UNIT V

PART –A:

1. **Synchronous machines with surface-mount magnets have very little difference between direct axis and quadrature axis inductances. Why? [April/May 2008]**

In synchronous machines with surface-mount magnets, as the magnets are on the rotor surface, and the shaft cross-section is circular, the sine wave motor is considered as a 'non-salient pole' synchronous machine. Hence there is very little difference between direct axis and quadrature axis inductance and they are considered as almost equal.

2. **What is the magnitude of stator current in PMSM to achieve demagnetization? [April/May 2008 April/May 2010]**

$$I = \frac{E_q}{X_s} \text{Amps}$$

which is many times greater than the normal continuous rating of the motor winding (or) the converter.

3. **What is meant by self control? [April/May 2010 Nov/Dec 2012 April 2017]**

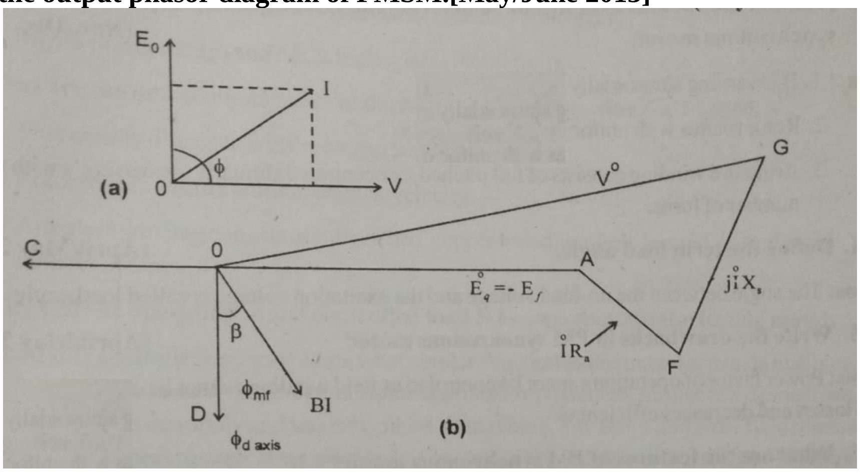
As the rotor speed changes the armature supply frequency is also a change proportionally so that the armature field always moves at the same speed as the motor. The armature and rotor field move in synchronism for all operating points. Here accurate tracking of speed by frequency is realized with the help of rotor position sensor.

4. **Define synchronous reactance in PMSM? [May/June 2013]**

It is the sum of armature leakage reactance and fictitious reactance.

$X_s = X_t + X_a$

5. **Draw the output phasor diagram of PMSM.[May/June 2013]**



6. **Write torque and EMF equation of PM synchronous motor. [Nov/Dec 2013]**

$$T = \left(\frac{3}{2}\right) I\sqrt{2} \frac{\pi r_1 l_1 B B_s}{2} \sin\beta N - m$$

$$E_{ph} = 4.44 f \phi_m T_{ph} \text{volts}$$

7. **Write the significance of power controllers of permanent magnet synchronous motors. [Nov/Dec 2013]**

The controller gets the signal from the rotor position sensor, reference speed signal and the signal from the output of power semiconductor circuit and then suitably turns on and off the concerned phase winding of SRM.

8. **What is load commutation? [Nov/Dec 2009 April/May 2010 Nov/Dec 2012]**

Commutation of thyristors by induced voltages of load is known as "load commutation". Here frequency of operation is higher and, it does not require commutation circuits. Load commutation is ensured only at high speeds, whereas at low speeds the emf generated is not sufficient for load commutation.

9. Briefly explain the vector control of PMSM. [Nov/Dec 2014]

The vector control technique is based on the reference frame transformation in which the armature mmf axis and field axis are made to be in quadrature in all operating conditions.

10. Define the term load angle. [April/May 2015]

The angle between the no-load voltage and the excitation voltage is called as the load angle.

11. Write the drawbacks in PMSM. [April/May 2015]

Power factor of operation cannot be controlled as field winding cannot be controlled. It leads to losses and decreases efficiency.

12. What are the features of PMSM?

1. Robust, compact and less weight.
2. No field current or rotor current
3. Copper loss.
4. High efficiency.

13. What are the advantages of load commutation?

1. It does not require commutation circuits.
2. Frequency of operation can be higher.
3. It can operate at power levels beyond the capability of forced commutation

14. What are the features of closed loop speed control of load commutated inverter fed synchronous motor drive?

1. Higher Efficiency
2. Four quadrant operation with regeneration breaking is possible.
3. Higher power ratings and run at high speeds (6000rpm).

15. Why PMSM operating in self controlled load is known as commutator less dc motor.

Load side controller performs some what similar function as commutator in a dc machine. The load side converter and synchronous motor combination functions similar to a dc machine. First, it is fed from a dc supply and secondly like a dc machine. The stator and rotor field remain stationary with respect to each other all speeds. Consequently, the drive consisting of load side converter and synchronous motor is known as ‘commutator less dc motor’ .

16. What is pulsed mode?

For speeds below 10% of base speed, the commutation of load side converter thyristors is done by forcing the current through the conducting thyristors to zero. This is realized by making source side converter to work as inverter each time load side converter thyristors are to be turned off. Since the frequency of operation of load side converter is very low compared to source frequency. Such an operation can be realized. The operation of inverter is termed as pulsed mode.

17. Differentiate the synchronous reluctance motor and PMSM.

Synchronous Reluctance Motor

1. Rotor has no permanent magnet
2. Less cost
3. Low efficiency

PMSM

1. Rotor has permanent magnet
2. High cost
3. High efficiency,

18. How are PMBLDC motor and PMSM different?

PMBLDC Motor

1. Rectangular distribution of magnetic flux in the air gap.
2. Rectangular current waveform.
3. Concentrated stator winding.

PMSM Motor

1. Sinusoidal or quasi-sinusoidal distribution of magnetic flux in the air gap.
2. Sinusoidal or quasi-sinusoidal current waveforms.
3. Quasi-sinusoidal distribution of stator conductors.

19. State the two classifications of PMSM and the types in each.

1. Sinusoidal PMSM
2. Trapezoidal PMSM

20. Differentiate between self-control and vector control of PMSM.

Self-Control:

1. Dynamic performance is poor. 2. Control circuit is simple.

Vector Control:

1. Better performance. 2. Control circuit is complex.

21. What is brushless a.c. motor?

The sinusoidal current fed motor, which has distributed winding on the stator inducing sinusoidal voltage is known as brush less a.c. motor. It is used in high power drives. The brushless a.c. motor is also known as PMSM.

22. What are the types of PMSM?[Nov 2016]

1. General classification
(i) Surface mounted motor
(ii) Interior motor.
The surface mounted motor is further classified as: (i) Projected type. (ii) Insert type
2. Based on rotor classification. (i) Peripheral (ii) Interior (iii) Claw-pole (iv) Transverse

23. When does a PM synchronous motor operate as a synchronous reluctance motor.

If the cage winding is induced in the rotor and the magnets are left out or demagnetized, a PM synchronous reluctance motor operates as a synchronous reluctance motor.

24. State the power controllers for PMSM.

1. PWM inverter using power MOSFETS with mciroprocessor control.
2. PWM inverter using BJT’s with microprocessor control (upto 100KW) .

25. Write the advantages of optical sensors.

1. Quite suitable for sinusoidal type motor as it is a high resolution sensor.
2. The signal from the photodiode rises and falls quite abruptly and the sensor outputs are switched high or low so the switching points are well defined.

26. Write the disadvantages of optical sensors.

1. It requires a clean environment.
2. Provision of high resolution sensor adds the cost of the system.

27. Draw the torque-speed characteristics of PMSM. [Nov/Dec 2010]

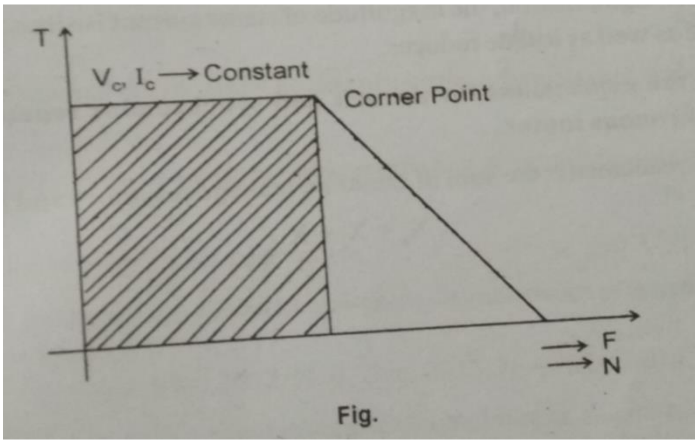


Fig.

28. **Define synchronous reluctance. [Nov/Dec 2010]**

The stator has a three phase symmetrical winding which creates a 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 and stator rotates at synchronous speed.

29. **Write the expressions for power input and torque of a permanent magnet synchronous motor. [April/May 2011]**

$$T = \frac{3EI\sin\beta}{\omega_m} N-m$$

$$\text{Power input} = 3V \times I$$
$$= 3\left(E_q + I_a Z_s\right) \cdot I_a$$
$$= 3\left(E_q I_a + I_a^2 R_a\right)$$
$$= 3E_q I_a + 3I_a^2 R_a$$

30. **What are the types of power controllers used for permanent magnet synchronous motor? [April/May 2011]**

1. Fuzzy logic controllers.
2. PI controller.

31. **What is the magnitude of stator current in PMSM to achieve demagnetization? [Nov/Dec 2009]**

To achieve demagnetization, the magnitude of stator current is sinusoidal distribution and current magnitude as well as torque reduces.

32. **What are the merits and demerits of PMSM?[May/June 2007 Apr/May 2015]**

Merits

i. It runs at constant speed.
ii. No field winding, no field loss, better efficiency.
iii. No sliding contacts. So it requires less maintenance.

Demerits

i. Power factor of operation cannot be controlled as field winding cannot be controlled.
ii. It leads to losses and decreases efficiency.

33. **What is meant by self control? Nov/Dec-12 & Apr/May-10**

As the rotor speed changes the armature supply frequency is also changes proportionally.So that the armature field always moves at the same speed as the motor. The armature and Rotor field move in synchronism for all operating points. Hence accurate tracking of speed.By frequency is realized with the help of RPS.

34. State the advantages of PMSM. **Apr/May-13**

1. Improved performance
2. Reliability increases.
3. Reduced components
4. Versatility of the controller.

35. What are the applications of PMSM. [Apr/May 2010 Nov/Dec 2011 May/June 2014]

1. Used as direct drive traction motor
2. Used as high speed and high power drives for compressors, blowers,conveyors,fans.

36. What are assumptions made in derivation of emf equation for PMSM? (Nov/Dec-14)

Assumptions

1. Flux density distribution in the air gap is sinusoidal.
2. Rotor rotates with an uniform angular velocity of wm (r/sec).
3. Armature winding consists of full pitched, concentrated similarly located coils of equal number of turns.

37. Why PMSM operating in self controlled mode is known commutator less dc motor? **Nov/Dec-13**

Load side controller performs some what similar function as commutator in a dCmachine. The load side converter and synchronous motor combination functions similarto a dc machine.

First, it is fed from a dc supply and secondly like a dc machine. The stator and rotor field remain stationary with respect to each other at all speeds. Consequentlydrive consisting of load side converter and synchronous motor is known as "Commutatorless dc motor".

38. Write the emf equation of PMSM. **(AU, Chennai/ME(PED)-May2008)**

$$E_{ph} = 4.44 f \phi_m K_{wl} T_{ph} \text{volts.}$$

This is the rms value of induced emf per phase. Where,
F – Frequency in hertz. T_{ph} – Turns per phase
ϕ **-** Flux per pole. K – Winding factor.

39. Explain the vector control of PMSM. **(Nov/Dec-14)**

PMSM are employed for variable speed applications. The process of controlling voltage and frequency to get the desired speed and torque is known as vector control of PMSM.

40.What are the types of magnets used in PM motors.[April 2017]

1.Alnico magnets
2.Cobalt-Samarium magnets
3.Barium and strontium ferrites.
4.Neodymium-Iron-Boron magnet

PART – B

1. **Explain the construction and operation of PMSM. (16)[Nov/Dec-14& Nov/Dec-13]**

(OR)

Enumerate the construction and performance of PMSM with suitable diagrams. [May/June 2007 April/May 2010 Nov/Dec 2014 April 2017]

(OR)

Discuss the different rotor configuration of PM synchronous machine. [Nov/Dec 2012]

CONSTRUCTIONAL FEATURES OF PERMANENT MAGNET SYNCHRONOUSMOTOR (OR) IDEAL SINE WAVE BLPM DC MOTOR

Constructional wise, the BLPM sinewave motor is similar to that of BLPM square wave motor. The armature windingand the shape of the permanent magnet areso designed that the flux densitydistribution of the airgap is sinusoidal (i.e..)the magnetic field set up by the permanentmagnet in the airgap is sinusoidal. Becauseof the presence of permanent magnet, inthis motor also, the slip rings and fieldwindings are absent. The cross-section ofpermanent magnet synchronous motor isshown in the Fig.

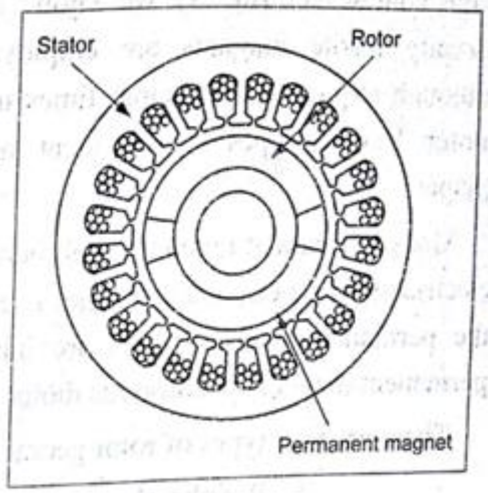


Fig. Permanent magnet svnchronous motor

The PM synchronous motor has stator and rotor

Stator

The stator which is the stationary member, houses the armature winding. Bymaking continuous strips of soft steel, the stator laminations for axial machines areformed. The thickness of the lamination depends upon the frequency of the armaturesource voltage. The cost is also a major constraint for selection of thickness. The yokeof the machine completes magnetic path.

A sinusoidal PMAC motor has distributed armature winding in the stator. Thearmature windings are generally double layer and lap wound. The individual coils areconnected together to form phasor groups. The phasor groups are connected togetherin series/parallel combinations to form star or delta connections and two phase orsignal phase windings.

The coils, phase groups and the phase must be insulated from each other in theend-turn regions and the required dielectric strength of the insulation will dependupon the voltage rating of the machine. In permanent magnet machine, the airgapplays a major role as the airgap length largely determines the operating point of thepermanent magnet in the no-load operating condition of the machine. Also longerairgaps reduce machine windage losses.

Rotor

The rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform. As we know, the rotor is made up of permanent magnet.Usually ferrite magnets are employed. Rare earth (cobalt-samarium) magnets,although expensive, are some times used to reduce the volume and weight of themotor. Various types of permanent magnets have been already studied in previouschapter.

Many permanent magnet synchronous machines may be physically cylindrical butelectrically the permanent magnet is equivalent to a salient pole structure. Actually,the permanent magnet poles are inherently salient type. Some of the rotors ofpermanent magnet synchronous motor have the magnets directly facing the airgap.

There are four types of rotor geometries in general. They are,

1. Peripheral 2. Interior
3. Claw-pole 4. Transverse

Peripheral type rotor

The peripheral type rotor of permanent magnet synchronous motor is shown in theFig. The permanent magnets are located on the rotor periphery. The flux pattemof permanent magnet is radial.

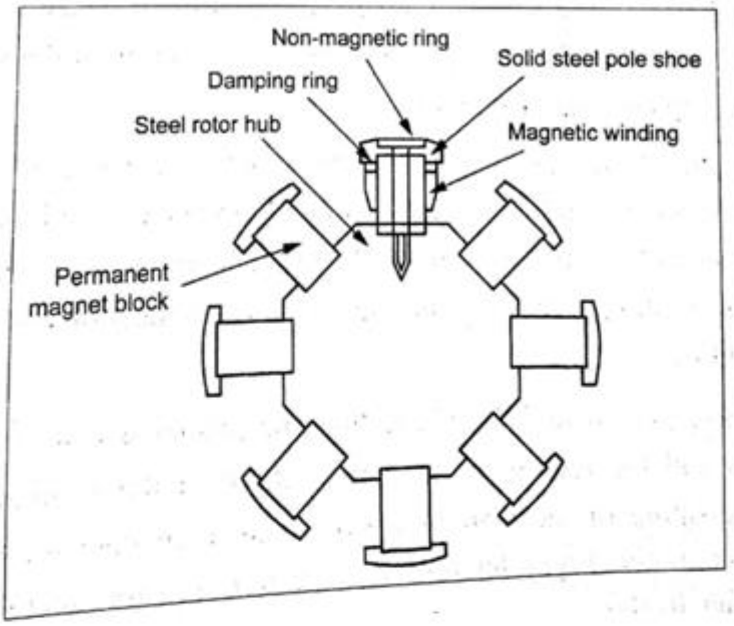


Fig. Peripheral type rotor

Interior type rotor

In this type, the permanent magnets are located in the interior of the rotor as shown in the Fig. The pattern of flux is generally radial.

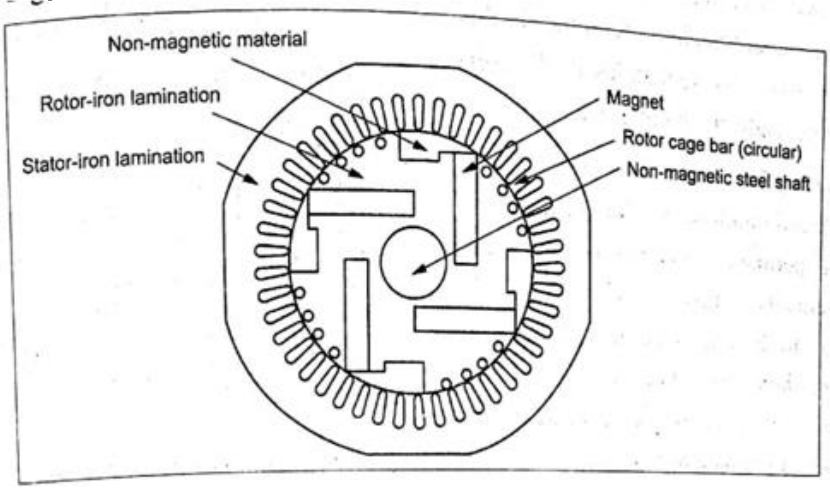


Fig. Interior type rotor

Interior type rotors are more robust but not easier to construct compared to peripheral type. They are suitable for high speed applications.

Claw-pole type rotor

The following Fig. shows the claw-pole type rotor configuration.

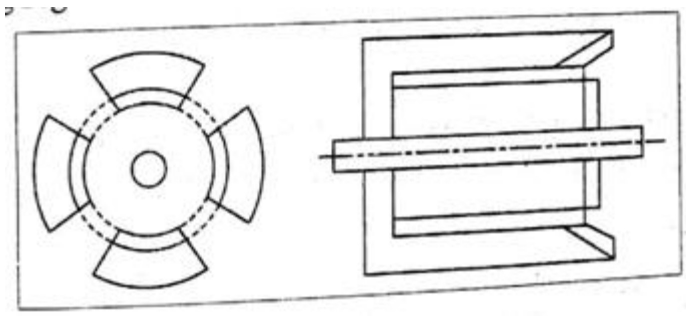


Fig. Claw-pole type rotor

The permanent magnets are generally disc-shaped and magnetized axially. The long, soft-extensions of the construction comes out axially from the periphery of the discs like ‘Claws’ or Lundell poles. Hence it is called as claw-pole type or Lundell type rotor. There is a set of equally-spaced alternate claws on each disc forming alternate north and south poles.

Transverse type rotor

The permanent magnet in the rotorare generally between soft-iron poles andthe flux pattern is circumferential. In thistype of rotor, the rectangles in the soft-iron poles indicate damper bars.
The Fig. shows the transverse typerotor configuration. As the permeabilityof the permanent magnet is very low,magnetically, this configuration issimilar to a reluctance machine rotor. Hence, there exist both the reluctancetorque as well as torque resulting fromthe flux of permanent magnet.

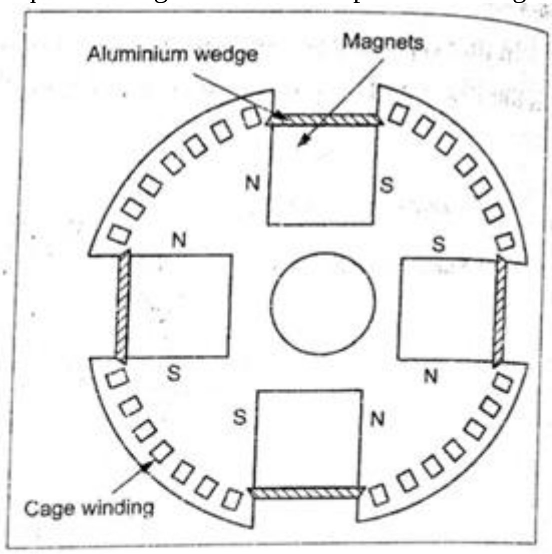


Fig. Transverse type rotor

2. Explain the principle of operation of a sine wave PM synchronous machine in detail. Draw its phasor diagram and derive its torque equation. [Nov/Dec 2007 Nov/Dec 2013]
(Note: For phasor diagram and torque equation refer below questions)

For a common 3-phase PM synchronous motor, a standard 3-phase power stage is used. So, the permanent magnet synchronous motor is fed directly from a three phase supply. When the armature winding draws a current, the current distribution within the stator armature winding depends upon the rotor position and the turning on process of the devices in the control circuit. The sinewave voltage output is to be applied to the 3-phase winding system in such a way that angle between the stator flux and the rotor flux is kept close to 90° to get the maximum generated torque. To meet this criterion, the motor requires electronic control for proper operation.

The armature supply frequency (armature is in stator, permanent magnet at the rotor) is changed in proportion to the rotor speed changes so that the stator field always moves at the same speed as the rotor. The rotor position sensor is required for accurate tracking of the speed in order to prevent the motor from pulling out of step and to avoid instability due to the change in torque or frequency. Sensors used with the brushless a.c motor are expensive compared to those required with brushless d.c. motor. Because of features like excellent dynamic performance and low torque ripple, the PMSM drive is widely used in high performance servo drives in spite of its high cost. For starting the large synchronous motor, the machine is operated in self-controlled mode.

3. Derive the EMF and Torque equation of PMSM. [Nov/Dec 2007 April/May 2010 May/June 2013 Nov/Dec 2013 Nov 2016 April 2017].
Derive the expression for torque developed in PMSM[April/May 2008 Nov/Dec 2012]

EMF Equation of BLPM Sinewave Motor

Now, let us determine the expression for the open-circuit phase emf due to the magnet. This emf equation of the permanent magnet synchronous motor can be derived by considering the emf induced in the elementary group of conductors. In the forthcoming derivation, the armature winding and shape of the permanent magnet are so designated that the flux density distribution of the airgap is sinusoidal.

The fig. depicts an ideal sinewave brushless motor with pure sine-distributed phase winding and permanent magnet rotor with sine-distributed flux.

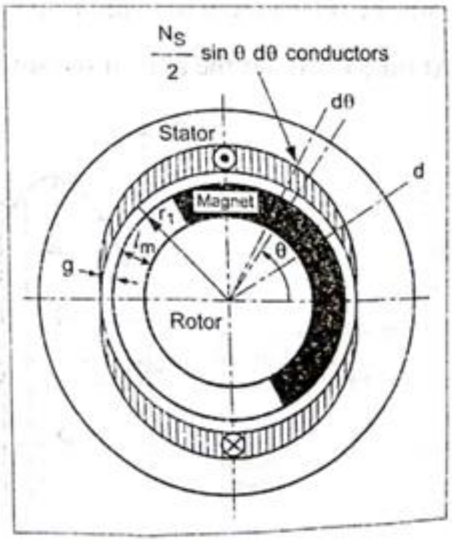


Fig.Ideal brushless sine wave motor with pure sine-distributed phase winding and permanent magnet rotor with sine-distributed flux.

As shown in the waveform of Fig., the magnetic field setup by the permanentmagnet in the airgap is sinusoidal.

Flux density distribution

The flux density can be expressed as B = B sin p θ or B cos p θ or B sin (p θ ±α)or B cos (pθ + α), where p = number of pole pairs depending upon the position of thereference axis

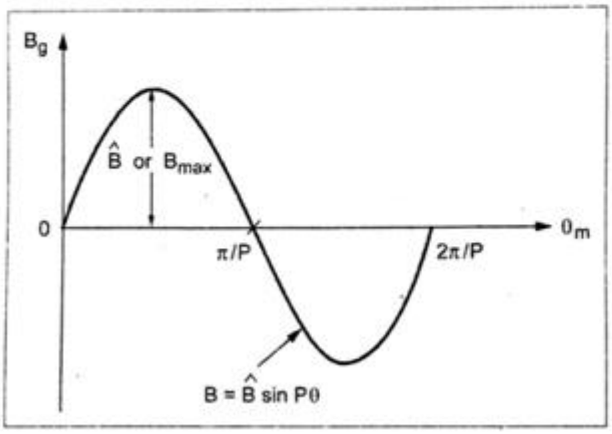


Fig. Flux density distribution

Now, consider a full pitched single turn armature coil as shown in the Fig.Letus rotor be revolving with a uniform angular velocity of$\omega_m$mec.rad/sec.

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

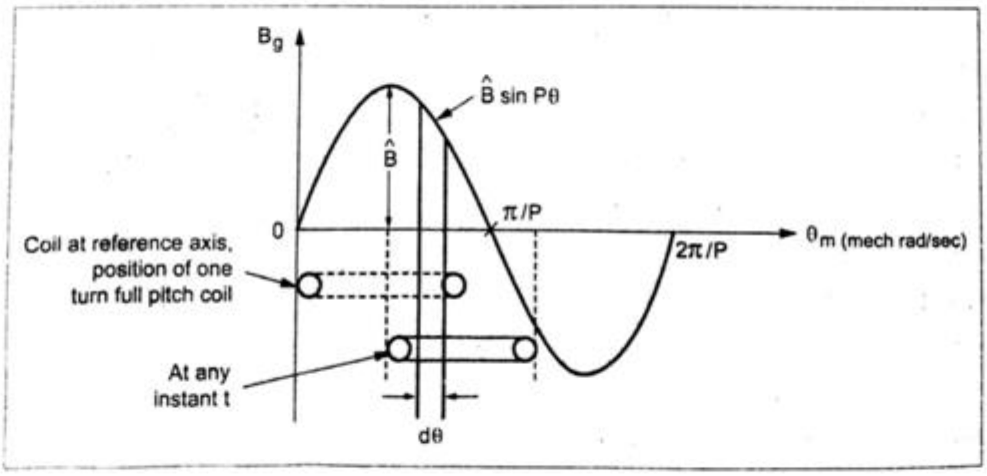


Fig. Flux density distribution of single turn armature coil of full pitched winding

Consider a small strip of$d\theta$ mech. radians at a position θ from the reference.

Flux density at the strip, $B = B\sin p\theta$ …1

Incremental flux in the strip $d\phi$ = B × area swept by the conductor

$$d\phi = B\sin p\theta \times lrd\theta$$

$$= Blrd\theta \text{webers} \quad ...3$$

Where l – length of the armature in m

r – radius of the armature in m

$$d\phi = \left(B\sin p\theta\right)lrd\theta$$

$$= Blr\sin p\theta \cdot d\theta \quad ...4$$

The flux enclosed by the coil after lapse of t sec is,

$$\phi = \int_{\omega_m t}^{\omega_m t+\pi/p} Blr\sin p\theta d\theta \qquad ...5$$

$$= Blr\left[-\frac{\cos p\theta}{p}\right]_{\omega_m t}^{\omega_m t+\pi/p}$$

$$= \frac{Blr}{p}\left[-\cos\left(p\omega_m t + \pi\right) + \cos p\omega_m t\right]$$

$$= \frac{Blr}{p}\left[2\cos p\omega_m t\right]$$

$$\phi = \frac{2Blr}{p}\cos p\omega_m t \qquad ...6$$

According to the Faradays law of electromagnetic induction, emf induced in the single turn coil is given by,

$$e = -N\frac{d\phi}{dt} \qquad ...7$$

$$= -\frac{d\phi}{dt} \text{as } N = 1$$

$$= -\frac{d}{dt}\left[\frac{2Blr}{p}\cos p\omega_m t\right]$$

$$= \frac{2Blr}{p} p\omega_m \sin p\omega_m t$$

$$e = 2Blr\omega_m \sin p\omega_m t \qquad ...8$$

Let the armature winding be such that all turns of the phase are concentrated fullpitched 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 emfs are equal and in phase.

$$e_{ph} = \left(2Blr\omega_m \sin p\omega_m t\right)T_{ph} \qquad ...9$$

$$= 2Blr\omega_m T_{ph} \sin p\omega_m t$$

$$= E_{ph} \sin p\omega_m t, \quad \text{where } p\omega_m = \omega_e$$

$$= E_{ph} \sin \omega_e t \qquad ...10$$

Where ω_e - Anular frequency in elec.rad/sec.

$$E_{ph} = 2BrlT_{ph}\omega_m \qquad ...11$$

Now, E_{ph}= rms value of the phase emf

$$= \frac{E_{ph}}{\sqrt{2}}$$

$$= \sqrt{2}BrlT_{ph}\omega_m$$

$$\therefore E_{ph} = \sqrt{2}BrlT_{ph}\omega_m \text{volts} \quad ...12$$

$$\text{Where, } \omega_m = \frac{\omega_e}{p} \qquad ...13$$

We know that, ϕ_m - sinusoidally distributed flux/pole.

$$\phi = B_{av}\tau l \qquad \dots 14$$

$$= B_{av} \times \frac{2\pi r}{2p} \times l \qquad ..15$$

$$\left.\begin{matrix}\text{The average value of flux} \\ \text{density for sinewave}\end{matrix}\right\} = \frac{2}{\pi} \text{ (normal value)} = \frac{2}{\pi}B \qquad \dots 16$$

The above equation is the practical emf equation of PMSM.

Hence, $K_{b1} < 1; \; K_{p1} < 1; \; K_{s1} < 1$

$$K_{w1} = K_{p1}K_{b1}K_{s1} < 1 \left(\text{winding factor}\right)$$

Thus the rms value of per phase emf is expressed as,

$$E_{ph} = 4.44f\phi_m T_{ph} K_{w1} \text{volts}$$

Torque Equation of an Ideal BLPM Sine wave motor

The emf equation of permanent magnet synchronous motor is studied in the previous section. Now, let us derive the torque equation.

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

$$A = A \sin P\theta$$

The flux density distribution set up by the rotor permanent magnet is also sinusoidal. Also, let us assume that the axis of armature ampere conductor distribution be displaced from the axis of the flux density distribution by an angle $\left(\frac{\pi}{2} - \alpha\right)$ as shown in Fig.

$$\text{Now, } B = B \sin\left[P\theta + \left(\frac{\pi}{2} - \alpha\right)\right]$$

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

$$= B \cos\left(P\theta - \alpha\right)$$

$B = B\cos(P\theta-\alpha) \qquad ...1$

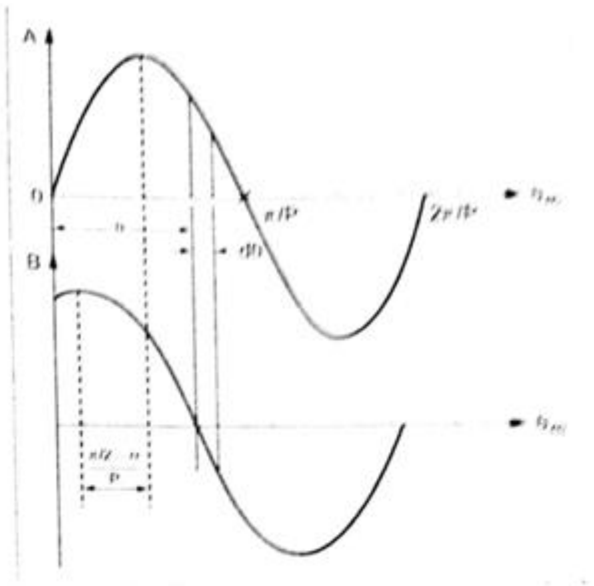


Fig. Ampere conductor and flux density distribution

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

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

Ampere conductors in the strip = Adθ

= A sin Pθ dθ …2

$$\left.\begin{array}{l}\text{Force experienced by the}\\ \text{armature conductors in the strip}\end{array}\right\} d\theta = BlAd\theta \qquad ...3$$

$$dF = B\cos(P\theta-\alpha)\,l\cdot A\sin P\theta\cdot d\theta \quad ...4$$

$$dF = ABl\sin P\theta\cos(P\theta-\alpha)d\theta$$

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

The torque experienced by the ampere conductors of the strip = dF× r …5

$$dT = ABrl\sin P\theta\cos(P\theta-\alpha)d\theta N-m \qquad ...6$$

Also, Torque experienced by the ampere conductors/pole $= T/\text{pole} = \int_{\theta=0}^{\theta=x/P} dT$

Hence, $T = \int_0^{\pi/p} ABrl\sin P\theta\cos(P\theta-\alpha)d\theta \quad ...7$

$$= \frac{ABrl}{2}\int_0^{\pi/p}\left(\sin\overline{P\theta+P\theta-\alpha}+\sin\alpha\right)d\theta$$

$$= \frac{ABrl}{2}\left[-\frac{\cos(2P\theta-\alpha)}{2P}+\theta\sin\alpha\right]_0^{\pi/p}$$

$$= \frac{ABrl}{2}\left[-\frac{\cos\alpha}{2P}+\frac{\cos\alpha}{2P}+\frac{\pi}{p}\sin\alpha\right]$$

$$T = \frac{ABrl}{2}\cdot\frac{\pi}{p}\sin\alpha N-m \quad ...8$$

The total torque experience by all armature conductors,

$= 2P\times \text{torque}/\text{pole}$

$$= 2P \times \frac{\pi}{p} \times \frac{ABrl}{2} \sin\alpha \qquad ...9$$

$$T = \pi ABrl \sin\alpha N - m \qquad ...10$$

As the armature conductors are located in stator of the BLPM SNW motor, the rotor experiences an equal and opposite torque.
The torque experienced by the rotor
= Torque developed by the rotor

$$= -\pi ABrl \sin\alpha$$

$$= -\pi ABrl \sin\beta \quad \text{where} \beta = -\alpha \qquad \ldots 11$$

$\beta$is known as power angle or torque angle.

$T = \pi ABrl \sin\beta$ is an ideal motor.

Now, consider the case of an armature winding which has three phases. Further the winding consists of short chorded coils and the coils of a phase group are distributed.
This 3ϕ armature winding carries a balanced 3ϕa.c. current which are sinusoidally varying. The phase windings are denoted as a, b, c.

The axes of phase winding are displaced by $\frac{2\pi}{3p}$ mechanical radians or $\frac{2\pi}{3}$ elec. radians. The current in the winding are also balanced. An armature winding is said to be balanced, if all the three phase windings are exactly identical in all respects but there axes are mutually displaced by $\frac{2\pi}{3p}$ 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°.

$$\left.\begin{aligned} i_a &= I_m \cos\omega t \ (\text{i.e.,}) \sqrt{2} I \cos\omega t \\ \text{Let, } I_b &= I_m \cos\left(\omega t - \frac{2\pi}{3}\right) = \sqrt{2} I \cos\left(\omega t - \frac{2\pi}{3}\right) \\ ic &= I_m \cos\left(\omega t + \frac{2\pi}{3}\right) = \sqrt{2} I \cos\left(\omega t + \frac{2\pi}{3}\right) \end{aligned}\right\} \qquad ...12$$

When the 3ϕa.c current passes through the 3ϕ balanced winding it sets up an armature mmf in the airgap. The space distribution of the fundamental component of armature ampere conductors is given by,

$$\left.\begin{aligned} f_a &= F_m \cos P\theta \\ f_b &= F_m \cos\left(P\theta - \frac{2\pi}{3}\right) \\ f_c &= F_m \cos\left(P\theta - \frac{4\pi}{3}\right) \end{aligned}\right\} \qquad ...13$$

Torque developed in a practical BLPM SNW motor

1. It is known that the ampere turn distribution of a phase winding consisting of full pitched coil is rectangular of amplitude iT_{ph}. But the fundamental component of this distribution is $4/\pi i T_{ph}$
2. 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 K_{s1} K_{p1} K_{d1}.

Here, K_{s1} = Skew factor

$$= \frac{\sin\sigma/2}{\sigma/2}; \qquad \sigma - \text{skew angle in elec. rad.}$$

$$K_{\rho 1} = \sin\frac{m\pi}{2}; \qquad m\pi - \text{coil span in elec. rad}$$

K_d = Distributor factor

$$= \frac{\sin q\, v/2}{q \sin v/2}$$

v = Slot angle in elec. rad

q = Slot per pole for 60° phase spread

$$K_{w1} = K_{s1}K_{p1}K_{d1} < 1$$

The fundamental component of ampere turns per phase of a practical case is written as,

$$= \frac{4}{\pi} i T_{ph} K_{w1} \qquad ...16$$

3. when a balanced sinusoidally varying 3 phase a.c current passes through a balanced 3 phase winding it can be shown that the total sinusoidally distributed ampere turns is equal to $\frac{3}{2} \cdot \frac{4}{\pi} I_{max} K_{w1} T_{ph}$

$$= \frac{4}{\pi} \cdot \frac{3}{2} \sqrt{2} I_{ph} K_{w1} T_{ph} \qquad ...17$$

4. The amplitude of the ampere conductor density distribution is shown as equal to the total sinusoidally distributed ampere turns divided by2.

$$\therefore \overline{A} \text{ in a practical 3 } \phi \text{ motor } = \frac{\frac{4}{\pi} \cdot \frac{3}{2} \sqrt{2} I_{ph} K_{w1} T_{ph}}{2} \qquad \ldots 18$$

Electromagnetic torque developed in a practical BLPM SNW motor

$$= \pi A B r l \sin\beta$$

$$= \pi \left[\frac{3\sqrt{2}}{\pi} I_{ph} K_{w1} T_{ph} \right] B r l \sin\beta$$

$$= 3\left(\sqrt{2} K_{w1} T_{ph} B r l\right) I_{ph} \sin\beta$$

$$= 3 \frac{E_{ph}}{\omega_m} I_{ph} \sin\beta \quad \ldots 19$$

4. Write about Self control of PMSM.

SELF CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Another method for controlling the speed of BLPM SNW motor is the self-control. In this method, the speed of permanent-magnet synchronous motor is controlled byfeedingthem from variable frequency voltage/currents. The rotor position sensors areemployed for operation in self-control mode. Alternatively, induced voltage can beused to achieve self-control.

The schematic diagram of self-control is shown in the Fig.The mainadvantage of the self-control is it ensures that for all operating points the armatureand rotor fields move exactly at the same speed. It is expected that the armature androtor field move in synchronous for all operating points.

When there is a change in rotor speed, proportionally the armature supplyfrequency also changes so that the armature field always moves at the same speed asthe rotor. With the help of rotor position sensor, the accurate tracking of speedisrealized by the armature supply frequency.

In the Fig., when the rotor rotates into certain predetermined angle, the firingpulses to the converter [rectifier-inverter] are varied. This firing of switches isproportional to the speed of motor. The torque angle is varied electronically, so thereis an additional controllable parameter possessing greater control of the motorperformance by changing the firing pulses to the semiconductor switches of invertercircuit.

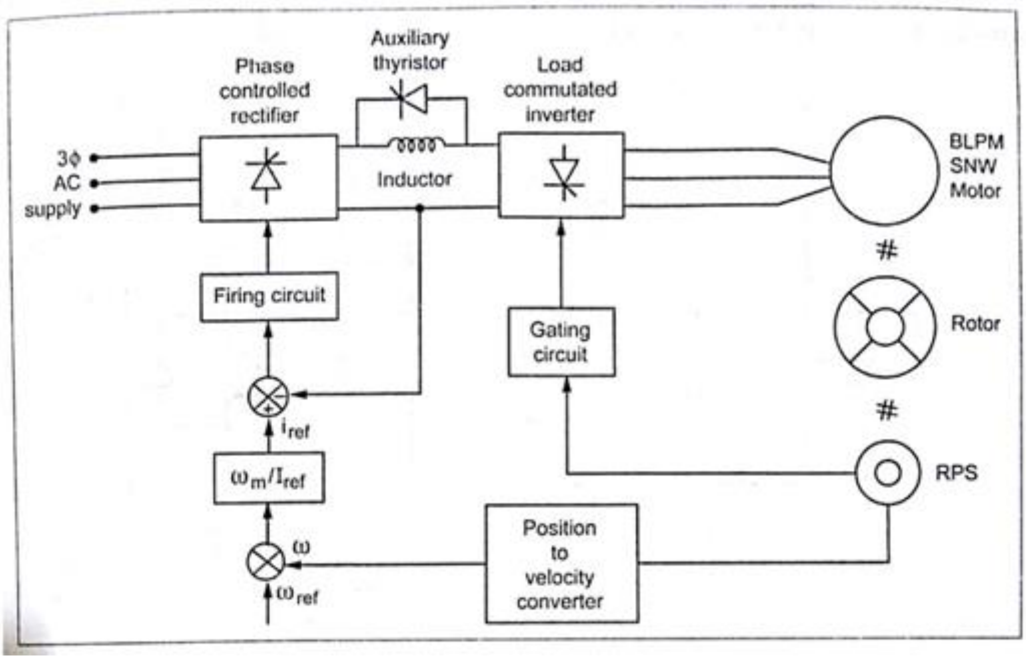


Fig.Self control of PASM motor

It is to be noted that at higher power levels, the current fed d.c. link converter isemployed. During the commutation at low speed, the d.c. link current is pulsed byphase shifting the gate signal of the supply side converter from rectification toinversion and back again.

When the current is zero, the motor side converter is switched on to a newconduction period and supply side converter is then turned on. The time required forthe motor current to fall to zero can be significantly shortened by placing a shuntthyristor in parallel with a d.c. link inductor. If the current zero is needed; the lineside converter is phased back to inversion and the auxiliary thyristor is gated. The d.c.link inductor is then short circuited and without affecting the motor, the current canbe supplied.

The auxiliary thyristor is immediately blocked when the line side converterturned on. This method of motor current interruption reduces the effects of pulsatingtorque.

5. Discuss the various power controllers used in PMSM. [Apr/May 2015]

POWER CONTROLLERS (OR) CLOSED LOOP CONTROLLER

The schematic diagram of Fig. shows the power controller for PMSMdrive. The main functions required are speed control and torque control.

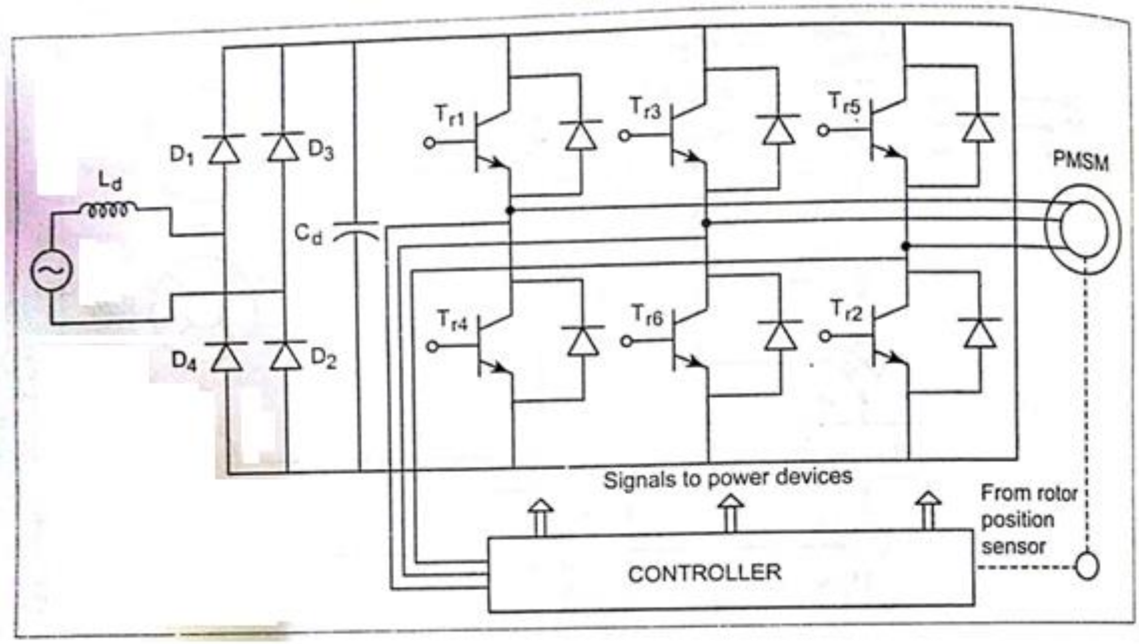


Fig. Power controller for permanent magnet synchronous motor

The permanent magnet synchronous motor rotates due to the torque produced bytwo interacting magnetic fields. On one hand, there is a magnetic field from the permanent magnets mounted in the rotor. On the other hand, there is a magnetic fieldgenerated by the coils of the stator.

For a common 3-phase PM synchronous motor, a standard 3-phase power stage isused. So, the permanent magnet synchronous motor is fed directly from a three phasesupply. When the armature winding draws a current, the current distribution withinthe stator armature winding depends upon the rotor position and the turning on process of the devices in the control circuit. The sinewave voltage output isapplied to the 3-phase winding system in a way that angle between the stator fluxthe rotor flux is kept close to 90° to get the maximum generated torque. To meet this criterion, the motor requires electronic control for proper operation.

Thearmature supply frequency (armature is in stator, permanent magnet at therotor) is changed in proportion to the changes in rotor speed so that the stator fieldalways moves at the same speed as the rotor. The rotor position sensor is requiredfor accurate tracking of the speed in order to prevent the motor from pulling out of stepand to avoid instability due to the change in torque or frequency.

The torque is related with the d-axis & q-axis currents. In order to achieve the maximum torque/current ratio the d-axis current is set to zero during the constant torquecontrol so that the torque is proportional only to the q-axis current. Therefore,this results in the control of q-axis current for regulating the torque in rotor referenceframe. The total drive system looks similar to that of BLDC motor and consists ofPMSM, power electronic devices, converter, sensors & controller.

With sinusoidally excited stator, the rotor design of the PMSM becomes moreflexible than the BLDC motor. If the motor windings are star connected without aneutral connection, 3-phase currents can flow through the inverter at any moment.

The PWMcurrent control isstill used to regulate the actual machine current.Either a hysteresis current controller, a PI controller with sinusoidal triangle or an SVPWM strategy is employed for this purpose. Unlike the BLDC motor, the 3switches are switched at any time.

6. Explain in detail the vector control of permanent magnet synchronous motor. [Nov/Dec 2012]

VECTOR CONTROL OF BLPM SNW MOTOR

As we know, the permanent magnet synchronous [BLPM SNW] motor has permanent magnets in rotor instead of a field winding. Hence, the field control is notpossible. So, in vector control.v/f ratio is kept constant so that both v, f are varied toget the desired speed and torque. Now, let us consider the two cases of followingFig. whose armature conductor currents and airgap flux are shown. In theFig.(a) the flux axis is in quadrature with the armature mmf axis. Each and everyconductor experiences a force which produces the torque. This torque contributed byvarious armature conductors have the same direction though there is a presence ofvariation in magnitude.

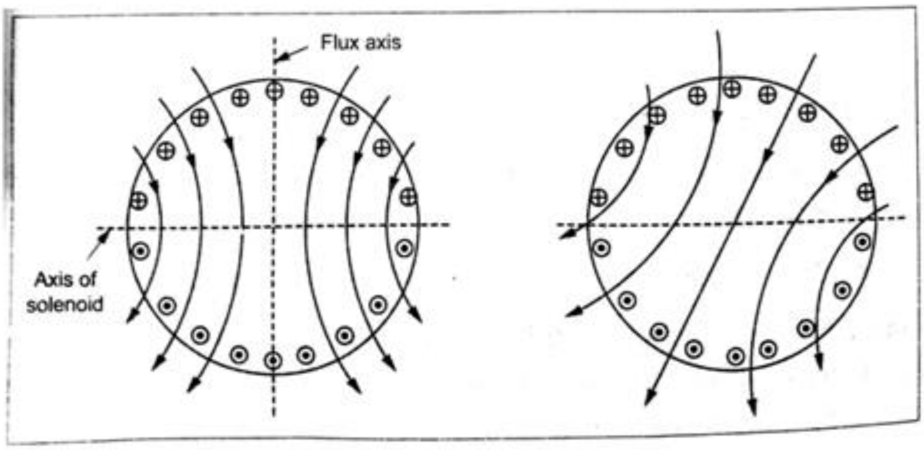


Fig. (a) Quadrature position of airgapflux and armature mmfaxis Fig.(b) Non-quadrature position of airgap fluxand armature mmf axis

Now, consider a case in which the angle between the axis of the airgap flux andthe armature mmf axis is 90° elect. and the armature conductor current distributionand airgap flux distribution are as shown in Fig. (b). In this case also, a torque isexperienced but the directions of the torque experienced by the conductors is not thesame. Consequently, the resultant torque gets reduced. It is realized that both thesteady state and dynamic performance of the machine in the case (b) is poorer thanthe case (a).

It is understood that the armature mmf axis and the axis of permanent magnet areshould be in quadrature for permanent magnet synchronous motor during alloperating conditions in order to have better steady state and dynamic performance.

The schematic diagram for vector control is shown in Fig.As the speed isvaried from a low value upto the corner frequency, the desired operating point ofcurrent is such that $I_d = 0$ and the current is along the q-axis.

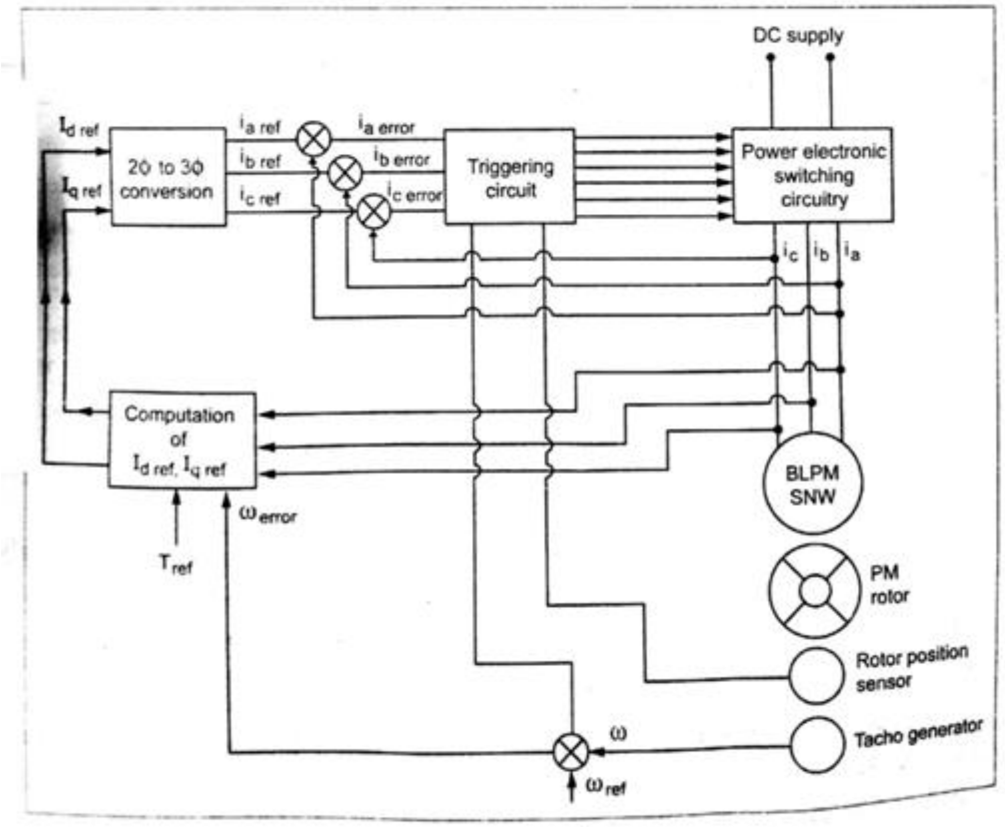


Fig. Vector control of PMSM motor

This condition can be obtained by controlling the voltage by PWM technique afteradjusting the frequency to a desired value. If the frequency is more than the cornerfrequency, it is impossible to make $I_d = 0$ because of voltage constraints. During suchconditions, after satisfying the voltage constraints a better operating point for currentcan be obtained with minimum value of I_d.

It is possible to set the values of $I_{d(ref)}$ and $I_{q(ref)}$ for the required dynamic andsteady state performance by knowing the desired values of torque, speed and thevoltage to which the motor is subjected to. These reference values of I_d and I_q aretransformed into reference values of currents such as $i_{a(ref)}$, $i_{b(ref)}$, $i_{c(ref)}$. These phasecurrents are compared with the actual currents and the error values actuate thetriggering circuitry which is also controlled by the signals obtained from rotorposition sensor and speed signal. To control the torque and speed independently, thereis a need to control the magnitude and phase of the three currents i_a, i_b, i_c through afast inverter. This is accomplished by the power electronic switching circuitry.

7.Explain the speed-torque characteristics of permanent magnet synchronous motor. [April/May 2008 Nov/Dec 2014 Nov 2016]

TORQUE - SPEED CHARACTERISTICS OF PERMANENT MAGNETSYNCHRONOUS MOTOR

The phasor diagram of permanent magnet synchronous motor has been studied insection It was alsothestudied that the direct axis current sets up mmf alongaxis of the permanent magnet and the quadrature axis current sets up mmf along theaxis perpendicular to the permanent magnet axis. The phasor diagram and associatedvoltage equations are used to derive the control laws and predict the performance ofthe permanent magnet synchronous motor in closed analytical form.

At a given speed, E_q is fixed by the magnetic flux [where E_q is the back emf] andthe torque is proportional to the speed. This relationship is valid even at zero speed. The linear relationship between torque and current is an important feature. Itsimplifies the controller design and makes the dynamic performance more regular andpredictable.

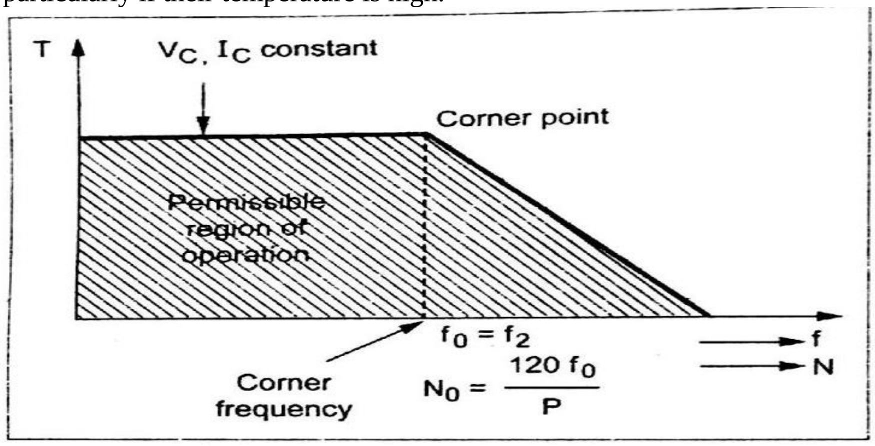
When the speed and frequency increase, the current limit locus remains fixed butthere comes a speed at which the radius of the voltage-limit locus begins to decrease.If PWM control is employed in the system under consideration, the PWM duty cyclereaches the maximum at the above said speed and the PWM control is sometimes saidto have saturated at this point. When the current reaches the rated value (I_C), theoperation along the quadrature axis is possible. The speed at which it happens iscalled the 'corner-point' speed. It is the maximum speed at which, rated torque can bedeveloped.

If the speed increases further, the radius of the voltage limit locus decreases.This decreasing radius of the voltage limit circle 'drags' the maximum currentphasor further and further ahead of the q-axis, consequently q-axis current decreasesand the d-axis current increases in negative or demagnetizing direction.

The above condition can be continued upto a stage (say point M) at which speed,the maximum current(I_c) can still be forced into the motor entirely in the d-axis. It isto be noted that no torque is developed as torque is proportional to the q-axis current.

If the speed is increased beyond the above said point M, there is a risk of overcurrent because the back emfE_q continues to increase while the terminal voltageremains constant. The current is then almost a pure reactive current flowing from themotor back to the supply. There is a small q-axis current and a small torque becauseof losses in the motor and in the converter. The power flow is thusreversed.

This mode of operation is possible only if the motor 'over runs' the converter or isdriven by an external load or prime mover. The reactive current is limited only by the synchronous reactance. As the speedincreases, it approaches the short circuit current,which may be many times larger than the normal current rating of the motor windings or the converter. This current may be sufficient to demagnetize the magnets particularly if their temperature is high.



Torque Speed Characteristics of PMSM

For a given maximum permissible voltage (V_c) and maximum permissible current (I_c), the maximum torque remains constant from a low frequency to corner frequency. Any further increase in frequency decreased the maximum torque. The shaded portion in the torque-speed characteristics represents the permissible region of operation in torque speed characterisics.

8. Write short notes on

i. Volt-ampere requirements in PMSM **[May/June 2013]**

CONVERTER VOLT-AMPERE REQUIREMENTS

The volt-amperes per watt of shaft power are sinewave values and represents thetotal apparent power at the motor terminals. Elsewhere the volt-amperes per watt hasbeen defined in terms of the volt-ampere product required in the ratings of thesemiconductor devices in the converter. The example calculations are all based on atwo-phase motor and it was assumed that each phase was supplied by a full bridgecircuit, requiring a total of eight transistors. The nominal converter volt-amperes,based on r.m.s. current in each device is the peak voltage times the number ofdevices, is thereforeThe same overall figure would result if a single full bridge was used to supply bothwindings connected in a center-tap arrangement. If a three-phase motor was used, theterminal volt-ampere requiremeconverter, the number of devices per phase is only two instead of four. Conseqjuentlythe total device volt-ampere requirement is only 6 VI.nts would be the same, but with a three-phase bridge

With a nominal a.c. apparent power requirement of about 1.1 VA/W, raised to perhaps 1.2 to allow for core losses and friction, the rough average requirement of both the hybrid and the surface-magnet motors can be reckoned as about 7.2 KVA/KW based on r.m.s. current, and about 10 KVA/KW based on peak current, assuming a three-phase motor.

A simple estimate of the converter 'rating' can be made in terms of the total KVA rating of its main switches, per KW of the power fed to the motor. The relevant parameters can be defined as follows.

With respect to the r.m.s. current in each switch, if 'q' is the phase number, then

$$\text{r.m.s} \quad \text{KVA/KW} = 2q \times I_S \times V_S \qquad \cdots 2$$

Where $I_S \rightarrow$ The r.m.s. current in each switch

and $V_S \rightarrow$ The peak voltage across each switch

In the sinewave motor, the line currents are assumed to be sinewaves and each switch conducts a half sinewave for 180° and is then off for 180°. The r.m.s. switch current is, hence $\frac{1}{\sqrt{2}}$ times the r.m.s. line current, which will be assumed to be the same as the phase current (Note that the motor is star connected). The peak device current is equal to the peak phase current.

The peak line-line voltage of the motor is,

$$V_l - l = V = \sqrt{3}\,\hat{V}_{ph} = \sqrt{6}\,V_{ph} \qquad \cdots 3$$

and

$$\text{r.m.s. switch} \quad VA = 6V \times \frac{I}{\sqrt{2}} \qquad \cdots 4$$

$$\text{Peak switch} \quad VA = 6V\,\hat{i} \qquad \cdots 5$$

$$\text{The converter power output} = 3V_{ph}I = 3\frac{V}{\sqrt{6}}\,I \qquad \cdots 6$$

9. Explain construction and phasor diagram of PMSM. **[April/May 2008 May/June-14 Nov 2016]**

PHASOR DIAGRAM OF A BRUSHLESS PM SNW OR BLPM SYNCHRONOUS MOTOR:

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

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 airgap which is sinusoidally distributed in space, having a number of poles equal to the poles of the rotor. It rotates in the airgap in the same direction as that of rotor and a speed equal to the speed of the rotor.

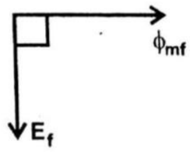
Rotor carries a permanent magnet. Its flux density is sine distributed. It also revolves in the airgap with a particular speed.

It is assumed that the motor acts as a balanced 3ϕ system. Therefore it is sufficient to draw the phaser diagram as shown in fig. 6.8 for only one phase. The armature winding circuit is influenced by the following emfs.

1. $\dot{V}$ – supply voltage per phase across each phase winding of the armature.

   The magnitude of this voltage depends upon dc voltage and switching techniques adopted.

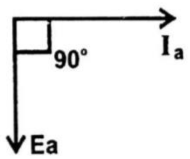
2. $\dot{E}f$ – emf induced in the armature winding per phase due to sinusoidally varying permanent magnetic field flux.



   Magnitude of $Ef = 4.44 f \phi_{mf} K_{w1} T_{ph} = |\dot{E}f|$ 1

   As per Faradays law of electromagnetic induction, this emf lags behind ϕ_{mf} – permanent magnet flux enclosed by armature phase winding by 90°.

3. $\dot{E}_a$ – emf induced in the armature phase winding due to the flux ϕ_a set up by resultant armature mmf $\phi_a \alpha I_a$



   $|E_a| = 4.44 f \phi_a K_{w1} T_{ph}$

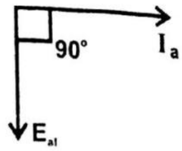
   $= 4.44 f (K I_a) K_{w1} T_{ph}$ 2

   $|E_a| = |I_a X_a|$ where $X_a = 4.44 f K K_{w1} T_{ph}$

   This lags behind ϕ_a by 90° or in other words E_a lags behind I_a by 90°.

   Therefore $\dot{E}a = -j X_a I_a$ 3

4. $\dot{E}_{al}$ – emf induced in the same armature winding due to armature leakage flux.



$$|\dot{E}_{al}| = 4.44\, f\, \phi_{al}\, K_{w1}\, T_{ph} \quad \ldots\ 4$$

ϕ_{al} is the leakage flux and is directly proportional to I_a. Therefore $|\dot{E}_{al}| = 4.44\, f\, (K_{al}\, |I_{al}|\, K_{w1}\, T_{ph})$

$$|\dot{E}_{al}| = I_a X_{al} \quad \ldots\ 5$$

where $X_{al} = 4.44\, f\, K_{al}\, K_{w1}\, T_{ph}$ in the leakage inductance. $\dot{E}_{al}$ lags behind ϕ_{al} or $\dot{I}_a$, by 90°

Therefore $E_{al} = -j\, \dot{I}_a X_{al}$ 6

Voltage equation:

The basic voltage equation of the armature circuit is

$$\dot{V} + \dot{E}f + \dot{E}_a + \dot{E}_{al} = \dot{I}_a R_a \quad \ldots\ 7$$

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

$$\dot{V} + \dot{E}f - j\, \dot{I}_a X_a - j\, \dot{I}_a X_{al} = \dot{I}_a R_a$$

$$\dot{V} + \dot{E}\, f - j\, \dot{I}_a (X_a + X_{al}) = \dot{I}_a R_a$$

$$\dot{V} + \dot{E}f - j\, I_a X_s = \dot{I}_a R_a \quad \ldots\ 8$$

where $X_s = X_a + X_{al}$ 9

X_s is known as synchronous reactance per phase or fictitious reactance.

$$\dot{V} = (-\dot{E}_f) + \dot{I}_a (R_a + j X_s)$$

$$\dot{\mathbf{V}} = \dot{\mathbf{E}}_{\mathbf{q}} + \dot{\mathbf{I}}_{\mathbf{a}} \mathbf{Z}_{\mathbf{s}} \quad \ldots\ 10$$

where Z_s is the synchronous impedance.

Let $\dot{E}_q$ be the reference phasor. Let it be represented by OA.

Let $\dot{I}$ be the current phasor. OB represents $\dot{I}$.

$\dot{E}_f$ be the emf induced in the armature winding by permanent magnet flux $= -\dot{E}_q$

OC represents $\dot{E}_f$

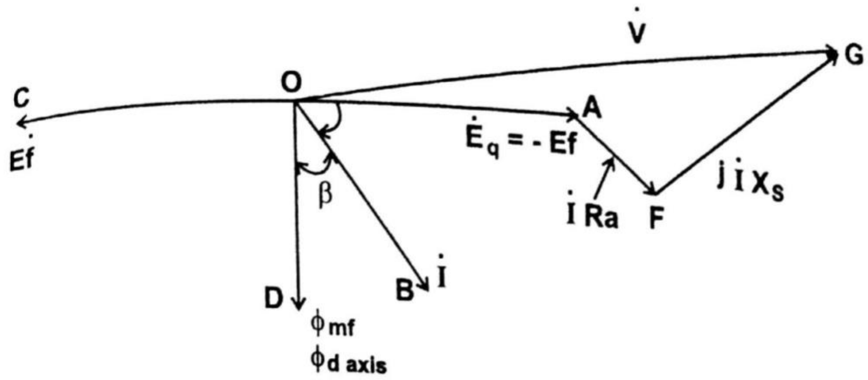


Fig. Phasor diagram of BLPM sine wave motor.

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

$\dot{E}f$ lags behind $\phi_{mf} = \phi_d$

AF represents $\dot{I}_a R_a$

FG represents $\dot{I}_a X_s$; FG is perpendicular to I phasor

OG represents $\dot{V}$

Angle between the $\dot{I}$ and $\dot{\phi}_{mf}$ is β the torque or power angle.

$$\text{Power input} = 3\,\dot{V} \cdot \dot{I} \quad \text{.... 11}$$

$$= 3\left[\dot{E}_q + \dot{I}\,R_a + j\,\dot{I}\,X_s\right] \cdot \dot{I}$$

$$= 3\,\dot{E}_q \cdot \dot{I} + 3I^2 R_a + O \quad \text{.... 12}$$

$3\,\dot{E}_q \cdot \dot{I}$ – electromagnetic power transferred as mechanical power.

$3\,I^2 R_a$ – copper loss.

$$\text{Mechanical power developed} = 3\,\dot{E}_q \cdot \dot{I} \quad \text{.... 13}$$

$$= 3\,|\,Eq\,|\,|\,I\,|\cos(90-\beta) \quad \text{.... 14}$$

$$= 3\,Eq\,I\sin\beta$$

$$= 3\,|\,E_f\,|\,I\sin\beta \quad \text{... 15}$$

The motor operates at N_s rpm (or) $\frac{120\,f}{2p}$ rpm.

Therefore electromagnetic torque developed $= \frac{60}{2\,\pi\,N_s} \times 3\,E_q\,I\sin\beta$

$$= \frac{P}{\omega_m}$$

$$= \frac{3\,E_q\,I\sin\beta}{\omega_m} \qquad \text{.... } 16$$

The same phasor diagram can be redrawn as shown in fig. with ϕ_d or ϕ_{mf} as the reference phasor.

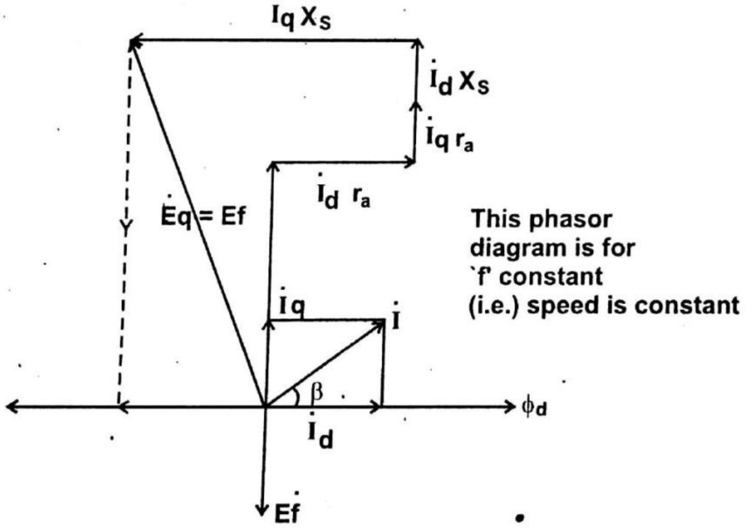


Fig. Phasor diagram of BLPM sine wave motor with ϕ_d or ϕ_{mf} as reference axis.

Further, the current $\dot{I}$ phasor is resolved into two components $\dot{I}_d$ and $\dot{I}_q$

$\dot{I}_d$ set up mmf along the direct axis (or axis of the permanent magnet).

$\dot{I}_q$ sets up mmf along quadrature axis (i.e.) axis perpendicular to the axis of permanent magnet.

$$\dot{V} = \dot{E}_q + \dot{I}r_a + j\,\dot{I}\,X_s \qquad \text{.... } 17$$

$$\dot{I} = \dot{I}_q + \dot{I}_d \qquad \text{.... } 18$$

Therefore $\dot{V} = \dot{E}_q + \dot{I}_d r_a + \dot{I}_q r_a + j\,\dot{I}_d X_s + j\,\dot{I}_q X_s$

$\dot{V}$ can be represented as a complex quantity.

$$\dot{V} = (V_{RP} + j\,V_{IP}) \quad \text{.... 19}$$

From the above drawn phasor.

$$\dot{V} = (I_d r_a - I_q X_s) + j\,(\,|\,E_q\,| + I_q r_a + I_d X_s) \quad \text{.... 20}$$

$\dot{I}$ can also be represented as a complex quantity

$$\dot{I} = I_d + j\,I_q$$

Power input $= \mathrm{Re}\,(3VI^*)$ $\qquad I^*$ – conjugate

$$= \mathrm{Re}\,[3\,((I_d r_a - I_q X_s) + j\,(E_q + I_q r_a + I_d X_s))\,((I_d - j\,I_q))] \quad \text{.... 21}$$

(i.e.,) Power input $= \mathrm{Re}\,[3\,[(I_d^2\, ra - I_d I_q X_s)$

$$+ (-j\,I_d I_q r_a + j\,I_q^2 X_s) + j\,(E_q I_d + I_q I_d r_a + I_d^2 X_s)$$

$$+ (E_q I_q + I_q^2 r_a + I_d I_q X_s)]$$

$$= 3\,(I_d^2 r_a - I_d I_q X_s) + 3\,(E_q I_q + I_q^2 r_a + I_d I_q X_s) \quad \text{.... 22}$$

$$= 3\,E_q I_q + 3\,(I_d^2 + I_q^2)\,r_a \quad \text{.... 23}$$

$$= 3\,E_q I_q + 3I^2 r_a \quad \text{... 24}$$

Electromagnetic power transferred $= 3\,E_q I_q$

$$= 3\,EI \sin\beta \quad \text{.... 25}$$

Torque developed

$$= \frac{60}{2\,\pi\,N_s} \cdot 3\,EI \sin\beta \quad \text{.... 26}$$

The electromagnetic torque developed $= \dfrac{3\,E_q I_q}{\omega_m}\ N-m$ 27

Note:

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

From eqn. **22**

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

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

Power input $= \mathrm{Re}\,3\,[(I_d r_a - I_q X_s) + j\,(E_q + I_d X_s + I_q r_a)\,(I_d - j\,I_q)$

$$= \mathrm{Re}\,3\,[((I_d r_a - I_q (X_d + X_q)) + j\,(E_q + I_d (X_d + X_q) + I_q r_a)\,(I_d - j\,I_q)]$$

$$= \mathrm{Re}\,3\,[I_d^2 r_a - I_q (X_d + X_q) I_d + E_q I_q + I_d I_q (X_d + X_q) + I_q^2 r_a]$$

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

Torque developed for a salient pole machine is given by

$$T = \frac{3P}{\omega_m}\left[\,E_q I_q + (X_d - X_q)\,I_d I_q\,\right] N - m \qquad \text{.... } \mathbf{28}$$

$\frac{3P}{\omega_m} E_q I_q$ – magnet alignment torque.

$\frac{3\,P}{\omega_m} (X_d - X_q)\,I_d I_q$ – reluctance torque.

In case of surface – magnet motors, the reluctance torque becomes zer(

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

$$\text{or } = \frac{3P}{\omega} E_q I_q\, N - m \qquad \text{.... } \mathbf{29}$$

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 magnet dc commutator motor.

phasor diagram shown in fig. 6.10.

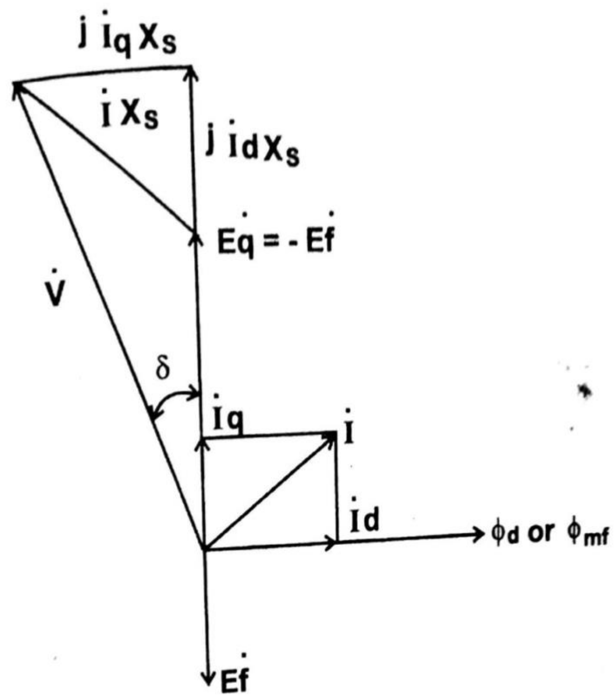


Fig. Phasor diagram neglecting the effect of resistance

Neglecting the effect of resistance, the basic voltage equation of BLPM SNW motor 30

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

As the effect of resistance is neglected.

$$\frac{\dot{V}}{j\,X_s} = \frac{\dot{E}_q}{j\,X_s} + \dot{I}$$

.... 31

$$\dot{I} = \frac{\dot{V} - \dot{E}_q}{j\,X_s}$$

For a particular frequency of operation the phasor diagram can be drawn as shown in fig.

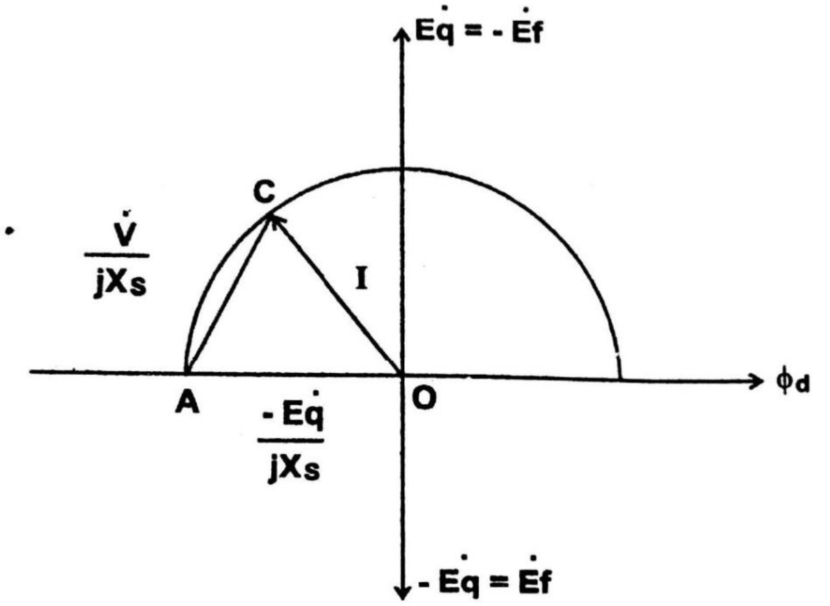


Fig. Phasor diagram for a particular frequency.

10. Discuss the
    i. Armature reaction in PMSM**[April/May 2015]**

ARMATURE REACTION

Figure shows the single phase, two pole sine distributed winding. The flux is now produced by the current in the stator winding and we assume that the magnet is unmagnetised while we calculate the inductance by determining the flux linkage of the winding due to its own current i. If the steel in the rotor and stator is assumed to be infinitely permeable, then the mmf is concentrated entirely across the two airgaps. Across each airgap the mmf drop is equal to one half of the ampere conductors enclosed within an "Ampere law contour" or flux line.

$$F_g = H_g g'' = \frac{1}{2}\int_{o}^{\pi/P-\theta} i\,\frac{N_s}{2}\sin P\theta\, d_\theta$$

$$= \frac{N_s i}{4}\int_{o}^{\pi/P-\theta}\sin P\theta\, d_\theta$$

$$= \frac{N_{si}}{4}\left[-\frac{\cos P\theta}{P}\right]_{o}^{\pi/P-\theta}$$

$$= \frac{N_{si}}{4}\cos P\theta \qquad .. \quad 1$$

The flux density across the gap and the magnet is assumed to be radial, and the magnet is assumed to be equivalent to an airgap of length lm/μ_{rec}. This gives on "effective airgap"

$$g'' = g' + lm/\mu_{rec} \qquad \dots \ 2$$

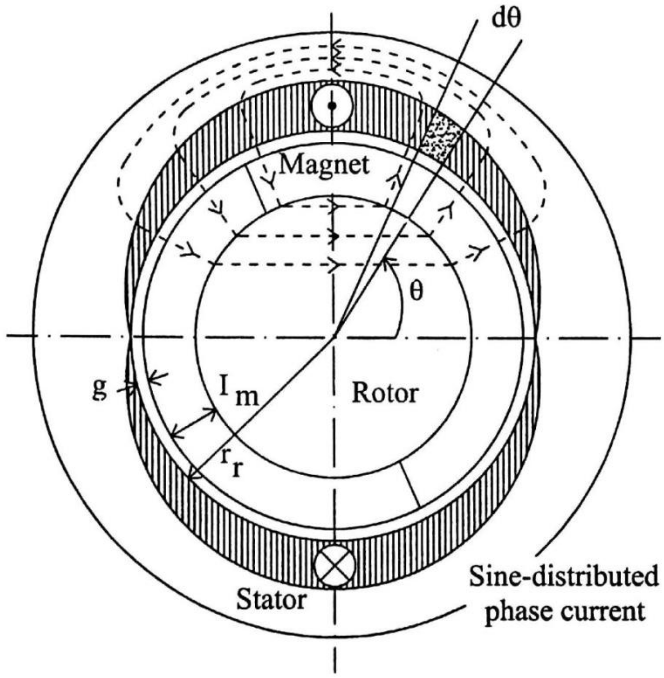


Figure calculation armature reaction m.m.f. of sinewave winding.

Hence

$$B(\theta) = \mu_o H_g$$

$$= \frac{\mu_o N_{si}}{2Pg''} \cos P\theta$$

$$= B_a(\max) \cos P\theta$$

$$= \hat{B}_a \cos P\theta \qquad \dots \ 3$$

The subscript 'a' has been added to the peak airgap flux density to denote that it is generated by armature current.

By integrating the flux density around the periphery of the airgap, the fundamental armature reaction flux per pole can be determined as

$$\phi_a = \frac{\hat{B}_a D i}{P} (\omega b) \qquad \ldots \; 4$$

Where D = 2r

r $\rightarrow$ radius of stator bore.

The above expression has exactly the same form as the flux per pole of the magnet and therefore is produces a flux linkage

$$\psi_a = \frac{\pi}{4} N_s \phi_a \qquad \ldots \; 5$$

The self inductance is obtained as the flux-linkage per ampere. with N_s turns in series per phase

$$L_g = \frac{\pi \mu_0 N_s^2 lr}{4P^2 g''} \text{ (H)} \qquad \ldots \; 6$$

The inductance is only half the value which would be obtained with the same number of turns concentrated into one pair of slots spanning 180 electrical degrees

The inductance calculated above is the actual 'airgap' inductance (ie) the value which would be measured with the rotor stationary and unmagnetised, with the other phases open circuited and with negligible leakage inductance from the slots or the end turns

ii. Synchronous reactance. **[Apr/May 2015]**

SYNCHROROUS REACTANCE FOR PMSM

In a PMSM, three sine distributed phase windings carry balanced 3ϕ sinusoidal currents. If produce a sine-distributed ampere conductor distribution represented by the expression.

$$\frac{3}{2} I \sqrt{2} \frac{N_S}{2} \sin(P\theta - \omega t)$$

This sets up a rotating flux wave

$$\hat{B}_a \sin(P\theta - \omega t)$$

Where

$$\hat{B}_a = \frac{\mu_o}{g''} \frac{3}{2} I \sqrt{2} \frac{N_S}{2P}$$

This rotating flux wave, established by armature reaction generates voltage in all the phase windings. In each phase the voltage is proportional to I and is therefore regarded as the voltage drop $X_s I$ across a fictitious reactance X_s. By substituting the peak flux density into the expression for emf dividing by I we get

$$X_s = \frac{3\pi\mu_0 N_s^2 l r_1 \omega}{\delta P^2 g''} \Omega$$

This expression applies to an ideal two-pole sine distributed 3ϕ winding with N_S turns in series per phase and it neglects the leakage inductance of the slot and N turns

11.Explain the microprocessor based control of PMSM. **[Nov/Dec 2007 May/June 2007 April/May 2008]**

MICROPROCESSOR BASED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

To meet the requirements of high demands on control accuracies, flexibility and ease of operation, the use of microprocessor based control has become imperative. As the microprocessor based control replaces the conventional hardware control, the control algorithms can easily be altered or improved without changing the hardware. The simplification of hardware, saves control electronics cost and improves the system reliability.

The schematic diagram for microprocessor based permanent magnet synchronous motor control is shown in the Fig.5.34. The permanent magnet synchronous motor is fed from a current source d.c. link converter system. The system consists of 3ϕ inverter–d.c. link – 3ϕ rectifier system in which the rectifier is fed from a three phase a.c. supply.

The machine has a stator which is fitted with a conventional three-phase winding and permanent magnets on the rotor. Motor operation is made self synchronous by the addition of a rotor position sensor that controls the firing signals for the solid-state inverter. In response to these firing signals, the inverter directs current through the stator phase windings in a controlled sequence. Nowadays, the self control has been the subject of increasing attention, as it ensures that the armature and the rotor fields move in synchronism for all operating points. The characteristics of the drive depends on the d.c. link current, field current, and the inverter firing angle. These variables are independently controlled by the microprocessor to provide the desired features for all operating conditions.

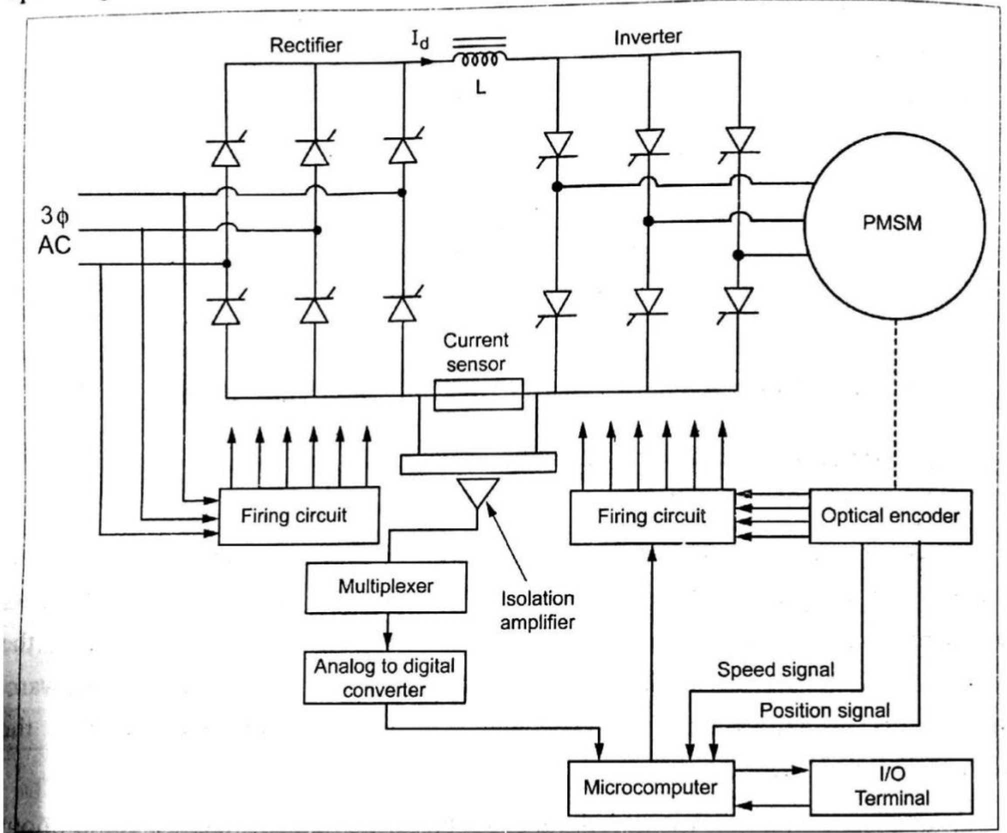


Fig. Micro processor based control of permanent magnet synchronous motor

In permanent magnet synchronous motor, the phase current is sinusoidal function of rotor position and an absolute encoder or resolver or other high resolution sensor is necessary to obtain position information with the required resolution. In this sinusoidal brushless motor, absolute rotor position information is required to atleast a 9 or 10 bit resolution. Sinusoidal reference current waveforms are generated with this precise position information. In the absolute optical encoder, an accurately patterned disk rotates between a light source, giving a unique digital output signal for every shaft position. Standard encoders are available with upto 16 bit resolution & with natural binary-gray code, or binary coded decimal output formats. However, each bit in the digital word represents an independent track on the encoder disk, resulting in a complex & costly sensor. Brushless resolver operation is based on inductive coupling between stator & rotor windings. The resolver with its resolver-to-digital (R/D) converter also gives precise absolute digital position information.

In the schematic diagram shown, the system employs optical encoder which is composed of a coded disk attached to the motor shaft and four optical sensors, thereby providing correlation between rotor speed and position signals. The inverter triggering pulses are synchronized to the rotor position signals with a delay angle determined by an 8 bit control input. During normal operation, the inverter SCRs are naturally commutated by the machine voltages. The programmable counter which is used for sensing the speed is fed with train of pulses having frequency proportional to the motor speed.

The microprocessor gets the system variable signals (like rotor position, speed. d.c. link current etc.) and the signal from input-output terminal, then accordingly issues control signals to the rectifier and inverter so as to get the desired motor performance.