductors/pole = \[ \frac{2i \, T_{ph}}{2P} \]

Equating eqn. 6.30 and eqn. 6.32

\[ \frac{2A^\wedge}{P} = \frac{2i \, T_{ph}}{2P} \]
\[ A^\wedge = \frac{i T_{ph}}{2} \] ..........(5.12)

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

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

\[ A = A^\wedge \sin P \theta \]

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

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

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

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

\[
= B^\wedge \cos (P \theta - \alpha)
\]

\[
B = B^\wedge \cos (P \theta - \alpha)
\] ..........(5.14)

Fig. 5.6 Ampere conductor and flux density distribution.

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

Flux density at the strip \(B = B^\wedge \cos (P\theta - \alpha)\)

Ampere conductors in the strip \(= A \, d\theta\)

\[
= A \, \sin P \theta \, d\theta
\] ..........(5.15)

Force experienced by the armature conductors in the strip \(d\theta = B I A d\theta\)

\[
dF = B^\wedge \cos (P\theta - \alpha) \cdot A \cdot B^\wedge \cdot A \sin P \theta \, d\theta
\]
\[ dF = A^B \hat{y} \sin \Theta \cos (P\Theta - \alpha) \ d\Theta. \]

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

Torque experienced by the ampere conductors of the strip = \(dF \times r\)

\[ dT = AB \ r_1 \ \sin P \Theta \cos (P \Theta - \alpha) \ \text{d}\Theta \ N\text{-m} \]

Torque experienced by the ampere conductors/pole \(T/\text{Pole} = \int_{0}^{\pi/p} dT\)

\[ T = \int_{0}^{\pi} A B \ r_1 \sin P \Theta \cos (P \Theta - \alpha) \ \text{d}\Theta \]

\[ = A B \ r_1/2 \left\{\sin (P \Theta + P \Theta - \alpha + \sin \alpha) \ \text{d}\Theta\right\} \]

\[ = A B \ r_1/2 \left[\frac{\cos (2P\Theta - \alpha)}{2p} + \sin \alpha\right] \]

\[ = A B \ r_1/2 \left[-\frac{\cos \alpha}{2p} + \frac{\cos \alpha}{2p} + \frac{\pi}{p} \sin \alpha\right] \]

\[ T = A B \ r_1/2 \frac{\pi}{p} \sin \alpha \ N\text{-m} \]

The total torque experienced by all the armature conductors

\[ = 2P \times \text{torque/pole} \]

\[ = 2P \times \frac{\pi}{p} \times \frac{A B r_1}{2} \sin \alpha \]

\[ T = \pi A B r_1 \sin \alpha \ N\text{-m} \]

As the armature conductors are located in stator of the BLPM SNW motor, the rotor experiences an equal and opposite torque.

Torque experienced by the rotor

\[ = \text{Torque developed by the rotor} \]

\[ = -\pi A B r_1 \sin \alpha \]

\[ = \pi A B r_1 \sin \beta \text{ where } \beta = -\alpha \]

\[ \text{B is known as power angle or torque angle.} \]

\[ T = \pi A B r_1 \sin \beta \text{ in an ideal motor.} \]

Consider the case of an armature winding which has three phases. Further the winding consists of short choreded 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 $2\pi/3p$ mechanical radians or $2\pi/3$ 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 $2\pi/3p$ 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

\[
i_a = l m \cos \omega t \ (i.e.) \sqrt{2} \ l \cos \omega t \quad \text{……(5.20)}
\]

\[
l_b = l m \cos \left(\omega t - \frac{2\pi}{3}\right) = \sqrt{2}l \cos \left(\omega t - 2\pi/3\right) \quad \text{……(5.21)}
\]

\[
l_c = l m \cos \left(\omega t + \frac{2\pi}{3}\right) = \sqrt{2}l \cos \left(\omega t - 4\pi/3\right) \quad \text{……(5.22)}
\]

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.

\[
f_a = F_m \cos P \theta \quad \text{……(5.23)}
\]

\[
f_b = F_m \cos \left[P \theta - 2\pi/3\right] \quad \text{……(5.24)}
\]

\[
f_c = F_m \cos \left[P \theta - 4\pi/3\right] \quad \text{……(5.25)}
\]

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 $4/\pi i$ Tph.

- In a practical motor, the armature turns are short chorded and distributed. Further they may be accommodated 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 $Ks1 \ Kp1 \ Kd1$

\[
Ks1 = \text{Skew factor}
\]

\[
= \frac{\sin \sigma/2}{\sigma/2}; \ \sigma = \text{skew angle in elec. rad.}
\]
Kp1 = sin \frac{m\pi}{2}; \ m\pi= \text{coil span in elec. Rad}

Kd = \text{distribution factor}
= \frac{\sin q v/2}{q \sin^2 \frac{\pi}{2}} \ v\text{-slot angle in electrical.rad, q-slot per pole for 60degree phase spread.}

Fundamental component of ampere turns per phase of a practical one

\[-4/\pi I_{Tph} K_w1 \quad \ldots \ldots (5.26)\]

\[\text{when a balanced sinusoidally varying 3 phase ac current pass through a balanced 3 phase}
\text{winding it can be shown that the total sinusoidally distributed ampere turns is equal to}
\[3/2.4/\pi I_{\text{Imax}} K_w1 T_{\text{ph}}.\]

\[-4/\pi.3/2 \sqrt{2} \ I_{\text{ip}} K_w1 T_{\text{ph}} \quad \ldots \ldots (5.27)\]

\[\text{The amplitude of the ampere conductor density distribution is shown is equal to the total}
\text{sinusoidally distributed ampere turns divided by 2.}

\[\text{Therefore } \bar{A} \text{ in a practical 3 phase motor } = \frac{4/\pi.3/2.\sqrt{2}}{2} I_{\text{ph}} K_w1 T_{\text{ph}}\]

Electromagnetic torque developed in a practical BLPL SNW motor

\[-\pi A B r l \sin \beta \quad \ldots \ldots (5.28)\]

\[-\pi \left[3 \sqrt{\frac{2}{\pi} I_{\text{ph}} K_w1 T_{\text{ph}}} \right] B r l \sin \beta \]

\[= 3(\sqrt{2}K_w1 T_{\text{ph}} B r l) I_{\text{ph}} \sin \beta \]

\[-3 \frac{E_{\text{ph}}}{\omega_m} I_{\text{ph}} \sin \beta \quad \ldots \ldots (5.29)\]

\[i_a T_{\text{ph}} = I_{\text{max}} \cos \omega t \cos \theta \quad \ldots \ldots (5.30)\]

\[i_b T_{\text{ph}} = I_{\text{max}} \cos \left(\omega t - \frac{2\pi}{3}\right) \cos \left(\theta - \frac{2\pi}{3}\right) \quad \ldots \ldots (5.31)\]

\[i_c T_{\text{ph}} = I_{\text{max}} \cos \left(\omega t - \frac{4\pi}{3}\right) \cos \left(\theta - \frac{4\pi}{3}\right) \quad \ldots \ldots (5.32)\]

\[i T_{\text{ph}} = i_a T_{\text{ph}} + i_b T_{\text{ph}} + i_c T_{\text{ph}} \quad \ldots \ldots (5.33)\]

\[-I_{\text{max}} \left(\frac{\cos(\omega t+\theta)+\cos(\omega t-\theta)}{2}\right) + I_{\text{max}} \left(\frac{\cos(\omega t+\theta-\frac{4\pi}{3})+\cos(\omega t-\theta)}{2}\right) + \]

\[-I_{\text{max}} \left(\frac{\cos(\omega t+\theta-\frac{8\pi}{3})+\cos(\omega t-\theta)}{2}\right)\]
Properties of ‘A’ (Ampere conductor density);

- Ampere conductor density is sinusoidally distributed in space with amplitude $A$. 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 $\omega_m$ rad/sec. or $\omega_{elec}$.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 $\sin \beta$.

$$\beta$$-torque angle or power angle.

Angle between the axes of the two fields is $\pi/2-\alpha$ and $\beta=-\alpha$

Torque developed by the motor = $3E_{ph}I_{ph}\sin \beta/\omega_m$ N-m

Where $\omega_m$-angular velocity in rad/sec.

$$\omega_m=2\pi N_s/60 \quad \text{where } N_s \text{ is in rpm}$$

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

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

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

It is a machine dependent conversion factor
5.5 PHASOR DIAGRAM OF A BRUSHLESS PM SNW OR BLPB SYNCHRONOUS MOTOR:

Consider a BLPM SNW motor, the stator carries a balanced 3φ 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 equal to the speed of the rotor.

Rotor carries a permanent magnet. Its flux density is sine distributed. It also revolves in the air gap with a particular speed agreed.

It is assumed that the motor acts as a balanced 3φ system. 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 $E_f = 4.44 f \mu mK_w T_{ph} = I E_f$.
   As per Faraday's law of electromagnetic induction, this emf lags behind $\phi_m$ - permanent magnet flux enclosed by armature phase winding by 90°.

3. $E_a$ - emf induced in the armature phase winding due to the flux $\phi_a$ set up by resultant armature mmf $\phi_a = I_a$
   
   $I E_a = 4.44 f \phi_a K_w T_{ph}$

   $= 4.44 f (K_{la}) K_w T_{ph}$

   $I E_a = I_a X_a I_a$ where $X_a = 4.44 f K K_w T_{ph}$

   This lags behind $\phi_a$ by 90° or in other words $E_a$ lags behind $I_a$ by 90°.

   Therefore $E_a = -j X_a I_a$

4. $E_{at}$ - emf induced in the same armature winding due to armature leakage flux.
   $|E_{at}| = 4.44 f \phi_{at} K_w T_{ph}$
\( \Phi_{al} \) 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 \( \Phi_{al} \).

Or \( I_a \) by 90º

Therefore \[ E_{al} = -jI_a X_{al} \]

**Voltage equation:**

The Basic voltage equation of the armature circuit is

\[ V' + \dot{E}f + \dot{E} al = I a Ra \] .......(5.35)

Where Ra is the resistance per phase of the armature winding.

\[ V' + \dot{E}f -j I a X_a -j I a X_{al} = I a Ra \]

\[ V' + \dot{E}f -j I a (X_a + X_{al}) = I a Ra \]

\[ V' + \dot{E}f -j I a X_s = I a Ra \] .......(5.36)

Where \( X_s = X_a + X_l \)

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

\[ V = (-Ef) + Ia(Ra + jXs) \]

\[ V' = \dot{E}q + I a Zs \]

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 \( Ef \)
\( \phi_{mf} \) be the mutual flux set up by the permanent magnet, but linked by the armature winding.

Ef lags behind \( \phi_{mf} = \phi_d \)

AF represents \( I_a R_a \)

FG represents \( I_a X_s \); FG is perpendicular to I phasor

OG represents \( V \)

Angle between the I and \( \phi_{mf} \) is \( \beta \) the torque or power angle.

Power input = 3VI

\[
3 VI = 3 (Eq + Ia Ra + j I Xs) I
\]

\[
= 3 Eq I + 3 I^2 Ra + O
\]

\[ \ldots \ldots (5.37) \]

3Eq I – electromagnetic power transferred as mechanical power.

3I^2 Ra – copper loss.

Mechanical power developed = 3 EqI

\[ \ldots \ldots (5.38) \]

\[
= 3 Eq I \cos(90 - \beta)
\]

\[ \ldots \ldots (5.38) \]

\[
= 3 Eq I \sin \beta
\]

\[ \ldots \ldots (5.39) \]

The motor operates at \( N_s \) rpm or 120f/2p rpm

Therefore electromagnetic torque developed = \( 60/2\pi N_s \times 3 Eq I \sin \beta \)

\[
= P/\omega_m
\]

\[ \ldots \ldots (5.40) \]
The same phasor diagram can be redrawn as shown in fig with $\phi_d$ or $\phi_{fm}$ as the reference phasor.

![Fig 5.8 Phasor Diagram of BLPM sine wave motor with $\phi_d$ or $\phi_{mf}$ as reference axis](image)

Further the current I phasor is resolved into two components $I_d$ and $I_q$

$I_d$ set up mmf along the direct axis (or axis of the permanent magnet)

$I_q$ sets up mmf along quadrature axis (i.e) axis perpendicular to the axis of permanent magnet.

$$V = Eq + I_{Ra} + j I_{Xs} \quad \ldots \ldots(5.41)$$

$$I = I_q + I_d \quad \ldots \ldots(5.42)$$

Therefore $V = Eq + I_{d} r_a + I_{q} r_a + j I_d Xs + j I_q Xs$

$V$ can be represented as a complex quantity.

$$V = (V_{rr} + j V_{lp})$$

From the above drawn phasor.

$$V = (I_d r_a - I_q Xs) + j (Eq + I_q r_a + I_d Xs)$$

$I$ can also be represented as a complex quantity

$$I = I_d + j I_q$$

Power input = $Re(3VI^*)$  

$I^* \text{ - conjugate}$

$$= Re(3((I_d r_a - I_q Xs) + j (Eq + I_q r_a + I_d Xs)) ((I_d - j I_q)))$$
(i.e.) power input = \[ \text{Re}(3(I_q^2 r_a - I_d I_q X_s) + (-j I_d I_q r_a + j I_q^2 X_s) + j(E_q I_d + I_q I_d r_a + I_q^2 X_s) + (E_q I_q + I_q^2 r_a + I_d I_q X_s)) \]

\[ = 3(I_q^2 r_a - I_d I_q X_s) + 3(E_q I_q + I_q^2 r_a + I_d I_q X_s) \]

\[ = 3 E_q I_q + 3(I_q^2 r_a + I_d I_q X_s) \]

\[ = 3 E_q I_q + 3 I_q^2 r_a \]  \hspace{1cm} \ldots \ldots (5.43)

Electromagnetic power transferred = 3 \( E_q I_q \)

\[ = 3 E I \sin \beta \]

Torque developed = \( 60/2\pi Ns \cdot 3 E I \sin \beta \)

Electromagnetic Torque developed = 3 \( E_q I_q/\omega_m \) N-m

**Note:**

In case of salient pole rotors the electromagnetic torque developed from the electrical power.

From eqn. (5.43)

\[ \frac{P}{\omega_m} = 3[I_q^2 r_a - I_d I_q X_s] + 3[E_q I_q + I_q^2 r_a + I_d I_q X_s] \]

\[ = 3[I_q^2 r_a - I_d I_q X_s + X_q] + 3[E_q I_q + I_q^2 r_a + I_d I_q X_s] \]

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

\[ = R_e \cdot 3[I_q^2 r_a - I_q X_s + X_q] + j(E_q + I_d X_s + X_q) + jI_d I_q + I_q^2 r_a \]

\[ = 3 E_q I_q + 3 I_q^2 R_a \]

Torque developed for a salient pole machine is given by

\[ T = 3 \left[ E_q I_q + (X_d - X_q) I_d I_q \right] N - m \]

\[ \frac{3p}{\omega_m} E_q I_q = \text{magnet alignment torque.} \]

\[ \frac{3p}{\omega_m} (X_d - X_q) I_d I_q = \text{reluctance torque.} \]
In case of surface – magnet motors, the reluctance torque becomes zero.

Therefore, torque developed = \( \frac{3E_q I_q}{\omega_m} \) N-m

Or = \( \frac{3P}{\omega} E_q I_q \) N-m

At a given speed, \( E_q \) is fixed as it is proportional to speed. Then torque is proportional to \( q \)-axis current \( I_q \).

The linear relationship between torque and current simplifies the controller design and makes the dynamic performance more regular and predictable. The same property is shared by the square wave motor and the permanent \( d_c \) 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

\( (i.e.,) \ \dot{V} = E_q + jX_s \)

As the effect of resistance is neglected

\[
\begin{align*}
\frac{\dot{V}}{jX_s} &= \frac{E_q}{jX_s} + j \\
\dot{j} &= \frac{\dot{V} - E_q}{jX_s}
\end{align*}
\]  

\[\text{……..}(5.44)\]

\[\text{……..}(5.45)\]

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

![Torque-Speed Characteristics](image)

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 $\frac{E_q}{X_q}$ 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 3φ winding in a 3φ 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.

![Diagram showing quadrature position of air gap flux and armature mmf axis](image1)

Fig. 5.11 Quadrature position of air gap flux and armature mmf axis.

![Diagram showing non-quadrature position of air gap flux and armature mmf axis](image2)

Fig. 5.12 Non-Quadrature position of air gap flux and armature mmf axis.

Each and every armature conductor experiences a force which contributes the torque. The torque contributed by various armature conductors have the same direction even though 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 up to 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 5.13. Knowing 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 \( i_{d,\text{ref}} \) and \( i_{q,\text{ref}} \) for the desired dynamic and steady state performance.

![Schematic Diagram of Vector Control](image)

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 \( i_{a,\text{ref}} \), \( i_{b,\text{ref}} \) and \( i_{c,\text{ref}} \). 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 $\Phi f/\beta$, it lies along the direct axis that rotates at a synchronous speed. The switches must be triggered by phase A current component when $\Phi f$ axis is $\beta$ electrical degrees behind the phase A axis. This is achieved by firing the switch when direct axis is $\delta+\beta$ behind axis of A as show shown in fig.

Self-control is applicable to all variable frequency converters, the frequency being determined by machine.

![Schematic diagram of self-control](attachment:fig5.14.png)

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.

5.8.2 Commutation 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 an 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 an 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.
## Glossary Chap. 5

1. **Permanent Magnet Synchronous Motor** -- It is also called as brushless permanent magnet sine wave motor. It has Sinusoidal magnetic flux in the air gap, Sinusoidal current wave forms, and Quasi-sinusoidal distribution stator windings.

2. **Flux density** -- The intensity of this flux

3. **Vector Control** -- Also called field-oriented control (FOC), is a variable frequency drive (VFD) control method which controls three-phase AC electric motor

4. **Self-Control** -- Self-control is the ability to control one's behavior, and desires in order to obtain some reward.

5. **Peripheral rotor** -- The permanent magnets are located on the rotor periphery and permanent magnet flux is radial.

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

7. **Resistivity** -- Also known as specific resistance, the measure of a material's natural resistance to current flow. Resistivity is the opposite of conductivity, so it follows that good conductors have low resistivity per circular mil foot.

8. **Specific Resistance** -- Another term for resistivity. Every material has a set specific resistance per circular mil foot at a specific temperature.

9. **Temperature Coefficient** -- A ratio of increased conductor resistance per degree Celsius rise in temperature. Most metals increase in resistance as temperature increases, giving them a positive temperature coefficient.

10. **Pole** -- One of two ends of the axis of a sphere. Poles also refer to the opposite ends of a magnet.

11. **Reluctance** -- A material's resistance to becoming magnetized.

12. **Residual Magnetism** -- The attractive force that exists in an object or substance after it has been removed from a magnetic field.
BANQUE DE QUESTIONS

Chap1 - MOTEURS À RELUCTANCE SYNCHRONE

PARTIE - A

1. Qu'est-ce qu'un moteur à réluctance synchrone?
2. Quels sont les avantages et les inconvénients du moteur à réluctance synchrone?
3. Mentionnez quelques applications du moteur à réluctance synchrone.
4. Définissez la réticence synchrone.
5. Définissez le couple de réluctance.
6. Distinguez les moteurs à entrefer axial et radial avec les chiffres pertinents.
7. Dessinez le diagramme de phaseur en régime permanent du moteur à réluctance synchrone.
8. Énumérez les principales considérations de conception du moteur à réluctance synchrone.
9. Énoncer les avantages du moteur à réluctance synchrone par rapport aux machines PM.
10. Quels sont les facteurs à considérer lors de la conception d'un moteur à vernier?

PARTIE - B

1. Expliquer les constructions et le principe de fonctionnement du moteur à réluctance synchrone.
2. Expliquez en détail la classification du moteur à réluctance synchrone.
3. Dessinez le diagramme de phaseur du moteur à réluctance synchrone.
4. Dérivez l'équation de couple du moteur à réluctance synchrone.
5. Dessinez et expliquez les caractéristiques du moteur à réluctance synchrone.
6. Expliquez en détail le moteur vernier
1. Qu'est-ce que le moteur pas à pas?
2. Définissez l'angle de pas.
3. Définissez l'orientation.
4. Esquissez le schéma d'un moteur pas à pas VR.
5. Quels sont les différents modes d'excitation utilisés dans les moteurs pas à pas à réluctance variable?
6. Mentionnez quelques applications du moteur pas à pas?
7. Définissez la résolution.
8. Quels sont les avantages et les inconvénients du moteur pas à pas?
9. Qu'entend-on par micro-pas dans un moteur pas à pas?
10. Différentiel entre VR, PM et moteur pas à pas hybride?
11. Définissez le couple de maintien.
12. Définissez le couple de détente.
13. Définissez le couple de traction et le couple de retrait.
14. Dessinez les caractéristiques dynamiques typiques d'un moteur pas à pas
15. Qu'est-ce que la gamme de balayage?
16. Qu'est-ce que le synchronisme dans le moteur pas à pas?
17. Dessinez le schéma de principe du système d'entraînement d'un moteur pas à pas.
18. Quel est l'angle de pas d'un moteur pas à pas à quatre phases avec 12 dents de stator et 3 dents de rotor?
19. Un moteur VR triphasé à pile unique a un angle de pas de 15 °. Trouvez le nombre de ses pôles de rotor et de stator.

PARTIE - B

1. Expliquez la construction et les différents modes d'excitation du moteur pas à pas VR.
2. Expliquer la construction et les différents modes d'excitation du moteur pas à pas PM.
3. Expliquez la construction et le principe de fonctionnement du moteur pas à pas hybride.
4. Énoncer et expliquer les caractéristiques statiques et dynamiques d'un moteur pas à pas.
5. Expliquez en détail les différents types de circuits d'entraînement de puissance pour le moteur pas à pas.

1. Expliquez le mécanisme de production de couple dans le moteur pas à pas VR.
2. Dessinez deux circuits d'entraînement pour le moteur pas à pas.
CHAP3 MOTEUR À RELUCTANCE COMMUTÉE

PARTIE - A

1. Qu'est-ce qu'un moteur à réluctance commutée?
2. Quelles sont les différences essentielles entre un moteur pas à pas et un SRM?
3. Mentionnez quatre avantages du moteur à réluctance commutée.
4. Écrivez sur les inconvénients de SRM.
5. Mentionnez quelques applications de SRM.
6. Dessinez le schéma fonctionnel simple de SRM.
7. Quels sont les différents contrôleurs de puissance utilisés pour le contrôle de SRM?
8. Pourquoi le capteur de position du rotor est essentiel pour le fonctionnement du SRM?
9. Qu'entend-on par rapport énergétique?
10. Tracez la courbe \_ - i pour SRM.
11. Qu'est-ce que l'enroulement de phase?
12. Quel est l'angle de pas d'un 3, SRM ayant 12 pôles de stator 8 pôles de rotor, calculez également la fréquence de commutation à chaque phase et la vitesse de 6000 tr / min?

PARTIE - B

1. Expliquer la construction et le principe de fonctionnement du moteur à réluctance commutée.
2. Décrire les différents circuits du contrôleur de puissance applicables au moteur à réluctance commutée et expliquer le fonctionnement de n'importe quel schéma avec un schéma de circuit approprié.
3. Dessinez un diagramme schématique et expliquez le fonctionnement d'un convertisseur de vidage _C'utilisé pour le contrôle de SRM.
4. Dérivez l'équation de couple de SRM.
5. Dessinez et expliquez les caractéristiques générales couple-vitesse de SRM et discutez du type de stratégie de contrôle utilisé pour différentes régions de la courbe. Esquissez les formes d'onde de courant de phase typiques d'un fonctionnement à basse vitesse.
6. Décrire le type de hystérésis et le régulateur de courant de type PWM pour une phase d'un SRM.
CHAP4
MOTEURS DC AIMANT PERMANENT SANS BALAIS

PARTIE - A

1. Quels sont les avantages des entraînements de moteur à courant continu sans balais DC?
2. Quels sont les inconvénients des entraînements de moteur à courant continu sans balais DC?
3. Énumérez les divers matériaux d'aimants permanents.
4. Dessinez le circuit magnétique équivalent du moteur CC sans balais à aimant permanent à 2 pôles
5. Pourquoi un moteur PMBLDC est appelé un moteur à commutation électronique?
6. Écrivez le couple et l'équation emf du moteur brushless à onde carrée.
7. Mentionnez quelques applications du moteur PMBLDC.
8. Quelles sont les différences entre le commutateur mécanique et électronique?
9. Quelle est la différence entre le moteur à courant continu conventionnel et le moteur PMBLDC?
10. Quelles sont les classifications du moteur PMBLDC?
11. Quels sont les deux types de capteurs de position du rotor?
12. Quels sont les matériaux utilisés pour fabriquer la palette Hall IC?
13. Un moteur à courant continu à aimant permanent a un couple de calage de 1 Nm avec un courant de calage de 5A. Estimez qu'il n'y a pas de vitesse de charge en tr / min lorsqu'il est alimenté à partir d'une alimentation en tension continue de 28 V.

PARTIE - B

1. Esquissez la structure du contrôleur pour le moteur PMBLDC et expliquez les fonctions des différents blocs.
2. Expliquer le schéma de commande en boucle fermée d'un entraînement de moteur à courant continu sans balai à aimant permanent avec un diagramme schématique approprié.
3. Piloter les expressions pour la FEM et le couple d'un moteur PMBLDC.
5. 
6. Discutez de l'utilisation des capteurs à effet Hall pour la détection de position dans le moteur PMBLDC.
7. 
8. Esquissez les caractéristiques couple-vitesse d'un moteur PMBLDC.
CHAP5
MOTEUR SYNCHRONE À AIMANT PERMANENT

PARTIE - A

1. Qu'est-ce qu'un moteur synchrone à aimant permanent?
2. Quels sont les avantages et les inconvénients du PMSM?
3. Quelles sont les applications du PMSM?
4. Quels sont les différents types de PMSM?
5. Comparez l'excitation électromagnétique avec l'aimant permanent de PMSM.
6. Expliquez clairement les différences entre le moteur à réluctance synchrone et le PMSM.
7. Quelles sont les différences dans les caractéristiques de construction du moteur PMBLDC et du PMSM?
8. Écrivez l'équation emf de PMSM.
9. Qu'est-ce que la maîtrise de soi?
10. Qu'est-ce que le « mode pulsé »?
11. Qu'est-ce que la commutation de charge?
12. Un rotor PM triphasé, quadripolaire et sans balais possède 36 fentes de stator. Chaque enroulement de phase est composé de trois bobines par pôle avec 20 tours par bobine. La portée de la bobine est de sept fentes. Si la composante fondamentale du flux magnétique est de 1,8 Mwb. Calculez la FEM en phase de circuit ouvert (Eq) à 3000 tr / min.

PARTIE - B

1. Expliquez la construction et le fonctionnement de PMSM.
2. Expliquer en détail le principe de fonctionnement d'une machine synchrone PM à onde sinusoïdale. Dessinez son diagramme de phaseur et dérivez son équation de couple.
3. Dérivez l'équation emf de PMSM.
4. Écrivez sur la maîtrise de soi du PMSM.
5. Dérivez les expressions pour la puissance absorbée et le couple d'un PMSM. Expliquez comment ses caractéristiques de vitesse de couple sont obtenues. Expliquer en détail le contrôle vectoriel de m permanent.