MAILAM ENGINEERING COLLEGE

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(Approved by AICTE, New Delhi, Affiliated to Anna University Chennai & Accredited by TCS)

Department of Electrical & Electronics Engineering

SUB CODE / NAME: EE 6703 / SPECIAL ELECTRICAL MACHINES
YEAR / SEC : IV / A & B

SYLLABUS

UNIT I SYNCHRONOUS RELUCTANCE MOTORS

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

UNIT II STEPPER MOTORS

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

UNIT III SWITCHED RELUCTANCE MOTORS (SRM)

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

UNIT IV PERMANENT MAGNET BRUSHLESS D.C. MOTORS

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

UNIT V PERMANENT MAGNET SYNCHRONOUS MOTORS (PMSM)

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

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MAILAM ENGINEERING COLLEGE

Department of Electrical and Electronics Engineering

SUB CODE: EE 6703 SUB NAME: SPECIAL ELECTRICAL MACHINES

UNIT-01

SYNCHRONOUS RELUCTANCE MOTOR

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

PART-A

1. What is a synchronous reluctance motor or SYNREL? Dec-2013, 2010

- A reluctance motor that utilizes an ***ac rotating field***, which allows for the possibility of extremely smooth torque and good operation at low speeds.
- Magnets are left out of the rotor or they are ***demagnetized***.
- Rotor has ***salient poles, no field windings, no permanent magnets***.

2. What are the types of synchronous reluctance motor? Dec-2016, May-2010, 2013

Classify the different types of synchronous reluctance motor. Dec-2017

a. The main types are

1. Cage less
2. Line-start

b. According to the magnetization

1. Salient rotor
2. Radially laminated rotor
3. Axially laminated rotor

3. Mention some applications of synchronous reluctance motor.

May-2017, 2016, 2015, Dec-2017, 2016, 2012

The applications of synchronous reluctance motor are,

1. Fiber-spinning mills
2. Industrial process equipment
3. Metering pumps
4. Wrapping and folding machines

4. What are the advantages of increasing L_d/L_q ratio in synchronous reluctance motor?

The advantages of synchronous reluctance motor are,

1. Motor power factor increases.
2. I^2R losses reduced.
3. Reduced volt-ampere ratings of the inverter driving the machine.

5. What is reluctance torque is synchronous reluctance motor? **Dec-2016, 2011**

Define reluctance torque with reference to synchronous reluctance motor. **May-2018**

The torque exerted by the reluctance motor because of the tendency of the salient poles to align themselves in the ***minimum reluctance position***. This torque is called reluctance torque.

6. Compare synchronous reluctance motor and induction motor? **Dec-2017, 2015, 2010**

S. No.	Synchronous Reluctance Motor	Induction Motor
1	Better efficiency	Poor efficiency
2	High cost	Low cost
3	Low power factor	High power factor
4	Used for low and medium power applications.	Used for high power applications.

7. Write down the voltage and torque equation of synchronous reluctance motor?

May-2010, Dec-2014

The voltage equation is,

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

$$E_{ph} = \frac{\pi}{2\sqrt{2}}\ \frac{Bl\omega\, N_s}{p}$$

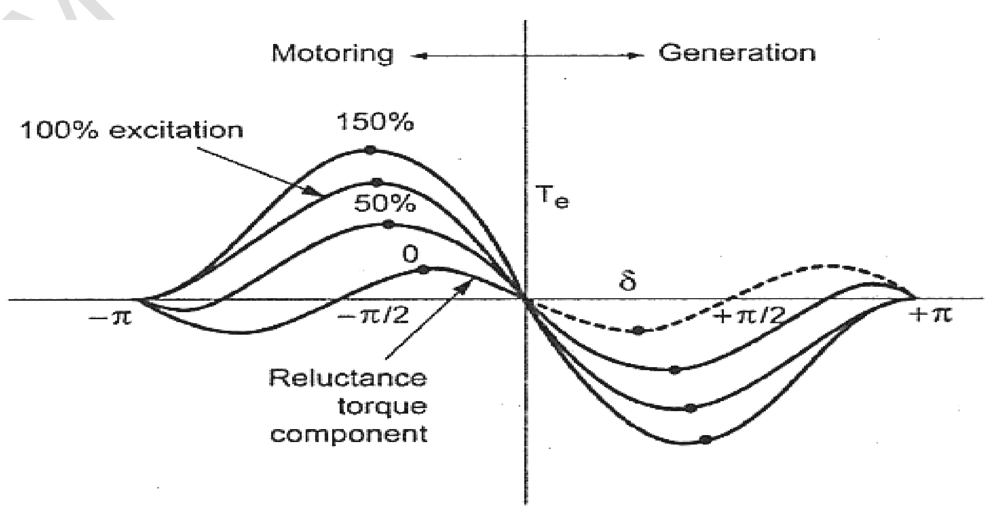
The torque equation is,

$$T = \frac{3\,V^2}{\omega_s}\left(\frac{X_{sd} - X_{sq}}{2\,X_{sd}\,X_{sq}}\right)\sin 2\delta$$

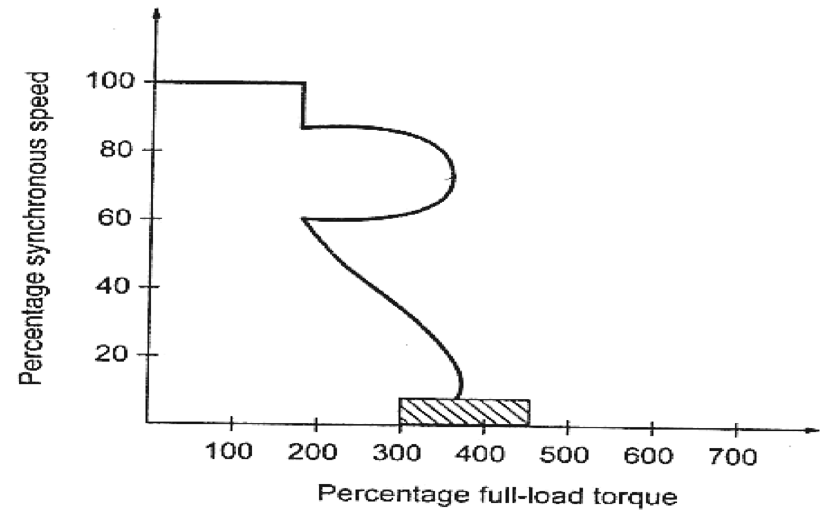
Where, V – supply voltage δ – load angle ω_s – synchronous speed

X_{sd} , X_{sq} – synchronous reactances of d and q axis

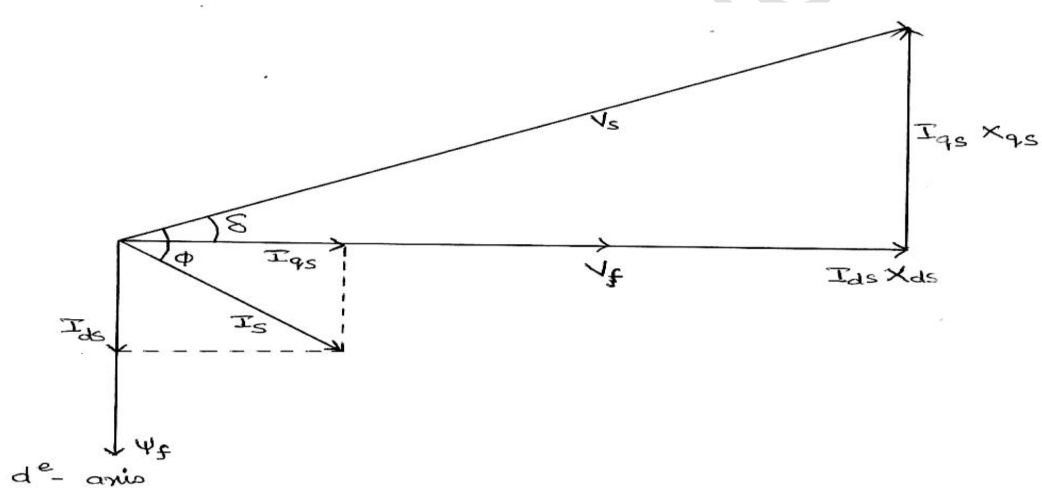
8. Draw the torque-angle characteristics of synchronous reluctance motor. May-2011



9. Draw the speed-torque characteristics of synchronous reluctance motor.



10. Draw the steady-state phasor diagram of synchronous reluctance motor.



11. Mention some advantages and disadvantages of synchronous reluctance Motor.

Mention any two advantages of synchronous reluctance motors. **May-2018**

Advantages:

1. There is ***no demagnetization***, hence synchronous reluctance.
2. There need be ***no excitation field at zero torque***, thus eliminating electromagnetic spinning losses.
3. Rotors can be constructed entirely from ***high strength, low-cost materials***.

Disadvantages:

1. Compared to induction motor it is ***slightly heavier*** and has ***low power factor***. But increasing the saliency ratio, the power factor can be improved.
2. ***High cost*** than induction motor.
3. ***Need speed synchronization*** to inverter output frequency by using rotor position sensor and sensor less control.

12. Write down any two properties of synchronous reluctance motor?

Properties of synchronous reluctance motor are,

1. High output power capability.
2. Ability of the rotor to withstand high speeds.
3. Negligible zero-torque spinning losses.
4. High reliability.
5. Lower torque ripple

13. What are the design considerations in synchronous reluctance motor? **Dec-2012**

Write the various design parameters of a synchronous reluctance motor. **Dec-2017**

The design considerations of synchronous reluctance motor are,

1. Power factor
2. Copper loss and core loss
3. Cost
4. Efficiency

14. Define Torque Angle.

In reluctance type synchronous motor, when the **load is increased** lightly, the ***rotor momentarily slows down***, causing the salient poles of the rotor to lag behind the rotating field. This angle of lag is called the torque angle.

15. What are the two types of stator current modes?

Types of stator current modes are,

1. Unipolar current mode.
2. Bipolar current mode.

16. Compare synchronous reluctance motor and Switched reluctance motor.

Dec-2016, 2010, May-2017, 2012, 2013

	Synchronous reluctance motor	Switched reluctance motor
1	Equal no. of stator and rotor poles.	It is a form of stepper motor that has lesser fewer poles.
2	Operate at pure ***sinusoidal*** voltage.	Optimal drive waveform is ***not a pure sinusoidal.***
3	The stator is cylindrical type with ***distributed*** winding.	The stator of SRM has salient poles with **concentrated coils** like a dc motor.
4	Used for ***low and medium power*** applications.	Used for ***high power applications***.
5	Speed control requires a variable - frequency drive.	Does not need any variable-frequency drive.
6	Excitation is a set of poly phase balanced sine wave currents.	Excitation is a sequence of current pulses applied to each phase.

17. Give the operating principle of radial flux motor. **May-2017, 2012**

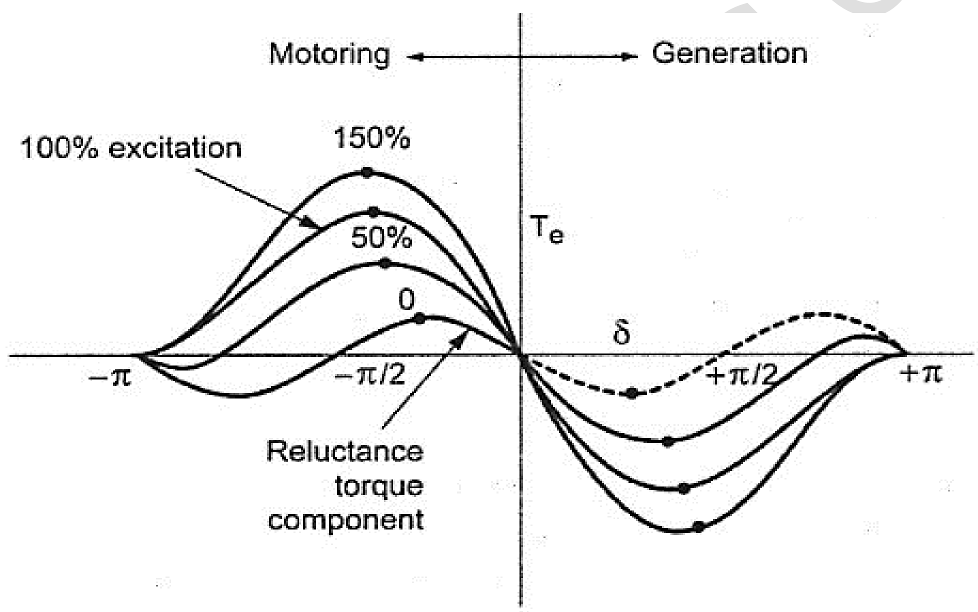
In radial flux motor, the magnets are alternately poled and radially magnetized, but because the magnet pole area is smaller than the pole area at the rotor surface, the air-gap flux density on open circuit is less than the flux density in the magnet; this design is essentially 'under excited' and relies on the addition of a magnetizing component of armature current to produce the total air gap flux.

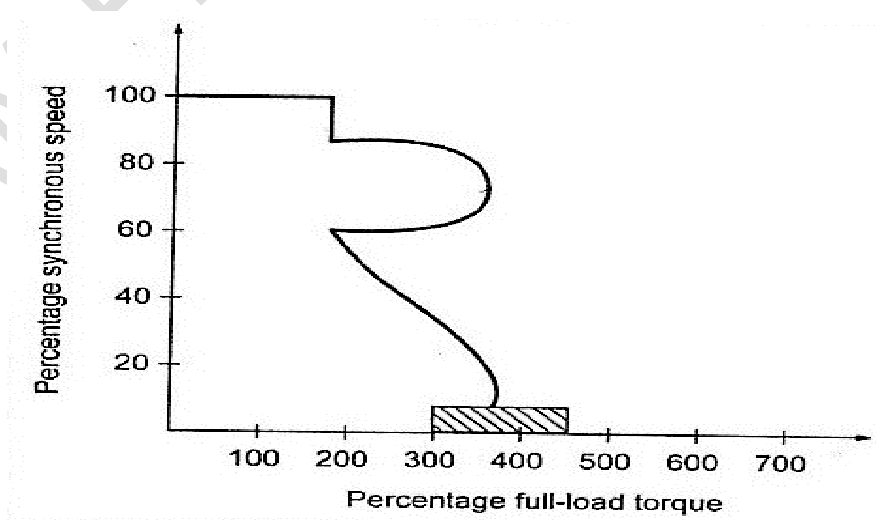
18. Write the different types of controllers used for synchronous reluctance motors. **Dec-2014**

Types of controllers for synchronous reluctance motor are,

- Maximum torque/ampere control
- Maximum power factor control
- Constant d-axis current control

19. Draw the voltage and torque characteristics of synchronous reluctance motor. **May-2016, 2015**





20. State the principle of operation of synchronous reluctance motors. **Dec-2015**

Whenever a piece of ***ferro-magnetic material*** is located in a magnetic field a ***force*** is exerted upon the material tending to align the material in a ***minimum reluctance position***. When stator winding is energized, reluctance torque is produced which starts the motor.

21. What are the types of rotor available in synchronous reluctance motor? **May-2017**

- Salient rotor (Segmental)
- Radially laminated rotor
- Axially laminated rotor

PART-B

Constructional features – Types – Axial and radial motors

1. Explain the constructional features of different types of synchronous reluctance motor.
Dec-2014, 2013, 2012, 2011, May-2013

Explain the construction and operation of axial and radial flux motors with neat diagram.
May-2016, 2015

Explain the construction of radial and axial flux machines. Discuss the advantages and disadvantages of each construction. **Dec-2016**

Explain in detail the operating principle and construction of synchronous reluctance motor with neat diagrams. **Dec-2016, 2015**

Explain with neat diagram, the construction, working principle and types of synchronous reluctance motor. **Dec-2016**

Discuss in detail the principle of operation and constructional features of different types of synchronous reluctance motor. **May-2017**

Discuss in detail about the construction and working of synchronous reluctance motor with neat diagrams. **Dec-2017**

Explain the constructional details and working principle of synchronous reluctance with neat diagrams. **May-2018**

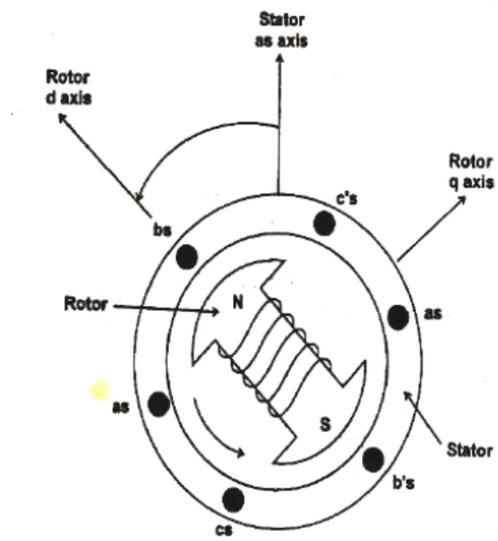
Properties:

- Combined reluctance and magnet alignment torque
- Field-weakening capability
- Under-excited operation
- High inductance
- High speed capability
- High temperature capability

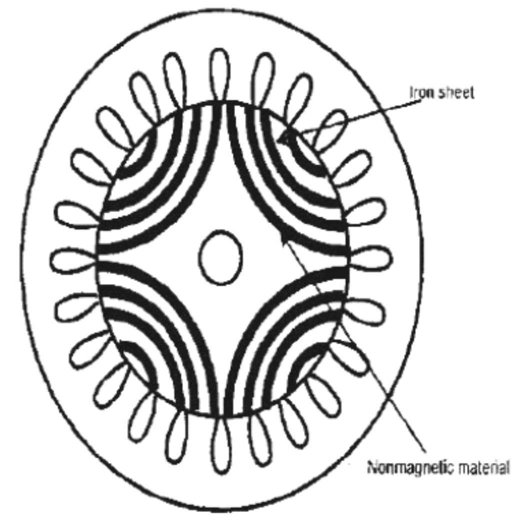
Construction:

- Derived from the 3-phase Synchronous machine.
- Does not have any field magnet.
- PM ac synchronous motor operates as synchronous reluctance motor if the magnets are removed from the rotor.
- Salient pole rotor.

- Two main parts
    - ✓ Stator
    - ✓ Rotor



a) Idalized 3 phase 2 pole synchronous machine



b) cross section of synchronous reluctance motor

Stator:

- Laminated iron core.
- Has smooth distributed poles.
- 3-phase symmetrical distributed winding.
- Similar to stator structure of 3-phase IM or 3-phase synchronous motor.
- Creates sinusoidal rotating magnetic field in the airgap.
- Due to reluctance torque, rotor aligns with stator poles in minimum reluctance position.
- Stator slots may be open or semi-closed uniformly distributed slots.

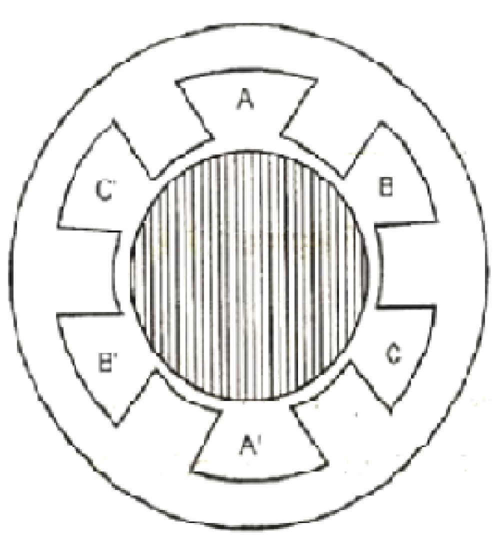


Fig. Open slot stator structure

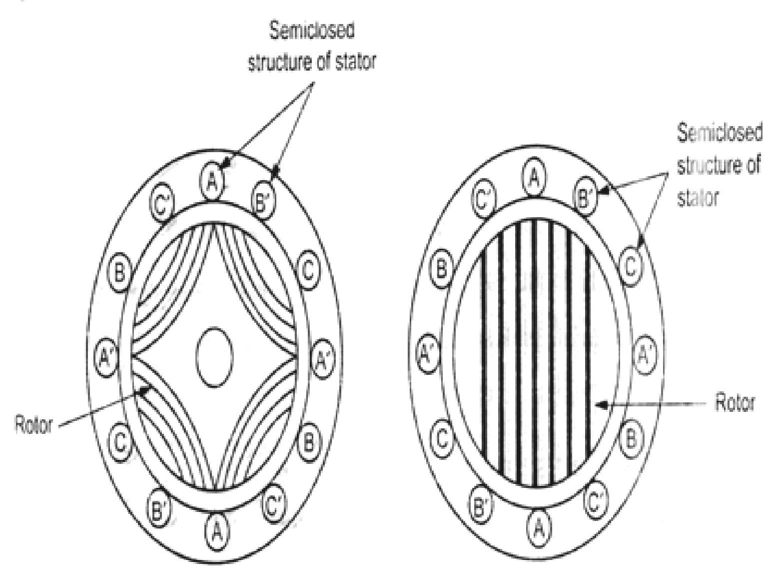


Fig. Semi closed stator structure

Rotor:

- Needs salient pole structure.
- Constructed such that armature inductance varies sinusoidally.
- Inductance is maximum along direct axis and minimum along quadrature axis.
- Consists of plurality of pair of slots.
- Slots may be outer or inner.
- Outer slots are formed at outer periphery.
- Inner slots are formed at inside of the rotor.
- Explosion bonding method is used for rotor construction.
- Rotor types:
  - Salient rotor (Segmental)
  - Radially laminated rotor
  - Axially laminated rotor

Salient type rotor (Segmental):

- Quadrature air-gap is much larger the direct air gap.
- The L_d/L_q ratio is in the range of 2 : 3.
- Circulating flux in the pole faces of rotor is high.
- Due to ruggedness and simplicity of the rotor structure, it is used for high speed applications.

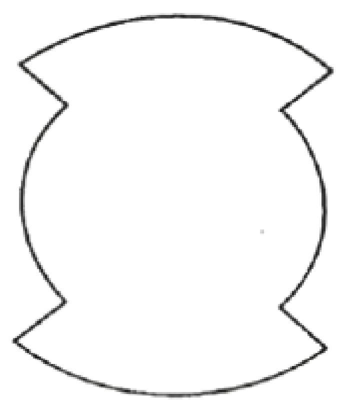


Fig. Salient type rotor

Radially laminated rotor:

- Laminations are single pieces.
- Construction is cheaper and easier
- Conventional circular laminations are used.
- Non magnetic flux barriers are introduced in the laminations.
- Narrow airgap channels are used in the places where flux barriers are to be introduced.
- Thin bridges are provided at both ends of airgap channels to hold the laminations together.
- Laminations are assembled in cylindrical shape.
- Assembled core is put in liquid aluminium bath under pressure.
- Aluminium fills up the air channels.
- In another construction, in addition to flux barriers, rotor laminations have slots on outer periphery.

Limitations:

- Poor choice for high speed design.

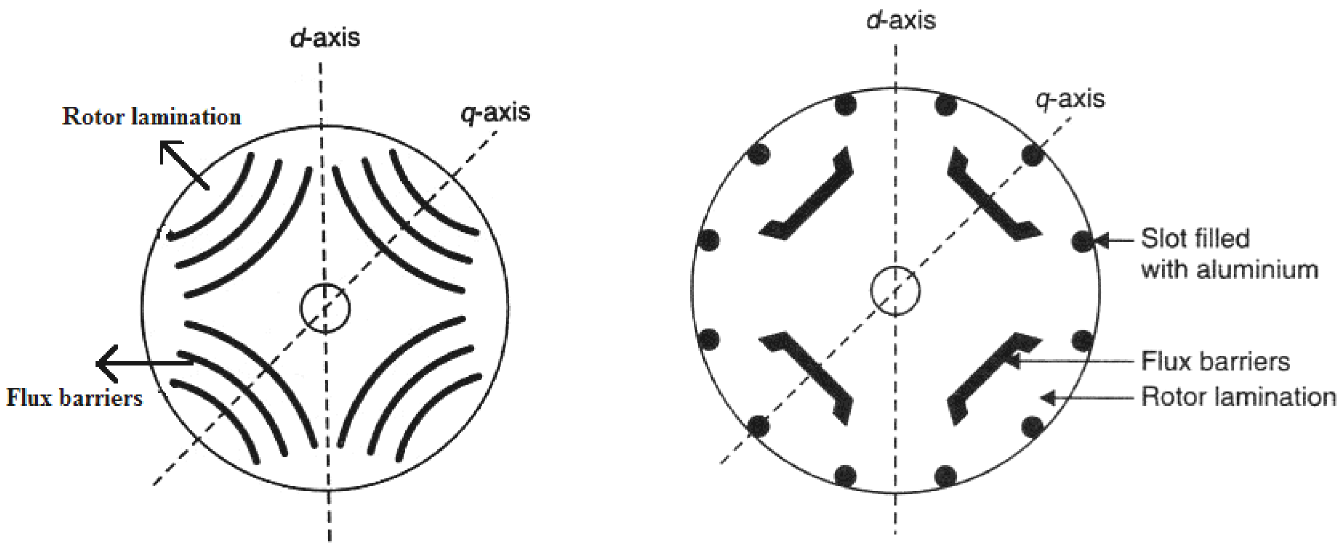


Fig. Radially laminated rotor

Axially laminated rotor:

- Flux barriers are introduced in the quadrature flux path.
- Flux barriers - thin sheets of non-magnetic material (Brass or aluminium).
- Direct axis synchronous inductance is not affected by flux barriers.
- Quadrature axis synchronous inductance is reduced by flux barriers.
- d-axis flux moves along the flux barriers.
- q-axis flux moves across the flux barriers.
- Cost of rotor is high.

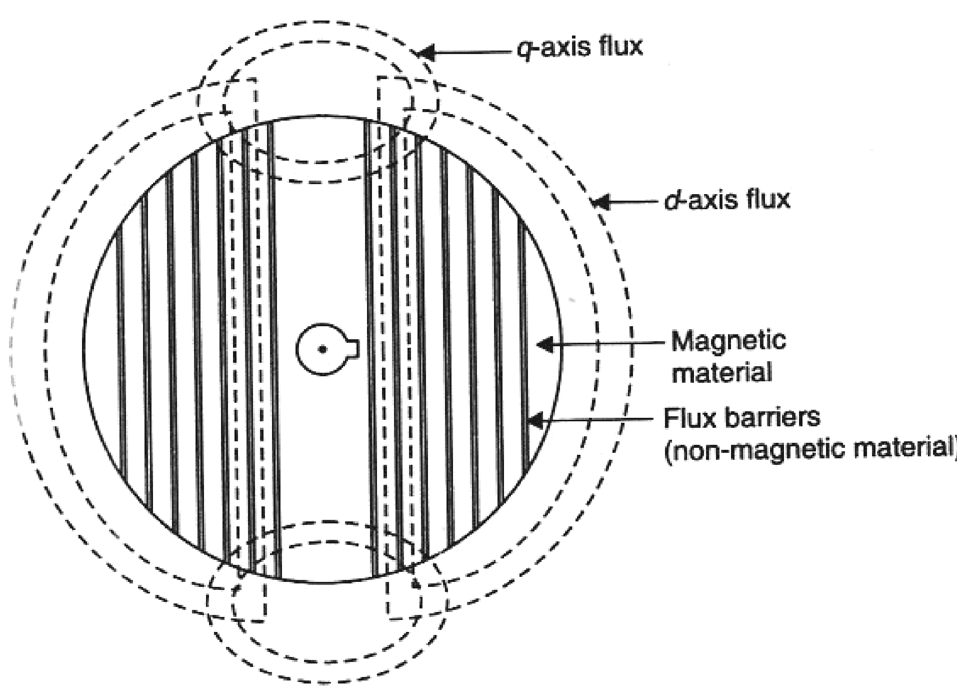


Fig. Axially laminated rotor

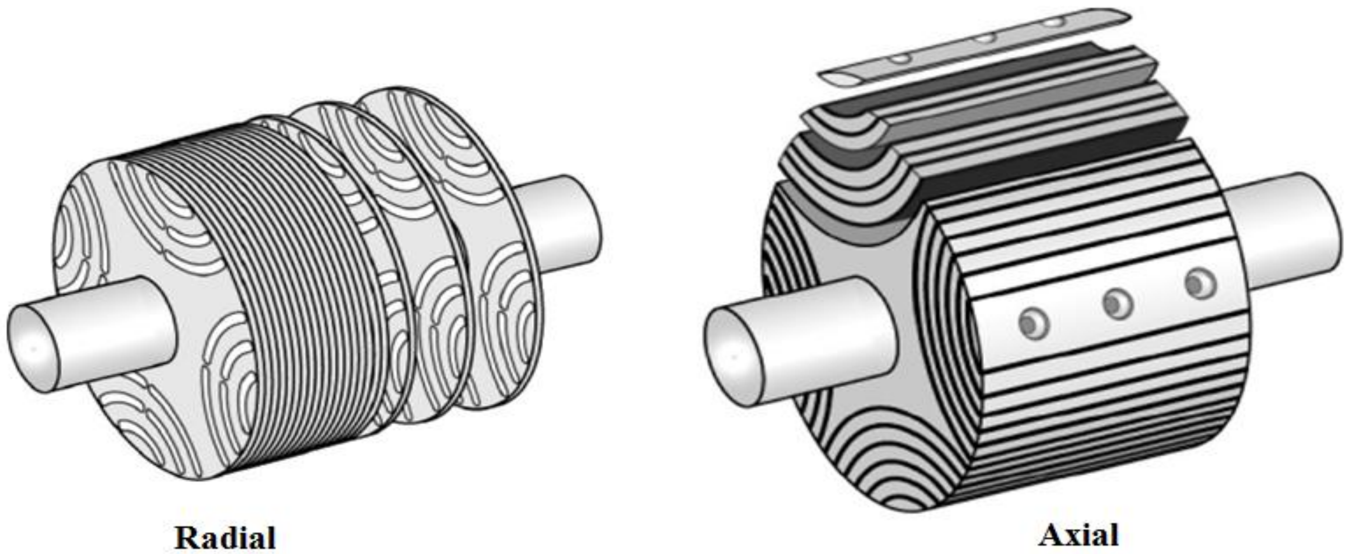


Fig. Radially laminated rotor and axially laminated rotor (not for examination)

Modified rotor design:

- Rotor consists of alternating layers of ferromagnetic and non magnetic steel.
- Choose the thickness of the steel such that the pitch of the ferromagnetic rotor segments matched the slot pitch of stator.
- Then regardless of the angle of rotation of the rotor, the ferromagnetic rotor segments always see a stator tooth pitch.
- This minimizes flux variations and hence iron losses in the rotor.

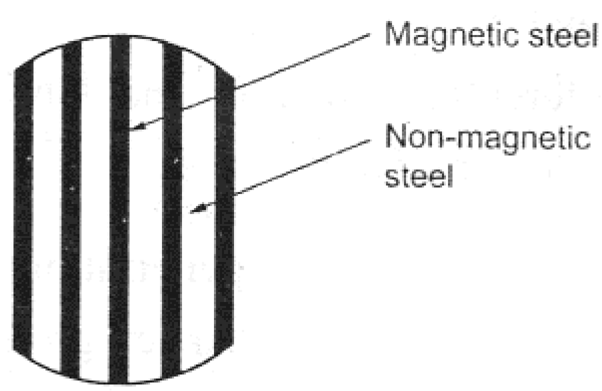


Fig. Modified rotor design

- Synchronous speed is achieved as the salient 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 field.

Explosion bonding:

- Uses explosive energy to force two or more metal sheets together at high pressures.
- High pressure causes several atomic layers on the surface to behave as a fluid.
- Sheets of ferromagnetic and non-magnetic steel are bonded, cut into rectangular blocks, then machined into rotor.
- Brazing, roll bonding, diffusion bonding.

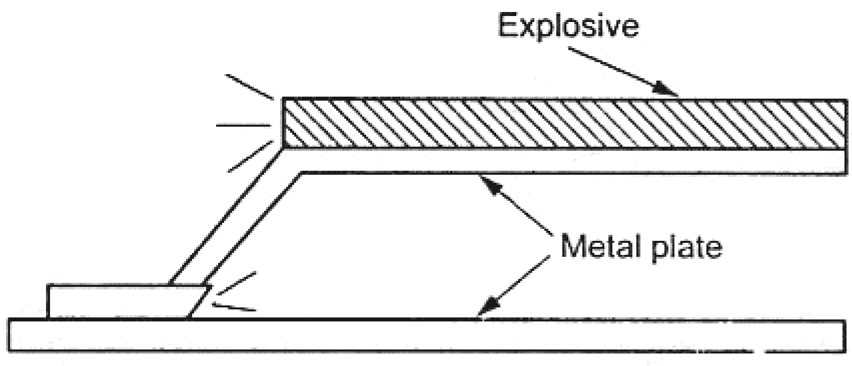


Fig. Explosion bonding

Advantages:

1. There is no concern with demagnetization, hence synchronous reluctance.
2. There need be no excitation field at zero torque, thus eliminating electromagnetic spinning losses.
3. Synchronous reluctance machine rotors can be constructed entirely from high strength, low-cost materials.

Disadvantages:

1. Compared to induction motor it is slightly heavier and has low power factor. But increasing the saliency ratio, the power factor can be improved.
2. High cost than induction motor.
3. Need speed synchronization to inverter output frequency by using rotor position sensor and sensor less control.

Operating principles:

2. Explain briefly working principle and operation of synchronous reluctance motor.

Dec-2017, 2016, 2013, 2012, May- 2018, 2012, 2017

Whenever a piece of Ferro-magnetic material is located in a magnetic field, a force is exerted upon the material tending to align it in the minimum reluctance position.

When supply is given to the stator winding, revolving magnetic field will exert reluctance torque on the unsymmetrical rotor. Rotor tends to align with the revolving magnetic field in minimum reluctance position.

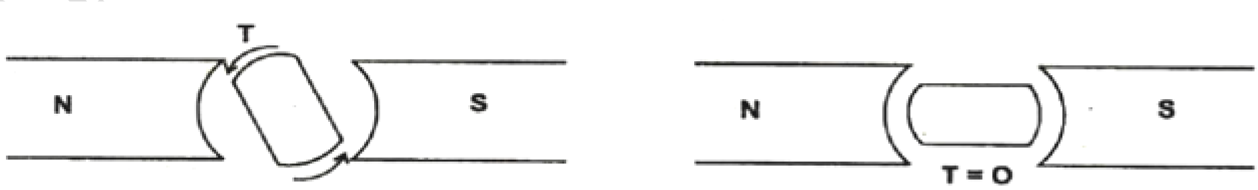


Fig. Rotor position due to revolving magnetic field

If reluctance torque is sufficient to start the motor and its load, then rotor will pull in to step with the revolving field and continue to run at the speed of the revolving field.

Actually the motor starts as 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. So, that the motor now runs as a synchronous motor.

Reluctance motor have approximately 1/3 the H.P rating they would have as IM which has cylindrical rotors. Although the ratio may be increased to one half by proper design of the field windings, power factor and efficiency is poorer than for the equivalent IM.

Voltage and torque equation – Phasor diagram:

3. Draw the phasor diagram of synchronous reluctance motor and from the phasor diagram derive torque and voltage equations of the machines? May-2013, 2012, Dec-2012

Draw and explain the phasor diagram with characteristics of synchronous reluctance motors. Dec-2017, 2014, May-2018

Derive the torque equation of synchronous reluctance motor. May-2017, 2016, Dec-2016, 2015

Investigate the performance of the synchronous reluctance motor with neat phasor diagram. May-2016, 2015

Draw the phasor diagram of synchronous reluctance motor. Dec-2016, 2015

Draw the steady state phasor diagram of synchronous reluctance motor and derive the expression for torque of synchronous reluctance motor. Dec-2016

The phasor diagram of the synchronous reluctance motor is as shown below:

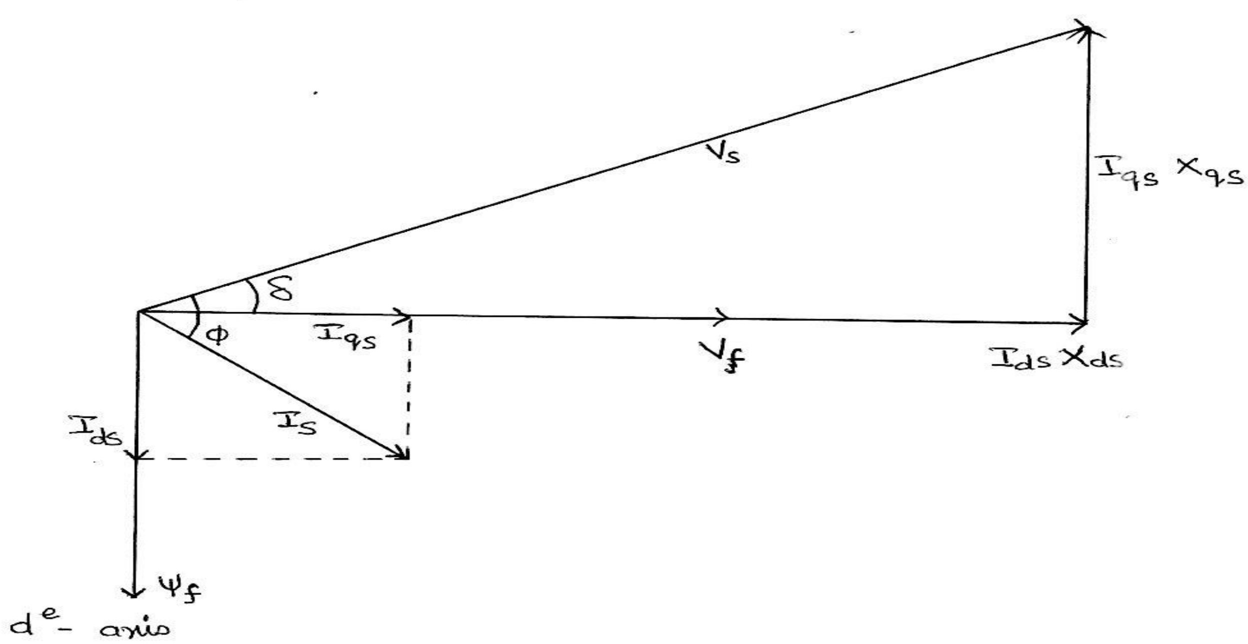


Fig. (a) Phasor diagram of synchronous reluctance motor with q-axis as reference

In synchronous reluctance motor, no dc excitation is used. So V_f is neglected. Stator resistance is also neglected.

$\overline{\psi_s}$ $-$ *space vector flux*

ψ_s $-$ *stator flux linkage*

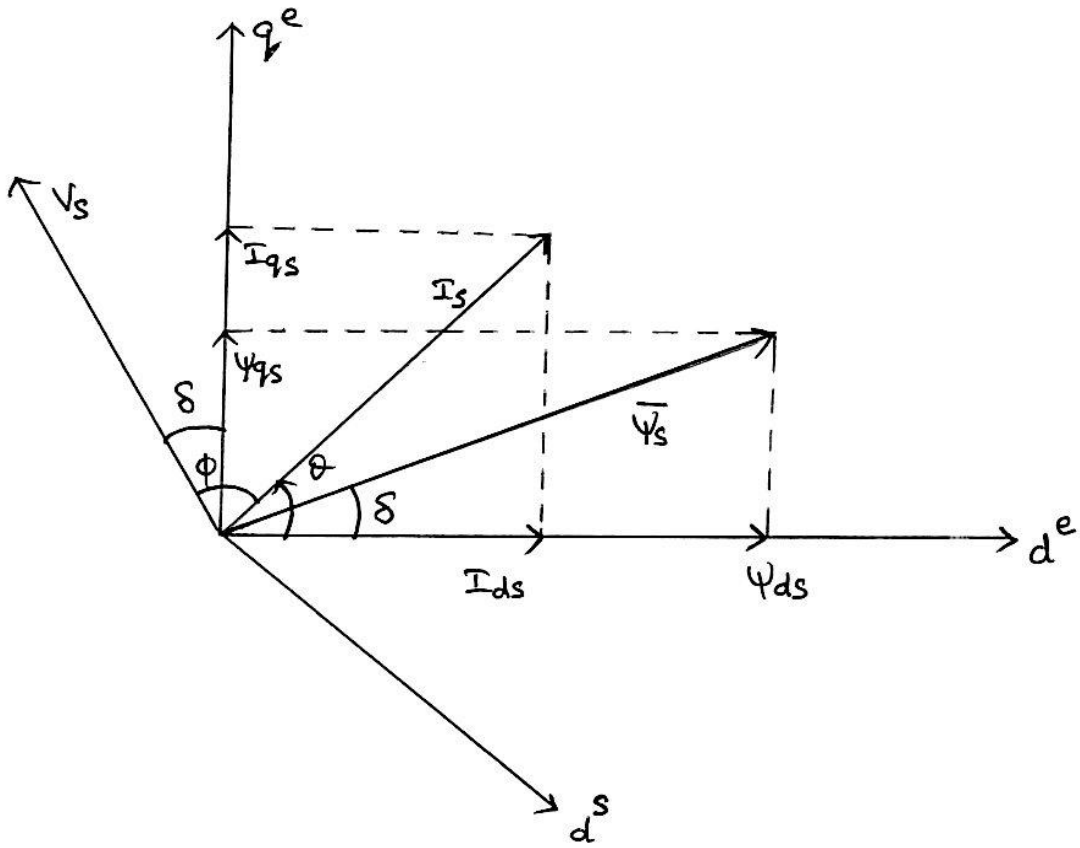


Fig. (b) Phasor diagram with d-axis as reference

$$V_s = V_f - j\, I_{ds}\, X_{ds} - j\, I_{qs}\, X_{qs}$$

From fig (a),

$$\cos\delta = \frac{V_f + I_{ds}\, X_{ds}}{V_s} \quad \Rightarrow \quad I_{ds} = \frac{V_s \cos\delta - V_f}{X_{ds}}$$

$$\sin\delta = \frac{I_{qs}\, X_{qs}}{V_s} \qquad \Rightarrow \quad I_{qs} = \frac{V_s \sin\delta}{X_{qs}}$$

Also,

$$I_s \cos\varphi = I_{qs} \cos\delta - I_{ds} \sin\delta$$

$$= \frac{V_s \sin\delta}{X_{qs}} \cos\delta - \frac{V_s \cos\delta - V_f}{X_{ds}} \sin\delta$$

$$= \frac{V_s}{X_{qs}} \sin\delta \cos\delta - \frac{V_s}{X_{ds}} \cos\delta\, \sin\delta + \frac{V_f \sin\delta}{X_{ds}}$$

$$= \frac{V_f \sin\delta}{X_{ds}} + V_s \sin\delta \cos\delta \left(\frac{1}{X_{qs}} - \frac{1}{X_{ds}}\right)$$

$$I_s \cos\varphi = \frac{V_f \sin\delta}{X_{ds}} + V_s \sin\delta \cos\delta \left(\frac{X_{ds} - X_{qs}}{X_{ds}\ X_{qs}}\right)$$

Since, $V_f = 0$,

$$I_s \cos\varphi = V_s \sin\delta \cos\delta \left(\frac{X_{ds} - X_{qs}}{X_{ds}\ X_{qs}}\right)$$

$$I_s \cos\varphi = V_s \left(\frac{X_{ds} - X_{qs}}{2\, X_{ds}\ X_{qs}}\right) \sin 2\delta$$

$$Input\ power,\ P_{in} = 3\, V_s\, I_s \cos\varphi$$

$$= 3\, V_s \quad V_s \left(\frac{X_{ds} - X_{qs}}{2\, X_{ds}\ X_{qs}}\right) \sin 2\delta$$

$$P_{in} = 3\, V_s^{\,2} \left(\frac{X_{ds} - X_{qs}}{2\, X_{ds}\ X_{qs}}\right) \sin 2\delta$$

If machine losses are neglected, $P_{in} = P_m = P$

$$P_{in} = \omega_m\, T_e$$

$$But, \quad \omega_e = \frac{p}{2}\, \omega_m \Rightarrow \omega_m = \frac{2}{p}\, \omega_e$$

$$\therefore\ P_{in} = \frac{2}{p}\, \omega_e\ T_e$$

$$T_e = \frac{p}{2}\ \frac{P_{in}}{\omega_e}$$

$$= \left(\frac{p}{2}\right) \frac{3\, V_s^{\,2}}{\omega_e} \left(\frac{X_{ds} - X_{qs}}{2\, X_{ds}\ X_{qs}}\right) \sin 2\delta$$

$$T_e = \left(\frac{p}{2}\right) \frac{3}{\omega_e}\, V_s^{\,2} \left(\frac{X_{ds} - X_{qs}}{2\, X_{ds}\ X_{qs}}\right) \sin 2\delta$$

But, $V_s = \psi_s \cdot \omega_e$

$X_{ds} = \omega_e L_{ds}$

$X_{qs} = \omega_e L_{qs}$

$$\therefore\ T_e = \left(\frac{p}{2}\right)\left(\frac{3}{\omega_e}\right)\frac{\psi_s{}^2\ \omega_e{}^2\ (X_{ds} - X_{qs})}{2\ X_{ds}\ X_{qs}}\ \sin 2\delta$$

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

$$= \left(\frac{p}{2}\right)\left(\frac{3}{\omega_e}\right)\frac{\psi_s{}^2\ \omega_e{}^2\ \omega_e\ (L_{ds} - L_{qs})}{2\ \omega_e{}^2\ L_{ds}\ L_{qs}}\ \sin 2\delta$$

$$\boxed{\boldsymbol{T_e = \left(\frac{p}{2}\right)\left(\frac{3}{2}\right)\frac{\psi_s{}^2\ (L_{ds} - L_{qs})}{L_{ds}\ L_{qs}}\ \sin 2\delta}}$$

Also,

$$\boxed{\boldsymbol{T_e = \left(\frac{p}{2}\right)\left(\frac{3}{2}\right)\frac{(L_{ds} - L_{qs})}{L_{ds}\ L_{qs}}\ \psi_{qs}\ \psi_{ds}}}$$

Or

$$\boxed{\boldsymbol{T_e = \left(\frac{p}{2}\right)\left(\frac{3}{2}\right)(L_{ds} - L_{qs})\ I_{qs}\ I_{ds}}}$$

Or

$$\boxed{\boldsymbol{T_e = \left(\frac{p}{2}\right)\left(\frac{3}{2}\right)(\psi_{ds}\ I_{qs} - \psi_{qs}\ I_{ds})}}$$

<u>Performance characteristics:</u>

4. Draw and explain torque-angle curve and speed - torque characteristics of synchronous reluctance motor. **Dec-2013, 2012**

Explain the torque speed characteristics of synchronous reluctance motor in detail. **May-2017, Dec-2017**

Explain the characteristics of synchronous reluctance motor. **May-2018**

Torque-angle characteristics:

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

- The torque-angle characteristic for different excitations can be drawn.
- The maximum points in the curve represent the steady state limit.
- In the synchronous reluctance motor, rotor has no field excitation.
- So the torque-angle characteristic for synchronous reluctance motor is the lowest curve with zero excitation.
- At $\delta = \pm \pi / 4$, steady state limit is reached.

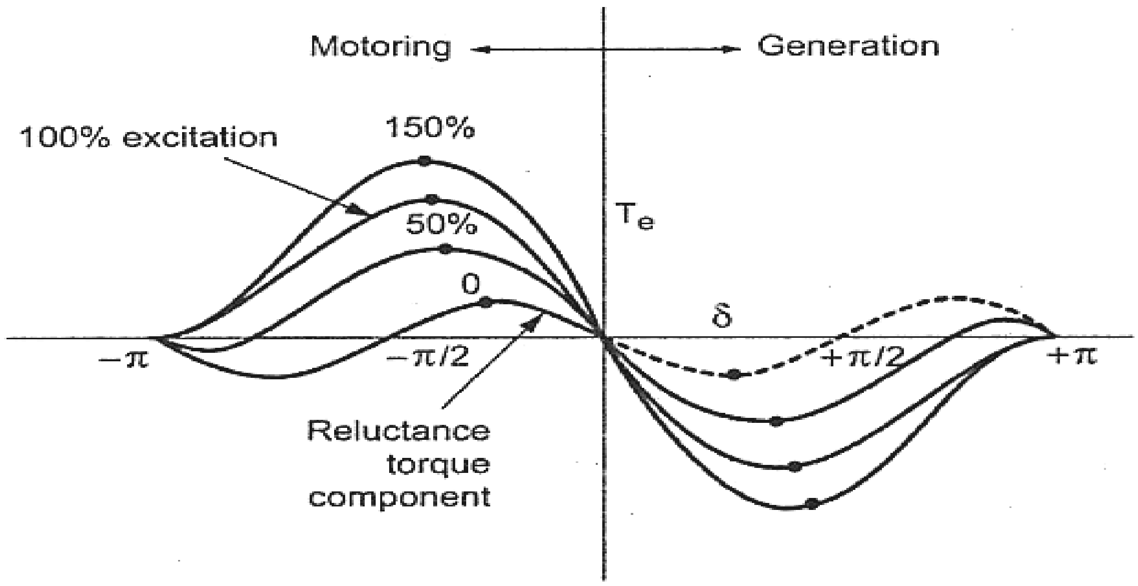


Fig. Torque-angle characteristics

Speed-Torque Characteristics:

In a fixed AC supply, synchronous reluctance motor is a non self starting motor. Hence it is fitted with a squirrel cage winding to start as a cage induction motor.

When the rotor speed approaches synchronous speed, reluctance torque is super imposed on the induction motor torque. So rotor speed oscillates below and above synchronous speed.

If load torque is not excessive, rotor speed reaches synchronous speed and locks into synchronism with the stator rotating field.

The motor starts as an induction motor at anywhere from 300 to 400 % of its full load torque. When it reaches its maximum speed, due to reluctance torque, it locks into synchronism and rotates at synchronous speed.

When torque is increased, motor speed remains constant. Above the maximum torque, motor losses synchronism. Motor acts as a synchronous motor till 200% of its full load torque.

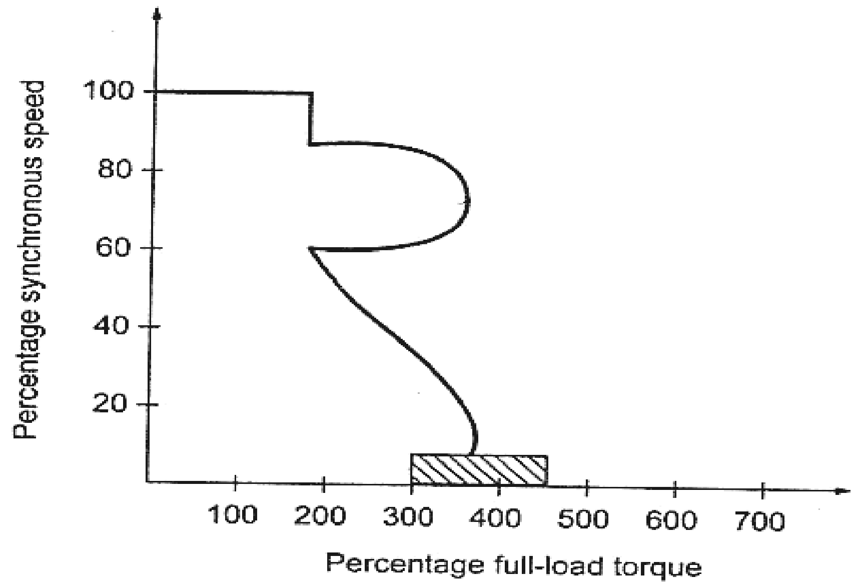


Fig. Speed-torque characteristics

Applications:

- Used in recording instruments
- Used in pumps (or) conveyors
- Synthetic fiber manufacturing equipments
- Wrapping and folding machines
- Auxiliary time mechanism
- Metering Pumps

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5) Distinguish between axial and radial air gap motors? **Dec-2011**

S.No	Axial airgap motors	Radial airgap motors
1	Axially laminated rotor.	Radially laminated rotor.
2	By increasing Ld / Lq ratio, we obtain more power factor and efficiency.	By decreasing Ld / Lq ratio, circulating flux in the rotor pole faces.
3	Designed to have high saliency.	Designed to have optimized flux guide.
4	Rotor has two design structures.	Rotor has one design structure.
5	Good choice for high speed applications.	Poor choice for high speed applications.

6. Discuss the various stator current modes in a synchronous reluctance motor in detail.

Dec-2014

The various stator current modes in synchronous reluctance motor are,

Constant d-axis current control method:

In this simple control method, the d-axis current is kept constant and the q-axis current is controlled.

$$T_e = \frac{3}{2}\frac{P}{2}\left(1 - \frac{L_q}{L_q}\right)\psi_d\, i_q$$

The position sensor and the signal conditioner provide speed signal ω_r and position signal θ_e. The d-axis reference current signal I_d^* is generated by a function generator by processing speed signal ω_r. I_d^* is constant for speed below the rated speed. The inverter currents are controlled by hysteresis band PWM, which is an instantaneous current control method. In this method, the real current follows the reference current within a specified hysteresis band.

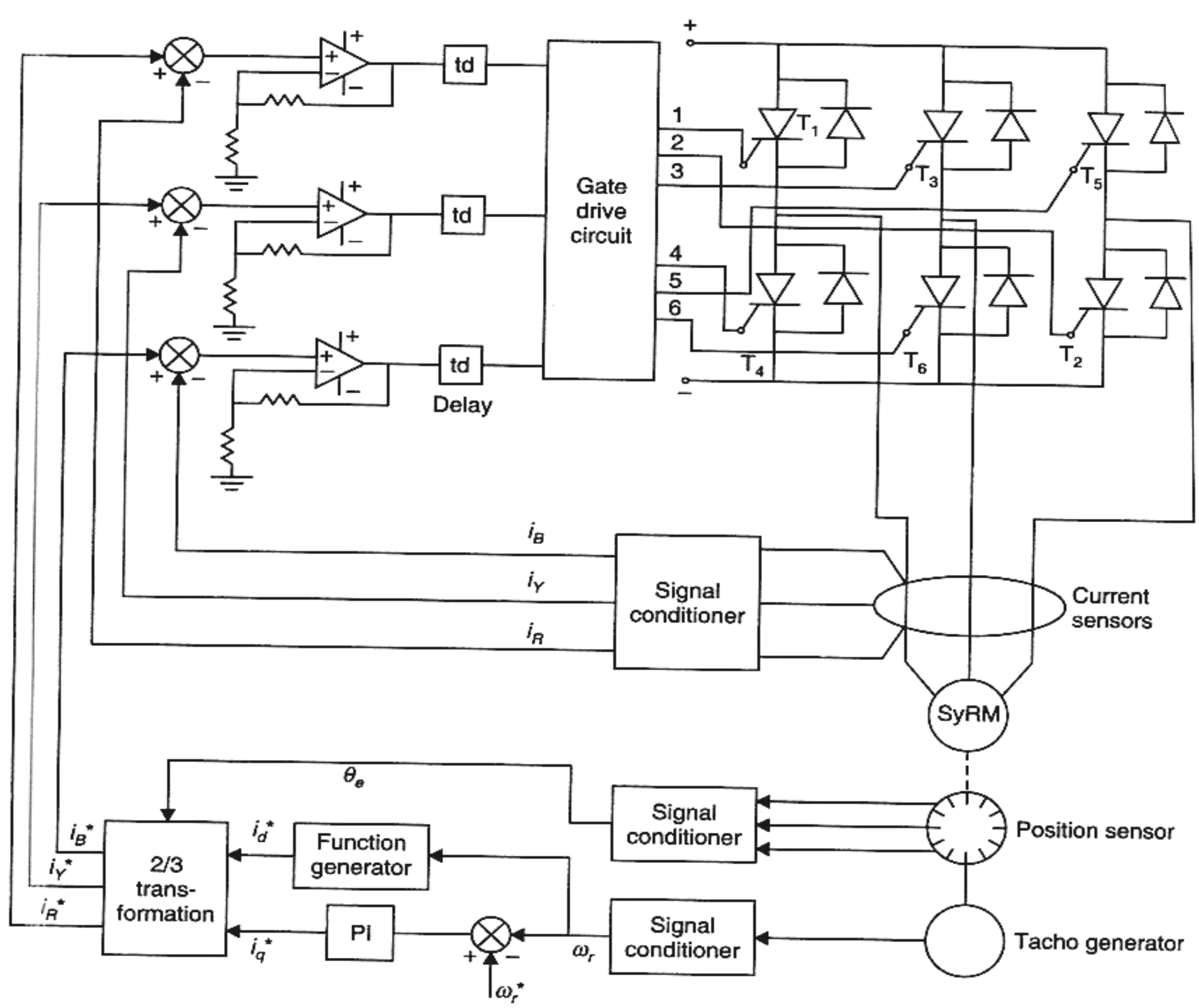


Fig. Constant d-axis current control method

Maximum torque/ampere control (or) Fast torque response control:

Maximum torque/ampere response control strategy, which tends to give maximum drive efficiency, is achieved when $i_d = i_q$.

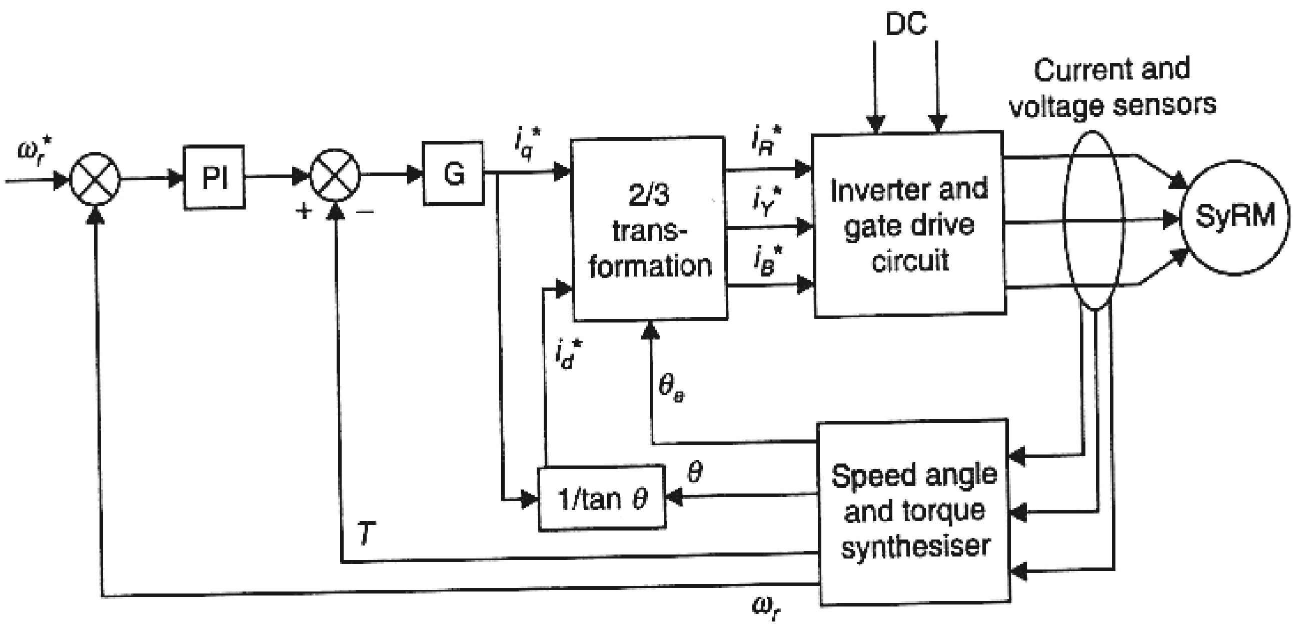


Fig. Fast torque response control method

Maximum power factor control:

To maintain the maximum power factor, ratio of d-axis and q-axis current should always be

$$\frac{i_q}{i_d} = \sqrt{\frac{L_d}{L_q}}$$

ANNA UNVERSITY QUESTIONS

PART-A

1. What is a synchronous reluctance motor? **Dec-2010**
2. What are the types of synchronous reluctance motor? **Dec-2017, 2016, May-2010, 2013**
3. Mention some applications of synchronous reluctance motor. **May-2017, 2016, 2015, Dec-2017, 2016, 2012**
4. Compare synchronous reluctance motor and induction motor. **Dec-2017, 2015, 2010**
5. Write down the voltage and torque equation of synchronous reluctance motor. **May-2010**
6. Draw the torque-angle characteristics of synchronous reluctance motor. **May-2011**
7. What is reluctance torque is synchronous reluctance motor? **May-2018, Dec-2016, 2011**
8. What are the design considerations in synchronous reluctance motor? **Dec-2017, 2012**
9. Compare synchronous reluctance motor and Switched reluctance motor. **Dec-2016, 2010, May-2017, 2012, 2013**
10. What are SYNREL motors? **Dec-2013**
11. Give the operating principle of radial flux motor. **May-2012, 2017**
12. Draw the voltage and torque characteristics of synchronous reluctance motor. **May-2016, 2015**
13. Write the different types of controllers used for synchronous reluctance motors? **Dec-2014**
14. State the principle of operation of synchronous reluctance motors. **Dec-2015**
15. What are the types of rotor available in synchronous reluctance motor? **May-2017**
16. Mention any two advantages of synchronous reluctance motors. **May-2018**

PART-B

1. Explain the constructional features of different types of synchronous reluctance motor. **Dec-2014, 2013, 2012, 2011, May-2013**

Explain the construction and operation of axial and radial flux motors with neat diagram. **May-2015**

Explain in detail the operating principle and construction of synchronous reluctance motor with neat diagrams. **Dec-2016, 2015, May-2017**

Explain the construction of radial and axial flux machines. Discuss the advantages and disadvantages of each construction. **Dec-2016**

Explain with neat diagram, the construction, working principle and types of synchronous reluctance motor. **Dec-2016**

Discuss in detail about the construction and working of synchronous reluctance motor with neat diagrams. **Dec-2017**

Explain the constructional details and working principle of synchronous reluctance with neat diagrams. **May-2018**

2. Explain briefly working principle and operation of synchronous reluctance motor.
Dec-2017, 2016, 2013, 2012, May- 2018, 2012

3. Draw the phasor diagram of synchronous reluctance motor and from the phasor diagram derive torque and voltage equations of the machines? **May-2013, 2012, Dec-2012**

Draw and explain the phasor diagram with characteristics of synchronous reluctance motors.
Dec-2017, 2014, May-2018

Derive the torque equation of synchronous reluctance motor.
May-2017, 2016, Dec-2016, 2015

Investigate the performance of the synchronous reluctance motor with neat phasor diagram.
May-2016, 2015

Draw the phasor diagram of synchronous reluctance motor. **Dec-2016, 2015**

Draw the steady state phasor diagram of synchronous reluctance motor and derive the expression for torque of synchronous reluctance motor. **Dec-2016**

4. Draw and explain torque-angle curve and speed -torque characteristics of synchronous reluctance motor. **Dec-2013, 2012**

Explain the torque speed characteristics of synchronous reluctance motor in detail.
May-2017

5. Distinguish between radial and axial type motors. **Dec-2011**

6. Discuss the various stator current modes in a synchronous reluctance motor in detail. **Dec-2014**

MAILAM ENGINEERING COLLEGE
Department of Electrical and Electronics Engineering

SUB CODE: EE 6703 **SUB NAME: SPECIAL ELECTRICAL MACHINES**

UNIT – 02
STEPPING MOTORS

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

PART-A

1. What is stepper motor?

A stepper motor is a digital actuator whose input is in the form of programmed energization of the stator windings and whose output is in the form of discrete angular rotation.

2. Define the term step angle or stepping angle. **May-2017, 2016, 2013, Dec–2013, 2010**

Step angle is defined as angle through which the stepper motor shaft rotates for each command pulse. It is denoted as β.

$$\beta = \frac{N_s - N_r}{N_s \ N_r} \ x \ 360°$$

$$\beta = \frac{360°}{m \ N_r}$$

Where, N_s - No. of stator poles or stator teeth
N_r - No. of rotor poles or rotor teeth
m – No. of stator phase

3. Define slewing?

The stepper motor may be operate at very high stepping rates i.e., 25000 steps per second. A stepper motor operates at high speeds is called slewing.

4. Write down the formula for motor speed of stepper motor?

$$Motor\ speed, \quad n = \frac{\beta \ f}{360°} \ rps$$

Where,
β = Step angle
f = Stepping frequency or pulse rate in pulses per second (pps)

5. Define resolution?

It is defined as the number of steps needs to complete one revolution of the rotor shaft.

6. State some application of stepper motor? **May-2017**

Applications of stepper motor are,

1. Floppy disk drives.
2. Quartz watches.
3. Camera shutter operation.
4. Dot matrix and line printers.
5. Machine tool applications.
6. Robotics.

7. What are the advantages and disadvantages of stepper motor?

Advantages

- It can driven open loop without feedback.
- Responds directly to digital control signals, so stepper motors are natural choice for digital computer controls.
- It is mechanically simple.
- It requires little or no maintenance.

Disadvantages

- Low efficiency with ordinary controller.
- Fixed step angle.
- Limited ability to handle large inertia load.
- Limited power output and sizes available.

8. What are the different types of stepper motor?

Different types of stepper motor are,

1. Variable reluctance stepper motor.
2. Permanent magnet stepper motor.
3. Hybrid stepper motor.

9. What are the different modes of excitation in a stepper motor?

Dec-2017, 2015, May-2018, 2012

Different modes of excitation in stepper motor are,

1. 1-phase on or full – step operation.
2. 2-phase on mode
3. Half – step operation
4. Micro stepping operation

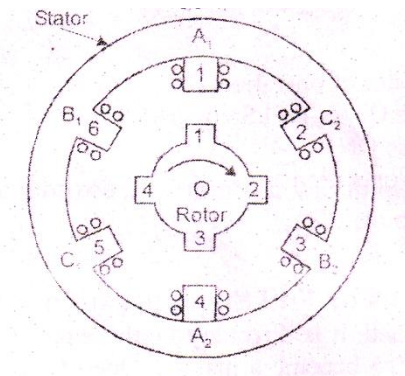
10. What is meant by full-step operation?

It is the one-phase on mode operation. It means, at that time only one winding is energized by energizing one stator winding, the rotor rotates some angle. It is the full-step operation.

11. What is meant by half-step operation?

It is the alternate one-phase on and 2-phase on mode operation. Here, the rotor rotate an each step angle is half of the full-step angle.

12. Sketch the diagram of a VR stepper motor?



13. Define the micro stepping mode of stepper motor. **Dec-2016, May-2015**

- Step angle of the VR stepper motor is very small.
- Also called mini-stepping.
- Can be achieved by two phases ON simultaneously as in 2-phase on mode but with the two currents deliberately made unequal.

14. Mention the applications of micro stepping VR stepper motor? **Dec-2014**

- Printing
- Graph plotters
- Photo type setting

A VR stepper motor with micro stepping provides very smooth low-speed operation and high resolution.

15. What is a multi – stack VR stepper motor?

Micro stepping of VR stepper motor can be achieved by using multi stack VR stepper motion. It has three separate magnetically isolated sections or stacks. Here the rotor and stator teeth are equal.

16. What are the advantages and disadvantages of VR stepper motor?

Advantages:

- Low rotor inertia
- High torque to inertia ratio
- Light weight
- Capable of high stepping rate
- Ability to freewheel

Disadvantages:

- Normally available in 3.6 ° to 30 step angles.
- No detent torque available with windings de – energized.

17. What are the advantages & disadvantages of permanent magnet stepper motor?

Advantages:

- Low power requirement
- High détente torque as compared to VR motor
- Rotor do not require external exciting current
- It produces more torque per ampere stator current

Disadvantages:

- Motor has higher inertia
- Slower acceleration

18. What is hybrid stepped motor? **Dec - 2011**

A hybrid stepper motor combines the features of both PM and VR stepping motors.

19. What are the advantages and disadvantages of hybrid stepper motor?

Advantages:

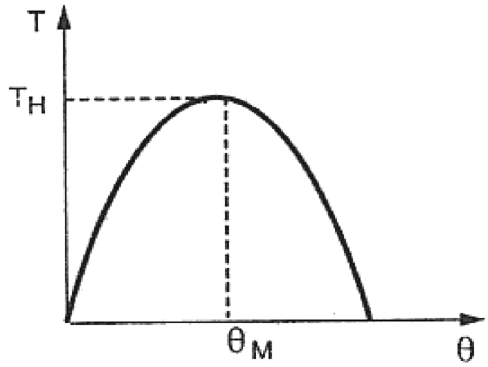
- Less tendency to to resonate.
- Provide détente torque with windings de-energized.
- Higher holding torque capability
- High stepping rate capability

Disadvantages:

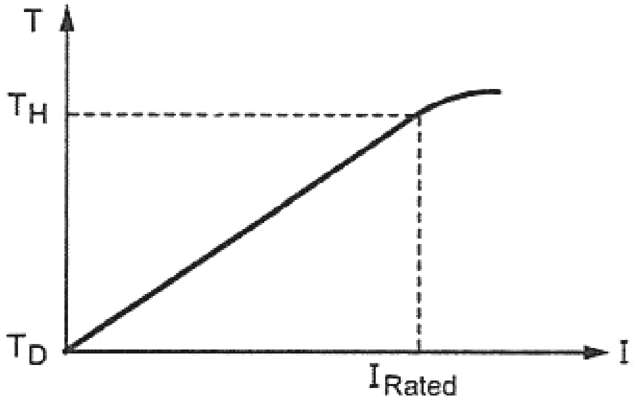
- Higher inertia and weight due to presence of rotor magnet.
- Performance affected by change in magnetic strength.

20. Draw the typical static characteristics of a stepper motor.

T-θ Characteristic:



T-I Characteristic:



21. Differentiate between VR, PM and hybrid stepper motor.

	VR Stepper motor	**PM Stepper motor**	**Hybrid stepper motor**
1	Low rotor inertia	High inertia	High inertia
2	Less weight	More weight	More weight
3	No detent torque available	Provides detente torque	Provides detente torque with windings de-energized
4	Rotor has no permanent magnet	Rotor is permanent magnet	Rotor is permanent magnet
5	Rotor is a salient pole type	Rotor is a cylindrical type	Rotor is a salient pole type

22. Define holding torque? **Dec-2015**

Holding torque is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position.

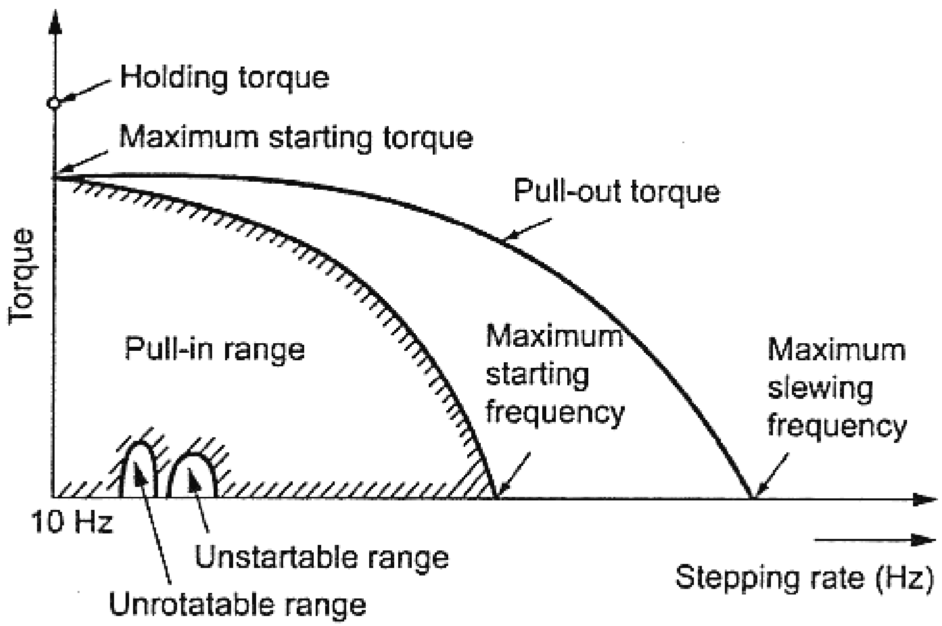
23. Define detent torque. Dec-2015

Detent torque is the maximum load torque which is un energized stepper motor can withstand without slipping. It is also known as cogging torque.

24. Define torque constant. Dec - 2012

Torque constant of the stepper motor is defined as the initial slope of the torque current curve of the stepper motor. It is also called as torque sensitivity.

25. Draw the typical dynamic characteristics of a stepper motor.



26. Define pull-in torque?

It is the maximum torque the stepper motor can develop in start-stop mode at a given stepping rate F (steps/sec), without losing synchronism.

27. Define pull-out torque.

It is the maximum torque the stepper motor can develop at a given stepping rate F (steps/sec), without losing synchronism.

28. Define pull-in rate.

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

29. Define pull-out rate.

It is the maximum stepping rate at which the stepper motor will slow, without losing synchronism against a given load torque.

30. What is response range?

It is the range of stepping rates at which the stepper motor can start or stop with losing synchronism, at a given load torque. Response range spans stepping rates the pull in rate.

31. What is slewing range?

It is the range of stepping rates at which the stepper motor can run in the slow mode, with losing synchronism, at a given load torque. The slewing range spans stepping rates.

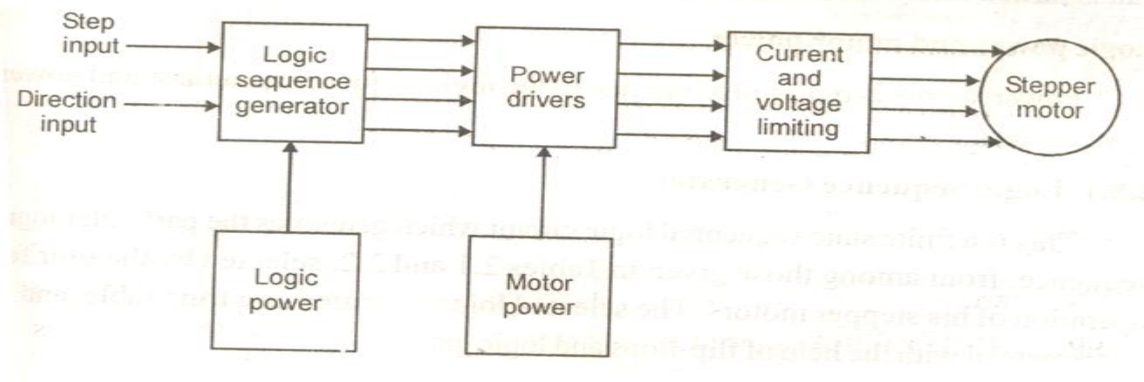
32. What is synchronism in stepper motor?

It is the one-to-one correspondence between the numbers of pulses applied to stepper motor controller and the number of steps through which the motor has actually moved.

33. What is mid-frequency resonance in stepper motor?

In the pull in curve of a stepper motor, suddenly dips very low in particular range of stepping rates. This phenomenon is known as mid-frequency resonance. This phenomenon is a manifestation of instability of motor operation.

34. Draw the block diagram of the drive system of stepping motor. **Dec-2011**



35. What is logic sequencer?

Logic sequence generator generates programmed logic sequences require for operation of a stepper motor.

36. What is the function of power drive circuit in stepper motor? **May-2017, 2013**

The output from the logic sequence generator signals are low level signals which are too weak to energize stepper motor windings. To increase the voltage, current and power levels of the logic sequence output by using power semiconductor switching circuit.

37. What is the use of current suppression circuit?

What is the need of suppressor circuits in stepper motor? **Dec-2016**

This circuit is used to ensure fast decay of current through the winding when the transistor is turned off.

38. What are the types of current suppression circuits?

1. Diode suppression
2. Diode resistor suppression
3. Diode-zener diode suppression
4. Active suppression

39. How the step of permanent magnet stepper motor controlled?

The step of the permanent magnet stepper motor is controlled by energization of phase winding with positive or negative current.

40. What are the main features of stepper motor which are responsible for its wide spread use? **Dec-2013**

- It can drive open loop without feedback.
- Responds directly to digital control signals, so stepper natural choice for digital computer controls.
- Mechanically simple.

- Requires little or no maintenance
- High torque or inertial ratio.

41. Calculate the stepping angle for a 3-phase 24 pole permanent magnet stepper motor.
Dec – 2012, 2013

$$Step\ angle, \qquad \beta = \frac{360°}{m\ N_r} = \frac{360}{3\ x\ 24} = 5°$$

42. Distinguish the half step and full step operations of a stepping motor. Dec-2017, 2014

S. No.	Half step operation	Full step operation
1.	The half step operation or half stepping can be obtained by exciting the three phases in the sequence a, ab, b, bc, c, etc.,	The full step operation can be obtained by exciting only one phase at any time.
2.	This mode is otherwise called as wave excitation.	This mode is otherwise called as one phase – ON mode.
3.	In this mode, the continuous half stepping produces smoother shaft rotation.	This mode of operation is the simplest and widely used way of making the motor step.

43. Write the principle of operation of variable reluctance motor. Dec-2014

A reluctance motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where inductance of the excited winding is maximized.

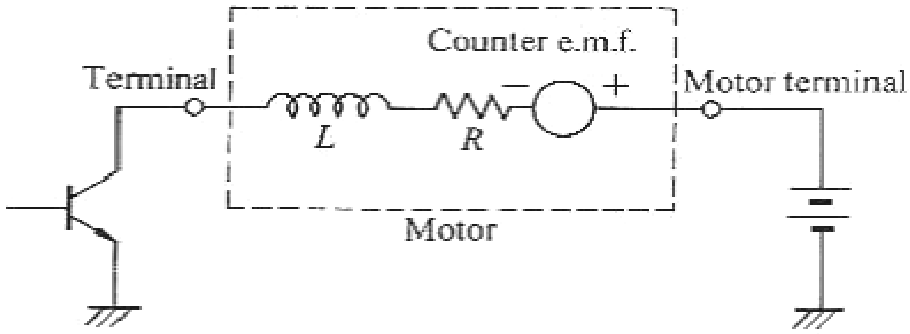
44. Name the various driver circuits used in stepper motor. Dec-2016, May-2016, 2015

- Simple power drive circuit
- L/R drive
- Dual voltage drive
- Chopper drive
- Bipolar drives for stepper motors
    - Basic bipolar drives
    - Bipolar L/R drives
    - Bipolar chopper drives

45. Define lead angle. May-2018, Dec-2016

Lead angle is the relationship between stepper motors electrical position and its mechanical position. The lead angle affects the motors torque and needs to be kept within certain bounds in order to maintain control of stepper motor.

46. Draw the equivalent circuit of winding in stepper motor. **May-2017**



47. Compare single stack and multistack configurations in stepping motors. **Dec-2017**

S. No	Single stack	Multi stack
1	Number of stator poles should be different that of rotor poles.	Number of stator poles should be equal to rotor poles.
2	Each and every stator pole carries a field coil.	It is used to obtain small step sizes. It consist of m identical single stack variable reluctance motor with the rotor mounts on single shaft.

PART-B

Constructional features - Principle of operation - Variable reluctance motor - Hybrid motor - Single and multi stack configurations

Introduction:

- Digital electro-mechanical device where each step command pulse results in a movement of the shaft by a discrete angle called step angle of the motor.
- Rotor rotates in discrete angular steps.
- Average motor speed is proportional to the rate at which the pulse command is delivered.
- At low command pulse rate – rotor moves in steps.
- At high command pulse rate – rotor moves smooth.
- **Torque** : 1 μN-m to 40 N-m.
- **Power output range**: 1 W to 2500 W

Requirements:

- High Torque-to-inertia ratio
- Smaller airgap
- Airgap size : 30 to 100 μm.

Types:

- Variable reluctance (VR) stepper motor
    - Single stack type
    - Multi stack type
- Permanent magnet stepper motor
- Hybrid stepper motor

Variable reluctance stepper motor:

1. Explain the construction and principle of operation of Variable Reluctance Stepping motor in detail. Dec–2013, 2012, 2010

Construct and evaluate the operation of single and multi stack stepper motor with a neat diagram. May-2016

Explain the working of single and multi stack configured stepping motors. Dec-2016

Describe the operation of variable reluctance type stepper motor with different modes of operation. May-2017

Describe construction and working of variable reluctance stepper motor with neat diagram. May-2017

- ***Variable reluctance principle*** – reluctance of the magnetic circuit is formed by the rotor and the stator teeth vary with the angular position of the rotor.

- Minimum reluctance position.
- Types of variable reluctance motor:
    - Single-stack type
    - Multi-stack type

Single stack VR stepper motor: **May-2013, 2015**

Construction:

Stator:

- No permanent magnets
- Salient poles
- concentrated windings
- Each pole carries field windings
- Even no. of poles
- Opposite poles are connected in series – phase windings.

Rotor:

- No permanent magnets
- Salient poles
- No windings
- Ferromagnetic material

- Number of poles on stator and rotor are different.

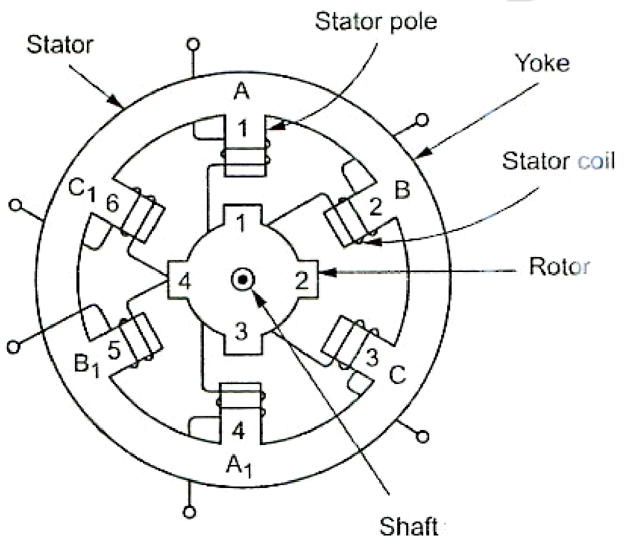


Fig. Construction of Single stack VR stepper motor

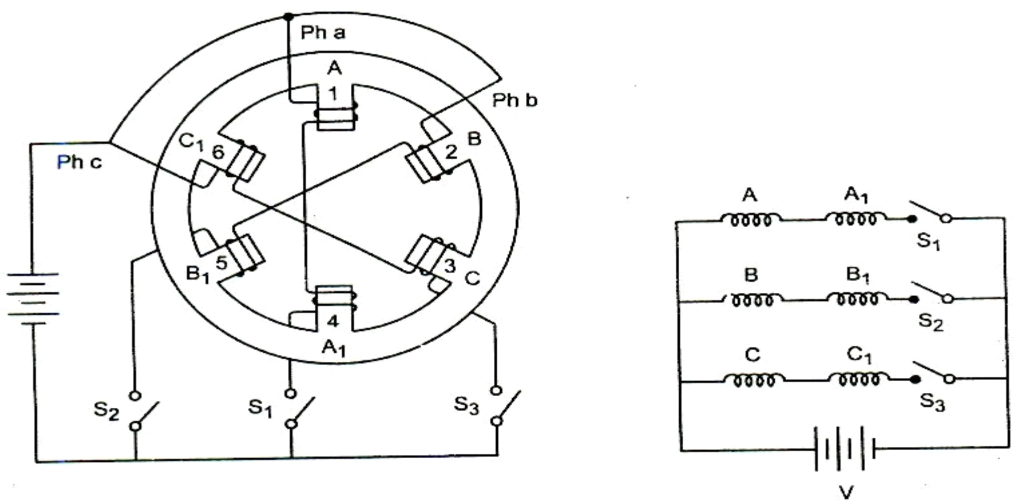


Fig. Schematic of VR stepper motor

Operation:

- Rotor tries to attain minimum reluctance position.

$$\beta = \frac{N_s - N_r}{N_s \ N_r} \ x \ 360°$$

$$\beta = \frac{360°}{m \ N_r}$$

where

N_s - No. of stator poles or stator teeth

N_r - No. of rotor poles or rotor teeth

m – no. or stator phases

Motor has the following modes of operation.

- Mode 1: one – phase ON or Full Step operation
- Mode 2: Two – phase ON
- Mode 3: Half – step operation
- Mode 4: Micro stepping

Mode 1: one – phase ON or Full Step operation:

- Only one phase is energized at any time.
- Each phase is excited by using switches.

Phase-A excited:

- A_1 A_2 gets aligned with rotor teeth 1 & 3.

Phase-B excited:

- B_1 B_2 gets aligned with rotor teeth 4 & 2.
- Rotor moves through an angle of θ = 30˚.
- Clockwise direction

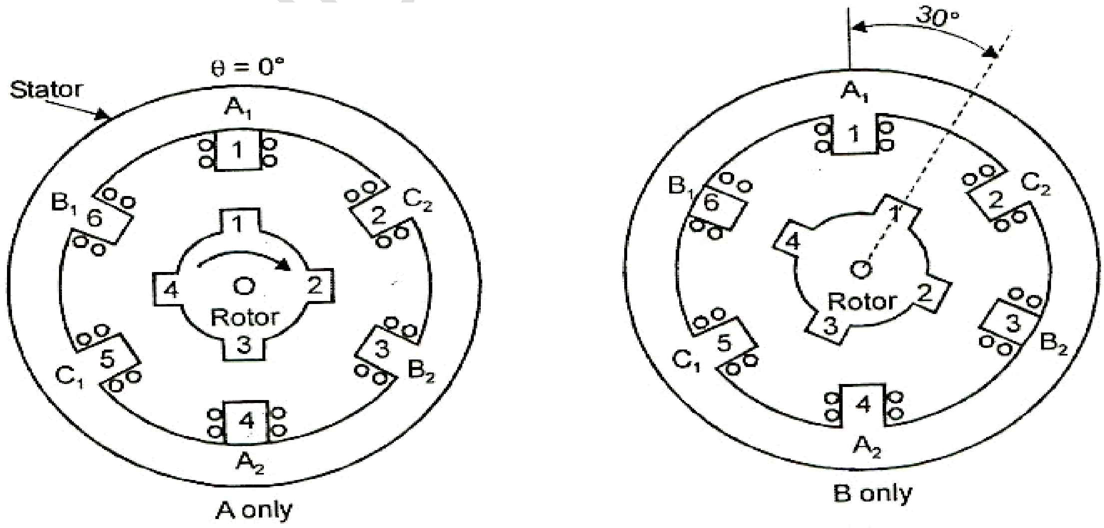


Fig. One-phase ON mode (Phase-A & Phase-B)

Phase-C excited:

- C_1 C_2 gets aligned with rotor teeth 3 & 1.
- Rotor moves through an angle of θ = 30˚.
- Total movement of rotor = 60˚.
- Clockwise direction.

Phase-A excited:

- A_1 A_2 gets aligned with rotor teeth 4 & 2.
- Rotor moves through an angle of $\theta = 30^\circ$.
- Total movement of rotor = 90˚.
- Clockwise direction.

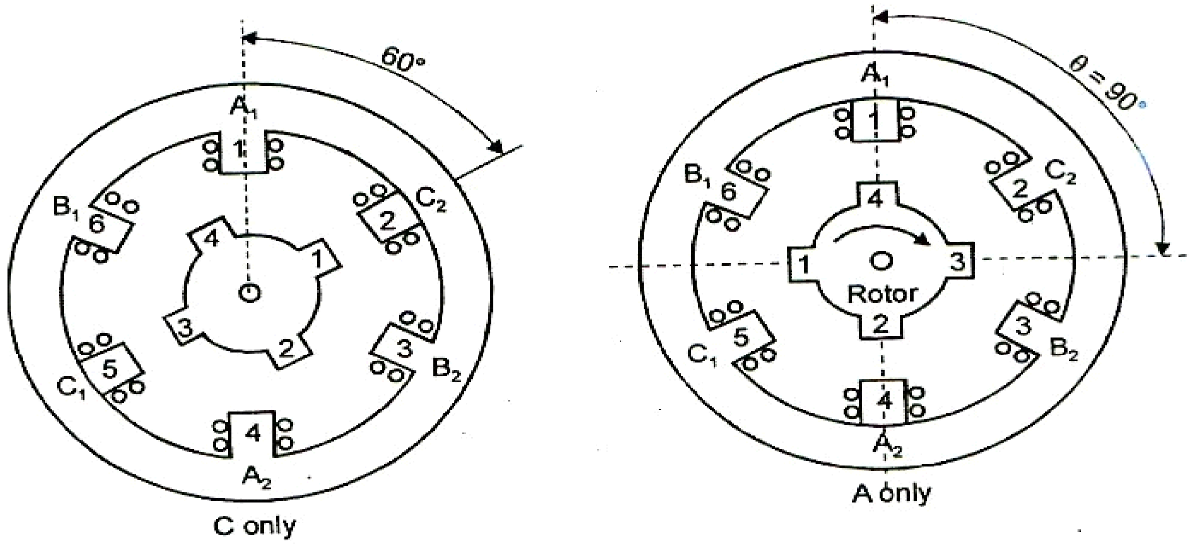


Fig. One-phase ON mode (Phase-C & Phase-A)

- Stator sequence : ABCA – clockwise direction
- Stator sequence : ACBA – anti-clockwise direction

Table: Truth table for one-phase ON mode

Clock Wise Direction				Anti Clock Wise Direction			
Phase-A	**Phase-B**	**Phase-C**	**Degree**	**Phase-A**	**Phase-B**	**Phase-C**	**Degree**
+	-	-	0°	+	-	-	0°
-	+	-	30°	-	-	+	30°
-	-	+	60°	-	+	-	60°
+	-	-	90°	+	-	-	90°
-	+	-	120°	-	-	+	120°
-	-	+	150°	-	+	-	150°
+	-	-	180°	+	-	-	180°
-	+	-	210°	-	-	+	210°
-	-	+	240°	-	+	-	240°
+	-	-	270°	+	-	-	270°
-	+	-	300°	-	-	+	300°
-	-	+	330°	-	+	-	330°
+	-	-	360°	+	-	-	360°

Mode 2: Two – phase ON operation:

- Two phases of stator windings are energized at any time.
- Rotor experiences torque from both phases and comes to rest at any point midway between two adjacent full step positions.

At initial:

- A_1 A_2 is aligned with rotor teeth 1 & 3.

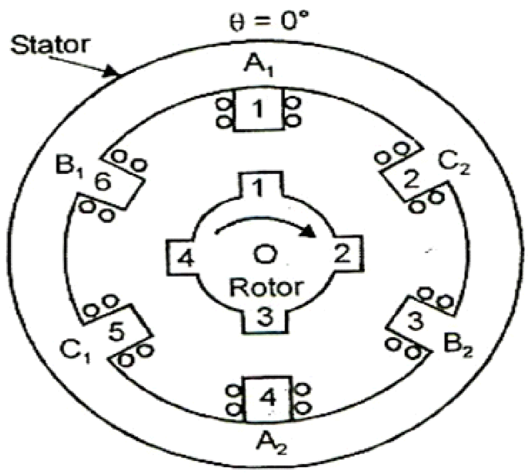


Fig. Initial position

Phase-A & B excited:

- Rotor experiences torque from both A and B phases.
- Rotor moves through an angle of θ = 15˚.
- Clockwise direction.

Phase-B & C excited:

- Rotor experiences torque from both B and C phases.
- Rotor moves through an angle of 30˚.
- Total movement of rotor is θ = 45˚.
- Clockwise direction.

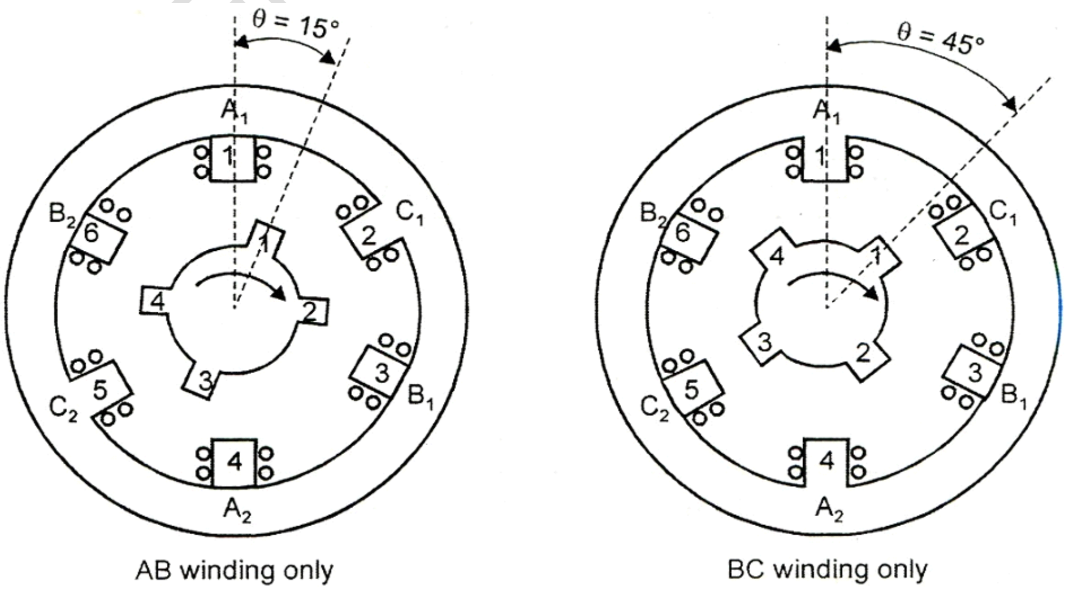


Fig. Two-phase ON mode (Phase-AB & BC)

Phase-C & A excited:

- Rotor experiences torque from both C and A phases.
- Rotor moves through an angle of 30˚.
- Total movement of rotor is θ = 75˚.
- Clockwise direction.

Phase-A & B excited again:

- Rotor experiences torque from both A and B phases.
- Rotor moves through an angle of 30˚.
- Total movement of rotor is θ = 105˚.
- Clockwise direction.

- Stator sequence : **AB, BC, CA – clockwise** direction
- Stator sequence : **AC, CB, BA – anti-clockwise** direction
- Torque developed in two-phase on mode is more than the one-phase mode on.
- In this mode, rotor transient damps more quickly compared to two-phase on mode.

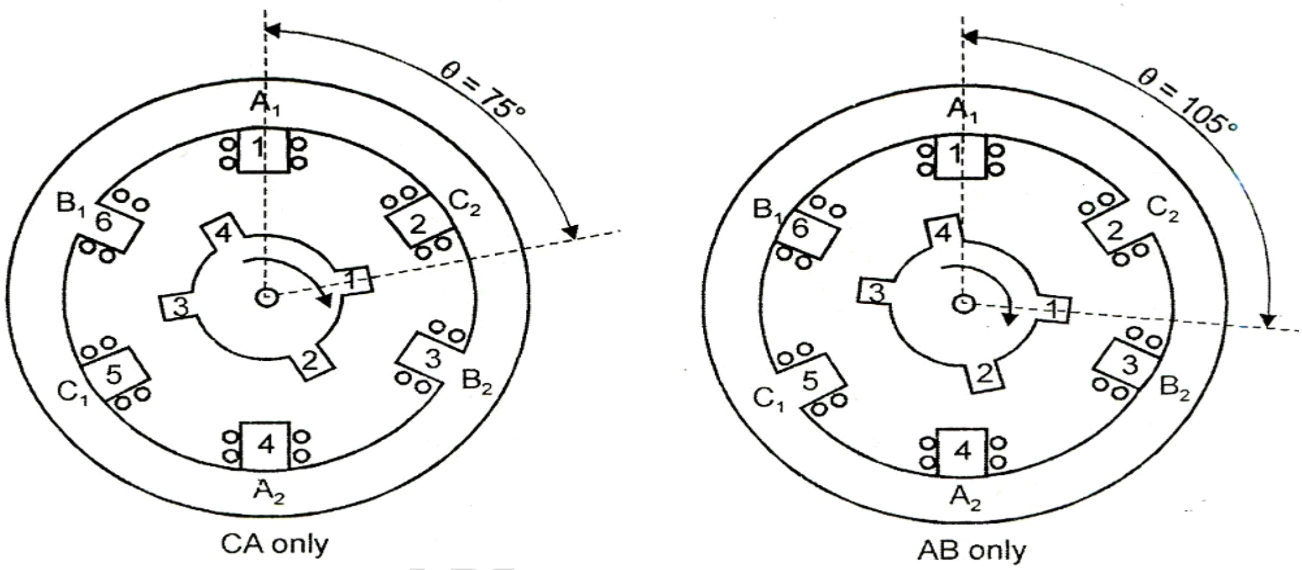


Fig. Two-phase ON mode (Phase-CA & AB)

Table: Truth table for Two-phase ON mode

Clock Wise Direction				Anti Clock Wise Direction			
Phase-A	**Phase-B**	**Phase-C**	**Degree**	**Phase-A**	**Phase-B**	**Phase-C**	**Degree**
+	+	-	15^0	+	-	+	15^0
-	+	+	45^0	-	+	+	45^0
+	-	+	75^0	+	+	-	75^0
+	+	-	105^0	+	-	+	105^0
-	+	+	135^0	-	+	+	135^0
+	-	+	165^0	+	+	-	165^0
+	+	-	195^0	+	-	+	195^0
-	+	+	225^0	-	+	+	225^0

+	-	+	255^0	+	+	-	255^0
+	+	-	285^0	+	-	+	285^0
-	+	+	315^0	-	+	+	315^0
+	-	+	345^0	+	+	-	345^0

Mode 3: Half-step operation:

- Alternately one-step and two-step modes are operated.
- Excitation sequence: A, AB, B, BC, C, CA …. etc.
- Rotor rotates at a step angle of 15˚.

Phase-A excited:

- A_1 A_2 gets aligned with rotor teeth 1 &3.
- Now rotor is at an angle of $\theta = 0˚$.

Phase-A & B excited:

- Phase A and B are excited.
- Rotor moves through an angle of $\theta = 15˚$.
- Clockwise direction.

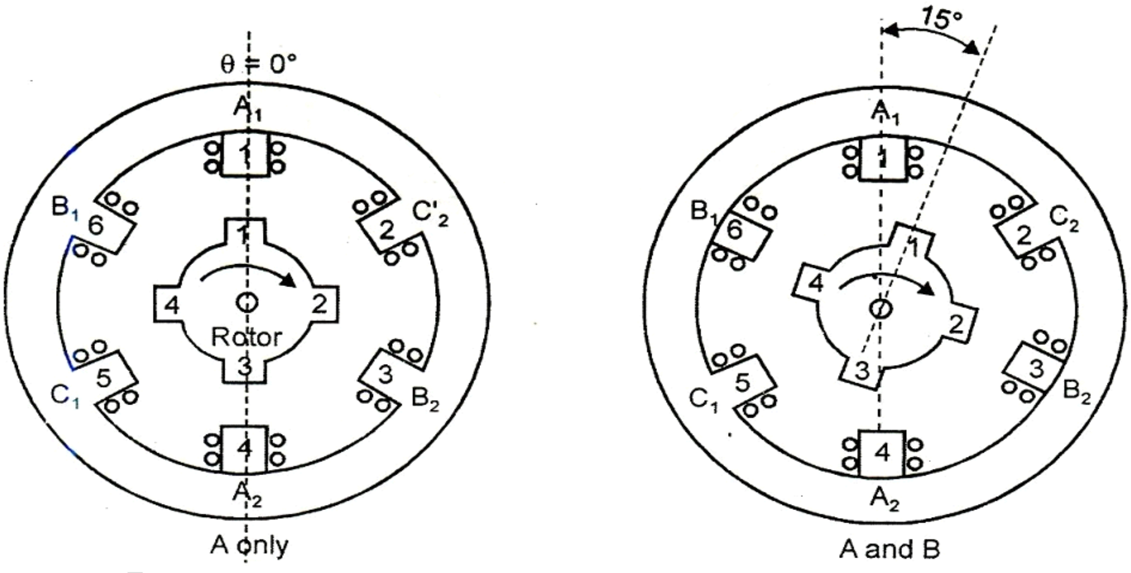


Fig. Half step mode (Phase-A & AB)

Phase- B excited:

- Phase B alone excited and A is de-energized.
- Rotor moves through an angle of 15˚.
- Total rotor movement is $\theta = 30˚$
- Clockwise direction.

Phase- B & C excited:

- Phase B and C are excited.
- Rotor moves through an angle of 15˚.
- Total rotor movement is $\theta = 45˚$
- Clockwise direction.

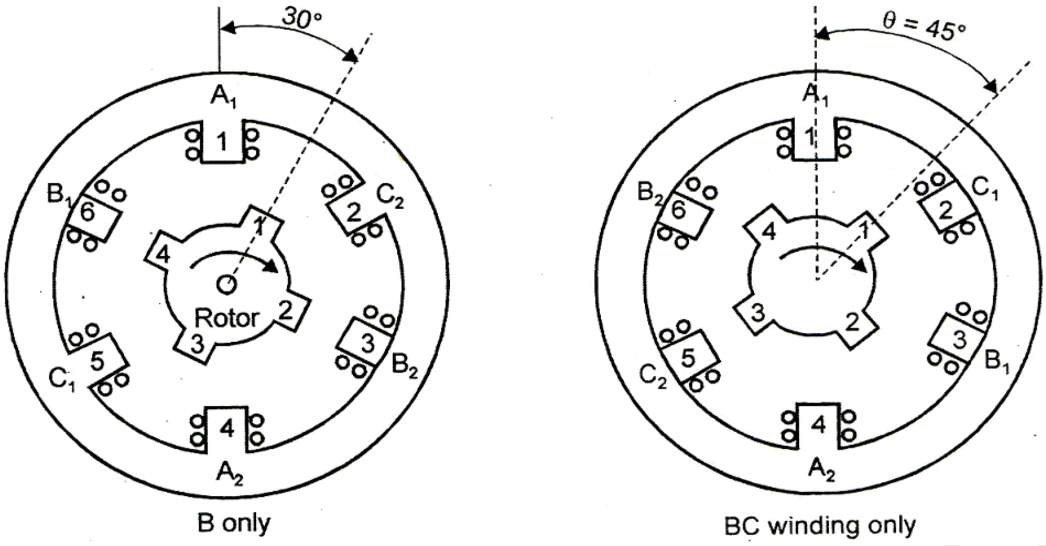


Fig. Half step mode (Phase-B & BC)

- Stator sequence : **A, AB, B, BC, C, CA – clockwise** direction.
- Stator sequence : **A, AC, C, CB, B, BA – anti-clockwise** direction.

Table: Truth table for Half step mode

Clock Wise Direction				**Anti Clock Wise Direction**			
Phase-A	**Phase-B**	**Phase-C**	**Degree**	**Phase-A**	**Phase-B**	**Phase-C**	**Degree**
+	-	-	0^0	+	-	-	0^0
+	+	-	15^0	+	-	+	15^0
-	+	-	30^0	-	-	+	30^0
-	+	+	45^0	-	+	+	45^0
-	-	+	60^0	-	+	-	60^0
+	-	+	75^0	+	+	-	75^0
+	-	-	90^0	+	-	-	90^0
+	+	-	105^0	+	-	+	105^0
-	+	-	120^0	-	-	+	120^0
-	+	+	135^0	-	+	+	135^0
-	-	+	150^0	-	+	-	150^0
+	-	+	165^0	+	+	-	165^0

Mode 4: Micro stepping: **Dec-2013**

- Step angle of VR stepper motor is made very small.
- Also called mini stepping.
- It uses two phases simultaneously, as in two-phase ON mode.
- But the two currents are made unequal.
- Current through Phase –A is made constant and current through phase-B is increased in very small increments until maximum current is reached.
- Then, phase-A is made zero, by decreasing in small increments.

$$when, \quad \beta = 1.8°$$

$$resolution = \frac{360°}{\beta} = \frac{360°}{1.8°} = 200\ steps/revolution$$

$$when, \quad \beta = 0.0018°$$

$$resolution = \frac{360°}{\beta} = \frac{360°}{0.018°} = 20{,}000\ steps/revolution$$

- So fine resolution can be obtained by using microstepping.
- Smooth low speed operation, high resolution.

Applications:

- Printing, photo type setting.

Multi-stack VR stepper motor:

2. Explain in detail the multi stack construction of stepper motor.
May-2016, 2015, 2013, Dec-2016

- Used to obtain the smaller step size in range of 2 to 15˚.
- Stacks vary from 3- 7.
- 3-stack machines are common.

Construction:

- m-stack VR stepper motor has m stacks on stator and m-stacks on rotor.
- Each m-stacks of stators and rotors have same no. of poles (teeth).
- Stator is mounted on a common outer casing.
- Rotor is mounted on a common shaft.

- m-stacks of stator have same pole alignment.
- Each rotor pole is displaced by 1/m of pole pitch from one another.
- Each stack is excited by separate winding. So m-stack machine has m-phases.
- Consider, a 3-stack stepper motor having 12 poles. It has, 3-stacks, 3-phase.
- Each stack has 12 stator and 12 rotor poles.

$$tooth\ pitch = \frac{360°}{N_r} = \frac{360°}{12} = 30°$$

$$step\ angle = \frac{360°}{m\ N_r} = \frac{360°}{3\ x\ 12} = 10°$$

- Each rotor pole is displaced by 10˚.

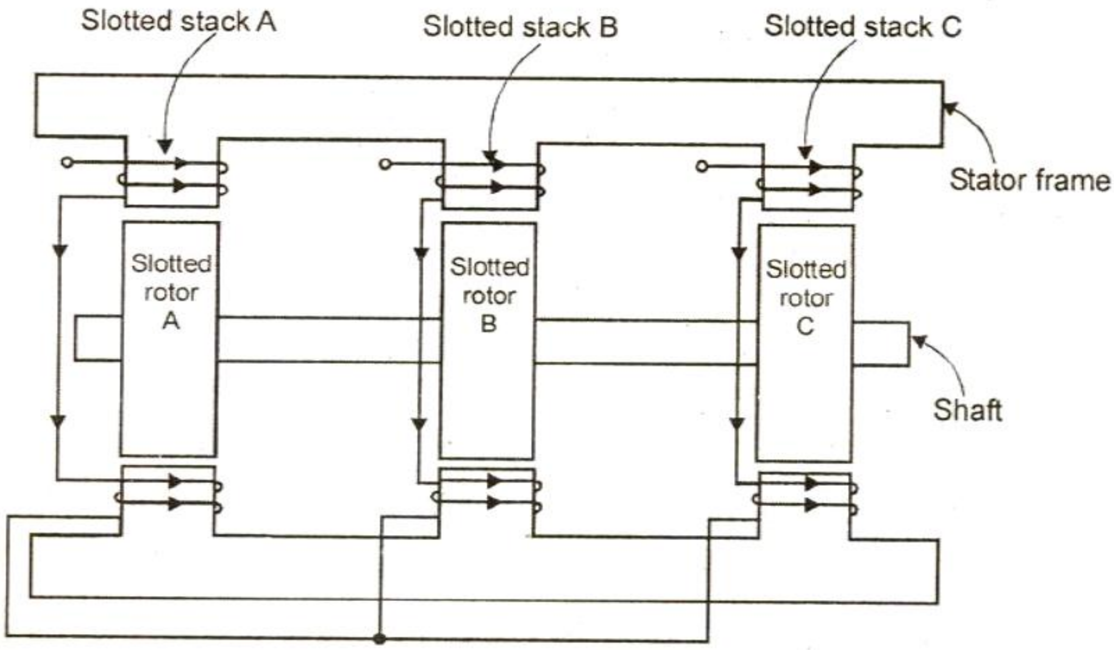


Fig. 3-stack stepper motor

Operation:

Phase-A excited:

- Stack –A gets excited.
- Rotor poles of stack-A gets aligned with stator poles.
- Due to offset, rotor poles of stack-B & C are not aligned.

Phase-B excited:

- Stack –B gets excited.
- Rotor poles of stack-B gets aligned with stator poles.
- Rotor moves by 10˚ in anti-clockwise direction.
- Due to offset, rotor poles of stack-A & C are not aligned.

Phase-C excited:

- Stack –C gets excited.
- Rotor poles of stack-C gets aligned with stator poles.
- Rotor moves by another 10˚ in anti-clockwise direction.
- Due to offset, rotor poles of stack-B & A are not aligned.

Advantages:

- Low rotor inertia
- High torque to inertia ratio
- Capable of high stepping rate
- High speed slewing capability
- Light weight
- 3,4 and 5 phase, single and multi-stack models available
- Ability to freewheel

Disadvantages:

- Normally available in 3.6˚ step angles.
- No detent torque available with windings de-energized.
- Exhibits mid-range resonance at some stepping rated under some drive conditions.
- Low efficiencies at low voltages and stepping rates.

Fig. Operation of 3-stack stepper motor

Permanent Magnet Stepper Motor :

3. Explain the construction and principle of operation of Permanent magnet Stepping motor in detail. Dec-2011

Construction:

Stator:

- Stack of steel laminations
- Projected poles
- Multipolar type

Rotor:

- Permanent magnet.
- Salient pole or cylindrical type.
- Cylindrical type used mostly.
- Made of ferrite or rare earth material.

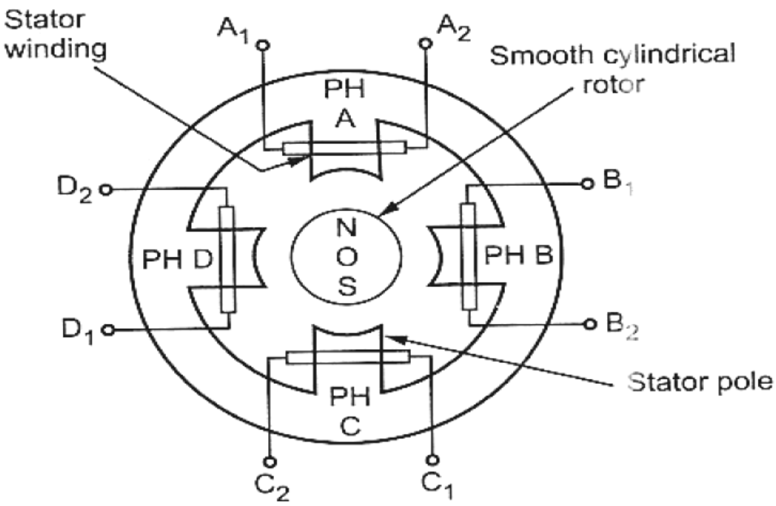


Fig. Construction of Permanent Magnet Stepper motor

Operation:

1-Phase ON mode:

- One of the stator winding is energized.
- Rotor poles move into alignment with energized stator poles.
- Stator windings can be excited with either polarity of current.
- A^+ - positive current flow through the phase winding A.
- A^- - negative current flow through the phase winding A.

Phase A with + current:

- Phase winding A is energized with positive current.
- Angle rotation is zero i.e., $\theta = 0^\circ$.

Phase B with + current:

- Phase B winding is energized with positive current.
- Rotor rotates 90˚ in the clockwise direction i.e., $\theta = 90^0$.

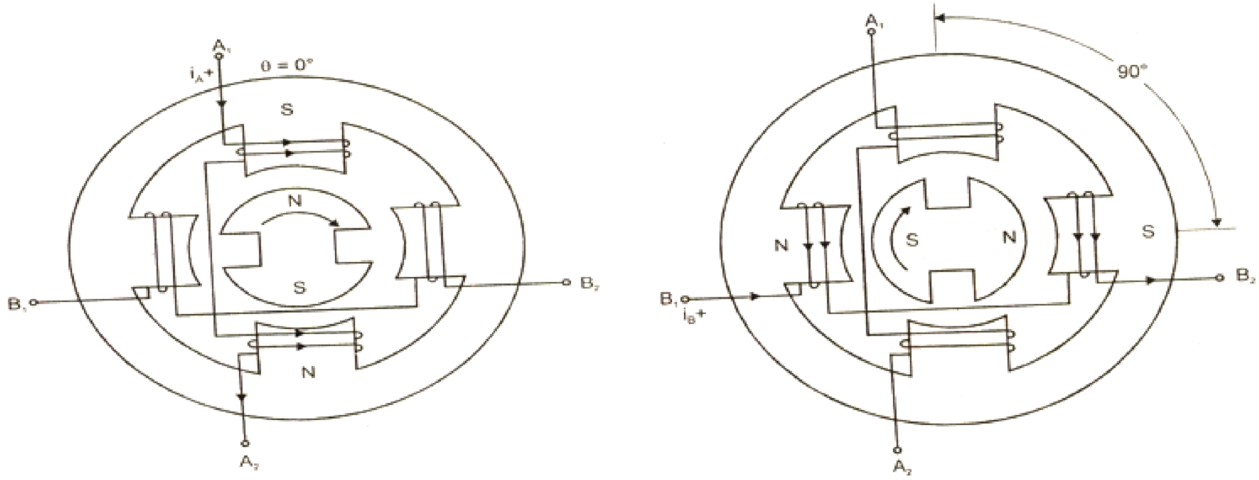


Fig. Phase A & B with + current

Phase A with - current:

- Phase winding A is energized with negative current (ie) current flows from A_2 to A_1.
- Rotor rotates through 90^0 in clockwise direction. $\theta = 180^0$.

Phase B with – current:

- Phase winding B is energized with negative current (ie) current flows from B_2 to B_1.
- Rotor rotates through 90^0 in clockwise direction. $\theta = 270^0$

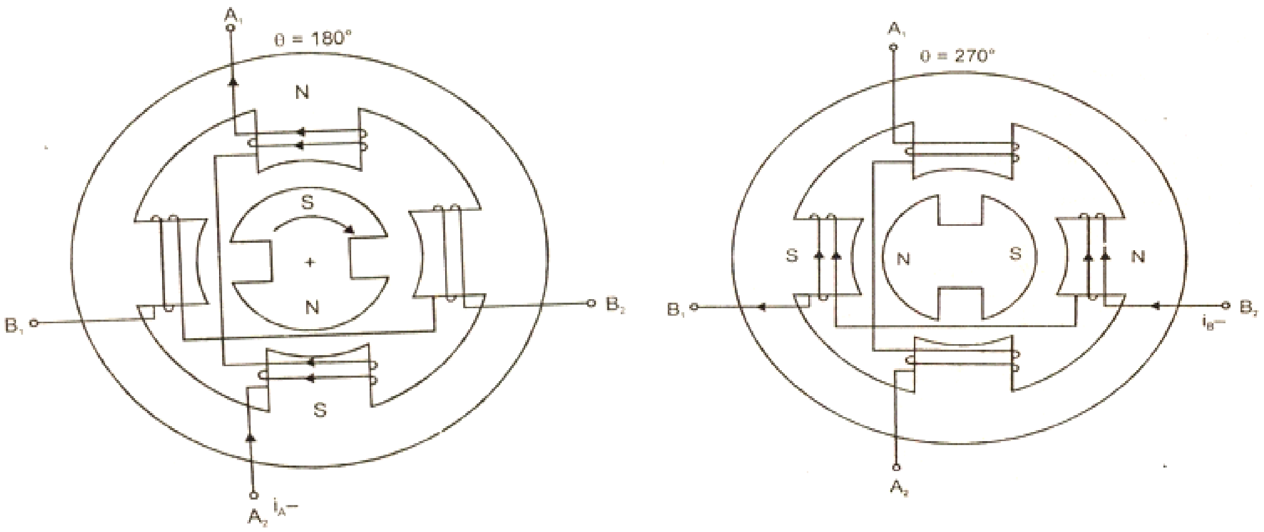


Fig. Phase A & B with - current

- Next the energization of phase winding A with makes the rotor rotates through one complete revolution of 360˚.

Truth table:

Phase A	Phase B	Rotation θ
+	0	0°
0	+	90°
–	0	180°
0	–	270°
+	0	0°

The motor direction depends on the polarity of the phase currents.

Clockwise direction	$I_A^+, I_B^+, I_A^-, I_B^-, I_A^+$
Counter clockwise direction	$I_A^+, I_B^-, I_A^-, I_B^+, I_A^+$

Hybrid Stepper Motor :

4. Explain about the hybrid stepper motor in detail.
Describe the principle of operation of hybrid stepper motor. May-2018

- Combines VR and PM motors.

Construction:

Stator:

- Stator carries concentrated winding like other stepping motors.

Rotor:

- Rotor consists of permanent magnet with North and south poles at each end.
- Along with it, end caps are attached at each end.
- End caps are made of ferromagnetic material.
- Two end caps are misaligned wrt each other by a half toothed pitch.
- They form alternate N and S pole at the rotor.
- North poles at front end are shown in full lines and south poles at far end are shown in dotted lines.

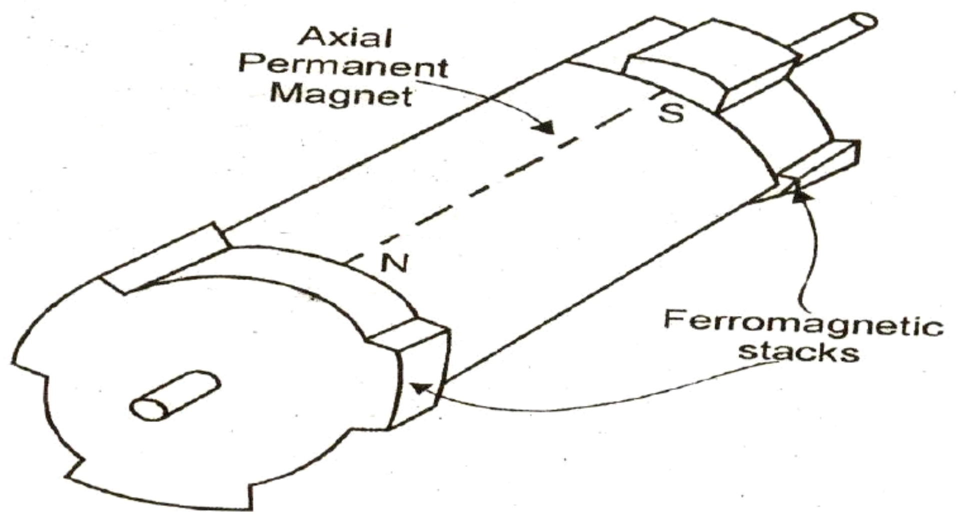


Fig. Construction of Hybrid Stepper motor

Operation:

- Stator has four phases: A_1, A_2, B_1, B_2.
- Two phases: phase-A, Phase-B

Phase- A excited with +ve current:

- Pole A_1 – north pole A_2 – south pole.
- A_1 attracts far end south pole.
- A_2 attracts front end north pole
- Rotor rotation = 0˚.

Phase- B excited with +ve current:

- Pole B_1 – north pole, B_2 – south pole.
- B_1 attracts far end south pole.
- B_2 attracts front end north pole
- Rotor rotation = 30˚.
- Total rotor rotation, $\theta = 30^\circ$
- Clockwise direction.

Phase- A excited with -ve current:

- Pole A_1 – south pole A_2 – North pole.
- A_1 attracts front end north pole
- A_2 attracts far end south pole.
- Rotor rotation = 30˚.
- Total rotor rotation, $\theta = 60^\circ$

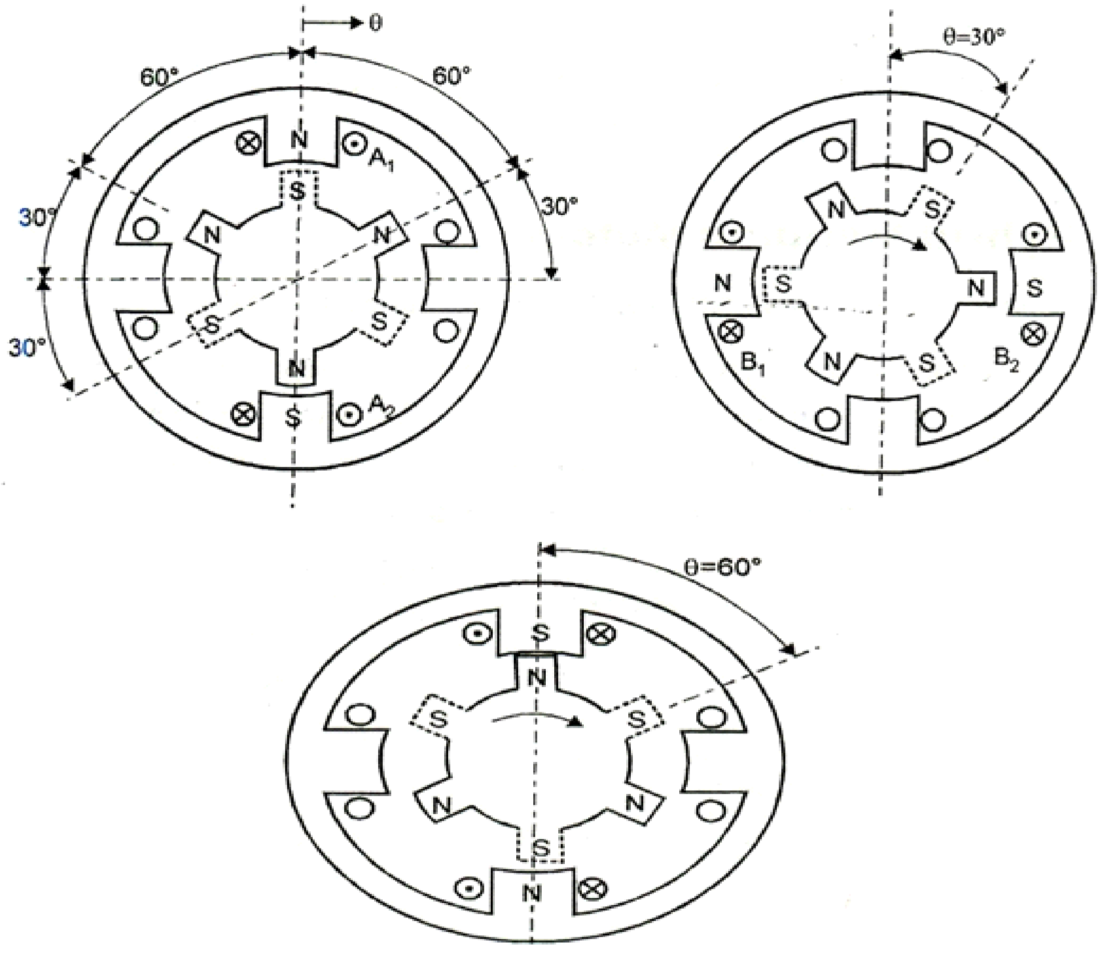


Fig. Operation of Hybrid stepper motor

- **A_1 B_1 A_2 B_2 A_1 - clockwise** direction.
- **A_1 B_2 A_2 B_1 A_1 – anti-clockwise** direction.

Advantages of hybrid stepper motor:

- Provide détente torque with windings de-energized.
- Fewer tendencies to resonate.
- High stepping rate capability.
- High efficiency at lower steeds and lower stepping rates.
- Higher holding torque capability.
- Better damping due to presence of rotor magnet.

Disadvantages of hybrid stepper motor:

- Higher inertia and weight due to presence of rotor magnet.
- Performance affected by change in magnet strength.

Torque Equations:

5. Derive the torque equations of the variable reluctance motor and illustrate the various dependent parameters. **Dec-2014**

Explain the mechanism of static torque production in a variable reluctance stepping motor **May-2018**

Theory of torque production in Variable reluctance stepper motor:

By faradays law,

$$e = -\frac{\partial \lambda}{\partial t}$$

$$= -\frac{\partial Li}{\partial t} \qquad (since\ \lambda = Li = N\varphi)$$

$$= -L\frac{\partial i}{\partial t} - i\frac{\partial L}{\partial t}$$

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

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

$$Magnitude\ of\ e = L\frac{\partial i}{\partial t} + i\,\omega\frac{\partial L}{\partial \theta}$$

$$stored\ energy\ in\ magnetic\ field, \qquad W_e = \frac{1}{2}L\,i^2$$

$$power\ due\ to\ variation\ in\ stored\ energy = \frac{\partial W_e}{\partial t}$$

$$= \frac{\partial\left(\frac{1}{2}Li^2\right)}{\partial t}$$

$$= \frac{1}{2}L\ \ 2i\frac{\partial i}{\partial t} + \frac{1}{2}i^2\frac{\partial L}{\partial t}$$

$$= Li\frac{\partial i}{\partial t} + \frac{1}{2}i^2\frac{\partial L}{\partial t}$$

$$input\ power\ from\ electrical\ source\ = e\,i$$

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

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

Input power = mechanical power (P_m) + power due to change in stored energy

P_m = input power – power due to change in stored energy

$$P_m = Li\frac{\partial i}{\partial t} + i^2\,\omega\frac{\partial L}{\partial \theta} - Li\frac{\partial i}{\partial t} - \frac{1}{2}i^2\frac{\partial L}{\partial t}$$

$$= Li\frac{\partial i}{\partial t} + i^2\,\omega\frac{\partial L}{\partial \theta} - Li\frac{\partial i}{\partial t} - \frac{1}{2}i^2\frac{\partial L}{\partial \theta}\frac{\partial \theta}{\partial t}$$

$$P_m = i^2\,\omega\frac{\partial L}{\partial \theta} - \frac{1}{2}i^2\omega\frac{\partial L}{\partial \theta}$$

$$P_m = \frac{1}{2}i^2\omega\frac{\partial L}{\partial \theta}$$

$$P_m = \omega\,T$$

$$\Rightarrow\ T = \frac{P_m}{\omega} = \frac{1}{2}\frac{i^2\omega}{\omega}\frac{\partial L}{\partial \theta}$$

$$\boxed{\boldsymbol{T = \frac{1}{2}i^2\frac{\partial L}{\partial \theta}}}$$

(i) *For motoring*, $\frac{\partial L}{\partial \theta} \rightarrow +ve$

(ii) *For generator*, $\frac{\partial L}{\partial \theta} \rightarrow -ve$

(iii) $T\ \alpha\ i^2$

Modes of Excitations:

6. Explain briefly the various modes of excitation of variable reluctance motor.May-2014

Describe the operation of variable reluctance type stepper motor with different modes of operation. Dec-2015

Explain the modes of excitation of a stepper motor with neat diagram. Dec-2016

Single phase excitation:

- One phase is excited at a time.
- The shaded parts represent the excited state and un shaded part represents the phases which current is not supplied.
- For clockwise rotation, the excitation sequence is Ph1, Ph2, Ph3, …
- For anti clockwise rotation, the excitation sequence is Ph3, Ph2, Ph1, ..

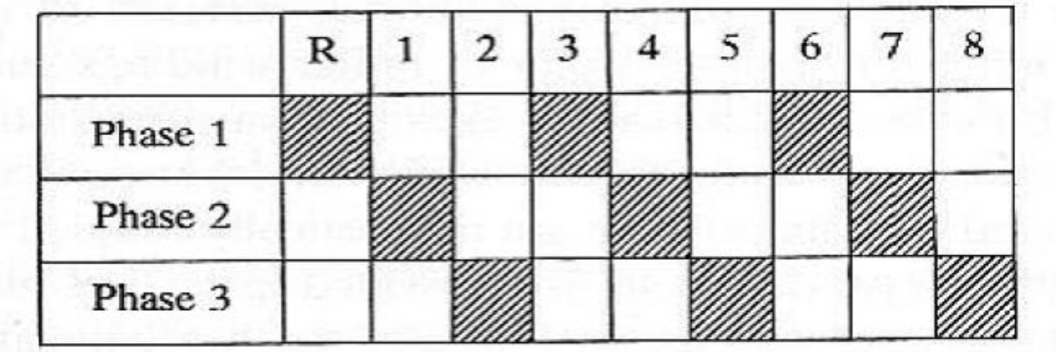


Fig. Single phase excitation sequence for 3-phase VR motor

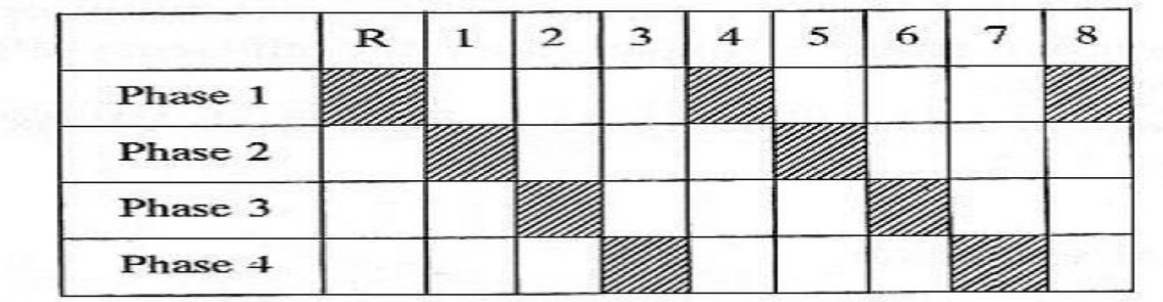


Fig. Single phase excitation sequence for 4-phase VR motor

Two phase excitation:

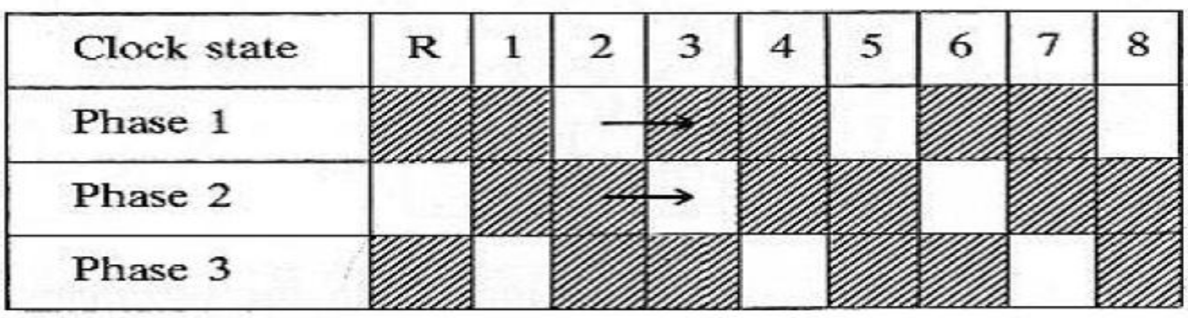


Fig. Two phase excitation sequence for 3-phase VR motor

Clock state	R	1	2	3	4	5	6	7	8
Phase 1	■	■			■	■			■
Phase 2		■	■			■	■		
Phase 3			■	■			■	■	
Phase 4	■			■	■			■	■

Fig. Two phase excitation sequence for 4-phase VR motor

Half step excitation:

- Combination of the single phase and two phase excitation is called as half step excitation.
- The number of clock states are taken in two methods as method 1 and method 2.

Clock state (A)	R	1		2		3		4		5	
Clock state (B)	R	1	2	3	4	5	6	7	8	9	
Phase 1	■	■				■	■	■			
Phase 2		■	■	■				■	■	■	
Phase 3				■	■	■				■	■

Fig. Half step excitation sequence for 3-phase VR motor

Excitation by a bridge circuit:

- In the unipolar drive of a bifilar-wound hybrid motor, the windings are not fully utilized.
- Complete utilization of the windings by means of the bipolar drive considerably increases motor output power.

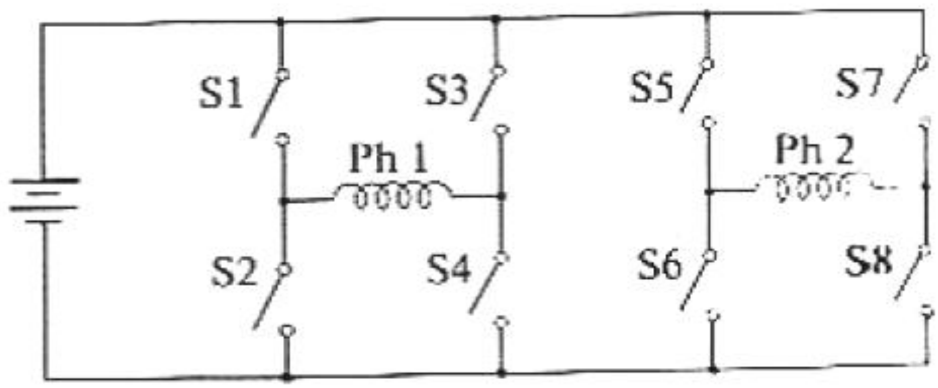


Fig. Bridge driver circuit for two-phase stepping motor

Clock state	R	1	2	3	4	5	6	7	8
S1	■	■			■	■			■
S2			■	■			■	■	
S3			■	■			■	■	
S4	■	■			■	■			
S5		■	■			■	■		
S6	■			■	■			■	■
S7	■			■	■			■	■
S8		■	■			■	■		

Fig. Excitation sequence for the bridge circuit operation for a two-phase motor

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Characteristics:

7. Explain briefly various characteristics of stepper motor? Dec – 2011

Compare the static and dynamic characteristics of stepper motor with necessary diagrams. May-2016, 2015

Explain in detail, the static and dynamic characteristics of a stepper motor. Dec-2016

Describe the dynamic characteristics of a variable reluctance stepper motor. May-2018

Stepper motor characteristics are divided into two groups.

- Static characteristics
- Dynamic characteristics

Static Characteristics:

- Torque-angle curve
- Torque-current curve

Torque-Angle Curve:

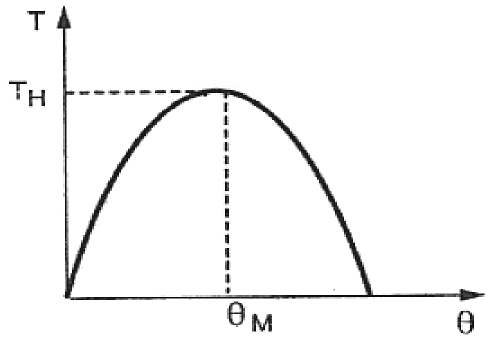


Fig. Torque-angle curve

- Torque increases sinusoidally with angle θ from equilibrium position.

Holding torque:

The maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. It is denoted as T_H.

If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the next stable equilibrium position.

Detent torque:

The maximum load torque which is unenergized stepper motor can withstand without slipping. It is denoted as T_D.

Detent torque occurs due to the residual magnetism present in the stepper motor.

Torque-Current Curve:

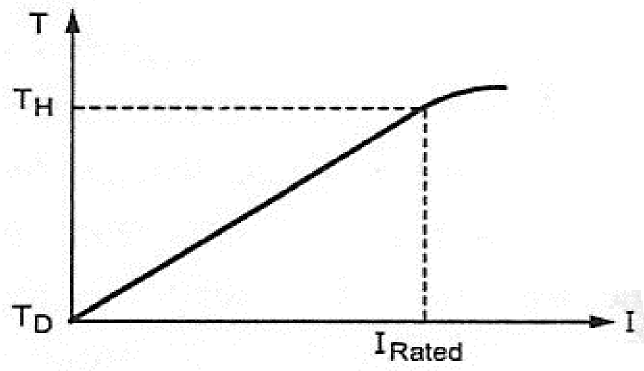


Fig. Torque-current curve

Curve is initially linear but later slope decreases as magnetic circuit saturates.

- Torque constant of the stepper is defined as the initial slope of the torque-current curve of the stepper motor.
- It is denotes as it is also called as torque sensitivity.
- Its units are N-m/A, Kg-cm/A.

Dynamic Characteristics:

- Characteristics of motor relating to motors which are in motion or about to start.

A stepper motor is said to be operating in synchronism when there exists one-one correspondence between the number of pulses applied and number of steps through which motor has actually moved.

The two modes of operation in dynamic characteristics are

- Start-stop mode
- Slewing mode

Start-stop mode:

- It is also called as pull in curve.
- In this mode, a second pulse is given to the stepper motor only after the rotor attains the rest position due to first pulse.

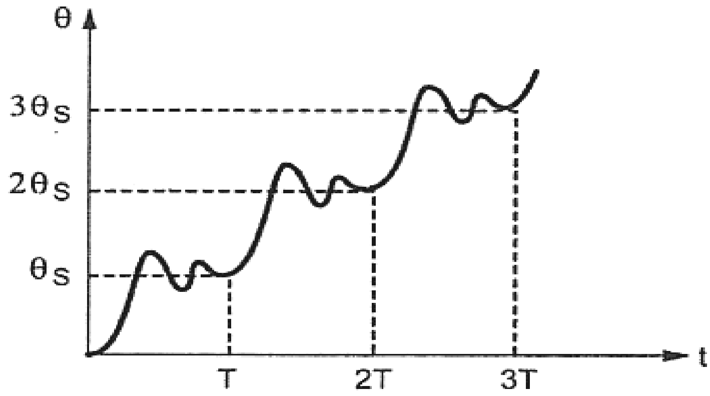


Fig. Start-stop mode

Slewing mode:

- In slewing mode of operation, second pulse is given to the rotor before the motor has attained rest position due to first pulse.
- Motor can run at faster rate in start stop mode.

- To operate the motor in slewing mode, motor is started at start-stop mode, then increase the stepping rate to attain slewing mode.
- To stop the motor, bring motor to start-stop mode and then stop giving the pulses.

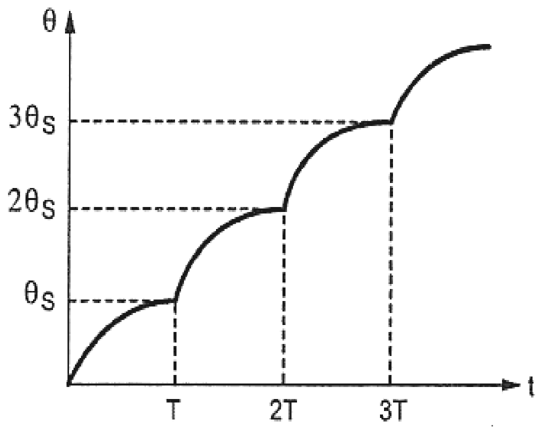


Fig. Slewing mode

The dynamic characteristic of the stepper motor is shown below:

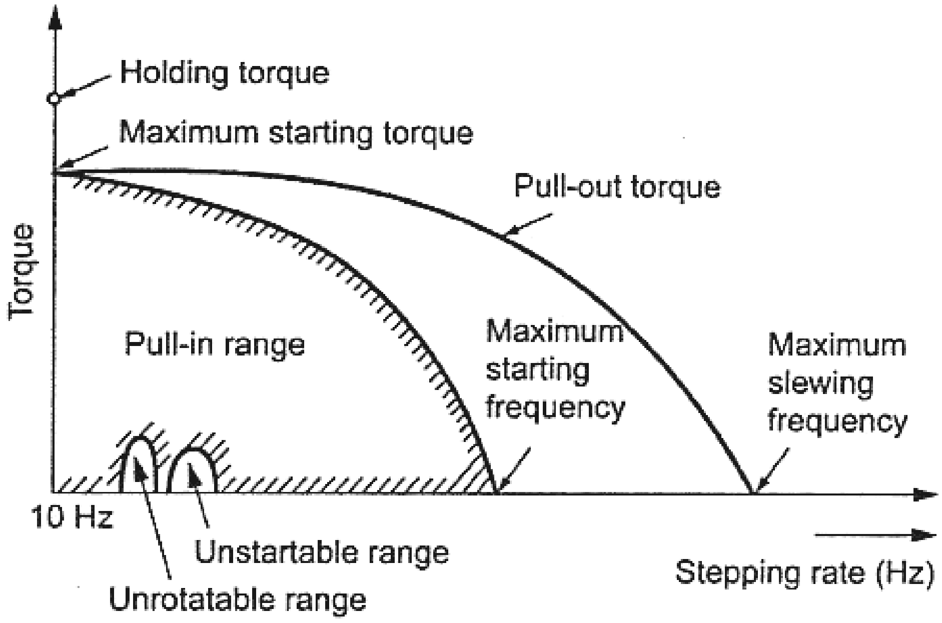


Fig. Dynamic characteristics

Pull in torque characteristics:

Range of load torque at which motor can start and stop without losing synchronism.

Pull out characteristics:

Relation between load torque and maximum frequency with which motor can synchronize.

Maximum starting frequency:

Maximum frequency at which unloaded motor can start and stop without losing steps.

Maximum slewing frequency:

Maximum frequency at which unloaded motor can slew without losing steps.

Maximum starting torque:

Maximum load torque with which the motor can start and synchronize with pulse train of 10 Hz frequency.

Torque-Speed Characteristics:

There are two curves:

- Pull in curve – ABC
- Pull out curve – ADE

OABCO – region for start-stop mode
ABCEDA – region for slewing mode

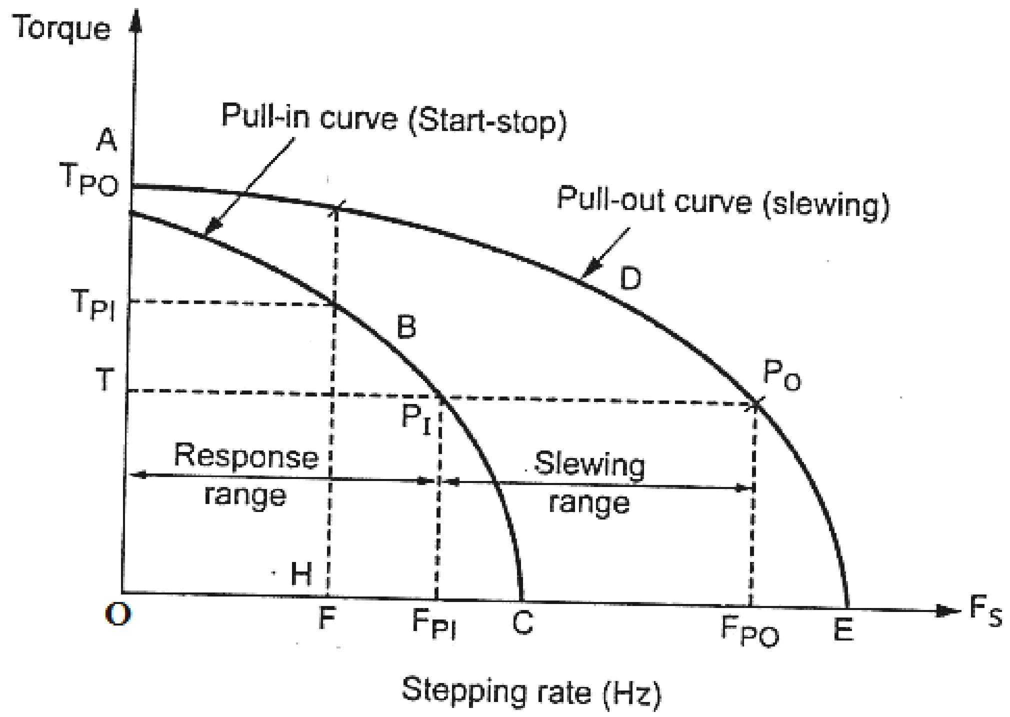


Fig. Torque-speed characteristics

Pull in torque:

Maximum torque developed by the stepper motor for a given frequency in start-stop mode without losing synchronism. (T_{PI}).

Pull out torque:

Maximum torque developed by the stepper motor for a given frequency in slewing mode without losing synchronism. (T_{PO}).

Pull in range:

Maximum stepping rate at which the stepper motor can operate in start-stop mode developing a specific load torque. It is also known as response range.

Pull out range:

Maximum stepping rate at which stepper motor can operate in slewing mode developing a specific load torque. It is also known as slewing range.

Pull in rate:

Maximum stepping rate at which stepper motor can start or stop against a given load torque without losing synchronism.

Pull out torque:

Maximum stepping rate at which stepper motor will slew against a given load torque without losing synchronism.

Mid-frequency resonance:

In the pull-curve of a stepper motor, suddenly dips very low in a particular range of stepping rates. This phenomenon is known as mid-frequency resonance.

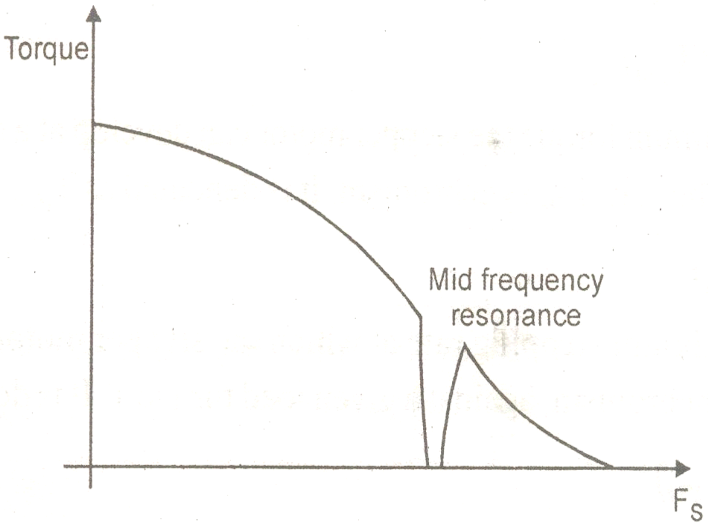


Fig. Mid-frequency resonance

Drive circuits:

8. Explain briefly drive circuits for stepping motor? Dec-2010, May–2012

- Drive system
- Logic sequencer
- Motor driver circuit
    - Connection of sequencer and driver
    - Problems with drivers
    - Suppressor circuit
    - Power driver circuit

Drive system:

- When a step command pulse is applied to the logic sequencer, the output terminals are changed which control the motor driver so as to rotate the motor in desired direction.
- The rotational direction is determined by the logic state at the direction input.
- High level (H) for clockwise (CW) direction and Low level (L) for anticlockwise (CCW) direction.
- In some applications, logic sequencer is unidirectional, having no direction signal terminal.
-

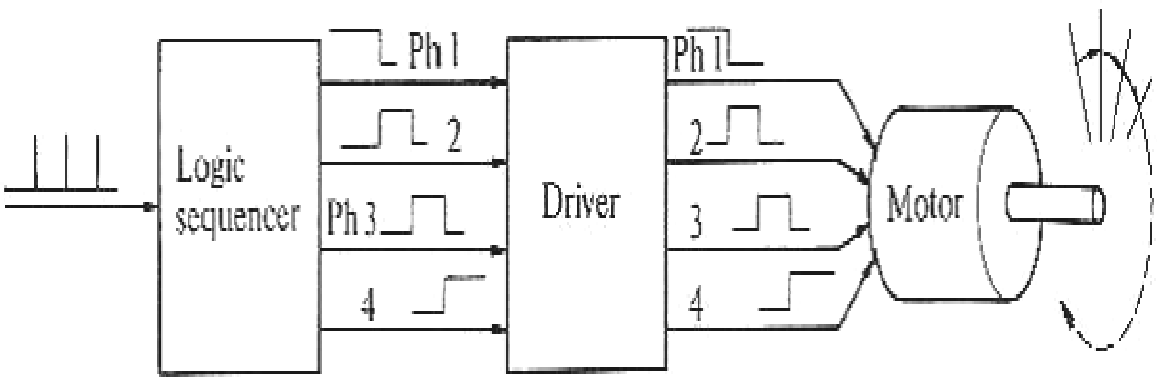


Fig. Drive system of a stepper motor

Logic Sequencer:

- Logic circuit which controls the excitation of windings sequentially, responding to step command pulses.
- Composed of a shift register (JK flip flop) and logic gates such as NAND, NOR etc. Nowadays purpose built logic sequencer ICs are available.
- Eg. Sanyo PMM8713.

(a) Two-phase on sequencer for a four-phase motor:

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

$$Q1 \quad - \quad Ph1$$
$$Q2 \quad - \quad Ph2$$
$$\overline{Q1} \quad - \quad Ph3$$
$$\overline{Q2} \quad - \quad Ph4$$

- If Q1 is in H level, the phase winding Ph1 is excited. If Q1 is in L level, the phase winding Ph1 is not excited.

	R	1	2	3	4	5	6	···
Ph1, Q1	0	1	1	0	0	1	1	···
Ph2, Q2	0	0	1	1	0	0	1	···
Ph3, $\overline{Q1}$	1	0	0	1	1	0	0	···
Ph4, $\overline{Q2}$	1	1	0	0	1	1	0	···

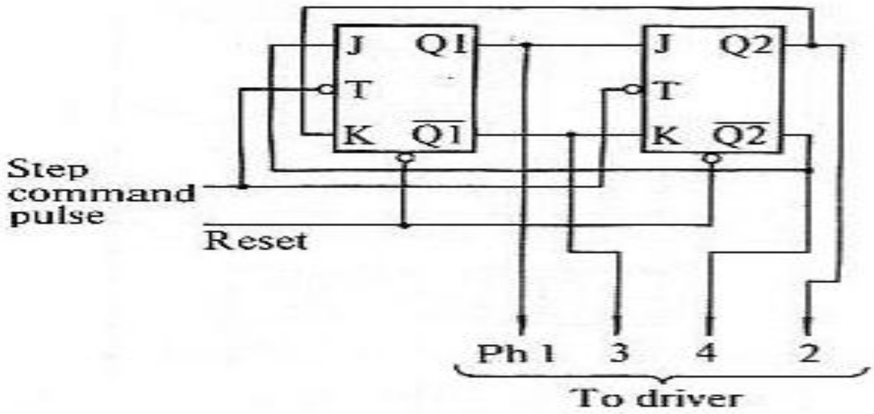


Fig. Unidirectional logic sequencer for two-phase on operation of a four-phase motor (clockwise operation)

	R	1	2	3	4	5	6	···
Ph1, Q1	0	0	1	1	0	0	1	···
Ph2, Q2	0	1	1	0	0	1	1	···
Ph3, $\overline{Q1}$	1	1	0	0	1	1	0	···
Ph4, $\overline{Q2}$	1	0	0	1	1	0	0	···

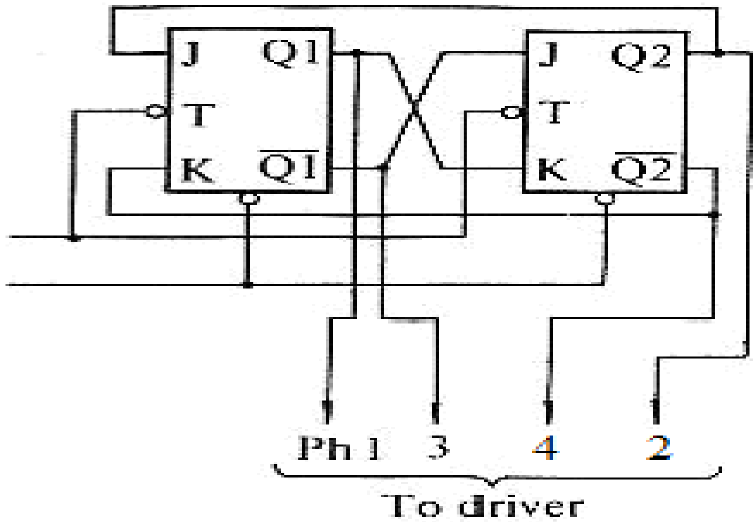


Fig. Unidirectional logic sequencer for two-phase on operation of a four-phase motor (anti-clockwise operation)

To reverse the rotational direction, connections of the sequencer must be interchanged. Also direction switching circuit can also be used as shown below.

Directional signal = H, C = A (clockwise)

Directional signal = L, C = B (anti-clockwise)

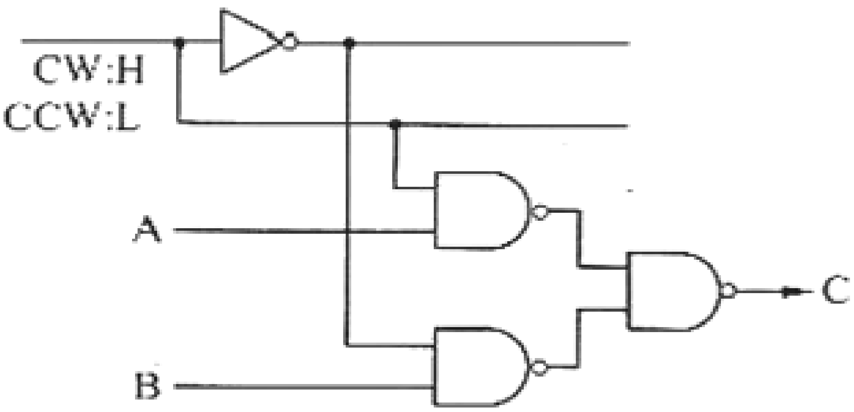


Fig. Logic selector circuit for rotational direction

$$Directional\ signal\ = H, \quad C = \overline{A} \quad (clockwise)$$
$$Directional\ signal\ = L, \quad C = \overline{B} \quad (anti-clockwise)$$

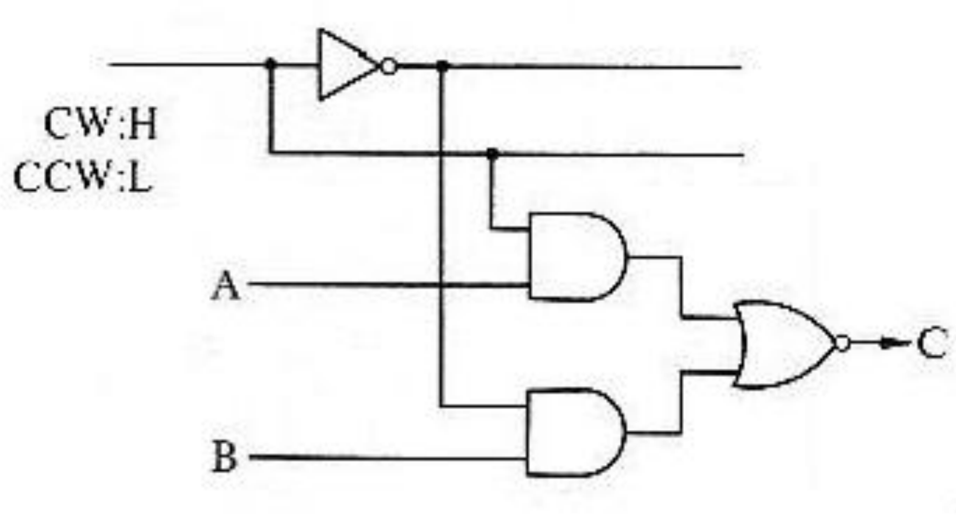


Fig. Logic selector circuit for rotational direction

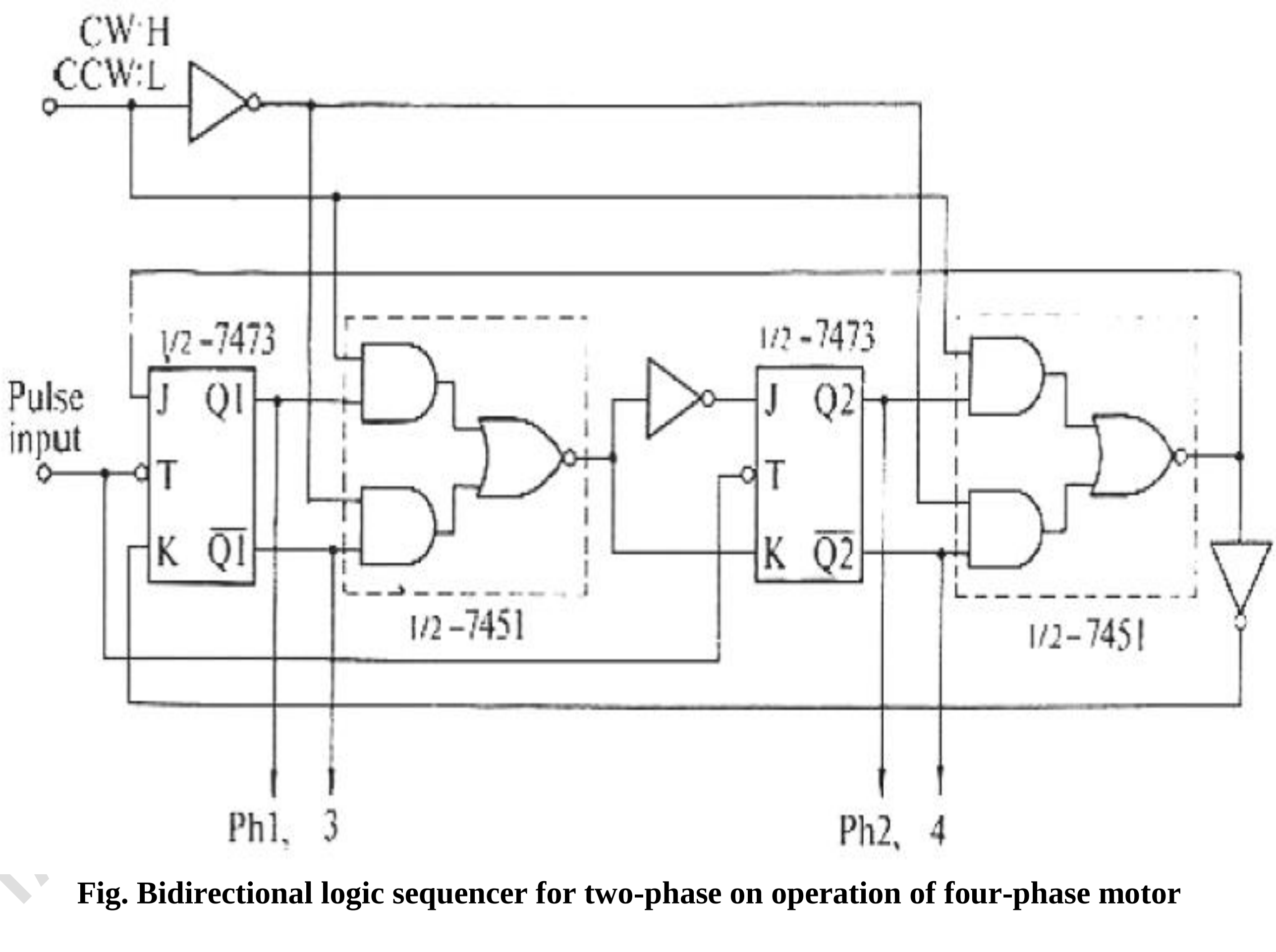


Fig. Bidirectional logic sequencer for two-phase on operation of four-phase motor

(b) Single-phase on sequencer for a four-phase motor:

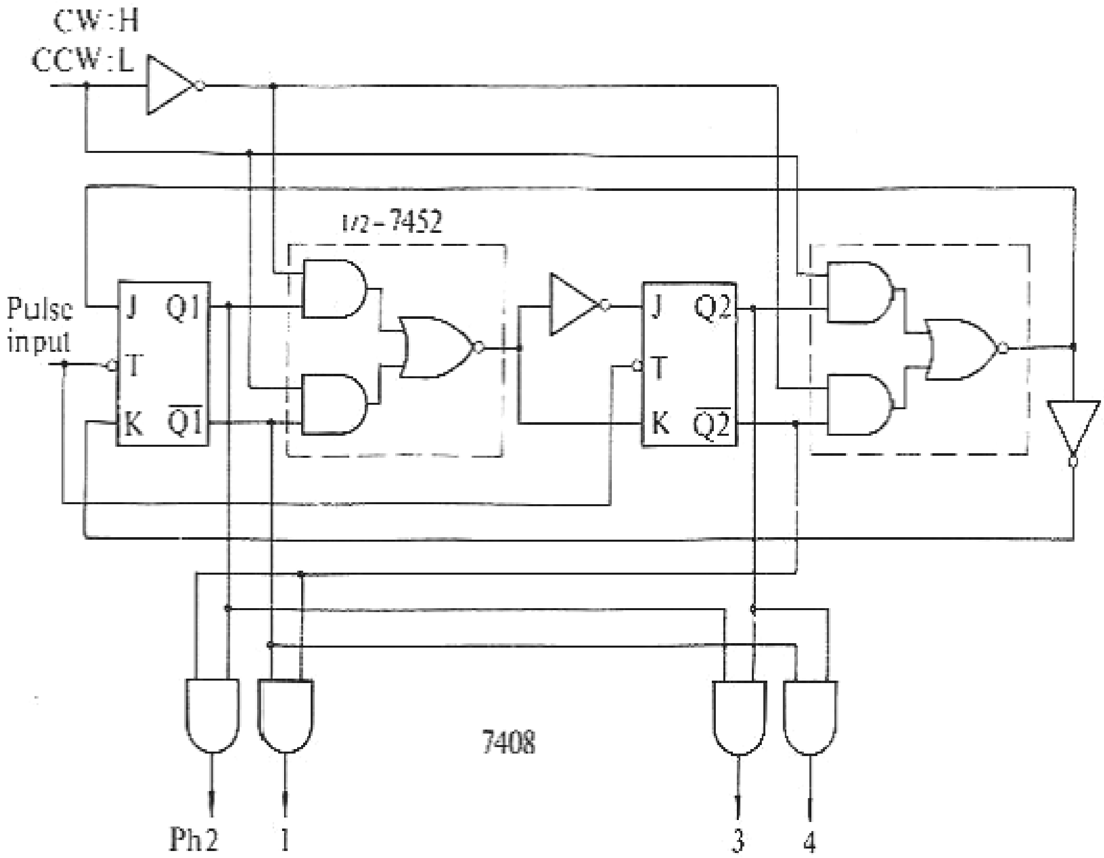


Fig. Bidirectional logic sequencer for single-phase on operation of four-phase motor

CW

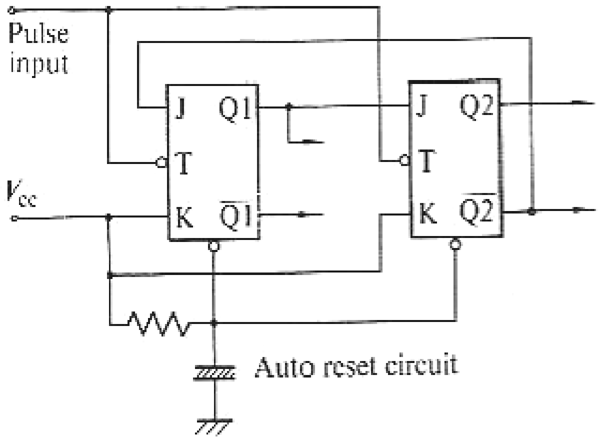
		R	1	2	3	4	5	6	···
	Q_1	0	1	0	1	0	1	0	···
	$\overline{Q}_1$	1	0	1	0	1	0	1	···
	Q_2	0	0	1	1	0	0	1	···
	$\overline{Q}_2$	1	1	0	0	1	1	0	···
Ph1	$\overline{Q}_1 \cdot \overline{Q}_2$	1	0	0	0	1	0	0	···
Ph2	$Q_1 \cdot \overline{Q}_2$	0	1	0	0	0	1	0	···
Ph3	$\overline{Q}_1 \cdot Q_2$	0	0	1	0	0	0	1	···
Ph4	$Q_1 \cdot Q_2$	0	0	0	1	0	0	0	···

CCW

		R	1	2	3	4	5	6	···
	Q_1	0	1	0	1	0	1	0	···
	$\overline{Q}_1$	1	0	1	0	1	0	1	···
	Q_2	0	1	1	0	0	1	1	···
	$\overline{Q}_2$	1	0	0	1	1	0	0	···
Ph1	$\overline{Q}_1 \cdot \overline{Q}_2$	1	0	0	0	1	0	0	···
Ph2	$Q_1 \cdot \overline{Q}_2$	0	0	0	1	0	0	0	···
Ph3	$\overline{Q}_1 \cdot Q_2$	0	0	1	0	0	0	0	···
Ph4	$Q_1 \cdot Q_2$	0	1	0	0	0	1	0	···

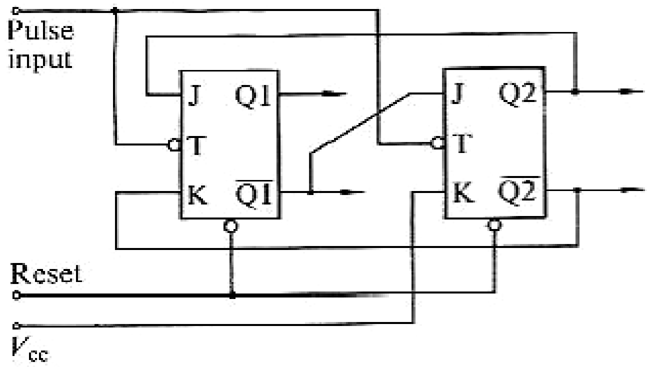
Fig. Bidirectional logic sequencer for single-phase on operation of four-phase motor

(c) Single-phase on sequencer for a three-phase motor:



		R	1	2	3	4	5	...
	Q_1	0	1	0	0	1	0	...
	$\bar{Q}_2$	1	0	1	1	0	1	...
	Q_2	0	0	1	0	0	1	...
	$\bar{Q}_2$	1	1	0	1	1	0	...
Ph1	$\bar{Q}_1 . \bar{Q}_2$	1	0	0	1	0	0	...
Ph2	$Q_1 . \bar{Q}_2$	0	1	0	0	1	0	...
Ph3	$\bar{Q}_1 . Q_2$	0	0	1	0	0	1	...

Fig. Unidirectional logic sequencer for single-phase on operation of three-phase motor (clockwise)



		R	1	2	3	4	5	...
	Q_1	0	0	1	0	0	1	...
	$\bar{Q}_1$	1	1	0	1	1	0	...
	Q_2	0	1	0	0	1	0	...
	$\bar{Q}_2$	1	0	1	1	0	1	...
Ph1	$\bar{Q}_1 . \bar{Q}_2$	1	0	0	1	0	0	...
Ph2	$Q_1 . \bar{Q}_2$	0	0	1	0	0	1	...
Ph3	$\bar{Q}_1 . Q_2$	0	1	0	0	1	0	...

Fig. Unidirectional logic sequencer for single-phase on operation of three-phase motor (anti-clockwise)

(d) Two-phase on sequencer for a three-phase motor:

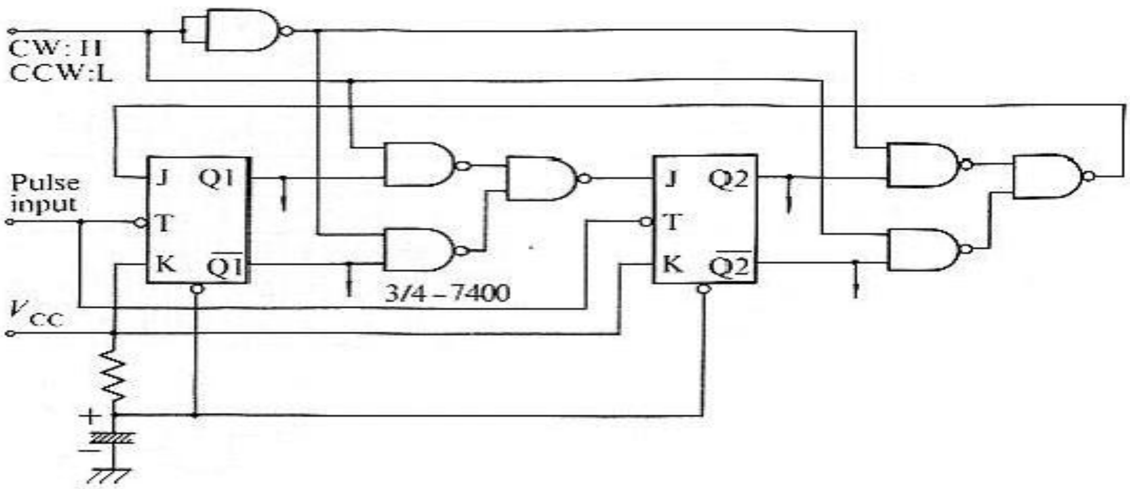
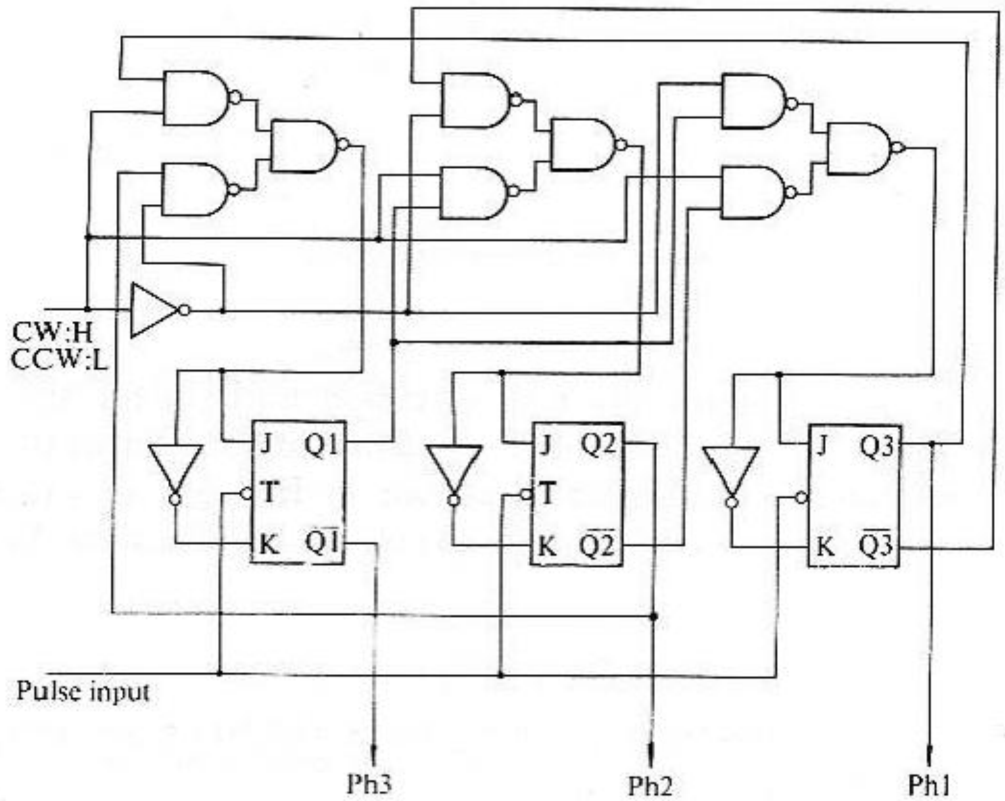


Fig. Bidirectional logic sequencer for two-phase on operation of three-phase motor

(e) Half-step sequencer for a three-phase motor:



CW

		R	1	2	3	4	5	6	7
Ph1,	$\overline{Q1}$	1	1	0	0	0	1	1	1
Ph2,	Q2	0	0	0	1	1	1	0	0
Ph3,	Q3	0	1	1	1	0	0	0	1

CCW

		R	1	2	3	4	5	6	7
Ph1,	$\overline{Q1}$	1	1	0	0	0	1	1	1
Ph2,	Q2	0	1	1	1	0	0	0	1
Ph3,	Q3	0	0	0	1	1	1	0	0

Fig. logic sequencer for half-step operation of three-phase motor

Motor driver circuit:

(a) Connection of sequencer and driver:

Output signals of the logic sequencer are transmitted to the input terminals of the power driver, by which on/off of the motor windings is governed.

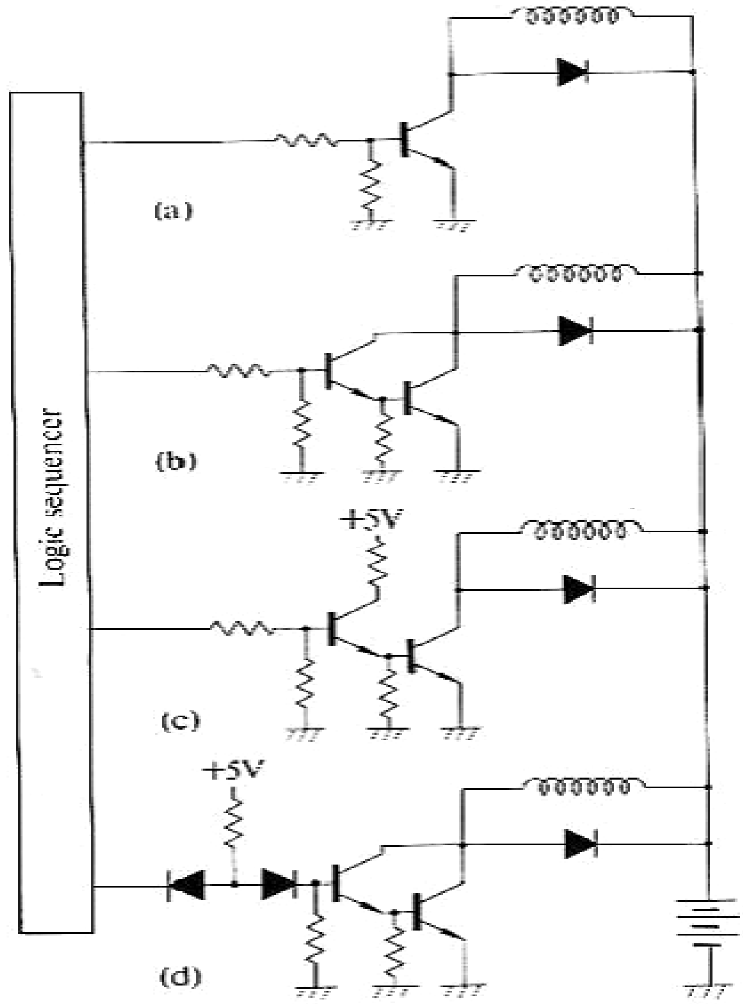


Fig. Connection between sequencer and driver

(b) Problems with drivers:

- A winding on a stepping motor is inductive and appears as a combination of inductance and resistance in series.
- In addition, as motor revolves, a counter emf is produced in the winding.
- On designing the power driver, one must consider power transistors, supply voltages, motor parameters and case temperature.

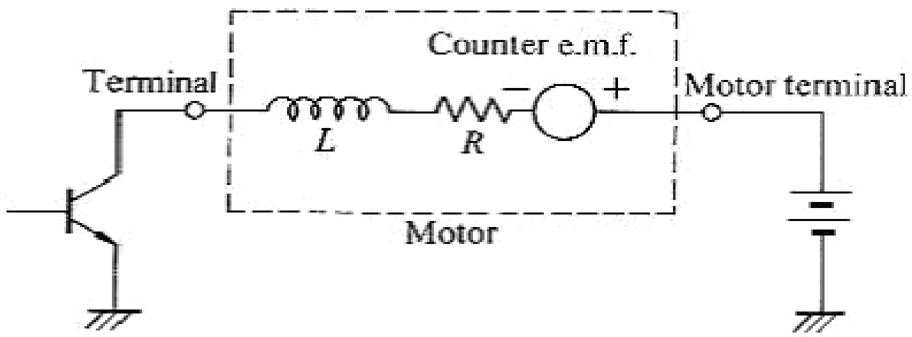


Fig. Equivalent circuit to a winding of a stepping motor

(c) Suppressors:

- When the transistor in driver circuit is turned off, a high voltage builds up due to L(di/dt).
- This voltage may damage transistor.
- There are several methods available to suppress this spike voltage and protect the transistor.

(1) Diode suppressor:

- Diode parallel with winding.
- At turn-off, circulating current flows as shown and decays.
- Takes long time for decay

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

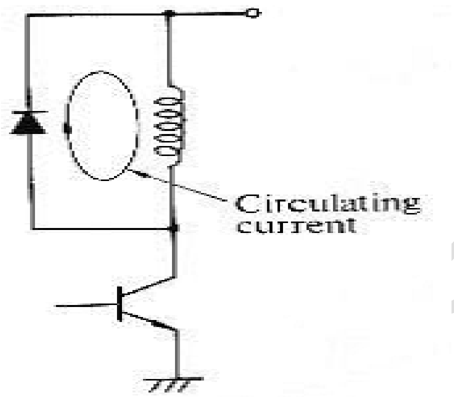


Fig. Diode suppressor

(2) Diode/resistor suppressor:

- Resistor in series with diode.
- Higher the resistance R_s, quicker the current decay after the turn-off.
- Needs high potential for decay.

$$V_{CE} = E + IR_s + V_{DF}$$

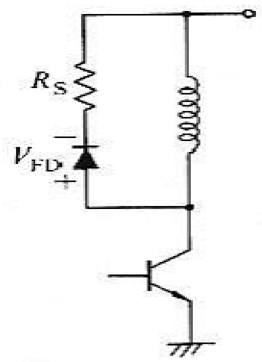


Fig. Diode/resistor suppressor

(3) Zener diode with suppressor:

- Zener diode in series with diode.
- Current decays more faster.

$$V_{CE} = E + V_Z + V_{DF}$$

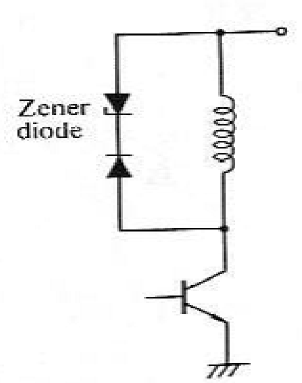


Fig. Zener diode suppressor

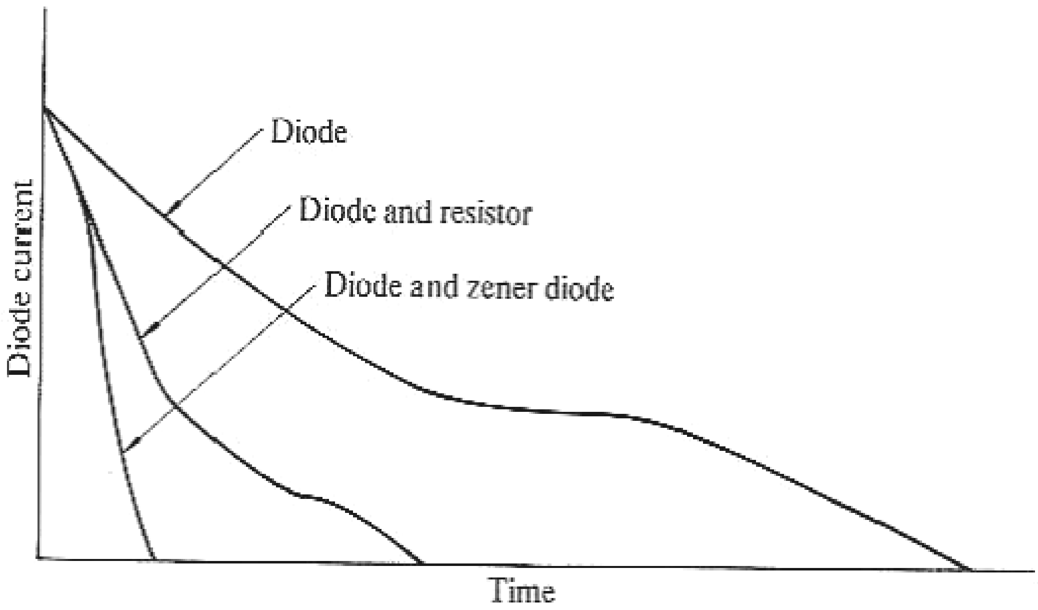


Fig. Comparison of various suppressor circuits

(4) Condenser suppressor:

- Used for bifilar motors.
- Condenser used here serves two purposes.
    - Absorbs the decaying current from the winding when transistor is turned-off.
    - Used as electrical damper.
    - Rotor oscillates – kinetic energy converted to joule heating.

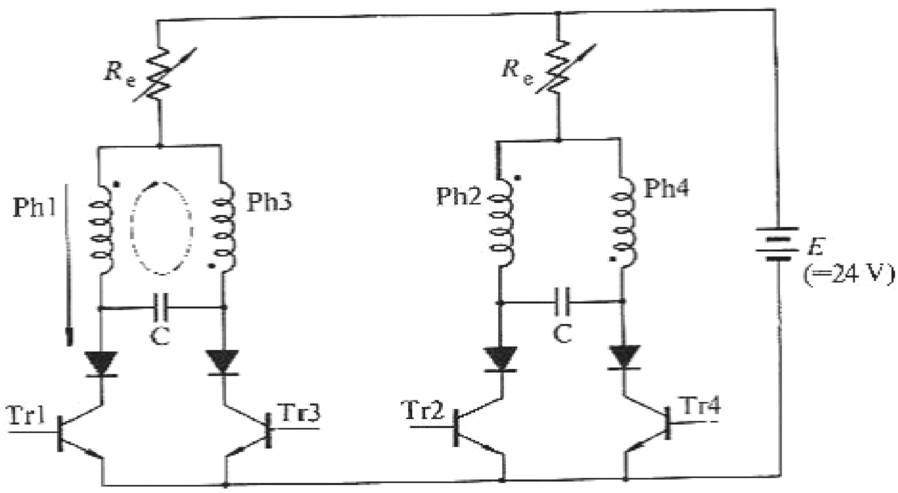


Fig. Condenser suppressor

(d) Power driver circuit:

9. Explain in detail the power driver circuits of stepper motor. May-2017

Draw and explain the drive circuits and their performance characteristics for stepper motor. Dec-2017, 2014

Explain the working of drive circuits used to drive the stepping motor.

- The output signals from the logic sequencer are low level signals which are too weak to energize stepper motor windings.
- To increase the voltage, current and power levels of signals, they are applied to the switching power amplifier circuits.
- This switching power amplifier circuits are called power driver circuits.

Some of the available power driver circuits are,

- Simple power drive circuit
- L/R drive
- Dual voltage drive
- Chopper drive
- Bipolar drives for stepper motors
    - Basic bipolar drive
    - Bipolar L/R drive
    - Bipolar chopper drive

(1) Simple power drive circuit:

- Power circuit is a Darlington pair power amplifier.
- It is capable of driving 3 to 5 A current through the stepper motor windings.

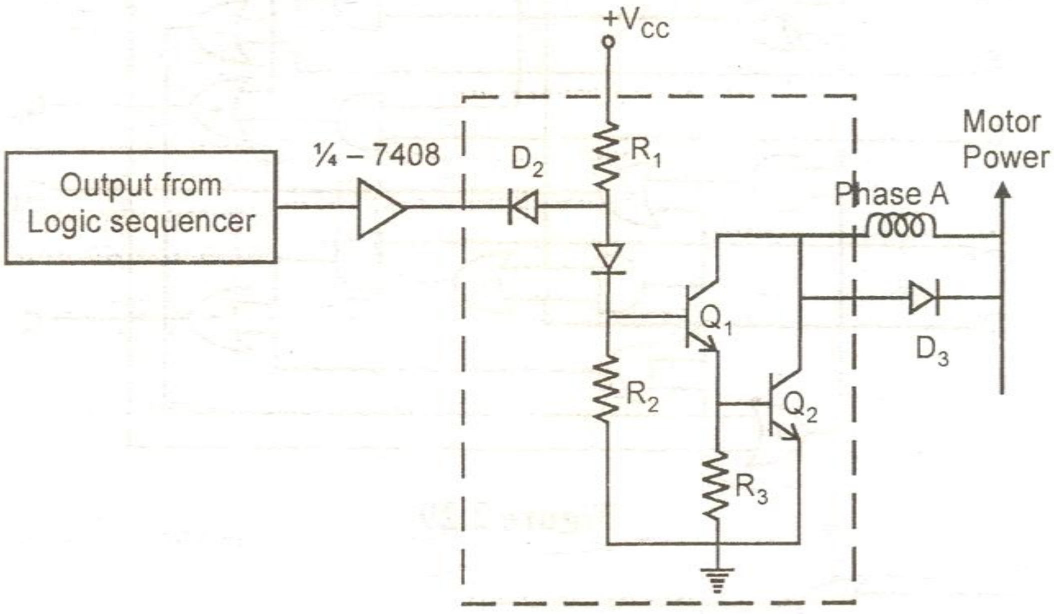


Fig. Simple power drive circuit

- Inverter gate is connected between logic sequencer and darlington pair circuit.
- It is used to isolate the logic sequencer and power driver.
- This isolation is very important to protect the logic sequencer against any faults.

(2) L/R drive or series resistance drive:

- Add a resistance in series with a winding.
- Time constant of the circuit is decreased from L / R_w to L / (R_e + R_w).
- Since time constant is reduced, motor current rises rapidly to give higher torque.
- More power loss at resistor.

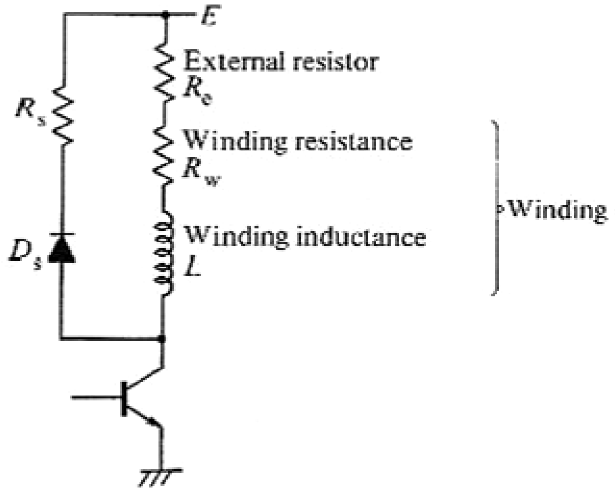


Fig. L/R drive

(3) Dual voltage drive:

- Used to reduce the power dissipation in the drive and increase the performance of the stepping motor.
- When step command pulse is given to logic sequencer, a high level signal will be put out from one of the output terminals, to excite a phase winding.

- Both Tr1 and Tr2 are turned on and the higher voltage E_H will be applied to the winding.
- Diode D1 is now reverse biased to isolate the lower voltage supply from higher voltage supply.
- Time constant of monostable multivibrator is selected so that transistor Tr1 is turned off when winding current exceeds rated current.

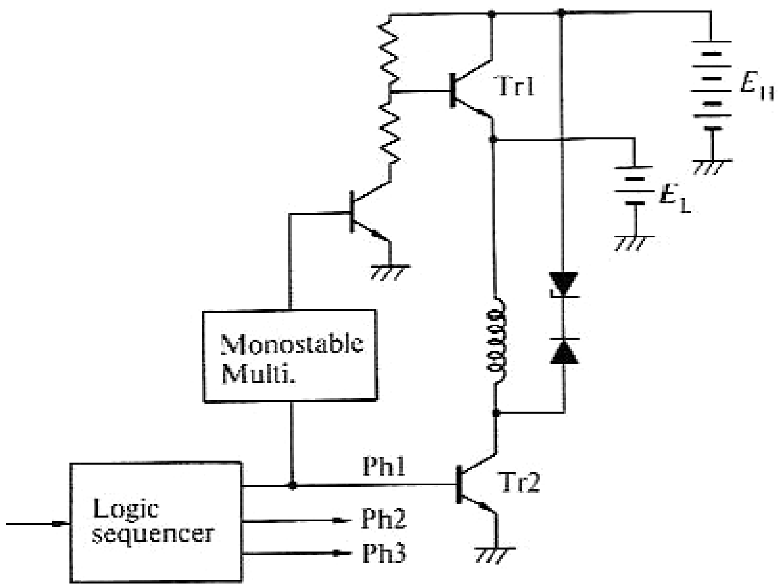


Fig. Dual voltage drive

- When higher voltage source is cut off, the diode is forward biased and winding current is supplied from lower voltage supply.

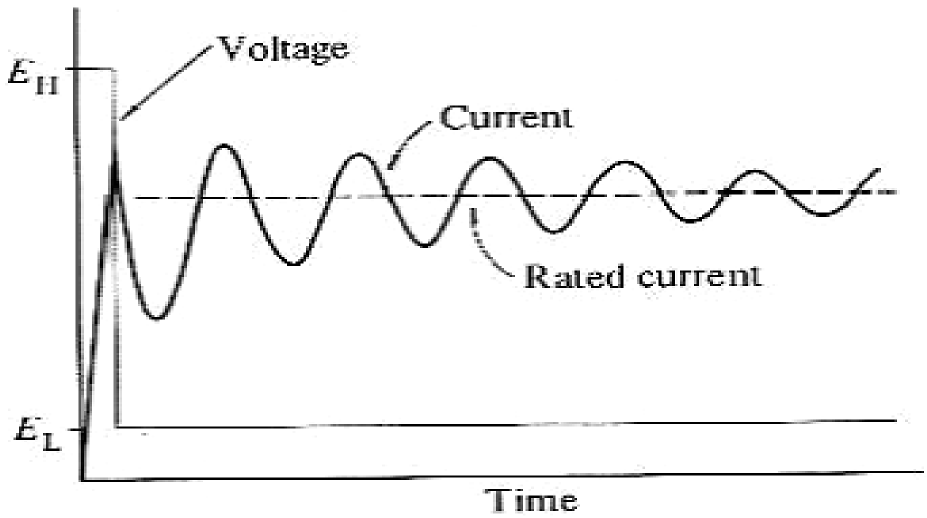


Fig. Current and voltage waveform of dual voltage driver

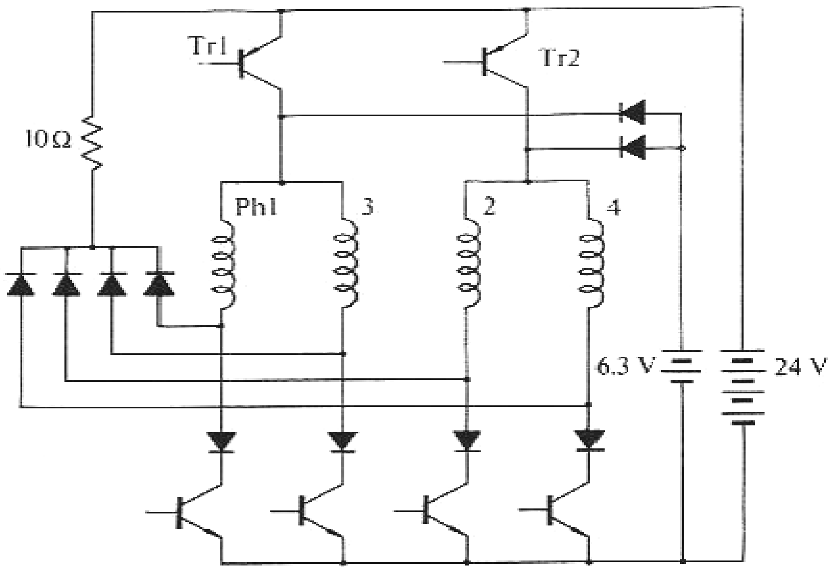


Fig. Dual voltage driver for two-phase on drive of a four-phase motor

(4) Chopper drive:

- Consists of one power transistor Q and current sense logic circuit, a high voltage V_H = (5 to 10 %) rated voltage is applied to the motor winding.

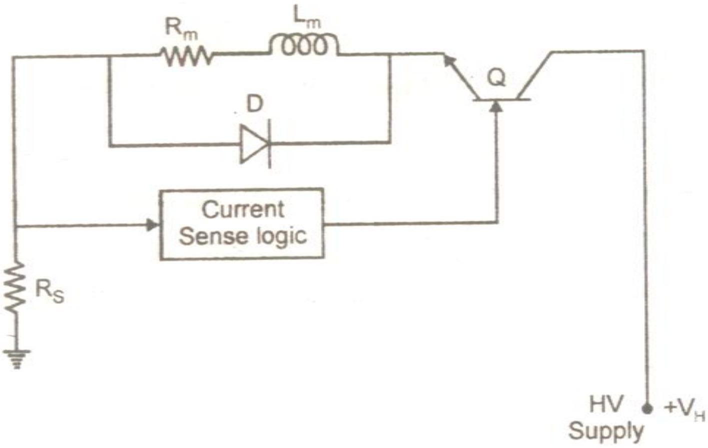


Fig: Chopper drive circuit

- When transistor Q is turned on, motor current increases.
- When motor current reaches maximum value I_{max}, transistor Q is turned off.
- Now current free wheels through diode and decreases exponentially.
- When current reaches minimum value I_{min} , again transistor Q is turned on.
- This causes current to oscillate between maximum and minimum value.
- Used in high torque stepper motors.

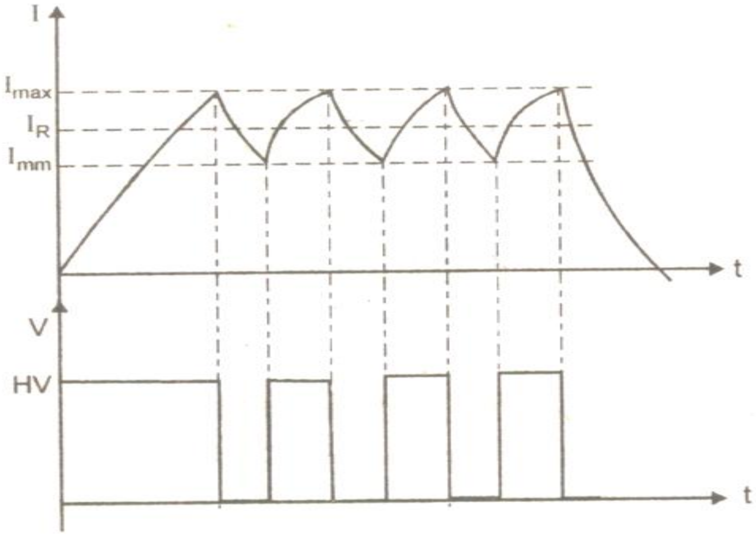


Fig. Voltage and current waveform of chopper drive

Advantages:

- Energy efficient.
- Simple circuit.

(5) Bipolar drives for stepper motors:

- Current through the motor winding will be either positive current ($+I_R$) or negative ($-I_R$) and zero (0).

Some of the bipolar drives are discussed below.

- Basic bipolar drives.
- Bipolar L/R drives.
- Bipolar chopper drives.

Basic bipolar drives:

- Consists of two transistors, two diodes and two power supply.

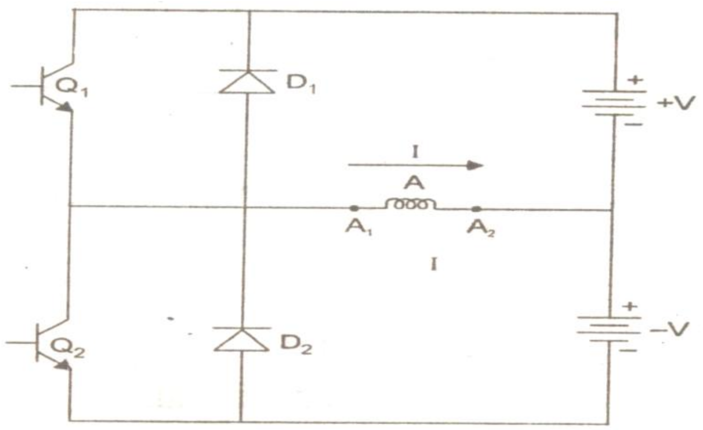
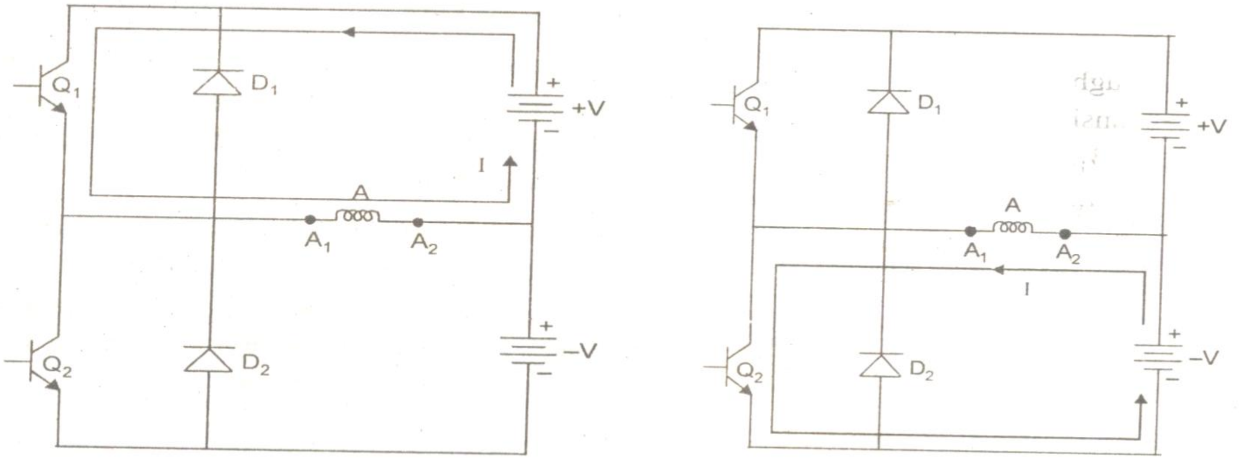


Fig. Basic bipolar drive

- Q_1 ON motor current (+I) flows from A_1 to A_2.



- Q_1 OFF, Q_2 ON, motor current (-I) flows from A_2 to A_1.
- Current is bi-directional in nature.
- D_1 and D_2 are free wheeling diodes.

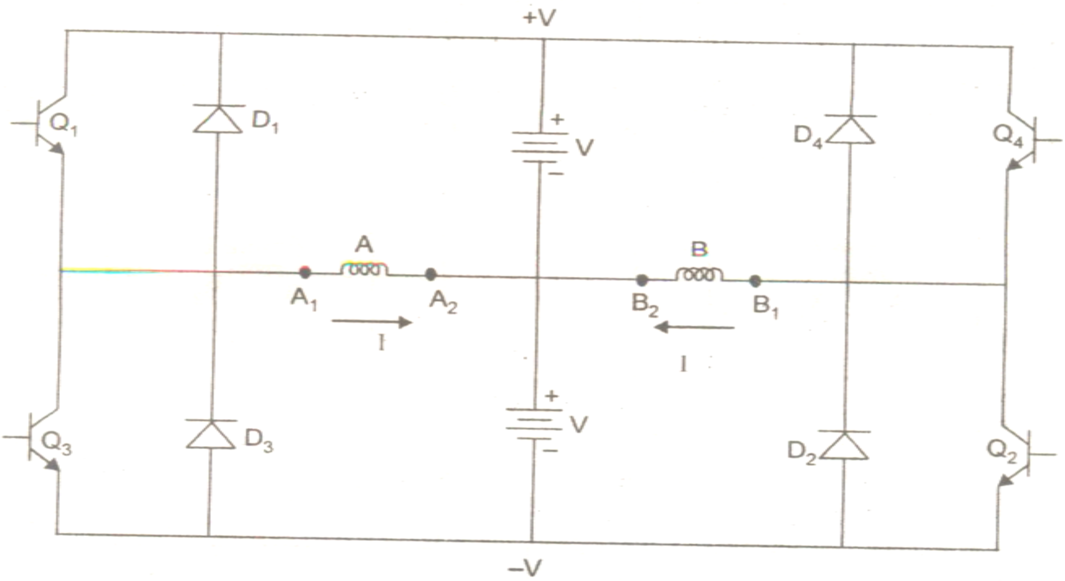


Fig. Bipolar drive for 4-lead PM hybrid stepper motor

Bipolar L/R drives:

- Resistance R_s is connected in series with A and B windings.
- Operation is similar to that of bipolar drive.

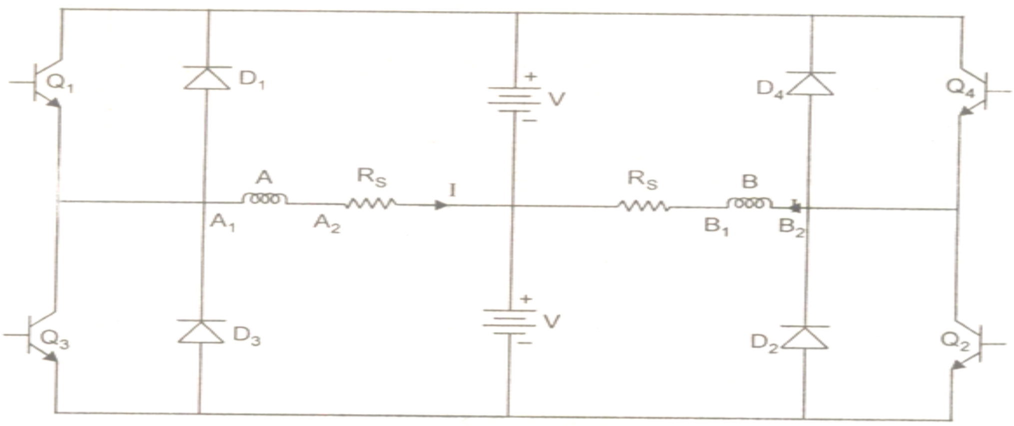


Fig. Bipolar L/R drive

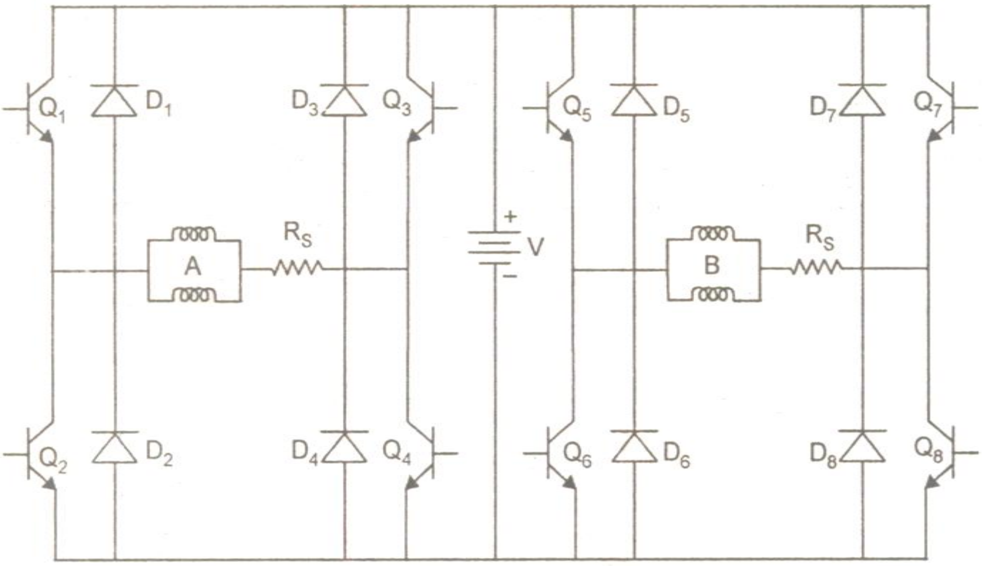


Fig. Practical Bipolar L/R drive

Bipolar chopper drives:

- Chopper drives requires much higher voltage from a power supply than the rated voltage of the motor winding.
- Motor current rise and torque are higher at stepping rates.
- Dynamic performance of the motor is improved.

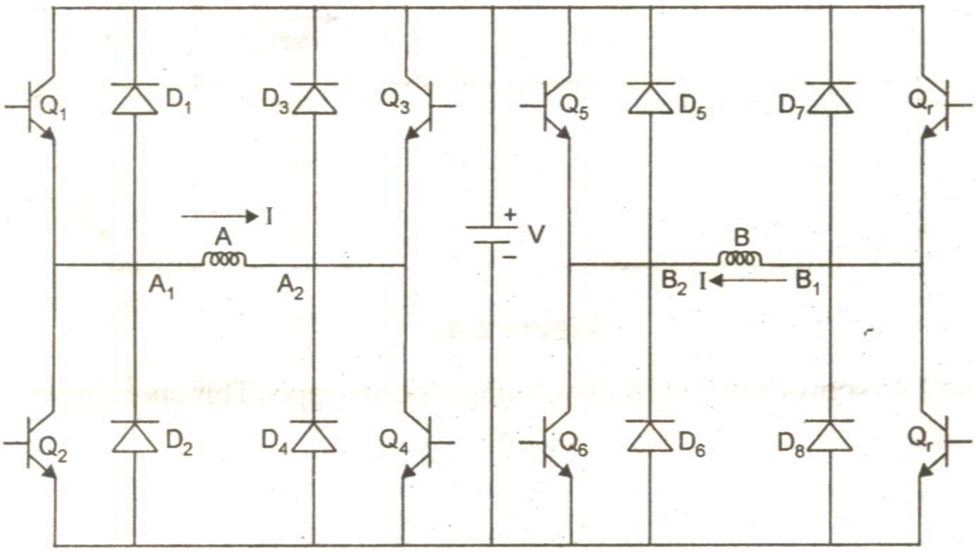


Fig. Bipolar chopper drive

Microprocessor control of Stepping motors:

10. With a neat block diagram explain microprocessor control of stepping motor.
Dec-2017, 2016, May-2013, 2012
Explain microprocessor based control of stepper motor with an example.
Dec-2015, May-2017
Explain briefly a closed loop operation system using a microprocessor for a hybrid stepping motor. May-2018

- The stepper motors are mainly used in the computer peripherals, plotters, robots and machine tools for precise incremental rotation.
- In stepper motor, the stator windings are excited by electrical pulses.
- For each pulse the motor shaft advances by one angular step.
- The stepper motor operates by digital pulses.

- The step angle in the motor is determined the number of poles in the rotor and the number of pairs of stator windings.
- The stator windings are called control windings.

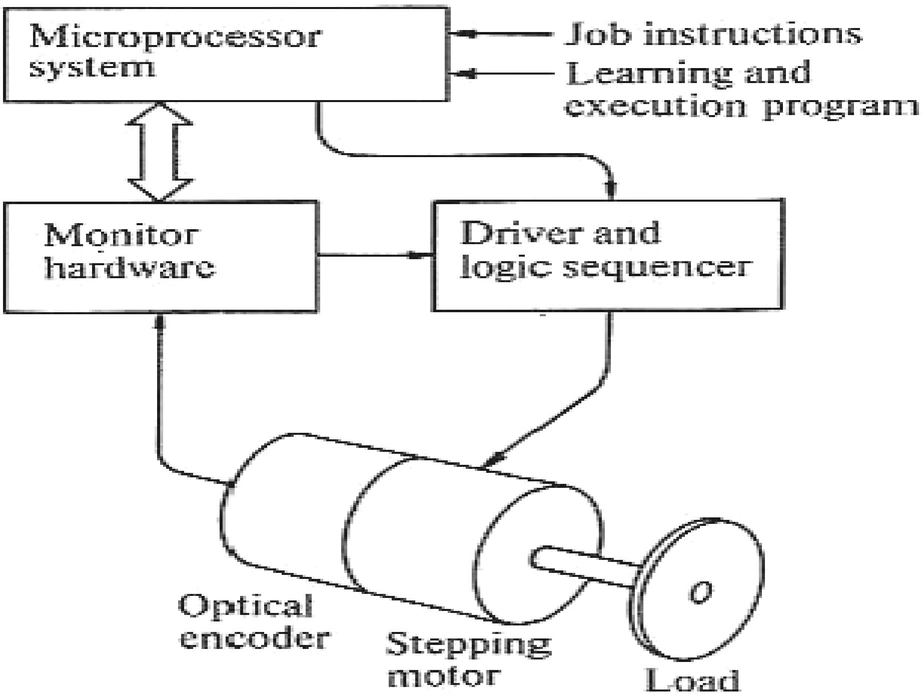


Fig. Microprocessor control of stepper motor

- The stepper motor is controlled by switching ON/OFF the stator windings.
- Generally the stepper motor has four stator winding and require four switching sequence.

- The stepper motor can operate in full step operation and half step operation.

Switching sequence	Clockwise rotation				Anticlockwise rotation			
	PA_3	PA_2	PA_1	PA_0	PA_3	PA_2	PA_1	PA_0
Sequence - 1	1	1	0	0	0	0	1	1
Sequence - 2	0	1	1	0	0	1	1	0
Sequence - 3	0	0	1	1	1	1	0	0
Sequence - 4	1	0	0	1	1	0	0	1

Fig. Switching sequence for full step operation

Clockwise rotation				Anticlockwise rotation			
PA_3	PA_2	PA_1	PA_0	PA_3	PA_2	PA_1	PA_0
1	1	0	0	0	0	1	1
0	1	0	0	0	0	1	0
0	1	1	0	0	1	1	0
0	0	1	0	0	1	0	0
0	0	1	1	1	1	0	0
0	0	0	1	1	0	0	0
1	0	0	1	1	0	0	1
1	0	0	0	0	0	0	1

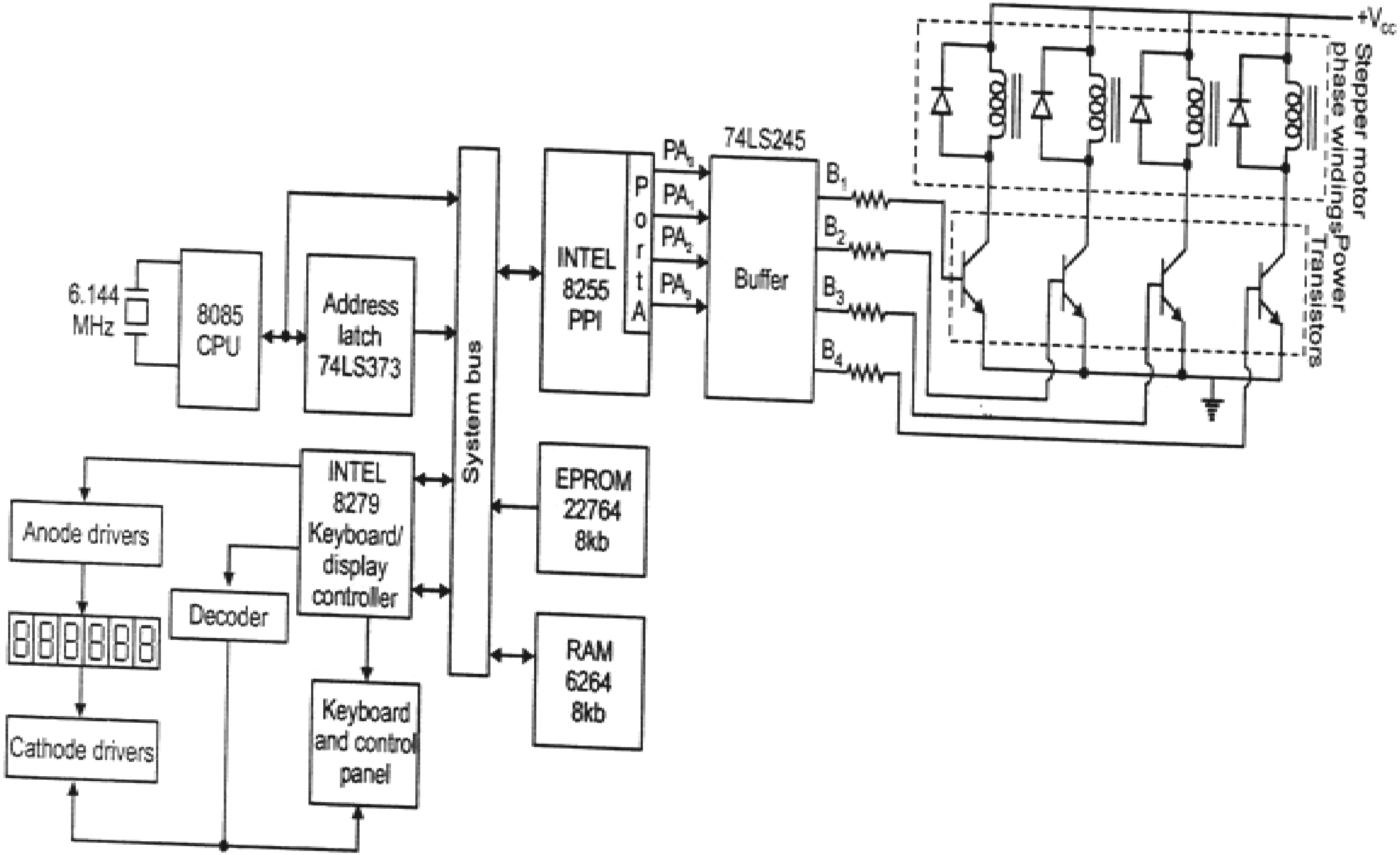
Fig . Switching sequence for half step operation

- Stepper motor consists of 4 phase windings.
- Freewheeling diode is connected across phase winding.
- Stepper motor windings can be energized by turning on the power transistor in the power circuit.

System consists of

- Microprocessor (8085, 8086 etc)
- EPROM and RAM memory - for program and data storage
- INTEL 8279
- Keyboard - to issue commands to the control system
- Six number of 7-segment LED display - to display messages to the operator.

- Phase or stator windings are energized by turning on the power transistor.
- Power transistors are switched ON/OFF by the microprocessor through the ports of 8255 and buffer.



6.144 MHz
8085 CPU
Address latch 74LS373
System bus
INTEL 8255 PPI
Port A
PA0
PA1
PA2
PA3
74LS245
Buffer
B1
B2
B3
B4
+Vcc
Stepper motor phase windings
Power Transistors
INTEL 8279 Keyboard/ display controller
EPROM 22764 8kb
RAM 6264 8kb
Anode drivers
Decoder
Cathode drivers
Keyboard and control panel

Figure shows the flowchart for stepper motor control. The processor has to output a switching sequence and wait for 1 to 5 ms before sending next switching sequence.

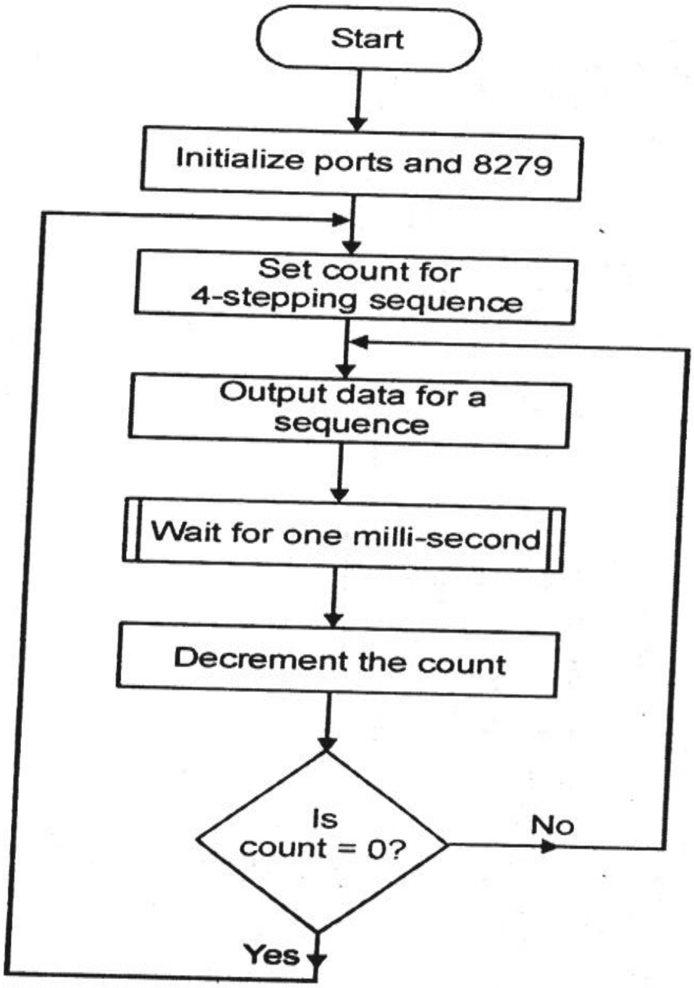


Fig. Flowchart for stepper motor control

Closed loop control:

11. Explain in detail about the closed loop control of stepper motor.
What are the advantages of closed loop control of stepper motor?
Dec-2015, May-2017

- Stepper motor cannot follow the pulse command when –
  - Frequency of pulse train is too high.
  - Initial load is too heavy.
- Performance can be improved by position feedback or speed feedback to determine proper phases to be switched.
- Position sensor – optical encoder.
- Relation between rotors present position and the phases to be excited is given by lead angle.

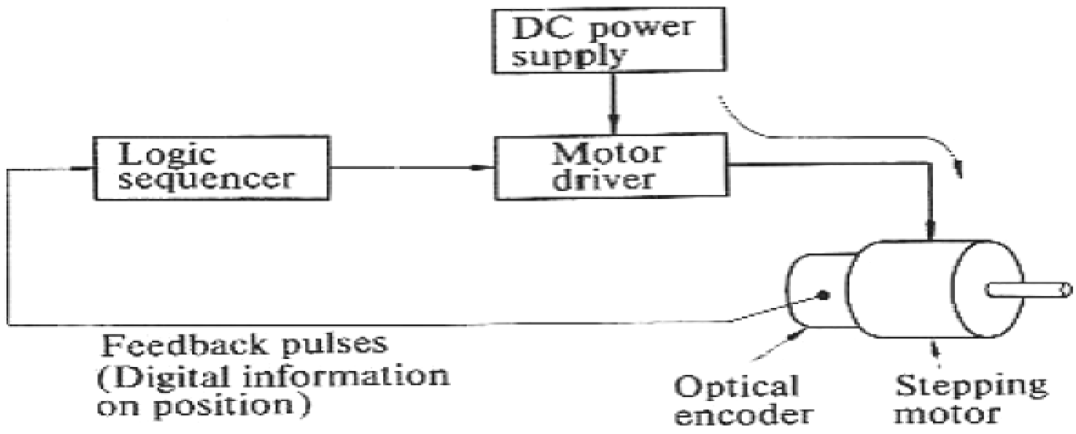
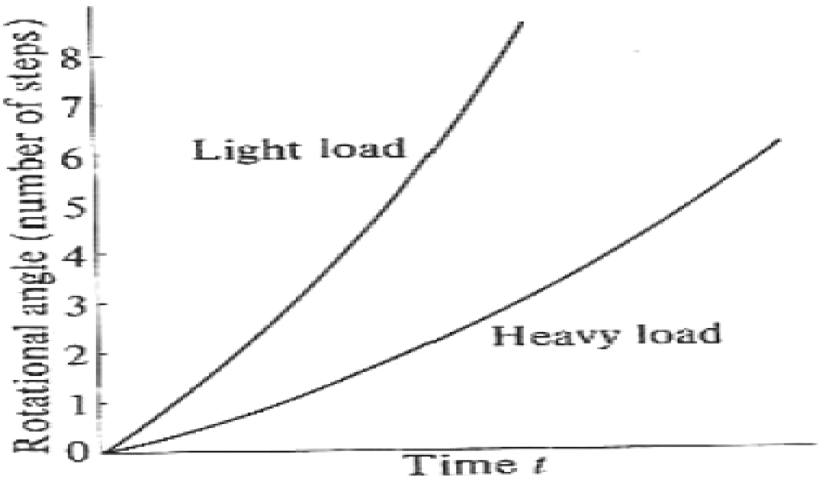


Fig. Closed loop control

- In closed loop : speed depends on load.
- Bigger the load – slower the speed.



- Lead angle = 1 step – not used in practice, since it does not ensure continuous rotation with frictional load.
- Step failure never occurs.
- Rotor detection methods : optical encoder, waveform detection method

Advantages:

- Responds directly to digital control signals, so stepper motors are natural choice for digital computer controls.
- It is mechanically simple.
- It requires little or no maintenance.

Applications:

- Robotics
- Process control system
- X-Y plotters
- Machine tools
- Printers
- Tape drives
- Integrated circuit fabrication
- Electric watches
- Floppy disc drives
- Milling machines

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12. A single stack, 3-phase variable reluctance motor has a step angle of 15°. Find the number of stator and rotor poles. **Dec-2012**

Given:

$\beta = 15°$

To find:

$N_s = ?$ $N_r = ?$

Solution:

$$\beta = \frac{360°}{m\, N_r}$$

$$N_r = \frac{360°}{m\, \beta} = \frac{360°}{3\ x\ 15} = 8$$

$$N_r = 8$$

For finding the value of N_s, we use the relation,

$$\beta = \frac{N_s \sim N_r}{N_s\ N_r}\ x\ 360°$$

(i) when $N_s > N_r$,

$$\beta = \frac{N_s - N_r}{N_s\ N_r}\ x\ 360°$$

$$15° = \frac{N_s - 8}{N_s\ 8}\ x\ 360°$$

$$N_s = 12$$

(ii) when $N_s < N_r$,

$$15° = \frac{N_r - N_s}{N_s\ 8}\ x\ 360° = \frac{8 - N_s}{N_s\ 8}\ x\ 360°$$

$$N_s = 6$$

13. What is the motor torque T_m required to accelerate an initial load of $2x10^{-4}$ kg – m^2 from 500 Hz to 1500 Hz in 50 ms. The frictional torque is 0.03 Nm and the step angle is 1.18°.

Dec-2012

Given:

$J = 2x10^{-4}$ kg – m^2 $f_1 = 500$ Hz $f_2 = 1500$ Hz

$\Delta t = 50$ ms $T_f = 0.03$ Nm $\beta = 1.18°$

Solution:

$$step\ angle\ in\ radians\ =\ \beta\ x\ \frac{\pi}{180}$$

$$= 1.18\ x\ \frac{\pi}{180}\ =\ 0.0205\ rad$$

$$\omega_1\ =\ \theta_s\ x\ f_1\ =\ 0.0205\ x\ 500\ =\ 10.25\ rad/sec$$

$$\omega_2\ =\ \theta_s\ x\ f_2\ =\ 0.0205\ x\ 1500\ =\ 30.75\ rad/sec$$

$$\frac{d\omega}{dt} = \frac{\omega_2\ -\ \omega_1}{\Delta t}\ =\ 410\ rad/sec$$

$$Motor\ torque,\qquad T_m\ =\ J\ \frac{d\omega}{dt}\ +\ T_f$$

$$=\ 2\ x\ 10^{-4}\ x\ \ 410\ \ +0.03$$

$$T_m\ =\ 0.112\ \ N-m$$

14. A stepper motor has resolution of 180 steps/rev. Find the pulse rate required in order to obtain a rotor speed of 2400 rpm.

Dec-2016

Given:

Resolution = 180 steps/rev N = 2400 rpm

To find:

f = ?

Solution:

$N = 2400\ rpm$

$$n = \frac{2400}{60}\ =\ 40\ rps$$

$$\beta\ =\ \frac{360°}{resolution}\ =\ \frac{360°}{180}\ =\ 2°$$

$$n = \frac{\beta\ f}{360°}\ \ \Rightarrow\ f = \frac{n\ x\ 360°}{\beta}\ =\ \frac{40\ x\ 360}{2}\ =\ 7200\ \ pps$$

Result:

f = 7200 pps

Anna University Questions

Part – A

1. Define the term step angle or stepping angle.
May-2017, 2016, 2013, Dec–2013, 2010
2. State some application of stepper motor? **May-2017**
3. What are the different modes of excitation in a stepper motor?
Dec-2017, 2015, May-2018, 2012
4. Define the micro stepping mode of stepper motor. **Dec-2016, May-2015**
5. Mention the applications of micro stepping VR stepper motor? **Dec-2014**
6. What is hybrid stepped motor? **Dec-2011**
7. Define holding torque? **Dec-2015**
8. Define detent torque. **Dec-2015**
9. Define torque constant. **Dec-2012**
10. Draw the block diagram of the drive system of stepping motor. **Dec-2011**
11. What is the function of power drive circuit in stepper motor?
May-2017, 2013
12. What is the need of suppressor circuits in stepper motor? **Dec-2016**
13. What are the main features of stepper motor which are responsible for its wide spread use? **Dec-2013**
14. Calculate the stepping angle for a 3-phase 24 pole permanent magnet stepper motor.
Dec–2012, 2013
15. Distinguish the half step and full step operations of a stepping motor.
Dec-2017, 2014
16. Write the principle of operation of variable reluctance motor. **Dec-2014**
17. Name the various driver circuits used in stepper motor.
Dec-2016, May-2016, 2015
18. Define lead angle. **May-2018, Dec-2016**
19. Draw the equivalent circuit of winding in stepper motor. **May-2017**
20. Compare single stack and multistack configurations in stepping motors.
Dec-2017

Part – B

1. Explain the construction and principle of operation of Variable Reluctance Stepping motor in detail. **Dec–2013, 2012, 2010**

Construct and evaluate the operation of single and multi stack stepper motor with a neat diagram. **May-2016**

Explain the working of single and multi stack configured stepping motors.
Dec-2016

Describe the operation of variable reluctance type stepper motor with different modes of operation. **May-2017**

Describe construction and working of variable reluctance stepper motor with neat diagram. **May-2017**

2. Explain in detail the multi stack construction of stepper motor.
May-2016, 2015, 2013, Dec-2016

3. Explain the construction and principle of operation of Permanent magnet Stepping motor in detail. **Dec-2011**

4. Describe the principle of operation of hybrid stepper motor. **May-2018**

5. Derive the torque equations of the variable reluctance motor and illustrate the various dependent parameters. **Dec-2014**

Explain the mechanism of static torque production in a variable reluctance stepping motor. **May-2018**

6. Explain briefly the various modes of excitation of variable reluctance motor. **May-2014**

Describe the operation of variable reluctance type stepper motor with different modes of operation. **Dec-2015**

Explain the modes of excitation of a stepper motor with neat diagram. **Dec-2016**

7. Explain briefly various characteristics of stepper motor? **Dec–2011**

Compare the static and dynamic characteristics of stepper motor with necessary diagrams. **May-2016, 2015**

Explain in detail, the static and dynamic characteristics of a stepper motor. **Dec-2016**

Describe the dynamic characteristics of a variable reluctance stepper motor. **May-2018**

8. Explain briefly drive circuits for stepping motor? **Dec-2010, May–2012**

9. Explain in detail the power driver circuits of stepper motor. **May-2017**

Draw and explain the drive circuits and their performance characteristics for stepper motor. **Dec-2017, 2014**

10. With a neat block diagram explain microprocessor control of stepping motor. **Dec-2017, 2016, May-2013, 2012**

Explain microprocessor based control of stepper motor with an example. **Dec-2015, May-2017**

Explain briefly a closed loop operation system using a microprocessor for a hybrid stepping motor. **May-2018**

What are the advantages of closed loop control of stepper motor? **Dec-2015, May-2017**

11. A single stack, 3-phase variable reluctance motor has a step angle of 15°. Find the number of stator and rotor poles. **Dec-2012**

12. What is the motor torque T_m required to accelerate an initial load of $2x10^{-4}$ kg – m^2 from 500 Hz to 1500 Hz in 50 ms. The frictional torque is 0.03 Nm and the step angle is 1.18°. **Dec-2012**

13. A stepper motor has resolution of 180 steps/rev. Find the pulse rate required in order to obtain a rotor speed of 2400 rpm. **Dec-2016**

MAILAM ENGINEERING COLLEGE

Department of Electrical and Electronics Engineering

SUB CODE: EE 6703 **SUB NAME: SPECIAL ELECTRICAL MACHINES**

UNIT-03
SWITCHED RELUCTANCE MOTORS

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

Part – A

1. What is Switched Reluctance Motor?

- Double salient, singly-excited motor.
- It has salient pole on both the rotor and the stator, but only one member carries windings.
- Rotor has no windings, magnets (or) cage winding.
- It works on variable reluctance principle.

2. What are the types of power controllers used for switched reluctance motor?
Dec-2016, 2015, May-2011

i) Using two power semiconductors and two diodes per phase

ii) (n + 1) power switching devices and (n + 1) diodes per phase

iii) Phase windings using bifilar wires

iv) Dump C- converter

v) Split power supply converter

3. Why rotor position sensor is essential for the operation of switched reluctance motor?
Dec-2011, 2012

Discuss the need of rotor position sensor in SRM. **Dec-2016, May-2015**

What is the significance of position sensors used in SRM. **Dec-2017**

- It is normally necessary to use a rotor position sensor for commutation and speed feedback.
- The turning ON and OFF operation of the various devices of power semiconductor switching circuits are influenced by signals obtained from rotor position sensor.

4. List the disadvantages of a switched reluctance motor? **May-2007**

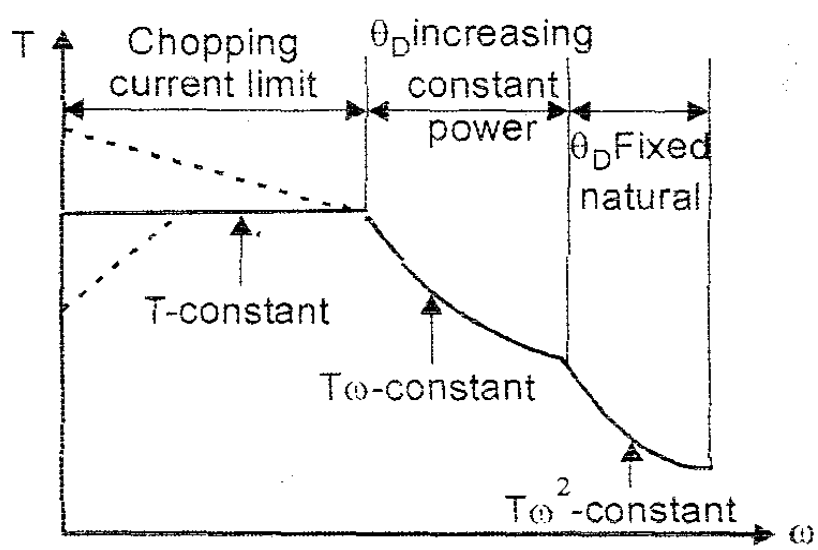
- Stator phase winding should be capable of carrying magnetizing current.
- For high speed operation developed torque has undesirable ripples which develop undesirable noises (or) acoustic noises.

- For high speed current wave form has undesirable harmonics, to suppress this effect large size capacitor is to be connected.
- It requires position sensors.

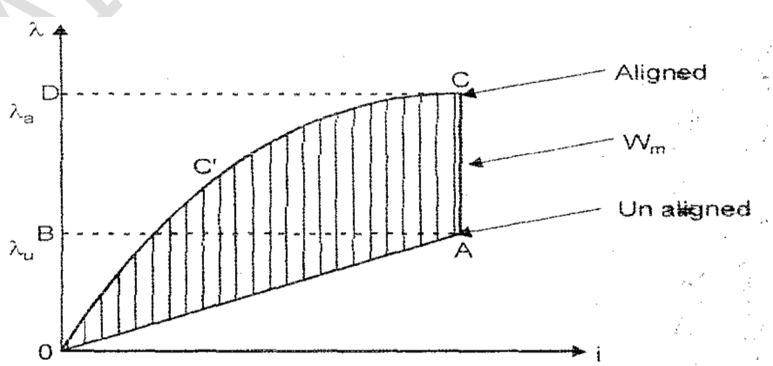
5. What are the advantages of switched reluctance motor? **May-2016, 2011, Dec-2013**

- Construction is simple and robust.
- Rotor carries no windings, no slip rings, no brushes, less maintenance.
- There is no permanent magnet.
- Ventilating system is simpler as losses takes place mostly in the stator.
- Power semi conductor switching circuit is simple.
- Developed torque doesn't depends upon the polarity of current in the phase winding.
- The operation of the machine can be easily changed from motoring mode to generating mode by varying the region of conduction.
- It is possible to get very high speed.
- It is the self starting machine.
- Energy stored in the phase winding is fed back to the supply through the feedback diodes.

6. Draw the general torque - speed characteristics of switched reluctance motor?
May-2018, 2017, 2010



7. Draw the λ- I curve for SRM?



8. What are the two types of current control techniques?

1. Hysteresis type control.
2. PWM type control.

9. What is meant by energy ratio? May-2017

$$Energy\ ratio = \frac{W_m}{W_m + R}$$

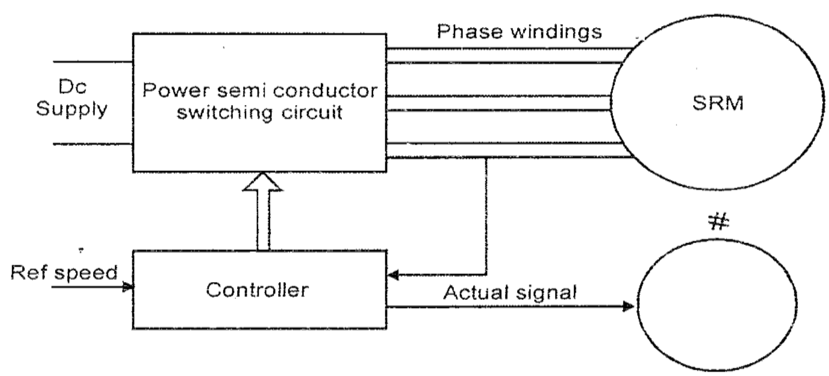
W_m – mechanical energy transformed

This energy ratio cannot be called as efficiency. As the stored energy R is not wasted as a loss but it is feedback to the source through feedback diodes.

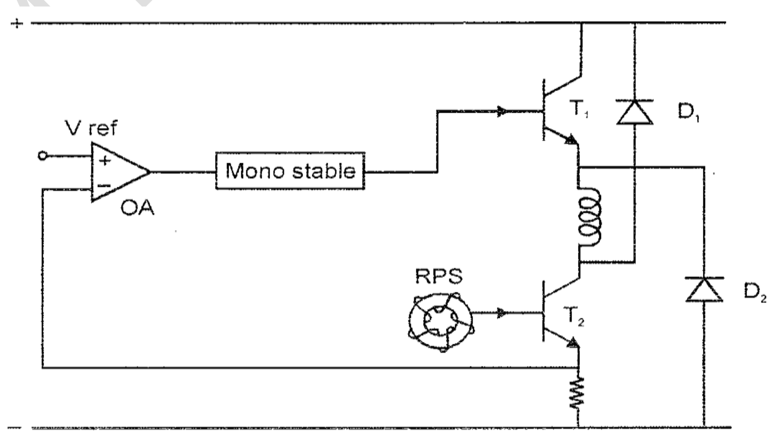
10. What is phase winding?

Stator poles carry field coils. The field coils of opposite poles are connected in series such that mmf's are additive and they are called "Phase windings" of SRM.

11. Draw the simple block diagram of SRM.



12. Draw the circuit of PWM type current control.



13. What are the essential difference between SRM and Stepper Motor?

S. No	SRM	Stepper motor
1	SRM is designed for continuous rotation	Stepper motor is designed to rotate in step by step rotation.
2	SRM requires a rotor-position sensor	It does not require rotor-position sensor.

14. Write down the Voltage and torque equation for a switched reluctance motor drive.

Dec-2017, May-2013, 2012

$$V = i\,R + L\,\frac{di}{dt} + \,e$$

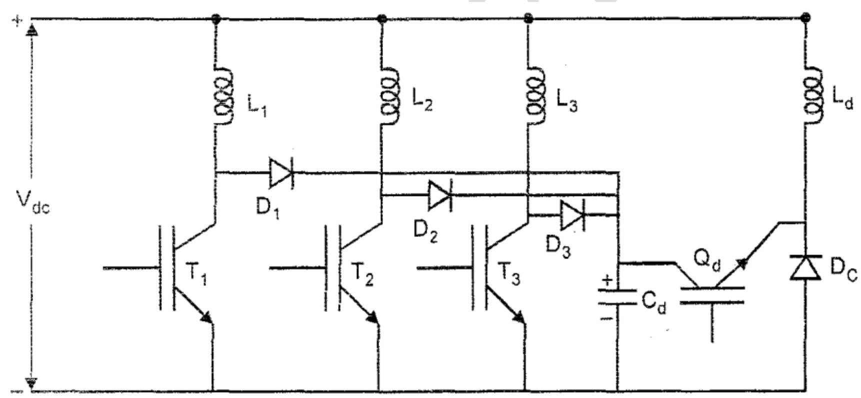
where iR-The ohmic drop

L - emf due to incremental inductance

e - self induced emf

$$T = \frac{1}{2}\,i^2\,\frac{\partial L}{\partial \theta}$$

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



16. What is hysteresis current control?

This type of current controller maintains a more or less constant current throughout the conduction period in each phase. This controller is called hysteresis type controller.

17. Define Chopping and single pulse mode of operation of SRM.

Chopping Mode

In this mode, also called low-speed mode, each phase winding gets excited for a Period which is sufficiently long.

Single-pulse mode

In single-pulse mode, also called high-speed mode, the current rise is within limits during the small time interval of each phase excitation.

18. State the principle of operation of switched reluctance motor. May-2011, 2014

- SRM develops electromagnetic torque due to variable reluctance principle.
- When air gap is minimum, the reluctance will be minimum; hence inductance will be maximum, so the rate of change of inductances zero.
- When the reluctance varies there will be a change in inductance so when a particular stator winding of SRM is excited, the rotor pole comes in alignment with the stator pole and the rotor rotates.

19. What is the need for shaft position sensor for SRM? May-2018, 2006

- For commutation (i.e.) turning on and turning off of various semiconductor devices in the switching circuitry is influenced by the signals obtained from the rotor position sensor.
- For speed control of motor. It is necessary to use the rotor position sensor.

20. Compare switched reluctance motor and synchronous reluctance motor. Dec-2010

S. No	Switched Reluctance Motor(SRM)	Synchronous Reluctance motor
1	It has less no of poles then the stator	The motor has the same No of poles on stator and Rotor
2	The stator of SRM motor has salient poles with concentrating windings	The stator of synchronous reluctance motor is cylindrical type with distributed windings.
3	Excitation is a sequence of current pulses applied to each phase in turn	Excitation is a set of poly phase balanced sine wave currents.
4	The phase flux linkage should have a triangular or saw tooth waveform but not vary with current	The phase self-inductance should vary sinusoidally with rotor position but not vary with currents.

21. Compare switched reluctance motor and variable reluctance motor. Dec-2010

S. No	Switched Reluctance Motor (SRM)	Variable Reluctance stepper motor
1	It's normally operated with shaft position feedback to synchronize with the rotor position sensor.	It's usually fed by a square wave of phase current without rotor position feedback.
2	SRM rotates continuously	It rotates in steps
3	The SRM usually operates at high speeds	The stepper motor is usually designed as a torque motor with a limited speed range.
4	No half step operation and micro stepping are possible.	It is capable of half step operation and micro stepping.

22. What is the need of power controller in SRM?

- In switched reluctance motor, the torque is independent of the direction of currents. This permits the use of unipolar devices in the circuit.
- It provides protection of winding against faults, also there is no possibility of shoot through fault.

23. Why SR machines are popular in adjustable speed drives? **Dec-2012**

As SR machines are more flexible control of driving a motor as motoring mode and generating mode of operations, it is used popularly in an adjustable speed drives.

24. What is the significance of closed loop control of switched reluctance motor? **May-2016, Dec-2013**

Stability and Repeatability

25. List out some position sensors. **May-2013**

i) Optical Position sensor
ii) Hall effect sensor

26. What are advantages of sensorless operation of Switched Reluctance motor? **Dec-2017, May-2014**

(i) Reliable
(ii) Precise
(iii) Low-cost position sensorless control seems necessary

27. List out the advantages and disadvantages of the converter circuit with two power semiconductor devices and two diodes per phase. **Dec-2014**

Advantages:

- Reduces switching losses of converter circuit.
- Control of each phase is completely independent of the other phases.

Disadvantages:

- Converter circuit expensive

28. List the characteristics of switched reluctance motor. **May-2017, 2015**

- T α i^2 → unidirectional current enough for unidirectional torque. So, one power switch for one phase winding.
- T α i^2 → resembles DC series motor. So, high starting torque.
- Generating action possible.
- Direction of rotation can be reversed by changing excitation sequence.
- Torque & speed control can be achieved using converter control.
- Requires controllable converter. Cannot be operated from 3-φ line directly.

29. State the reluctance principle. **May-2017, 2015**

Whenever a piece of ferromagnetic material is located in a magnetic field; a force is exerted on the material, tending to align the material in a minimum reluctance position.

30. What are the applications of SRM? **May-2010, Dec-2016, 2011**

- Washing machines, Vacuum cleaners
- Fans
- Low cost brushless applications
- Future auto mobile applications
- Robotics control application, Aerospace applications

31. Mention the different modes of operation of SRM. **Dec-2017, 2016, 2015**

- Low speed operation mode
- High speed operation mode

PART-B

Introduction:

- *Switched* Reluctance Motor – switched means *switching of phase currents* which is essential to operation of motor.
- Motion – Rotary or linear.
- Rotor type – interior or exterior.
- In motoring: each phase of stator is excited when its inductance is increasing and unexcited when its inductance is decreasing.
- In generation: Vice-versa
- Stator & rotor have salient poles.
- It is a derivative of single stack variable reluctance stepper motor.

Features:

- $T \alpha i^2$ → unidirectional current enough for unidirectional torque. So, one power switch for one phase winding.
- $T \alpha i^2$ → resembles DC series motor. So, high starting torque.
- Generating action possible.
- Direction of rotation can be reversed by changing excitation sequence.
- Torque & speed control can be achieved using converter control.
- Requires controllable converter. Cannot be operated from 3-φ line directly.

Similar to stepper motor except it has:

- Fewer poles
- Large stepping angle
- One tooth per pole
- Higher power output capability

Constructional features

1. Explain the Constructional features and working principle of Switched Reluctance Motor (SRM). **May-2017, 2015, 2011, Dec-2013**

Draw the cross sectional view of SRM. **May-2018**

- Electro magnetic & electro dynamic equipment.
- Single excited, doubly salient machine
- Electromagnetic torque produced due to variable reluctance principle.
- Salient poles on stator and rotor. But winding only on stator.
- Rotor has no windings, magnets and cage structure.

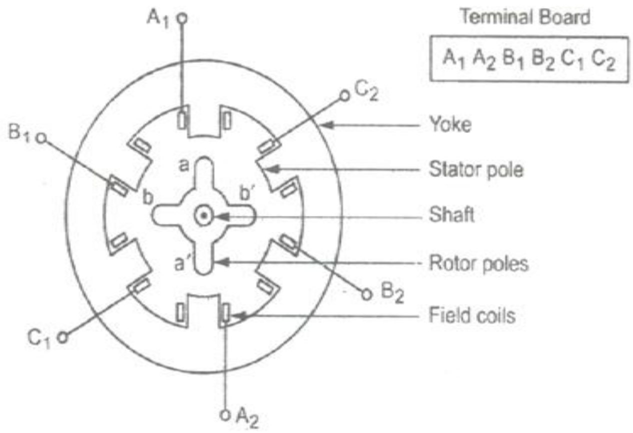


Fig. Schematic of SRM

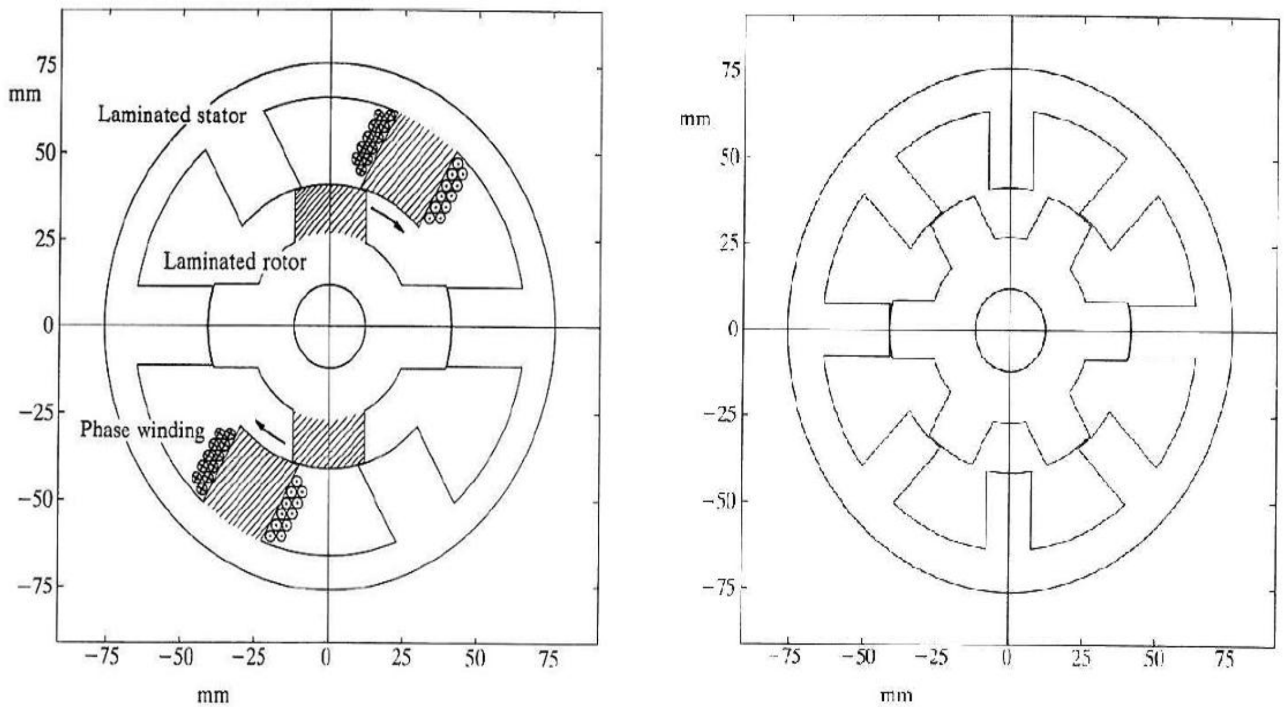


Fig. Cross sectional view of SRM

Stator:

- Made up of silicon steel stampings with inward projected poles.
- No. of Stator poles may be odd or even.
- Stator poles have field coils.
- Field coils of opposite poles are additive.
- Requires more turns of thinner wire.

Rotor:

- Made up of silicon steel stampings with outward projected poles.
- Carries no windings or magnets.
- Usually has 4 poles.
- Shaft carries the rotor position sensor.

Block diagram of SRM:

- DC power is given to power semiconductor switching circuitry.
- Output of switching circuit is given to phase windings of SRM.
- Shaft carries Rotor position sensor which gives information about the position of rotor.
- Controller gets the information from rotor and reference speed signal and turns ON and OFF the concerned power device in switching circuit.
- Current signal is also feedback to the controller to limit the current.

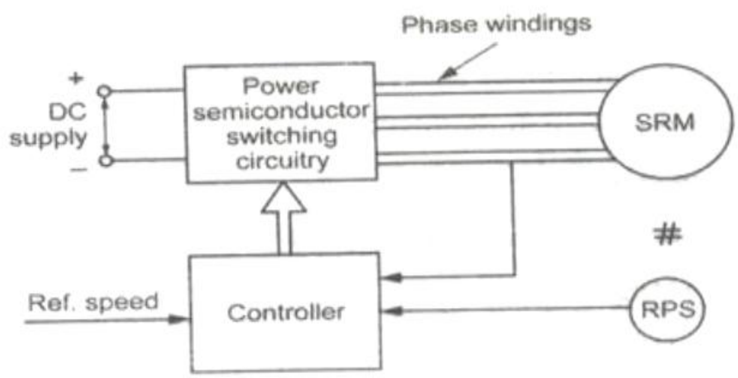
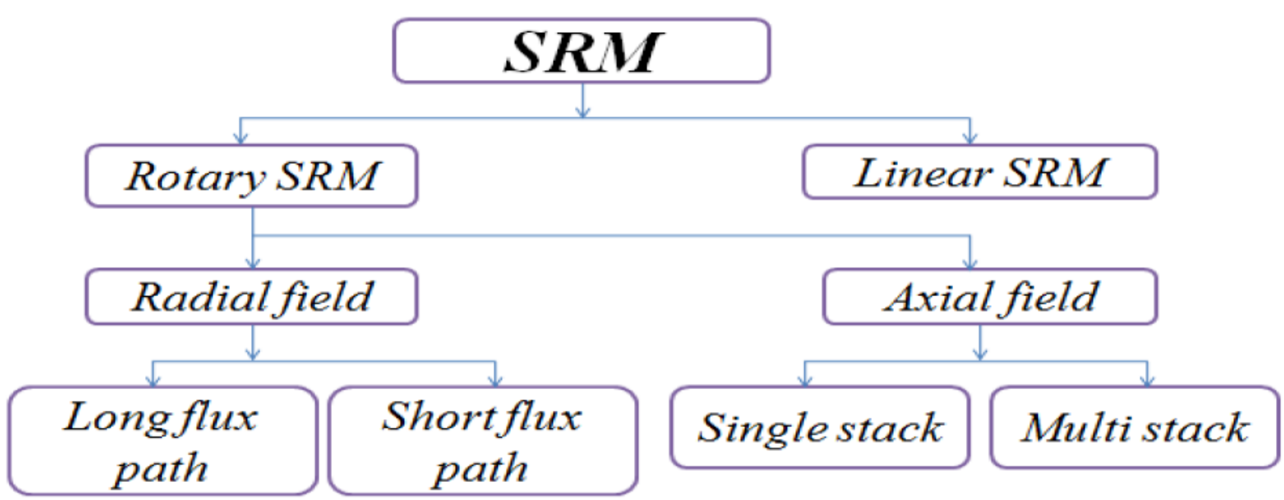


Fig. Block diagram of SRM

Rotary and Linear SRM:

2. Describe the working and construction of rotary and linear switched reluctance motor.
Dec-2017, 2016, 2014, May-2017, 2012, 2013

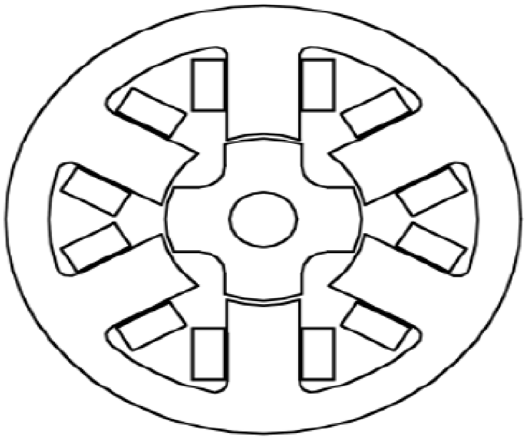
Explain with neat diagrams the constructional details and operation of rotary switched reluctance motors. **May-2016, Dec-2017, 2015**



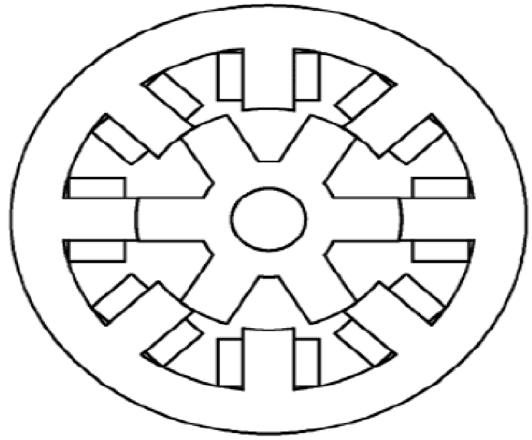
1. Rotary SRM

➢ ***Radial field SRM:***

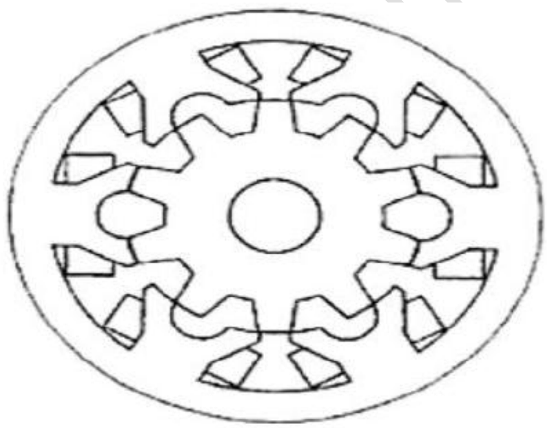
- Magnetic field perpendicular to axial length of machine (or) magnetic field along the radius of stator or rotor.



6/4 Pole



8/6 Pole



Two teeth per pole

Fig. Various stator and rotor combinations of radial field SRM

(a) Long flux path:

- Diametrically opposite windings are in series to form a phase winding.

(b) Short flux path:

- Adjacent pole windings are in series to form a phase windings.

Advantages:

❖ Low core loss

Disadvantages:

❖ Higher mutual inductance
❖ Uneven magnetic pull on rotor

- ***Axial field SRM:***
  - Flux path along the axial direction (or) flux path is parallel to shaft.

  Eg: Ceiling fan

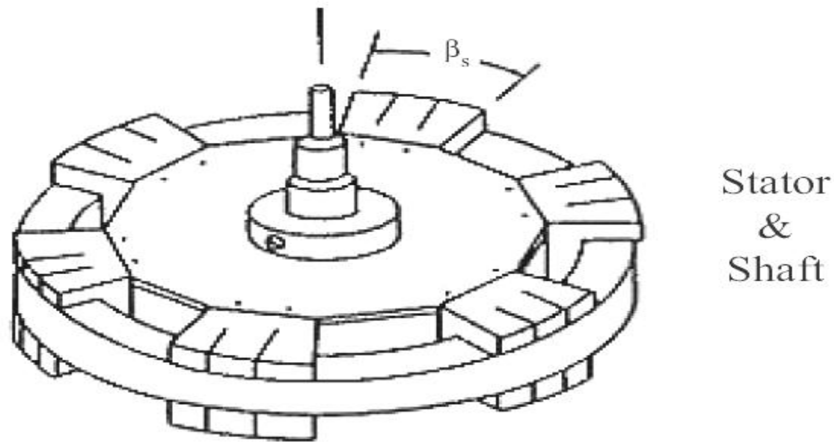


Fig. Axial field SRM

(a) Single Stack axial field SRM:

- Pair of one rotor-one stator stack (or) one rotor-two stator (or) two rotor-one stator stack

(b) Multi stack axial field SRM:

- Multiples of single stack arranged in same shaft.

Disadvantage:

- Stator laminations have to be folded one on top of the other.

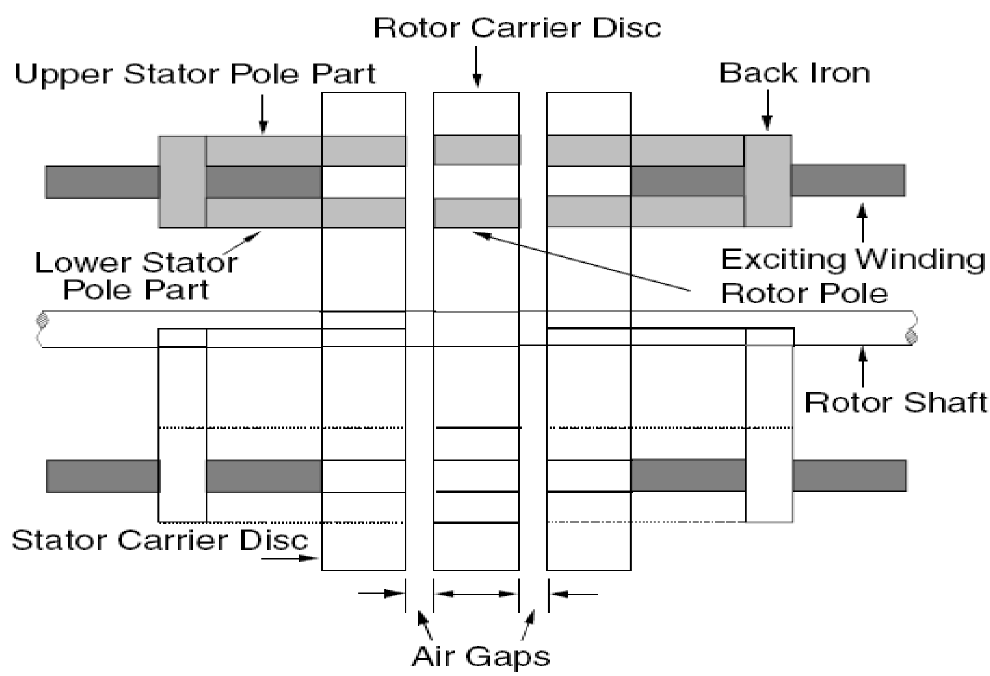


Fig. Axial field SRM

2. Linear SRM (LSRM):

- LSRM are counterparts (opposite or complement) of rotating SRM.
- Obtained from RSRM by cutting along shaft over its radius & rolling them out.

Two parts: (a) Stator (b) Translator (moving part)

Two types:

(i) Longitudinal flux SRM:

Unroll radial field SRM

(ii) Transverse flux SRM:

Unroll the axial field SRM

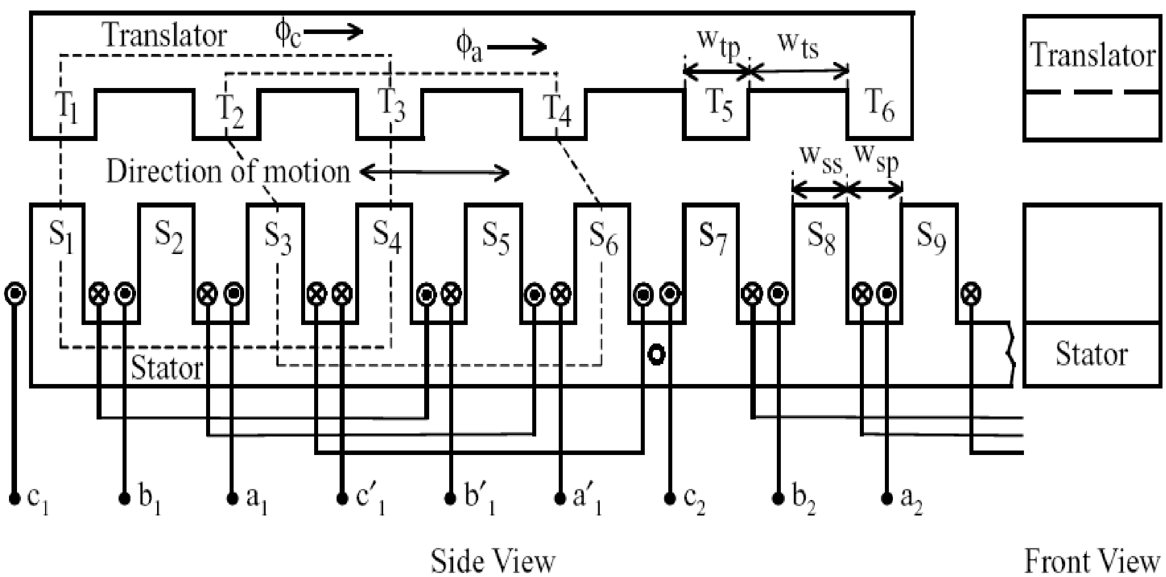


Fig. Linear SRM

Principle of operation:

3. Discuss about the operation of SRM. **May-2018, Dec-2014**

- Motor is excited by a sequence of current pulses applied at each phase.
- Individual phases are consequently excited, forcing motor to rotate.
- Rotor tries to align in
  - ✓ Minimum reluctance position (or)
  - ✓ Maximum inductance position
- When voltage is applied to the stator phase, the motor creates torque in the direction of increasing inductance.

Phase A energized:

- aa' gets aligned with AA'.
- Minimum reluctance position.
- Inductance is maximum.

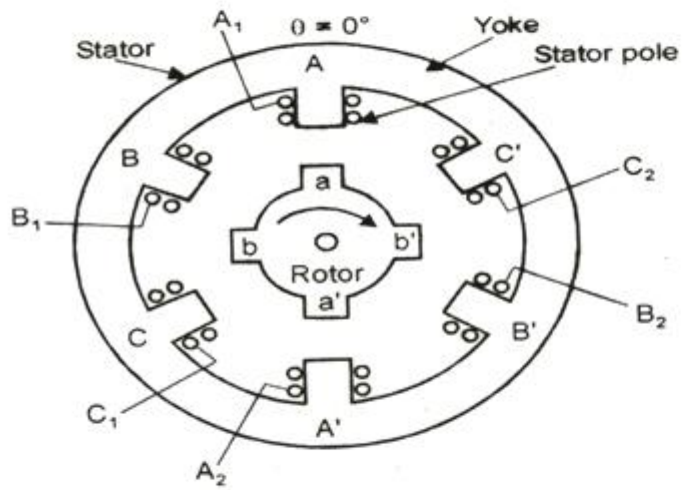


Fig. Phase A energized

Phase B energized:

- bb' gets aligned with BB'.
- Minimum reluctance position.
- Inductance is maximum.
- Torque developed is , $T = \frac{1}{2} i_B^{\ 2} \frac{\partial L_B}{\partial \theta}$

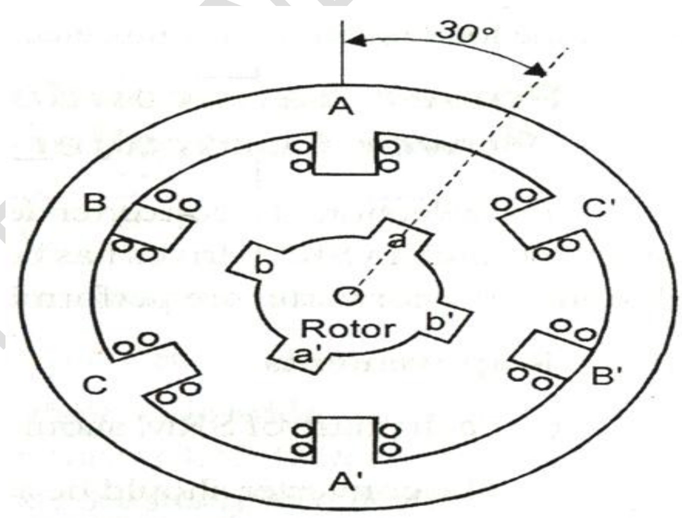


Fig. Phase B energized

Phase C energized:

- aa' gets aligned with CC'.
- Minimum reluctance position.
- Inductance is maximum.
- Torque developed is , $T = \frac{1}{2} i_C^{\ 2} \frac{\partial L_C}{\partial \theta}$

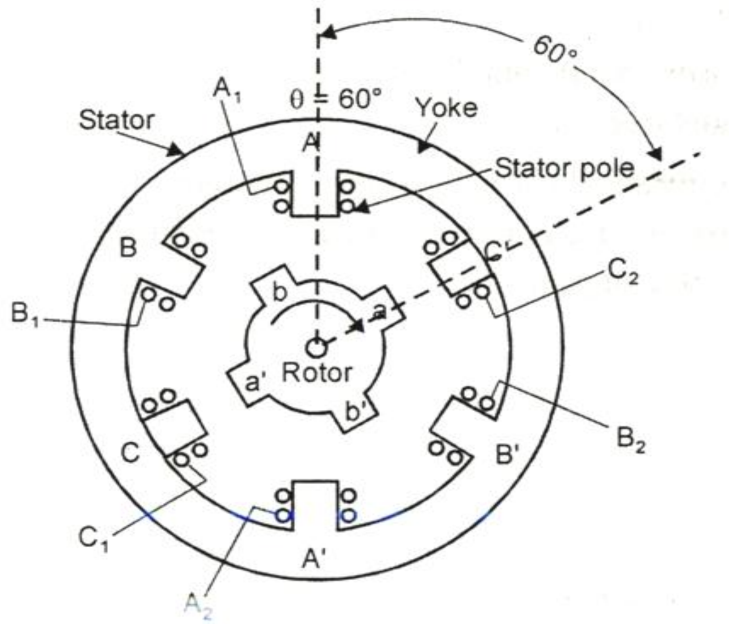


Fig. Phase C energized

Torque production:

4. Derive the voltage and torque equation of SRM. **May-2015**

Derive the expression for static torque in SRM. **Dec-2016**

Voltage and power equation:

$$V = i\,R + \frac{d\,\lambda}{dt}$$

$$\lambda = L\,i$$

$$V = i\,R + \frac{d\,Li}{dt}$$

$$= i\,R + L\,\frac{di}{dt} + i\,\frac{dL}{dt}$$

$$= i\,R + L\,\frac{di}{dt} + i\,\frac{dL}{d\theta}\,\frac{d\theta}{dt}$$

$$V = i\,R + L\,\frac{di}{dt} + i\,\omega\,\frac{dL}{d\theta}$$

$$\boxed{V = i\,R + L\,\frac{di}{dt} + e}$$

$$V\,i = \left(i\,R + L\,\frac{di}{dt} + i\,\omega\,\frac{dL}{d\theta} \right) i$$

$$V\,i = i^2\,R + L\,i\,\frac{di}{dt} + i^2\,\omega\,\frac{dL}{d\theta} = input\ power$$

$$stored\ energy\ in\ magnetic\ field = \frac{1}{2}\,L\,i^2$$

$$Rate\ of\ change\ in\ stored\ magnetic\ energy = \frac{d\,W_e}{dt}$$

$$= \frac{d\left(\frac{1}{2}\,L\,i^2\right)}{dt}$$

$$= \frac{1}{2}\,L\,2i\,\frac{di}{dt} + \frac{1}{2}\,i^2\,\frac{dL}{dt}$$

$$= L\,i\,\frac{di}{dt} + \frac{1}{2}\,i^2\,\frac{dL}{dt}$$

$$= L\,i\,\frac{di}{dt} + \frac{1}{2}\,i^2\,\frac{dL}{d\theta}\,\frac{d\theta}{dt}$$

$$= L\,i\,\frac{di}{dt} + \frac{1}{2}\,i^2\omega\,\frac{dL}{d\theta}$$

$$input\ power = P_m + i^2R + rate\ of\ change\ of\ stored\ magnetic\ energy$$

$$P_m = input\ power - i^2R - rate\ of\ change\ of\ stored\ magnetic\ energy$$

$$= i^2R + Li\,\frac{di}{dt} + i^2\,\omega\,\frac{dL}{d\theta} - i^2R - Li\,\frac{di}{dt} - \frac{1}{2}\,i^2\,\omega\,\frac{dL}{d\theta}$$

$$\boxed{P_m = \frac{1}{2}\,i^2\,\omega\,\frac{dL}{d\theta}}$$

Torque equation:

By faradays law,

$$e = -\frac{\partial\lambda}{\partial t}$$

$$= -\frac{\partial\,Li}{\partial t} \qquad (\,since\ \lambda = Li = N\varphi\,)$$

$$= -L\ \frac{\partial i}{\partial t} - i\ \frac{\partial L}{\partial t}$$

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

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

$$Magnitude\ of\ \ e\ =\ L\ \frac{\partial i}{\partial t} + i\ \omega\ \frac{\partial L}{\partial \theta}$$

$$input\ power\ from\ electrical\ source\ =\ e\ i$$

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

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

$$stored\ energy\ in\ magnetic\ field,\qquad W_e = \frac{1}{2}\ L\ i^2$$

$$power\ due\ to\ variation\ in\ stored\ energy\ =\ \frac{\partial\ W_e}{\partial t}$$

$$= \frac{\partial\ \left(\frac{1}{2}\ Li^2 \right)}{\partial t}$$

$$= \frac{1}{2}\ L\ \ 2i\ \frac{\partial i}{\partial t} + \frac{1}{2}\ i^2\ \frac{\partial L}{\partial t}$$

$$= Li\ \frac{\partial i}{\partial t} + \frac{1}{2}\ i^2\ \frac{\partial L}{\partial t}$$

$$= Li\ \frac{\partial i}{\partial t} + \frac{1}{2}\ i^2\ \frac{\partial L}{\partial \theta}\ \frac{\partial \theta}{\partial t}$$

$$= Li\ \frac{\partial i}{\partial t} + \frac{1}{2}\ i^2 \omega\ \frac{\partial L}{\partial \theta}$$

Input power = mechanical power (P_m) + power due to change in stored energy

P_m = input power – power due to change in stored energy

$$P_m\ =\ Li\ \frac{\partial i}{\partial t} + i^2\ \omega\ \frac{\partial L}{\partial \theta} - Li\ \frac{\partial i}{\partial t} - \frac{1}{2}\ i^2 \omega\ \frac{\partial L}{\partial \theta}$$

$$P_m\ =\ \frac{1}{2}\ i^2 \omega\ \frac{\partial L}{\partial \theta}$$

$Also, \quad P_m = \omega T$

$$\Rightarrow T = \frac{P_m}{\omega} = \frac{1}{2}\frac{i^2\omega}{\omega}\frac{\partial L}{\partial \theta}$$

$$\boxed{\boldsymbol{T = \frac{1}{2}\, i^2\, \frac{\partial L}{\partial \theta}}}$$

(i) $For\ motoring\ ,\ \frac{\partial L}{\partial \theta} \rightarrow +ve$

(ii) $For\ generator\ ,\ \frac{\partial L}{\partial \theta} \rightarrow -ve$

(iii) $T\ \alpha\ i^2$

Power converters and their controllers or Power Controllers:

5. What is the necessity of the converter circuits for switched reluctance motor? Draw and explain the different types of converter circuits in detail. May-2009

Discuss the various converter topologies for a 3 phase switched reluctance motor with merits and demerits of each. Explain any two of them. Dec-2011

Explain with neat circuit any two configurations of power converters used for the control of switched reluctance motor. May-2016, Dec-2017, 2015

Explain with neat diagram any two converter topologies for SRM. Dec-2016

Explain in detail the power controllers for SRM. May-2017

Necessity for Power converters:

- $T\ \alpha\ i^2$ (ie) T is independent of direction of current. So ***one switch per phase*** winding is enough.
- Phases of SRM are ***independent***. (ie) if one phase winding gets failure, operation is not affected.
- ***Mutual coupling*** between phases is negligible.
- Due to lack of mutual coupling between phases, the ***stored magnetic energy has to be handled properly*** during commutation. Otherwise it leads to excessive voltage across winding and device failure occurs.
- The magnetic energy should be
  - Free wheeled, partially converted to mechanical/electrical energy, partially dissipated in machine winding.
  - Return it to DC source.
- Based on the above methods, different power controller configurations are proposed.

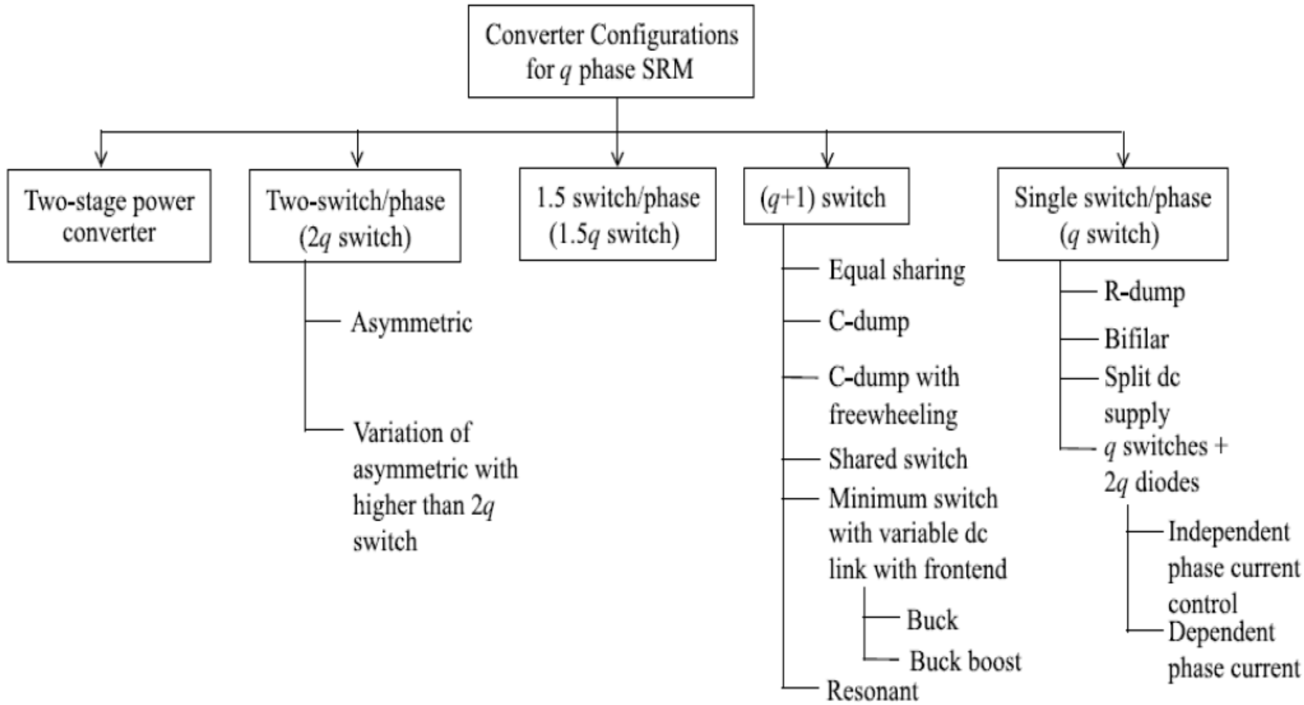


Fig. Classification of power converters

Basic requirements of power converters:

- Each phase should conduct independently.
- Able to free wheel.
- Converter should demagnetize the phase before it steps into the generating region.
- Should be able to utilize the demagnetization energy from the off going phase.

Few of the most used converter configurations are:

- Two power semi-conductor switch per phase or classic converter.
- (n+1) power device for n-phase motor.
- Phase windings using Bifilar wires.
- Split power supply converter.
- Dump C circuit.

1. Two power semi-conductor switch per phase or classic converter:

- Two power switches and two diodes per phase.
- To energize the phase windings A, the devices T_1 and T_2 are turned ON.
- Current flows through: +, T_1, A_1, A_2, T_2, -.
- To disconnect the phase, devices T_1 and T_2 are turned OFF.
- The stored energy in the phase winding A tends to maintain the current in the same direction.
- Stored energy is fed back to mains by: A_1, A_2, D_1, +, -, D_2.
- Other phases are excited in the similar manner.

- Upper devices T_1, T_3 and T_5 are turned ON and OFF from the signals obtained from the rotor position sensor.
- Lower devices T_2, T_4 and T_6 are controlled by the signals obtained from chopping frequency signal of power semiconductor devices.

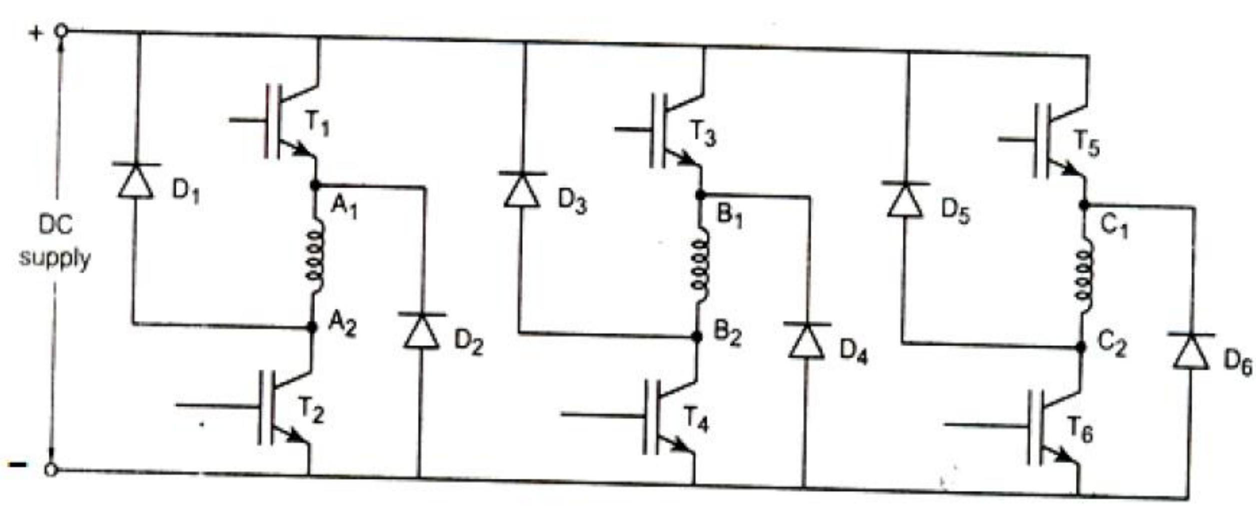


Fig. Two-power semiconductor switching devices per phase

Advantages:

- ✓ Reduces switching losses of converter circuit.
- ✓ Control of each phase is completely independent of the other phases.

Disadvantages:

- ✓ Converter circuit is expensive.

2. (n+1) power switching devices for n-phase motor:

- Uses (n+1) semiconductor switches for n phase motor.
- To energize the phase windings A, the devices T and T_1 are turned ON.
- Current flows through: +, T, A_1, A_2, T_1, - .
- To disconnect the phase, device T_1 is turned OFF.
- The stored energy in the phase winding A tends to maintain the current in the same direction.
- Stored energy is fed back to mains by: A_1, A_2, D_1, +, -, D.
- Other phases are excited in the similar manner.

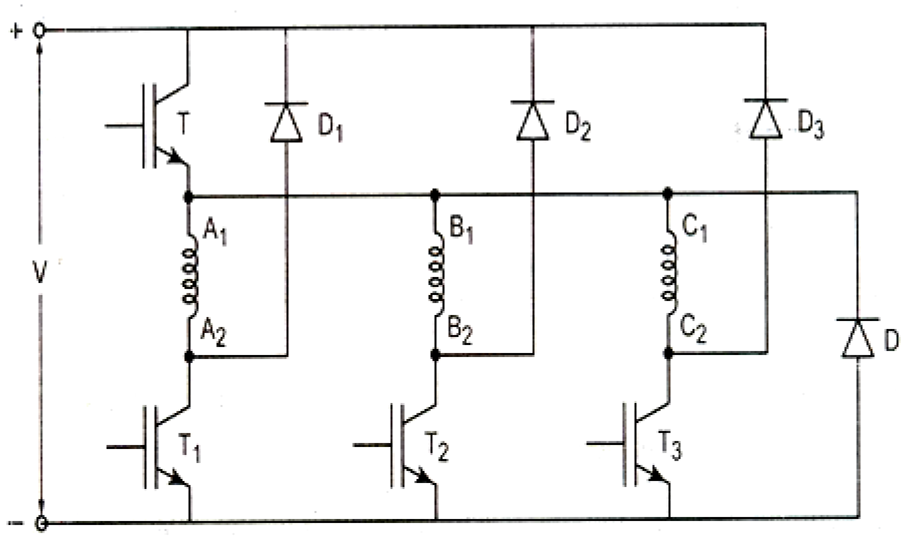


Fig. (n+1) power switching devices for n-phase motor:

Advantages:

- ✓ Numbers of devices are reduced.
- ✓ It run smoothly at low speeds.

Disadvantages:

- ✓ It is difficult task that the phase quickly gets de-energized.

3. Phase winding using bifilar wires:

- Each stator pole carries a coil using bifilar wires.
- When T_1 is turned ON, corresponding phase windings A gets energized.
- When T_1 is turned OFF, stored energy feed back to the dc source through A and diode D_1.
- Operation is similar for phase winding B and C also.

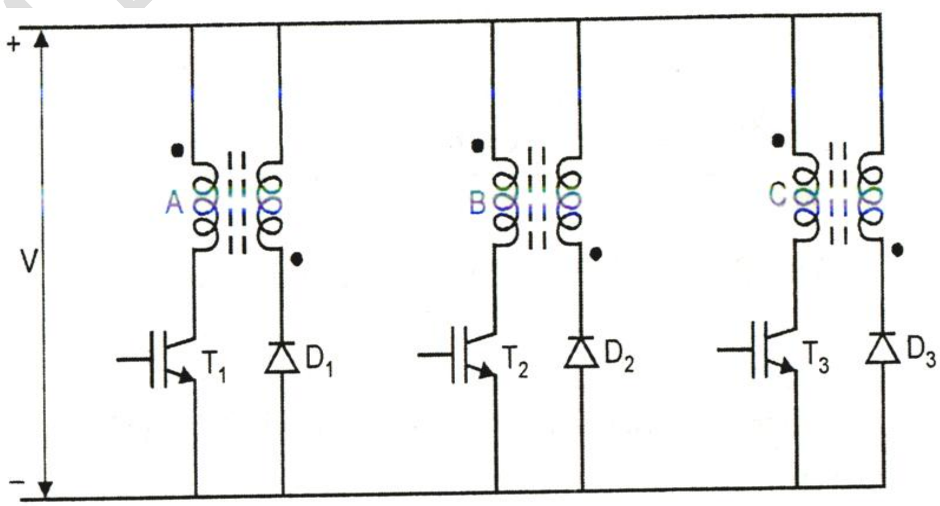


Fig. Phase winding using bifilar wires

Advantages:

- ✓ Cost is low.
- ✓ Fast demagnetization.

Disadvantages:

- ✓ Presence of voltage spikes in bifilar windings.
- ✓ Poor utilization of copper.
- ✓ Copper losses are high.

4. Split link power supply converter:

- Used with GTO, thyristor or IGBT's.
- Main power supply of 2 V_{dc} is split into two halves using split capacitors.
- During the conduction period, energy supplied by one half of the power supply.
- During turn OFF period, the phases demagnetize into other half of the power supply.
- When T_1 is turned ON, phase 1 gets energized by capacitor C_1.
- When T_1 is turned OFF, the stored energy in the phase winding 1 is feedback to capacitor C_2, through the diode D_2.

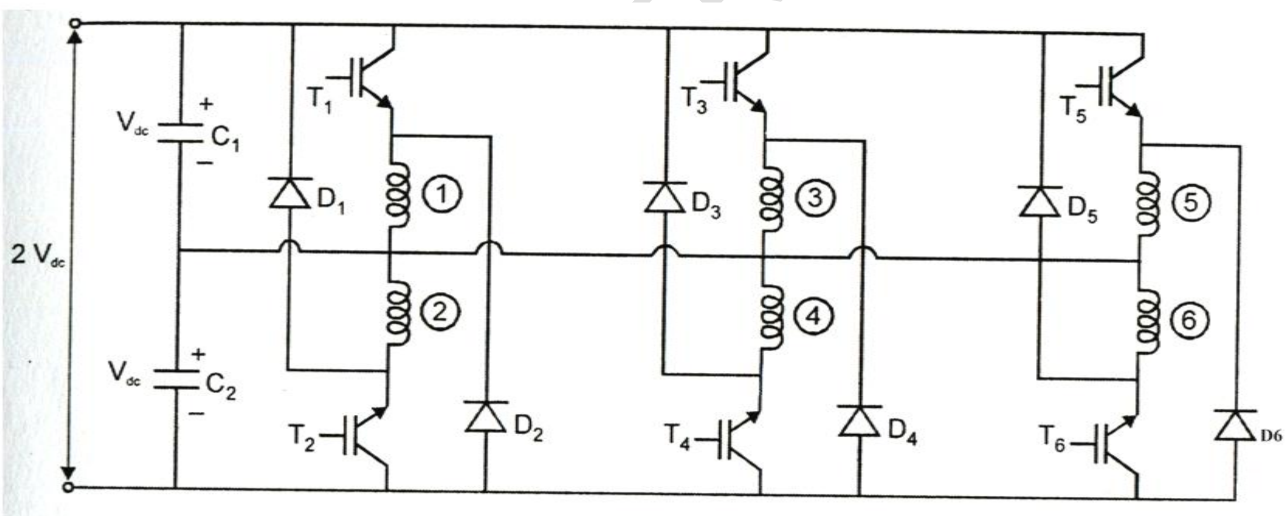


Fig. Split link power converter

Advantages:

- ✓ Optimum choice for highly efficient drive.
- ✓ Capable of compete with bifilar wire circuit.

Disadvantages:

- ✓ If fault occurs in one phase means, circuit imbalance occurs.
- ✓ For low voltage applications, it is poor choice.

5. C-dump circuit:

- Uses (n+1) diodes to feedback the energy from the dump capacitor to supply via step down chopper circuit.
- T_1 is turned ON to initiate the conduction process. Winding Ph1 is in series with T_1. Phase Ph1 is energized.
- During commutation period, D_1 is forward biased, energy transferred to the dump capacitor C_d.
- Phases are demagnetized by turning OFF the respective phase switches.
- The excess energy from dump capacitor C_d is transferred into the source, through the diode D_c by turning on the power switch Q_d.

Advantages:

- ✓ It uses lower number of switching devices.
- ✓ Faster demagnetization.

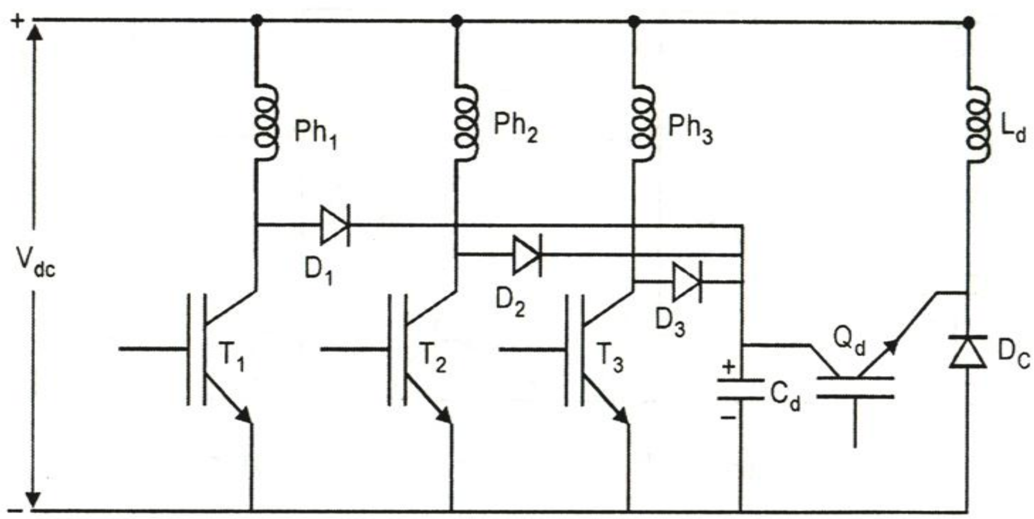


Fig. C-Dump circuit

Disadvantages:

- ✓ Complicated circuit.
- ✓ Use of inductors and capacitors in the circuit.

Methods of rotor position sensing:

6. Explain the "Shaft positioning sensor" of motor. **May-2009**

Discuss the various methods of rotor position sensing in SRM.

Dec-2017, 2014, May-2017, 2013

- Rotor position information is important for the operation of SRM.
- Rotor angle information must be accurate for the high speed drives.
- Inaccurate position sensing results in decreased torque & efficiency.
- In high speed motors, error in 1° decreases the torque by 8%.
- Position sensing sensor is enough.

- Disadvantages of electromechanical sensors are:
  - ✓ Unreliable due to dust, high temperature, humidity, vibration.
  - ✓ Cost increases with resolution.
  - ✓ Additional manufacturing expenses.
  - ✓ Extra electrical connections.
  - ✓ Need more space at the shaft.

- To overcome the above problems, sensorless rotor position estimation methods are developed.
- Sensorless methods employ motor electrical parameters for position detection.

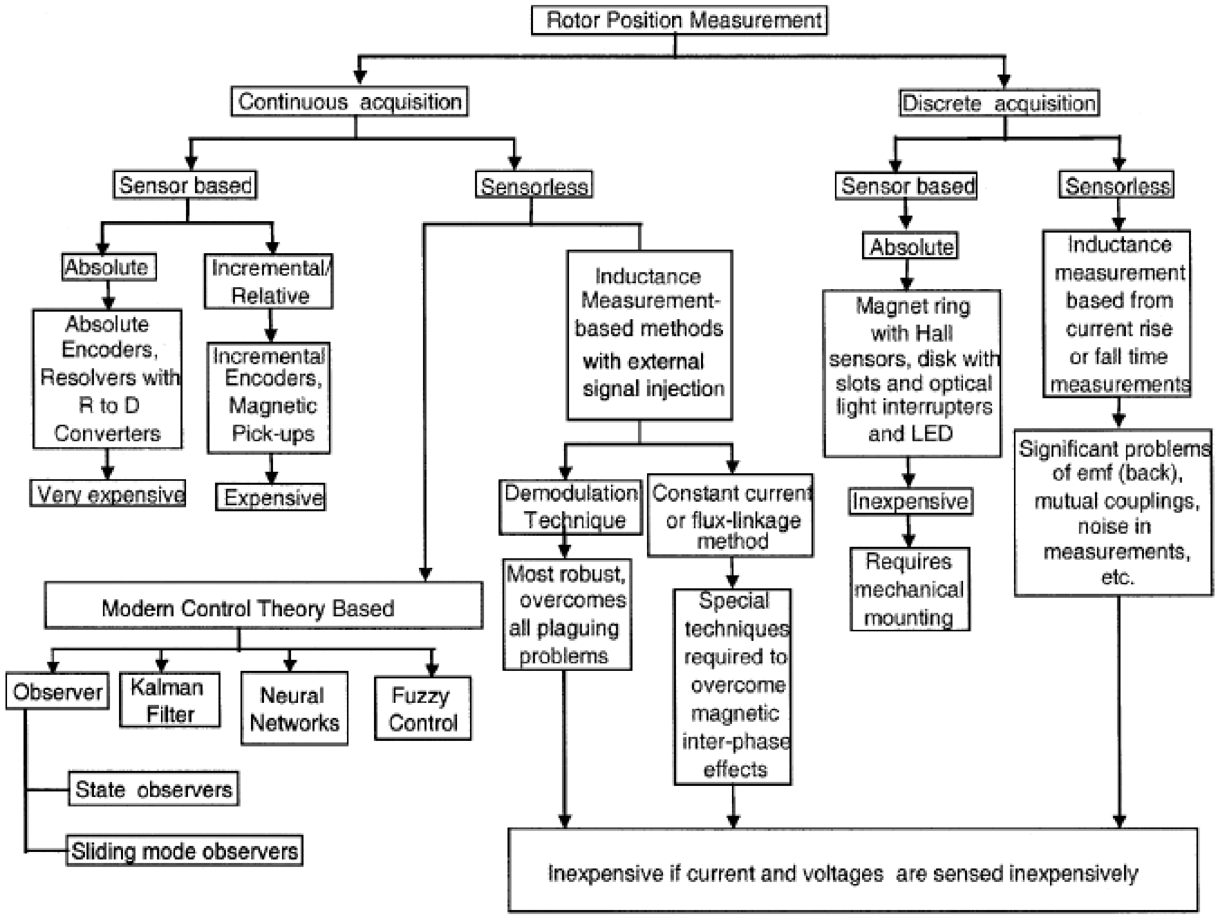


Fig. Classification of rotor position estimation

1. Photo transistor sensor or optical position sensor:

- Based on photo electric principle.
- On shaft, a revolving shutter with 120° electric gap angle is installed.
- On stator, 3 photo transistors are placed.
- When gap gets aligned with phototransistor, it produces the current (ie) that phase of the motor is turned on.

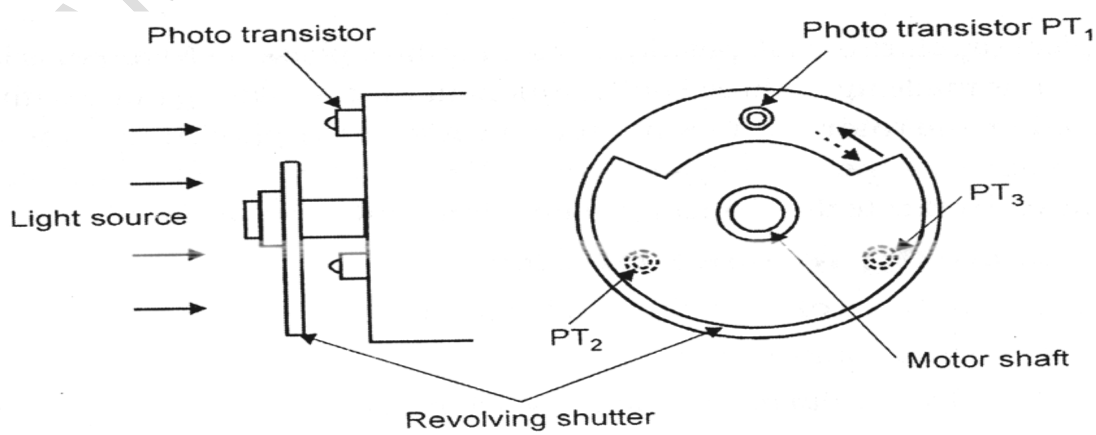


Fig. optical position sensor

2. Hall position sensor:

- Based on Hall principle.
- On rotor shaft, 3 hall components, rotating plate with permanent magnet.
- Output of hall components indicate the rotor position.

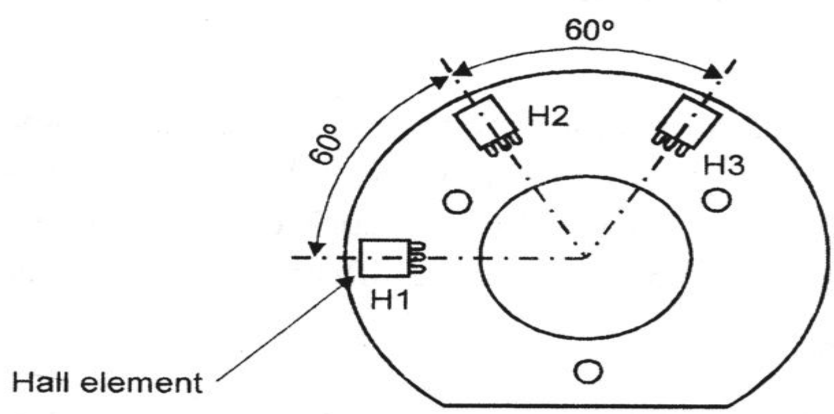


Fig. Hall position sensor

Sensorless methods:

- ❖ Observer based sensing methods
- ❖ Incremental inductance based sensing
- ❖ Direct inductance based sensing
- ❖ Intelligent control based sensing methods

Advantages:

- Compactness in weight and volume.
- Lower cost due to elimination of the mechanical assembly and mounting associated with a rotor position sensor.
- No rotating parts.

1. Observer based sensing methods:

- Use a state observer or a sliding mode observer
- Depends on the inductance slope for their convergence and functioning.
- Computationally intensive and have the problem of convergence.

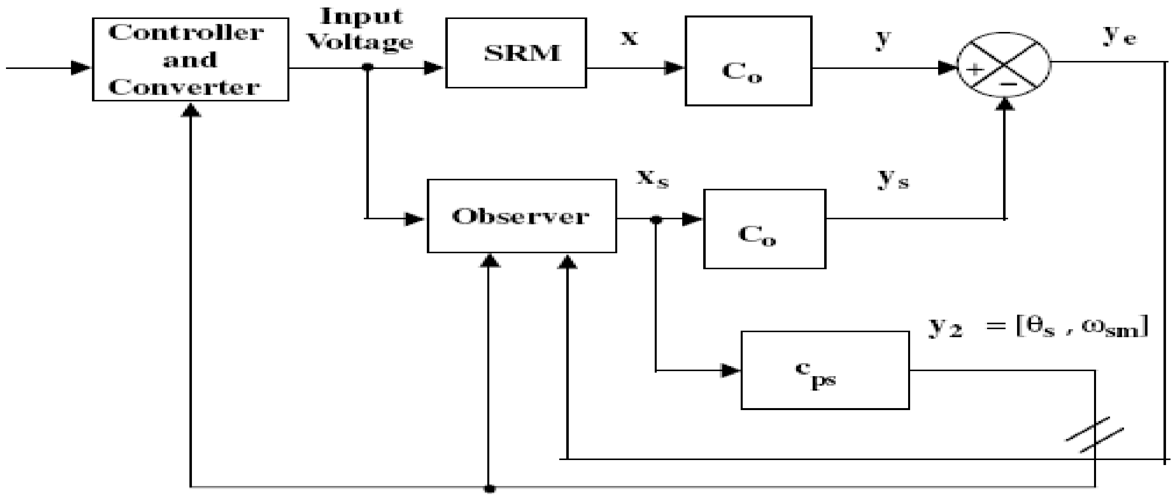


Fig. An observer for SRM drive system

2. Incremental inductance-based measurement method:

- Current rise time and fall times are proportional to the incremental inductance.
- The rise time and fall times reflect the incremental inductance and hence the rotor position itself.

3. Inductance-based estimation method:

- Exploit the inherent unique characteristic of the three-dimensional relationships among the flux linkages or inductance, current and rotor position.
- Availability of the first two variables leads to resolution of the third unknown, which is rotor position.
- Uses the two different techniques of **demodulation** and **constant current or constant flux linkage** applied to sensor signals and sensing phases respectively to give a continuous estimation.

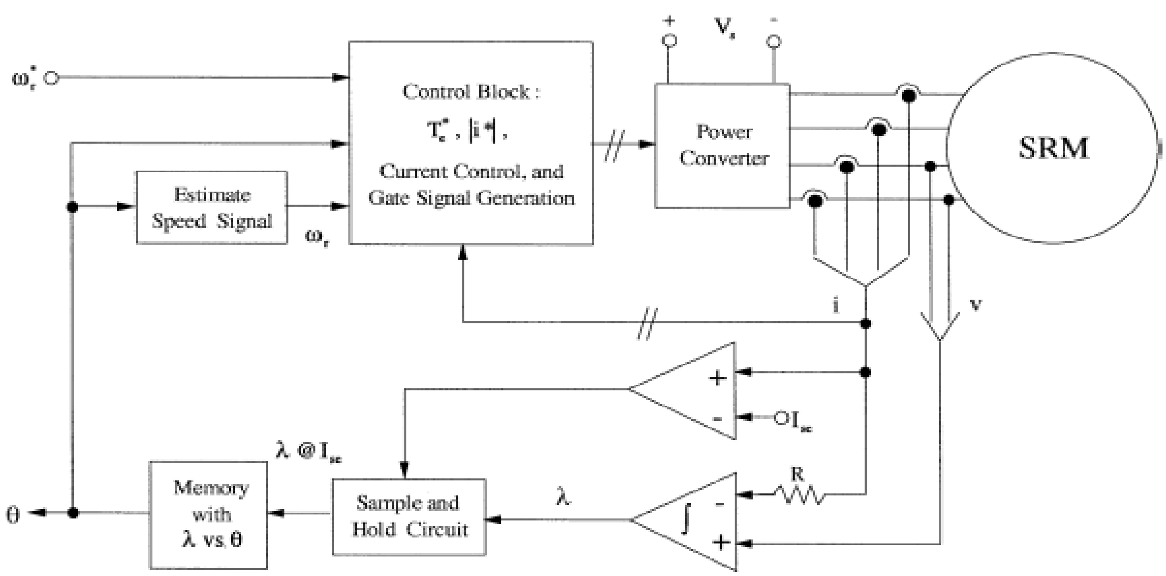


Fig. Rotor position estimation based on constant current/flux linkage

4. Intelligent control based estimation:

- Uses estimators based on artificial neural network and fuzzy control.
- Computationally less intensive.
- Due to their learning capability they provide adaptive control.

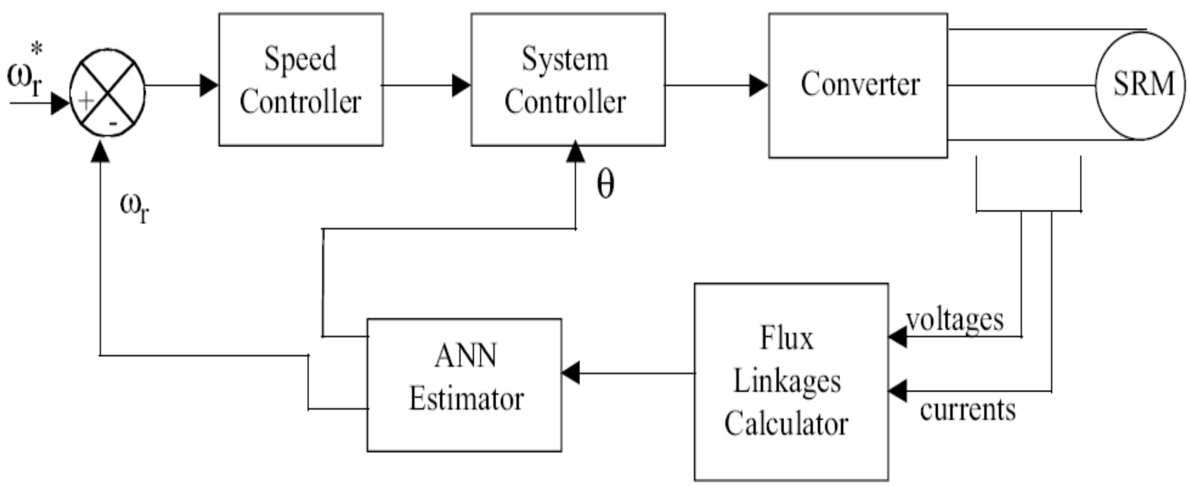


Fig. ANN based SRM drive system

Sensorless operation of SRM:

7. Explain the closed loop control of SRM using sensorless operation.

Dec-2017, 2016, May-2017, 2012

State the advantages of sensorless operation. **May-2016, Dec-2015**

- Based on variation of flux linkage with change in angular position of the rotor.
- Sensorless control is based on fuzzy based rotor position estimation model.
- Fuzzy logic is used as rotor position estimator.
- Flux estimator:
  - ✓ Input : phase voltage and current
  - ✓ Output : flux linkage
- Fuzzy angle estimator:
  - ✓ Input : flux linkage , phase current
  - ✓ Output : rotor angle

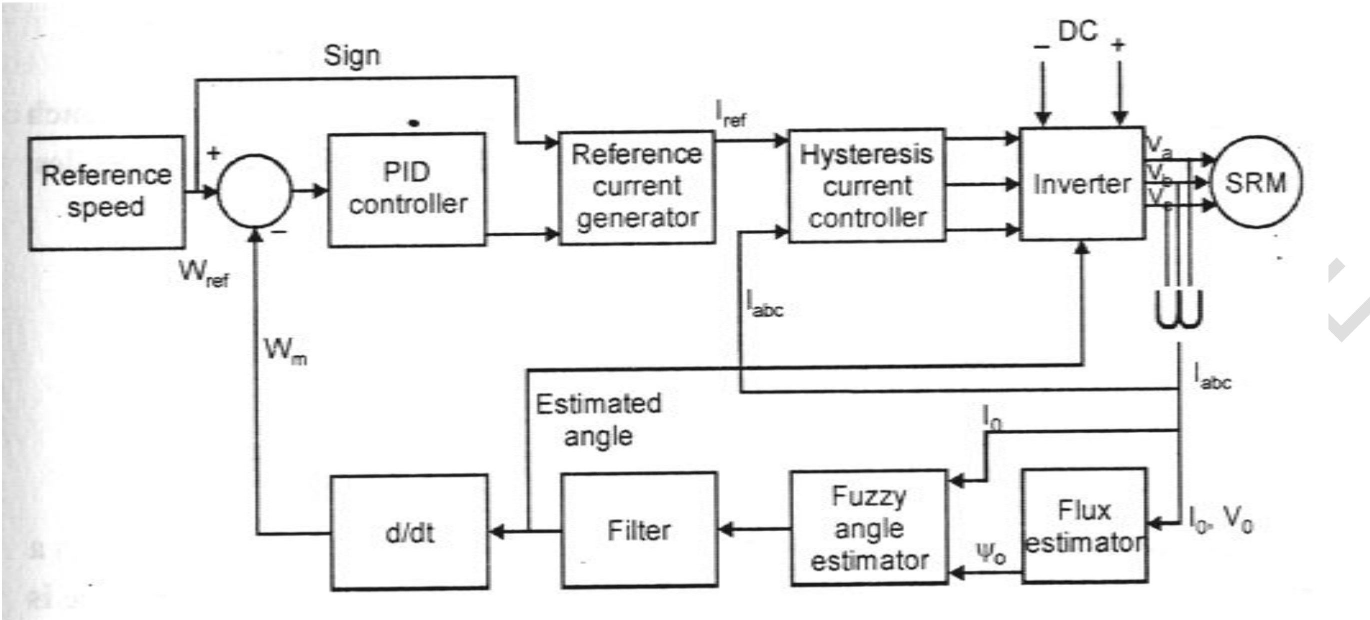


Fig. Sensorless Control of SRM with Fuzzy Rotor Position Estimator

- Artificial neural network based model are also been used in SRM drives.

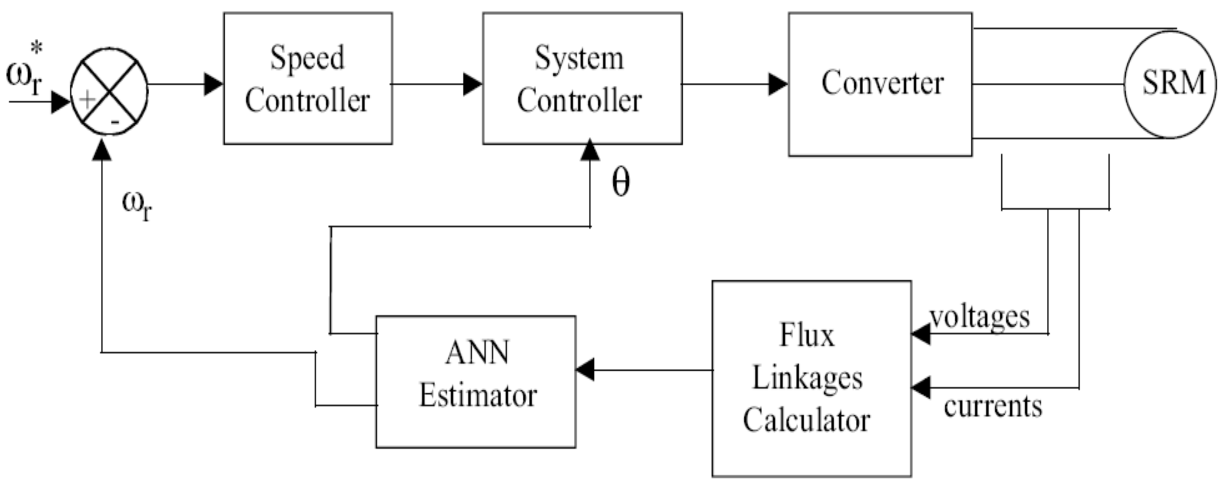


Fig. Sensorless Control of SRM with Artificial Neural Network

Advantages:

(i) Reliable
(ii) Precise and
(iii) Low-cost position sensorless control seems necessary

Microprocessor control of SRM:

8. With a neat sketch, explain the control of Switched Reluctance Motor using Microprocessor based controller. **Dec-2014, 2011, 2012**

Discuss the microprocessor based control of SRM.

Explain with neat diagram, the microprocessor based control of SRM. **Dec-2016**

Explain the role of microprocessors in control of SRM. **May-2017**

- The microprocessor or computer acts as a controller for SRM drive.
- Microprocessor is used to have,
  - ✓ control accuracy
  - ✓ flexibility
  - ✓ ease of operation
  - ✓ repeatability of parameters

- Consists of power semiconductor switching circuit, SRM with rotor position sensor and microprocessor system.
- The microprocessor generates control pulses or gives command signals to the power semi - conductor switching circuits.
- The power semiconductor switching circuit is fed by a DC supply.
- SRM carries a rotor position sensor, which gives information about the position of the rotor, with reference to the reference axis to the microprocessor.
- Microprocessor gets,
  - ✓ Rotor position signal,
  - ✓ reference speed signal
  - ✓ signals from the output of the power semiconductor circuit

- From the above signals, it turns ON and OFF the concerned phase winding of the SRM.

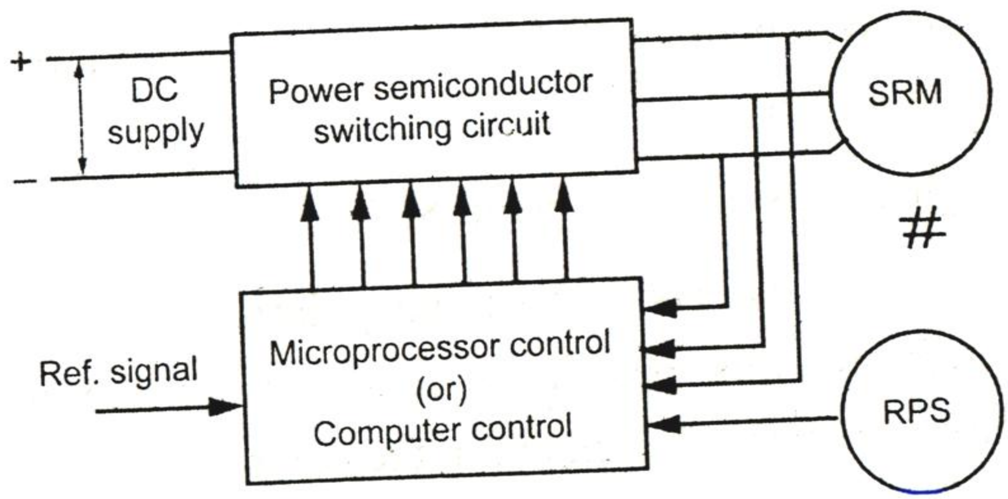


Fig. Microprocessor control of SRM

Closed loop control of SRM:

9. Explain the closed loop control analysis of SRM. **May-2014**

Explain the closed loop control operation of SRM and its performance characteristics in detail. **Dec-2014**

- Closed loop speed control is considered.
- From reference speed and actual speed, speed error is determined.
- Speed error is processed through PI controller & limiter to produce reference torque.
- From reference torque, reference current is obtained.
- Reference current is added and subtracted with Δi to produce i_{max} , i_{min} which determines switching of the phase.
- Based on the rotor information, current is injected into the phase windings.

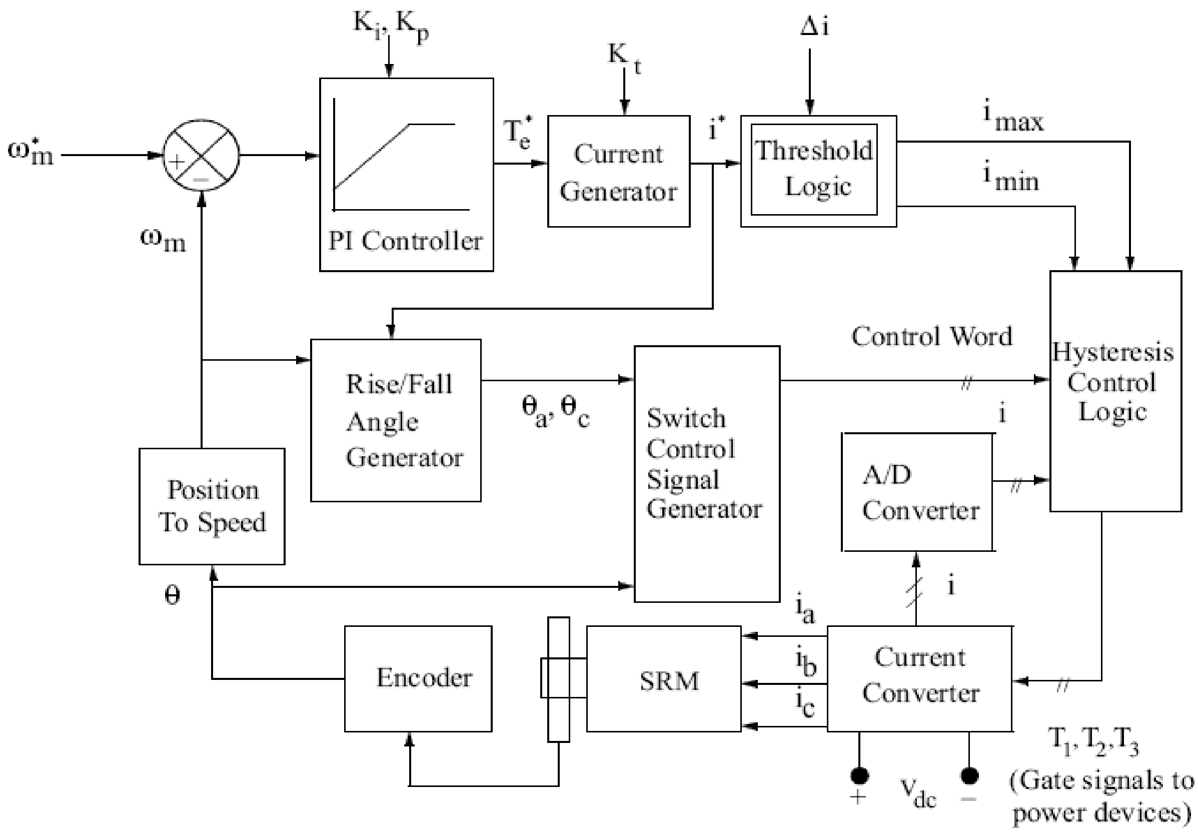


Fig. Closed loop control of SRM

- Simplified model of the closed loop control of SRM is as shown below.

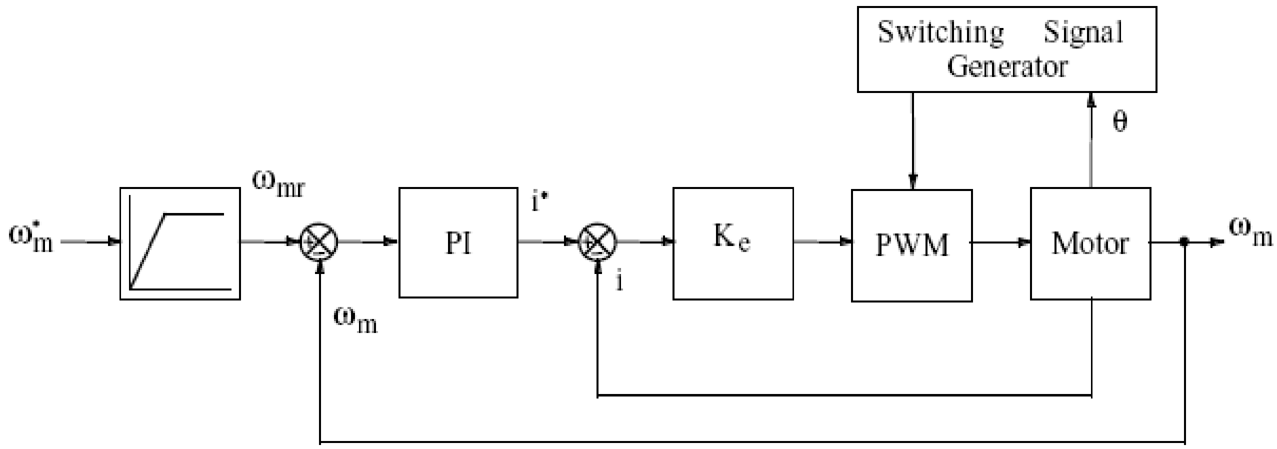


Fig. Simplified closed loop model of SRM

Characteristics:

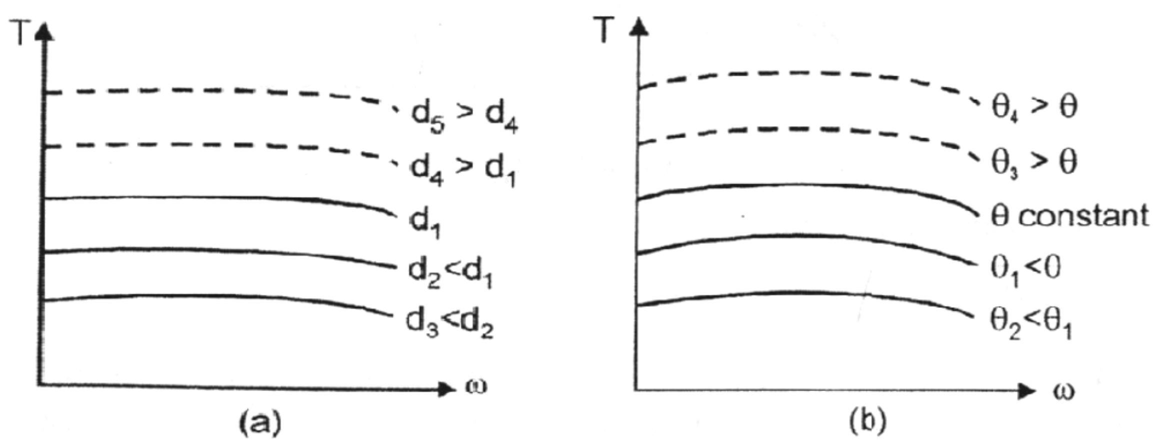
10. Explain the Speed- Torque characteristics of Switched Reluctance motor. Dec-2016, 2012

1. Torque – speed characteristics:

- Torque depends on current waveforms of each phase winding.
- Current waveform depend on conduction period (θ), chopping duty cycle and speed.

Consider, θ = constant, duty cycle = 1

- For low speed operation, current is flat, torque = constant.
- For high speed operation, current changes, torque reduces.



θ = constant   Duty cycle = constant

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

2. Torque-speed capability curve:

- Maximum torque developed and maximum power transferred are restricted by mechanical subsystem design parameters.
- For a given conduction angle, T can be varied by the duty cycle of chopper.

In region AB:

- ✓ Maximum torque region.
- ✓ θ = constant, duty cycle = varied, T = constant
- ✓ At B –> conduction angle = θ, point with maximum speed and constant torque. P = Tω.

In region BC:

- ✓ Max permissible torque at each speed without exceeding max power transfer.
- ✓ P = Tω = constant, vary θ to its maximum value.
- ✓ At C -> max power, max θ, duty cycle = 1.

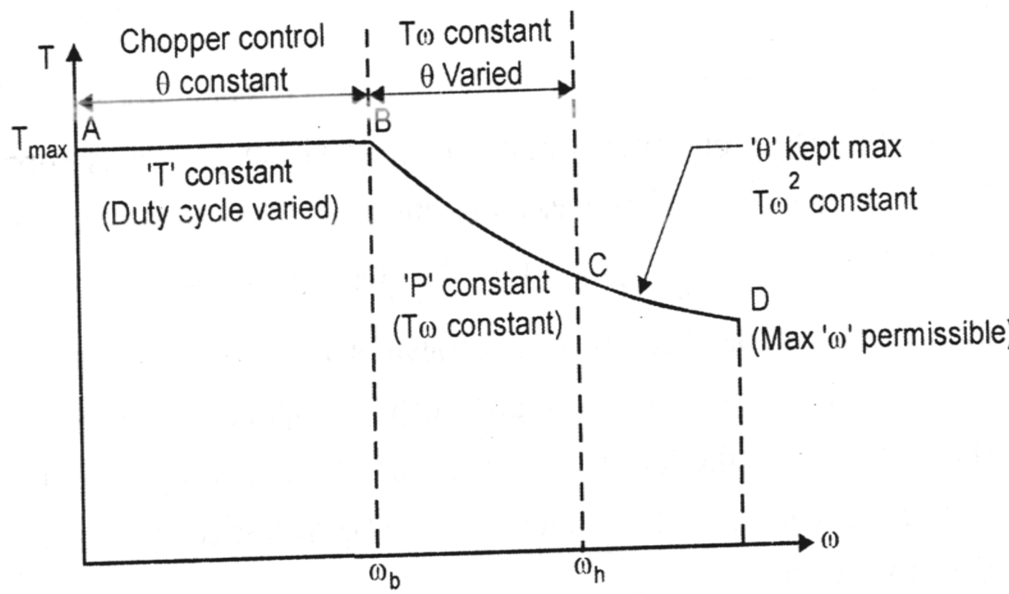


Fig. Torque-speed capability characteristics

In region CD:

- ✓ $T\omega^2$ = constant, θ = max, duty cycle = max.
- ✓ At D –> ω = max
- ✓ Region ABCD -> operating region of SRM

11. Describe the control circuits/methods of Switched Reluctance motor.

Along with circuit diagrams explain the hysteresis type and Pulse width modulation type current regulator for one phase of a Switched Reluctance motor. **Dec-2014**

- For motoring mode operation, pulses of the phase current should coincide with increasing inductance.
- Conduction period (dwell) of current pulse determines the torque, efficiency and other parameters.

Control methods:

- ➢ Hysteresis type current regulator
- ➢ Voltage PWM control or duty cycle control

1. Hysteresis type current regulator:

- Transducer (tachogenerator) is connected to the rotor.
- Output signal from the transducer is given as feedback signal to the transistor T_2.
- This signal is fed at the input of the operational amplifier.
- The operational amplifier compares signal with the reference current and then amplified signal is given to the transistor T_1.
- This signal in combination with collector current flow through the emitter of the transistor T_1 through the phase winding.
- The current limiting resistor R_{CL} limits the current according to the design requirement.

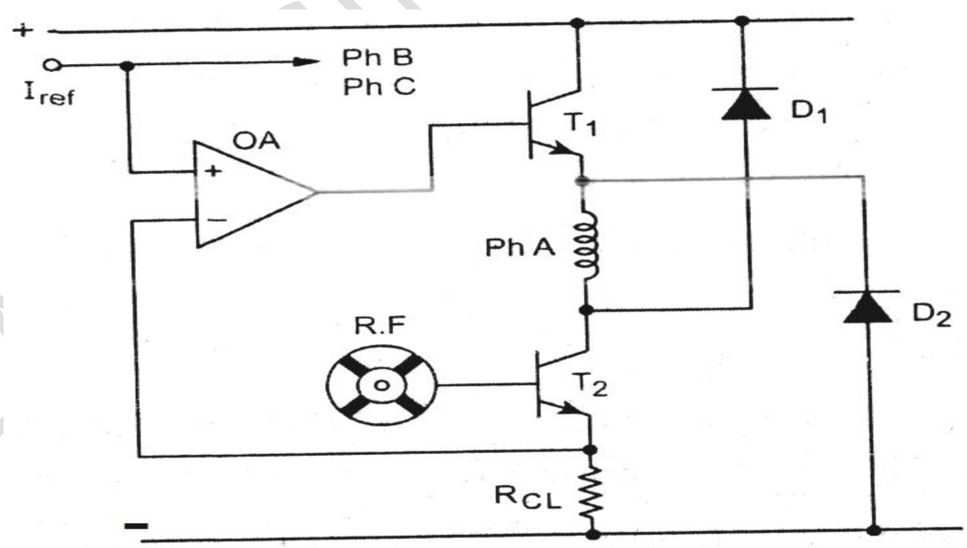


Fig. Hysteresis type current regulator

- When the reference current increase, the torque developed also increases.
- At low currents, $T \alpha I^2$ and this relationship becomes more linear at higher values of current.
- At high current, torque/ampere reduces due to saturation.

- When torque varies monotonically with speed, the speed adjustment is possible even without feedback.
- But to have accurate speed control, speed adjustment is needed.

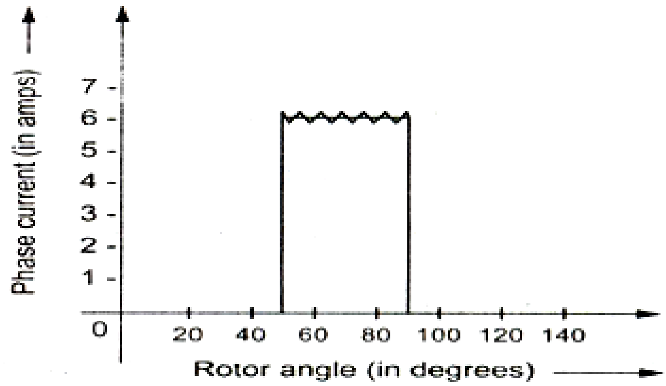


Fig. Rotor angle

- To obtain the speed feedback signals shaft position sensor, optical encoders are used.
- The 'hysteresis type' current regulator uses hall-effect sensors with built in current sensing.
- This type of control produces a constant – torque type of characteristics.

2. Voltage-PWM control or duty cycle control:

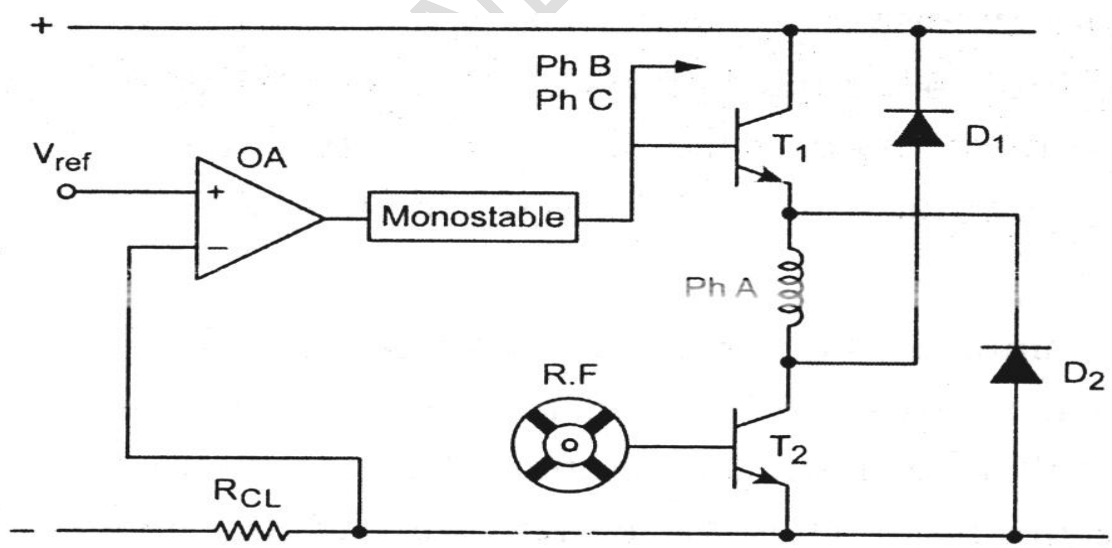


Fig: Voltage-PWM control

- Speed of the motor is converted into electrical signal (current), through the transducer (tachogenerator), which is fed to the transistor T_2.
- The resultant current from the emitter of the transistor T_2 flows through the current limiting resistor (R_{CL}) to the negative of the supply.

- The voltage at phase-A changes, because of the feedback signal.
- This feedback voltage is given as an input to the operational amplifier, which compares this input signal with the reference voltage.
- The difference of these two signals is amplified and fed to the monostable circuit.
- Monostable circuit modulates the pulse width of the incoming signal based on the requirement and the modulated signal is given at the base of T_1.
- This signal combines with collector current of T_1 and flows through phase A.
- Thus the current is regulated or controlled using pulse width modulation and rotor feedback.

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12. Compare Switched Reluctance motor and Variable Reluctance motor. Dec-2013

S. NO.	SWITCHED RELUCTANCE MOTOR	VARIABLE RELUCTANCE MOTOR
1.	SRM is normally operated with shaft position feedback to synchronize with the rotor position thereby controlling conduction angle and commutation of the phase currents.	The stepper motor is usually fed by a square wave of phase current without rotor position feedback.
2.	SRM is designed for efficient power conversion upto at least 300KW.	Normally designed to maintain step integrity rather than to achieve efficient power conversion.
3.	SRM usually operates at high speeds.	The stepper motor is usually designed as a torque motor with a limited speed range.
4.	It is meant for continuous rotation.	It rotates in steps.
5.	Closed loop control is essential for its optimal working	It works in open loop operation.
6.	No half step operation and micro stepping operation	It is capable of half step and micro stepping operation
7.	It has power ratings upto 75 KW.	It has comparatively lower power rating.
8.	It has higher overall efficiency. The SRM is naturally designed to operate efficiently for wide range of speed.	It has lower efficiency. Efficiency is not an important factor for stepper motor.
9.	SRM requires rotor position sensor.	It does not require rotor position sensor.
10.	Mainly used in domestic applications like vacuum cleaner, washing machines and general purpose industrial drives.	Mainly applied in computer controlled systems and robotics.

13. Enumerate the various operating modes of SR motors with neat diagram. **Dec-2012**

There are two modes of operation in SRM. They are,

- Low speed operation mode
- High Speed operation mode

Low speed Operation mode:

$Let, \theta - conduction\ angle$

$\omega_L - speed\ corresponding\ to\ low\ speed\ operating\ mode$

$$Conduction\ period\ of\ the\ switching\ device = \frac{\theta}{\omega_L}\ sec$$

- During the period of conduction of current in a particular phase winding, if the current reaches almost its steady state value, then the current waveform can be assumed to be flat shaped one.
- The semiconductor switching devices will be turned on during the period from θ_{on} to θ_{off} and during the θ_{off} the feedback diodes will conduct.
- For varying the developed torque, vary the average value of current.
- To achieve this, vary the duty cycle of the chopper or by PWM techniques.

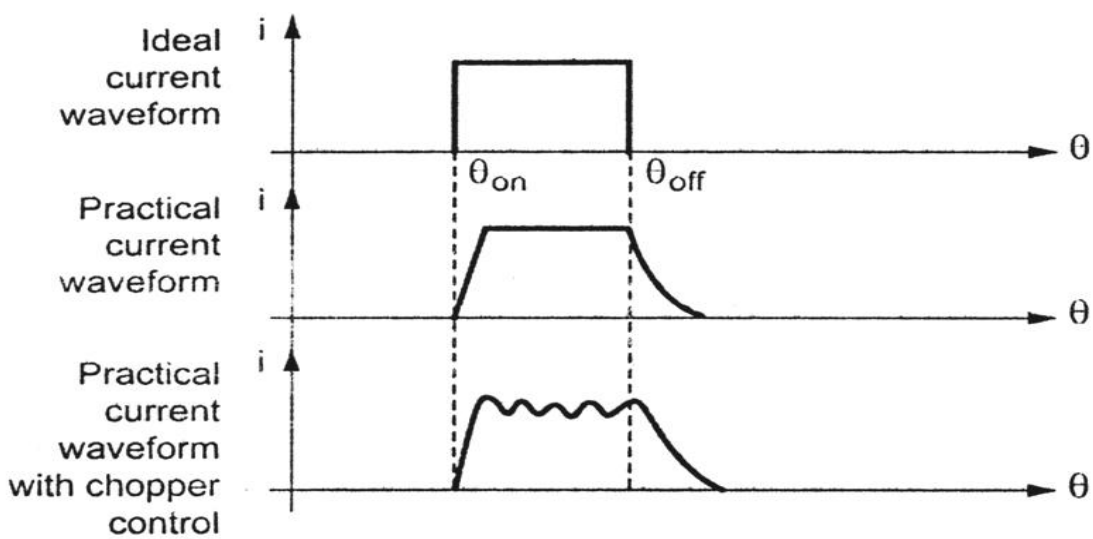

Fig. Ideal and practical current waveform for low speed operating mode.

High Speed operation mode:

- In this mode, though the conduction period of the switching devices of the winding is same.
- But the time duration of conduction is made small.

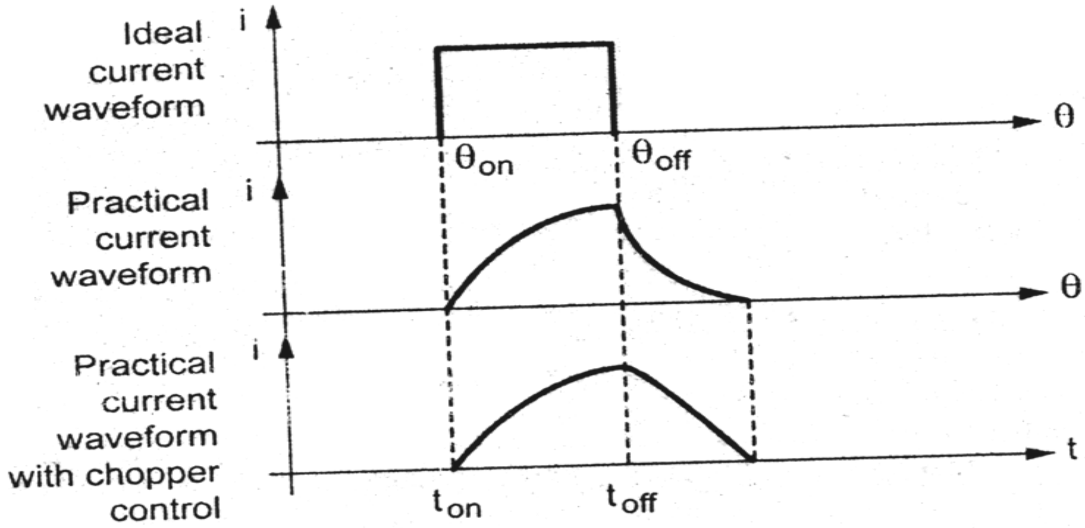

Fig. Ideal and practical current waveforms for high speed operating mode

- The average value of current is varied by varying the conduction period θ.
- As T α i^2 , the electromagnetic torque developed in high speed operating mode can be varied by varying the conduction angle θ.

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14. Explain the steady state analysis of Switched reluctance motor. **May-2014**

Steady State Analysis :

There are three cases in steady state performance analysis.

(i) Linear Case (or) unsaturated condition

(ii) Practical Case

(iii)Idealized case with extreme saturation

(i) Linear Case (or) unsaturated condition:

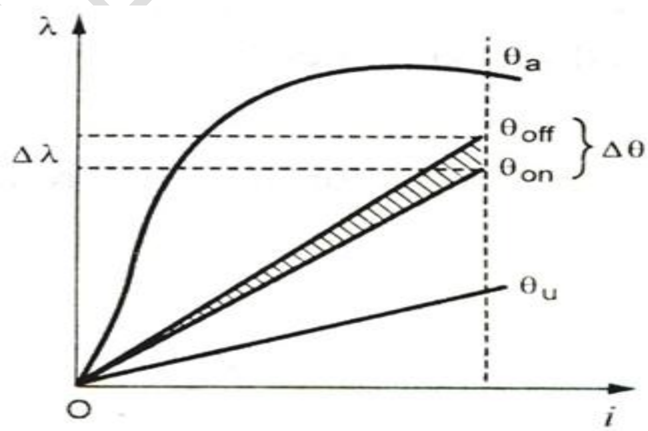


Fig. λ-i curve of SRM during energy conversion without saturation

The λ-i curve of SRM during energy conversion without saturated condition for aligned and unaligned position is shown above.

We know that the torque equation of SRM is given by,

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \qquad ----(1)$$

Also we know that $P_m = \omega T$

$$P = \frac{1}{2} \omega i^2 \frac{dL}{d\theta} \qquad ----(2)$$

The above equation (2) gives the linear expression for instantaneous torque as before.

The triangular are ΔW_m which represents the mechanical energy conversion is one – half of the rectangular are ΔW_e representing the electrical energy supplied, since it has the same base $[\Delta\psi]$ and the same height, the current i being constant through the small rotation.

The change in electrical energy input for this small rotation $\Delta\theta$ is

$$\Delta W_e = \Delta\lambda \times i[\text{part of lines indicated in rectangulat area}]$$

The change in mechanical energy transferred,

$$\Delta W_m = \frac{1}{2}\Delta\lambda \times i[\text{Area of triangle shown by shaded portion}]$$

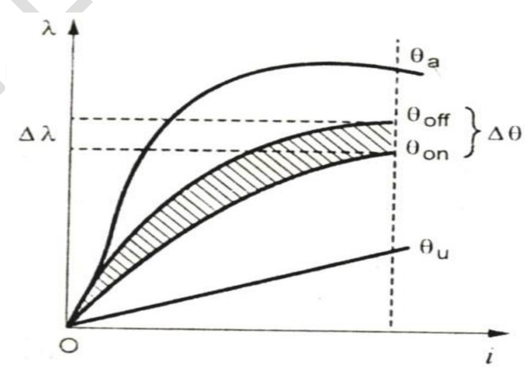
$$\Delta W_m = \frac{1}{2}\Delta\lambda \times i$$

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

The partition of input energy into mechanical energy work and stored field energy is improved if the motor saturates.

(ii) Practical case:

Practically, the magnetization curve is in saturation level as shown in following figure.



If at a given rotor position, if the magnetization curve is saturated as shown in the above figure then the area representing the mechanical work can exceed half the area of supply rectangle ($\boldsymbol{\Delta W_e = \Delta\lambda \times i}$) near the knee point.

The change in electrical energy input to the machine $\boldsymbol{\Delta W_e = \Delta\lambda \times i}$

Change in the mechanical energy transferred = ΔW_m

The mechanical energy transferred $\Delta W_m > \frac{1}{2}\Delta W_e$

(iii) Idealized case [Extreme Saturation]:

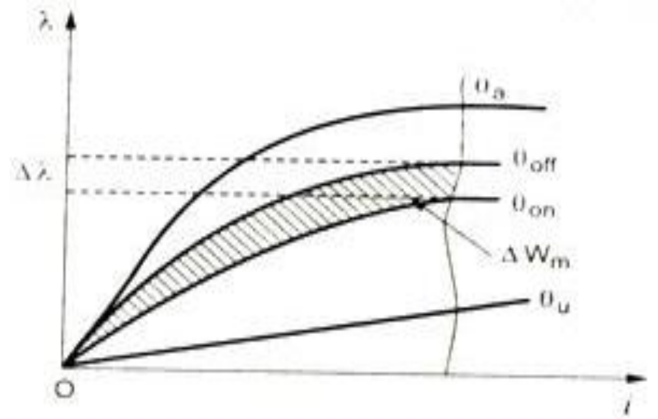


Fig. λ-i curve of SRM during energy conversion with high saturation

As shown in above figure, a sharp saturation results for a lower current level and extreme high inductance below this level. Here, the change in mechanical energy transfer ($\Delta W_m \cong \Delta W_e$) approximately equals the change in electrical energy input.

In this case, practically all the electrical energy supplied is converted into mechanical energy. The amount of energy stored in the magnetic field is very small.

From the above discussions, it is concluded that as the saturation level increases, the mechanical energy transferred is increased, but the energy stored in the magnetic field is decreased.

Applications:

15. What are the applications of SRM? **May-2017**

- Washing machines, Vacuum cleaners
- Fans
- Low cost brushless applications
- Future auto mobile applications
- Robotics control application, Aerospace applications

Advantages:

16. What are the advantages of switched reluctance motor? **Dec-2017, May-2018, 2017**

- Construction is simple and robust.
- Rotor carries no windings, no slip rings, no brushes, less maintenance.
- There is no permanent magnet.
- Ventilating system is simpler as losses takes place mostly in the stator.
- Power semi conductor switching circuitry is simpler
- No shoot through fault likely to happen power short circuits,
- Developed torque doesn't depends upon the polarity of current in the phase winding.
- The operation of the machine can be easily changed from motoring mode to generating mode by varying the region of conduction.
- It is possible to get very high speed.
- It is the self starting machine.
- Energy stored in the phase winding is fed back to the supply through the feedback diodes

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ANNA UNIVERSTY QUESTIONS

PART-A

1. What are the types of power controllers used for switched reluctance motor? Dec-2016, 2015, May-2011
2. Why rotor position sensor is essential for the operation of switched reluctance motor? Dec-2011, 2012

   Discuss the need of rotor position sensor in SRM. Dec-2016, May-2015

   What is the significance of position sensors used in SRM. Dec-2017

3. List the disadvantages of a switched reluctance motor? May-2007
4. What are the advantages of switched reluctance motor? May-2016, 2011, Dec-2013
5. Draw the general torque - speed characteristics of switched reluctance motor? May-2018, 2017, 2010
6. What is meant by energy ratio? May-2017
7. Write down the Voltage and torque equation for a switched reluctance motor drive. Dec-2017, May-2013, 2012
8. State the principle of operation of switched reluctance motor. May-2011, 2014
9. What is the need for shaft position sensor for SRM? May-2018, 2006
10. Compare switched reluctance motor and synchronous reluctance motor. Dec-2010
11. Compare switched reluctance motor and variable reluctance motor. Dec-2010
12. Why SR machines are popular in adjustable speed drives? Dec-2012
13. What is the significance of closed loop control of switched reluctance motor? May-2016, Dec-2013
14. List out some position sensors. May-2013
15. What are advantages of sensorless operation of Switched Reluctance motor? Dec-2017, May-2014
16. List out the advantages and disadvantages of the converter circuit with two power semiconductor devices and two diodes per phase. Dec-2014
17. List the characteristics of switched reluctance motor. May-2017, 2015
18. State the reluctance principle. May-2017, 2015
19. What are the applications of SRM? May-2010, Dec-2016, 2011
20. Mention the different modes of operation of SRM. Dec-2017, 2016, 2015

PART-B

1. Explain the Constructional features and working principle of Switched Reluctance Motor (SRM). May-2017, 2015, 2011, Dec-2013

Draw the cross sectional view of SRM. May-2018

2. Describe the working and construction of rotary and linear switched reluctance motor. Dec-2017, 2016, 2014, May-2017, 2012, 2013

Explain with neat diagrams the constructional details and operation of rotary switched reluctance motors. May-2016, Dec-2017, 2015

3. Discuss about the operation of SRM. May-2018, Dec-2014

4. Derive the voltage and torque equation of SRM. May-2015

Derive the expression for static torque in SRM. Dec-2016

5. What is the necessity of the converter circuits for switched reluctance motor? Draw and explain the different types of converter circuits in detail. May-2009

Discuss the various converter topologies for a 3 phase switched reluctance motor with merits and demerits of each. Explain any two of them. Dec-2011

Explain with neat circuit any two configurations of power converters used for the control of switched reluctance motor. May-2016, Dec-2017, 2015

Explain with neat diagram any two converter topologies for SRM. Dec-2016

Explain in detail the power controllers for SRM. May-2017

6. Explain the "Shaft positioning sensor" of motor. May-2009

Discuss the various methods of rotor position sensing in SRM. Dec-2017, 2014, May-2017, 2013

7. Explain the closed loop control of SRM using sensorless operation. Dec-2017, 2016, May-2017, 2012

State the advantages of sensorless operation. May-2016, Dec-2015

8. With a neat sketch, explain the control of Switched Reluctance Motor using Microprocessor based controller. Dec-2014, 2011, 2012

Discuss the microprocessor based control of SRM.

Explain with neat diagram, the microprocessor based control of SRM. Dec-2016

Explain the role of microprocessors in control of SRM. May-2017

9. Explain the closed loop control analysis of SRM. May-2014

Explain the closed loop control operation of SRM and its performance characteristics in detail. Dec-2014

10. Explain the Speed- Torque characteristics of Switched Reluctance motor. Dec-2016, 2012

11. Along with circuit diagrams explain the hysteresis type and Pulse width modulation type current regulator for one phase of a Switched Reluctance motor. Dec-2014

12. Compare Switched Reluctance motor and Variable Reluctance motor. Dec-2013

13. Enumerate the various operating modes of SR motors with neat diagram. Dec-2012

14. Explain the steady state analysis of Switched reluctance motor. May-2014

15. What are the applications of SRM? May-2017

16. What are the advantages of switched reluctance motor? Dec-2017, May-2017

MAILAM ENGINEERING COLLEGE

Department of Electrical and Electronics Engineering

SUB CODE: EE 6703 SUB NAME: SPECIAL ELECTRICAL MACHINES

UNIT – 04
PERMANENT MAGNET BRUSHLESS DC MOTORS

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

PART-A

1. What is a brushless permanent magnet DC motor?

- Similar to salient pole motor, except there is ***no field winding on rotor***.
- Field is provided by employing ***permanent magnet*** at the ***rotor***.
- The permanent- magnet DC motor is fed by ***rectangular current*** which have ***concentrated windings*** on the stator inducing a ***square or trapezoidal voltage***.

2. Compare conventional DC motor and PMBLDC motor? Dec - 2012

S. No	Conventional DC motor	PMBLDC motor
1	Field magnets are located in stator.	The rotor has permanent magnets.
2	Maintenance requirement is high because of the presence of commutator and brushes.	Low maintenance.
3	Standardized design procedures are available.	The motor can be designed for higher voltages subjected to the constraint caused by the power semiconductor switching circuit.
4	Motor size is large.	Size of the motor is small.
5	Power semiconductor devices are not used.	Electronic switching is implemented using power semiconductor devices.
6	No rotor position sensor.	Rotor shaft position can be detected by using sensor.

3. Give the merits of BLPMDC motor compared to conventional motor.
What are the advantages of BLPM dc motor over conventional DC motor? Dec-2015
What are the merits of brushless dc motor drives? Dec-2016

- There is no field winding and so there is no field copper loss.
- Efficiency is higher.
- It is possible to have very high speeds.

4. What are the types of PM brushless square wave D.C. motor?

- 180 degree pole arc BLPM square wave DC motor.
- 120 degree pole arc BLPM square wave DC motor.

5. State the principle of operation of PM brushless DC motor. **Dec-2017, 2014**

When DC supply is given to the motor, the armature winding draws a current. This current sets up an mmf which is perpendicular to the main mmf set up by the permanent magnet field. Hence, a force is experienced by the armature conductors according to fleming's left hand rule. As it is in the stator, a reactive force and frictional torque, the motor starts rotating.

6. What is an electronic commutator? **May-2017, Dec - 2011**

The electronic commutator is an equipment used in PM brushless DC motor to transfer the current to the armature. In this, power semiconductor devices are used as switching devices. Usually six switching devices are employed in a normal electronic commutator. Hence, the armature should have three tappings, which can be connected either in star or delta.

7. Write down the EMF equation of PM brushless DC motor. **May-2017**

The emf induced per phase of PM brushless DC motor is,

$$E_{ph} = 2\, B_g\, r\, l\, T_{ph}\, \omega_m \;\; volts$$

8. Write the torque equation of PMBLDC motor. **Dec-2017**

$$T = 4\, B_g\, r\, l\, T_{ph}\, I \qquad N - m$$

9. Name the two comparators used in the power controllers of PMBLDC motor?

- Speed comparator
- Current comparator

10. State the different types of permanent magnets that are used in electrical machines?

List any four permanent magnet materials. **May-2018, 2014**

What are the requirements of materials used for permanent magnet in PMDC motors?

- Alinco magnet
- Cobalt- Samarium magnet
- Barium and Strontium ferrites
- Neodymium – Iron - Boron (NdFeB) magnet

11. State the features of various permanent magnets that are used in electrical machines.

- Alinco has good thermal stability and high flux density.
- Cobalt- Samarium magnet has high remanence and high energy density.
- Barium and Strontium ferrites are easy to produce and suitable for moderate temperature.

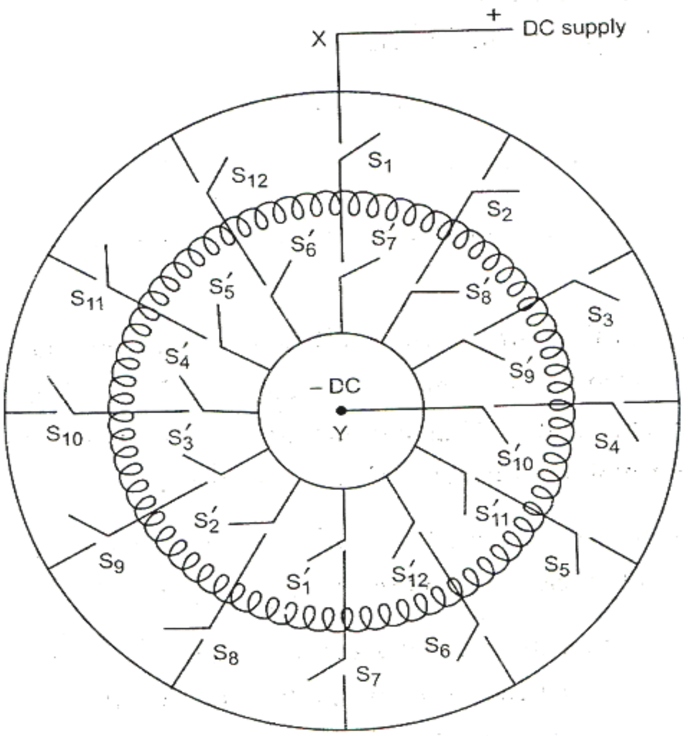
12. Name the position sensors that are used for PMBLDC motor?

- Optical position sensor
- Half effect position sensor

13. What are the materials used for making Hall IC pallet?

- Indium - antimony
- Galium - arsenide

14. Draw the circuit diagram of electronic commutator.



15. Compare PMBLDC motor and switched reluctance motor? **May – 2014, 2013**

PMBLDC Motor	Switched Reluctance Motor
Rotor is a permanent magnet.	No permanent magnet in the rotor
High cost	Cost is less compared with PMBLDC
More efficient	Less efficient

16. What is hall sensor?

A sensor is operated with hall effect principle. It is called hall sensor. It is used to sense the rotor position in the BLPMDC motor.

17. What is optical sensor?

A sensor is operated with photo transistor, it is the optical sensor. It is mainly used to sense the rotor position of the BLPMDC motor.

18. What is permanent magnet DC commutator motor?

A DC motor consists of permanent magnet in the stator and armature winding, commutator in the rotor. The motor is called permanent DC commutator motor.

19. List out some applications of BLPMDC motor? **May-2018, 2016, Dec-2017, 2015**

- Turn table drive for record player
- Tape drive for video recorders
- Driver for cooling fans of electronic circuit and heat sinks
- Drive for air conditioner blower and wind shield wipers.

20. Compare PMSM and PMBL DC motor.

PMBLDC	PMSM
It has concentrated winding on the stator.	It has distributed winding on the stator.
Induces square or trapezoidal voltage	Induces sinusoidal voltage.
Known as brushless dc motor.	Known as brushless ac motor.
Used as low power device.	Used as high power device.

21. What is permeance co-efficient? Dec-2016, May - 2012

It is defined as the ratio of air-gap permeance of the permanent magnet assuming the same relative permeability.

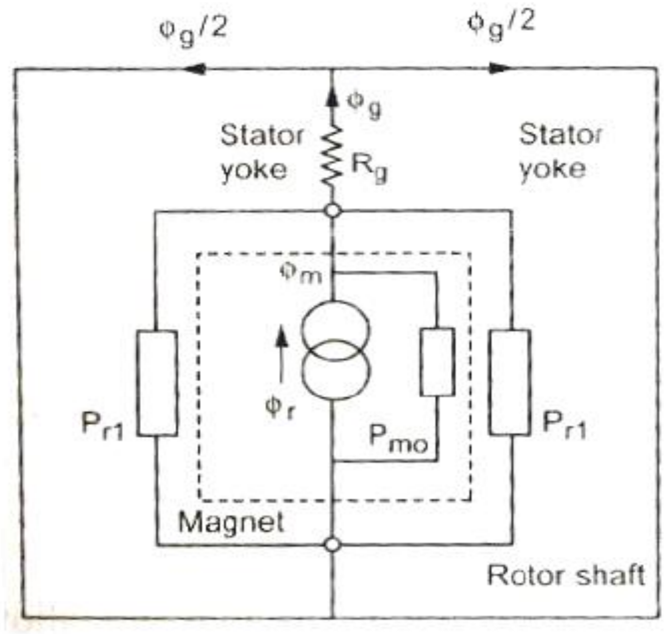
22. Comparison between mechanical and electronic commutator. May-2017, Dec – 2016, 2013

Refer Page No. 08 Q. No. 02

23. Name the power controllers used in the PMBLDC. Dec-2016, May - 2012

- Vector control
- Current control

24. Draw the magnetic equivalent circuit of PMBLDC motor. May-2017, 2014, Dec - 2013



25. What is commutation? May–2013

Commutation is the process of switching current in the phases in order to generate motion. The method of commutation depends on the application of the motor.

26. Define soft magnetic materials and hard magnetic materials.

Soft magnetic materials – narrow hysteresis loop
Hard magnetic materials – wide hysteresis loop

27. How are the directions of rotations reversed in case of PMBLDC motor? Dec – 2011

Reversing the direction of BLDC Motor:

For Anticlockwise direction:	*For clockwise direction:*
PT1 – Tr1	PT1 – Tr3
PT2 – Tr2	PT2 – Tr1
PT3 – Tr3	PT3 – Tr2

Where PT1, PT2, PT3 – photo transitors

28. Classify the types of BLDC motor. May-2015

- 180° pole arc BLPM square wave DC motor
- 120° pole arc BLPM square wave DC motor

29. What is meant by demagnetization in PMBLDC motor? Dec-2014

The most important part of the B-H loop is the second quadrant. This is called the demagnetization curve. In the absence of externally applied ampere-turns the magnets operating point is at the intersection of the demagnetization curve and the load line, whose slope is the product of μ_0 and the permeance coefficient of the external circuit.

30. How the demagnetization occurs in PMBLDC motor? May-2015

During the normal operation of motor, when the torque and back emf are constant, if the field flux level becomes low, then demagnetization occurs.

31. Why Brushless permanent magnet DC motor is called as electronically commutated motor? May-2016, Dec-2017, 2015

The PMBLDC motor is called as electronically commutated motor because the phase windings of PMBLDC motor is energized by using power semiconductor switching circuits. Here power semiconductor switching circuit acts as commutator.

32. Define recoil line.

Area of the minor loop is generally very small and we can replace the same by a straight line whose slope is same as major axis of the minor hysteresis loop. This line is called recoil line.

PART - B

Introduction:

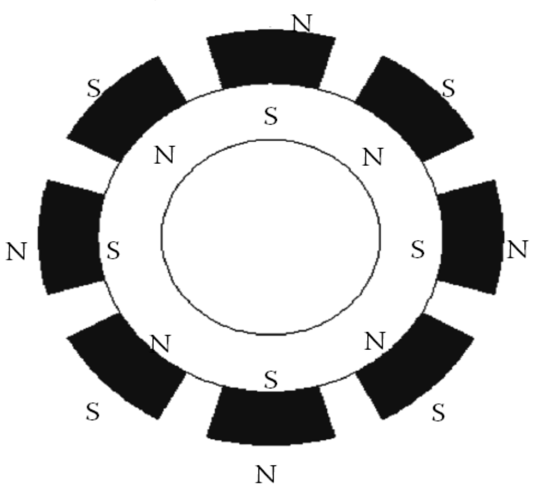
- In general classified as
    - PM dc commutator motors
    - PM brushless dc motors
    - PM AC synchronous motors
- PM bldc & PM AC synchronous motor designs are same with poly phase stator and PM rotor.
- Difference lies in control and shape of excitation voltage.
- ***PM AC syn. motor*** – sinusoidal excitation voltage which produces rotating magnetic field.
- ***PM bldc Motor*** – square (trapezoidal) excitation, only two phase windings conduct current at the same time.
- 40% size reduction.

Constructional designs of PM dc commutator motors

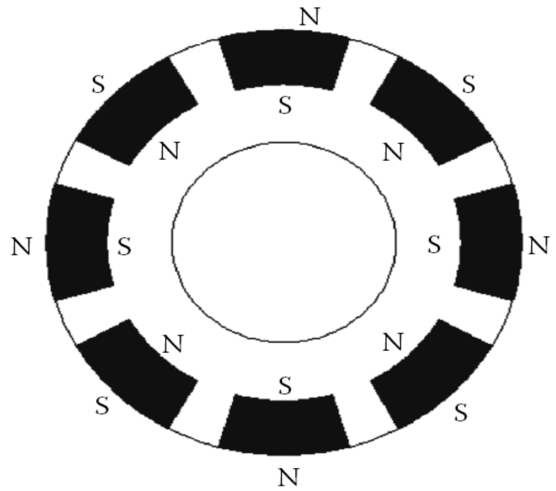
- Conventional slotted rotors
- Slotless (surface-wound) rotors
- Moving coil (coreless) rotors
    - Outside field type
        - ✓ Cylindrical
        - ✓ Wound disk rotor
        - ✓ Printed circuit disk rotor
    - Inside field type with cylindrical rotor
        - ✓ Honeycomb armature winding
        - ✓ Rhombic armature winding
        - ✓ Bell armature winding
        - ✓ Ball armature winding

Constructional designs of PM dc brushless & ac synchronous motors

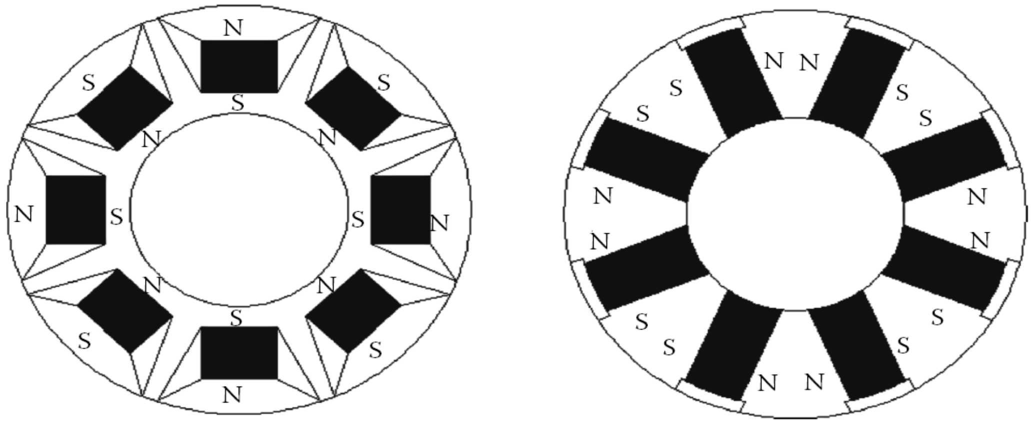
- Conventional slotted stators
- Slotless (surface-wound) stators
- Cylindrical type
    - Merrill's rotor
    - Interior magnet rotor
    - Inset magnet rotor
    - Rotor with buried magnets symmetrically distributed
    - Rotor with buried magnets asymmetrically distributed
- Disk type
    - Single sided
        - Armature winding with distributed parameters
        - Armature winding with concentrated parameters
    - Double sided
        - Internal rotor
        - Internal stator (armature)



(a) Surface PM rotor



(b) Surface inset PM rotor



(c) Interior PM rotor

Fig. Different rotor structures of BLDC motors

1. Comparison between conventional DC motor and PMBLDC motor. **May-2017**

What are the advantages of BLPM over conventional DC motor. Dec-2017, 2015

Features	Conventional DC motor	PMBLDC motor
Mechanical structure	Field magnets on the stator.	Field magnets on the rotor.
Maintenance	Maintenance is high	Low maintenance
Life	Shorter	Longer
Speed/Torque characteristics	Moderately flat – at higher speeds, brush friction increases, thus reducing useful torque	Flat – Enables operation at all speeds with rated load.
Efficiency	Low / Moderate	High
Rotor inertia	High	Low
Speed range	Low – Mechanical limitations	High – No mechanical limitation
Efficiency	Moderate	High
Control	Simple & inexpensive	Complex and expensive

2. Comparison between mechanical and electronic commutator. Dec – 2013, 2011, May-2017

S. No	Mechanical Commutator	Electronic commutator
1	Commutator is made up of commutator segments and mica insulation. Brushes are made up of carbon graphite.	Power electronic switching devices are used in the commutator.
2	Commutator arrangement is located in the rotor.	Commutator arrangement is located in the stator.
3	Shaft position sensing is inherent in the arrangement.	It requires a separate rotor position sensor.
4	Number of commutator segments is very high.	Number of switching devices is limited to 6.
5	Sliding contact between commutator and brushes.	No sliding contacts.
6	Sparking takes place.	There is no sparking.
7	It requires a regular maintenance.	It requires less maintenance.
8	Difficult to control the voltage available across tappings.	Voltage available across armature tapping can be controlled by PWM techniques.
9	Highly reliable.	Reliability can be improved by specially designed devices and protecting circuits.

Construction:

3. Explain briefly constructional and working principle of PMBLDC motors.

May-2014, Dec-2016, 2013

Discuss the construction of permanent magnet dc motor. May-2016

- In runner configuration
- Out runner configuration

➢ *In runner configuration:*

✓ PM is mounted on rotor.

✓ Armature windings surround the rotor.

➢ *Out runner configuration:*

✓ Armature (stator) windings form the center of motor.

✓ PM surround the stator.

Stator:

✓ Made of silicon steel stampings.

✓ Slots in interior surface.

✓ Open or closed type slots.

✓ Connected to dc supply through a power electronic circuit.

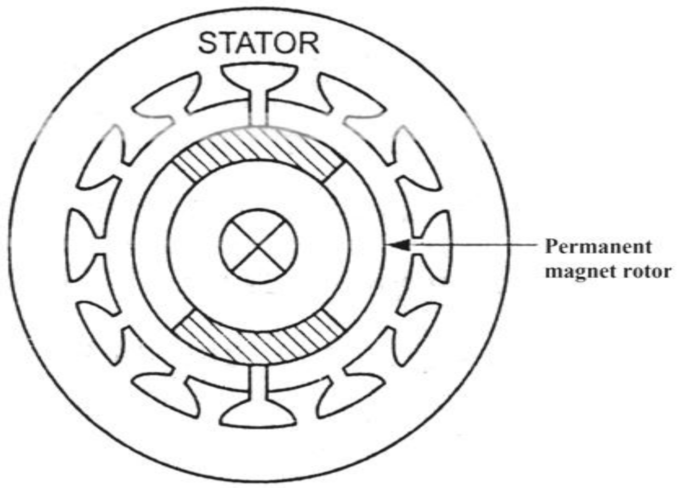


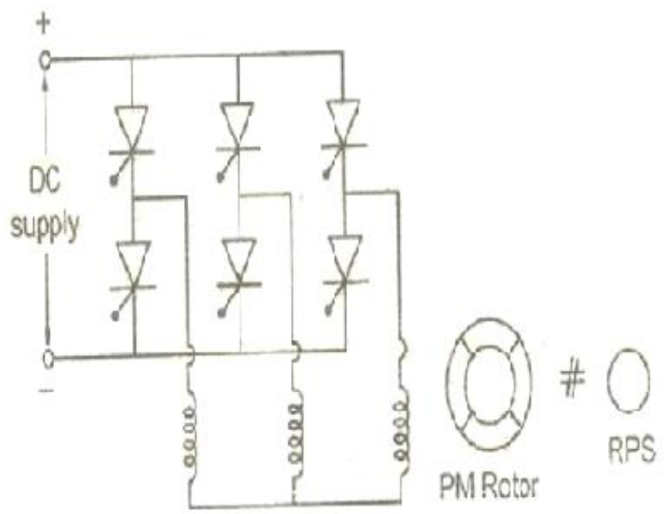
Fig. construction of BLDC motor

Rotor:

- ✓ Made of forged steel.
- ✓ Has permanent magnet.
- ✓ Carries rotor position sensor (RPS).
- ✓ RPS gives information about the position of shaft at any instant.

Armature Winding:

- ✓ Can be star or delta connected.
    - ➢ *In delta connected motor,*
        - ❖ Low torque at low rpm.
        - ❖ Can be operated at higher ranges of rpm.
    - ➢ *In star connected motor,*
        - ❖ High torque at low rpm.
        - ❖ Cannot be operated in higher rpm ranges.



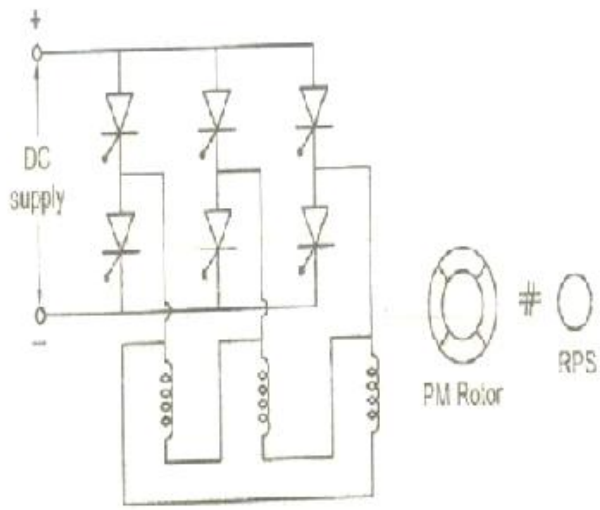


Fig. (a) Star connected **(b) delta connected motors**

Principle of Operation:

4. Explain the operation of PMBLDC motor. **Dec-2016**

1. ***Starting:***

- DC supply is given to motor, armature winding draws current.
- This current produces an mmf.
- Rotor is a permanent magnet. It produces a main mmf (main flux).
- According to fleming's left hand rule, it produces a force in armature conductors.
- But armature conductors are stationary, so it produces a reactive force, which produces a torque in rotor.
- If developed torque > load torque, then motor starts rotating.
- Self starting motor.

2. Dynamic equilibrium (steady state):

- When motor rotates, there exists a relative velocity between stationary armature conductors & rotating rotor.
- By faraday's law, emf is induced in armature conductors.
- By len'z law, this emf opposes the cause (armature current).
- Supply voltage is constant, so current drawn from mains is reduced.
- So, developed torque is reduced.
- When developed torque = load torque, rotor attains steady state speed.

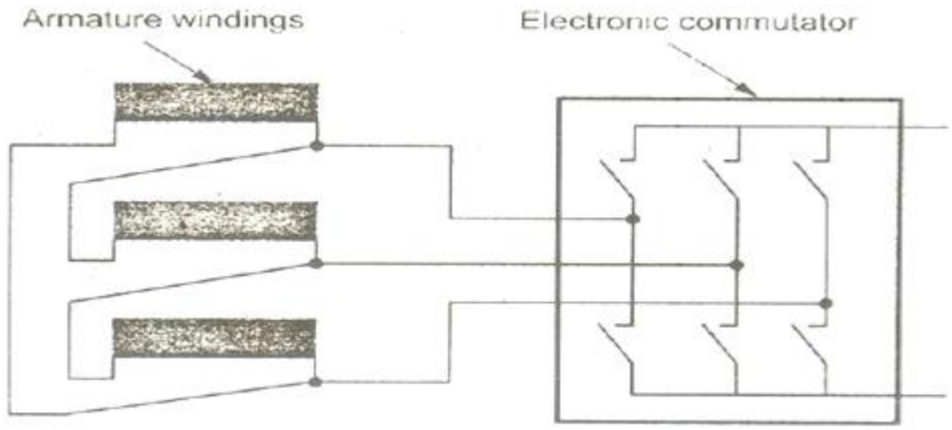


Fig. PM excited DC motor – equivalent circuit

3. Electro-mechanical power transfer:

- $T_L \uparrow$, $N \downarrow$, back emf $\downarrow$.
- $I \uparrow$, $T \uparrow$.
- Developed torque = new load torque, motor attains new equilibrium position.
- Input power = mechanical power + power loss in motor.
- Thus electrical power to mechanical power transfer takes place.

Types:

5. Explain the operation of different types of BLPM DC motor. **May-2014, Dec - 2012**

Types of BLDC based on magnetic arc:

The BLPMDC motor can be classified on the basis of flux-density distribution in the air gap of the motor. They are,

- BLPM square wave DC motor.
- BLPM sine wave DC motor.

BLPM square wave dc motor:

There are two types of BLPM square wave DC motor

- 120° pole arc BLPM square wave DC motor
- 180° pole arc BLPM square wave DC motor

Three rings:

- Outer ring – stator phase belt, stationary, 60° sectors
- Inner ring – rotor ring, 120° or 180° ring
- Middle ring – mmf ring

(a) 120° magnetic arc BLDC motor:

- 120˚ magnetic arc, 180˚ square wave phase current.
- Phase windings are delta connected.

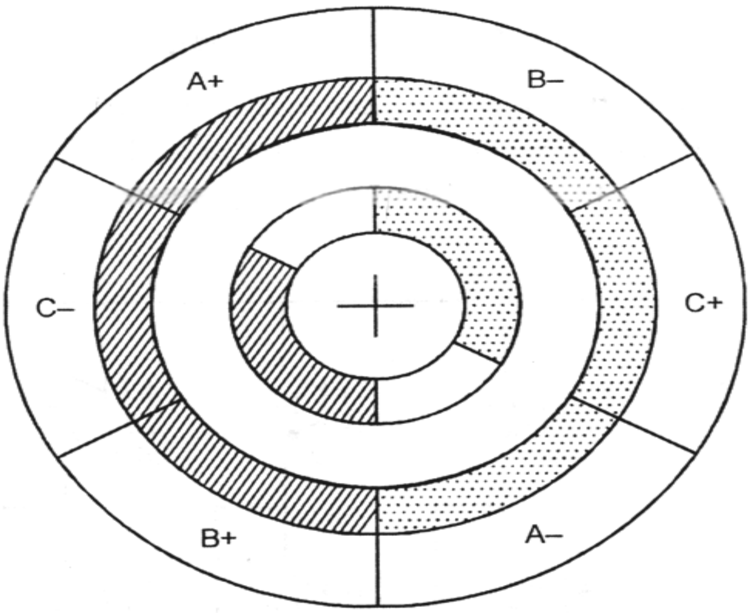


Fig. BLDC motor with 120˚ magnetic pole arc

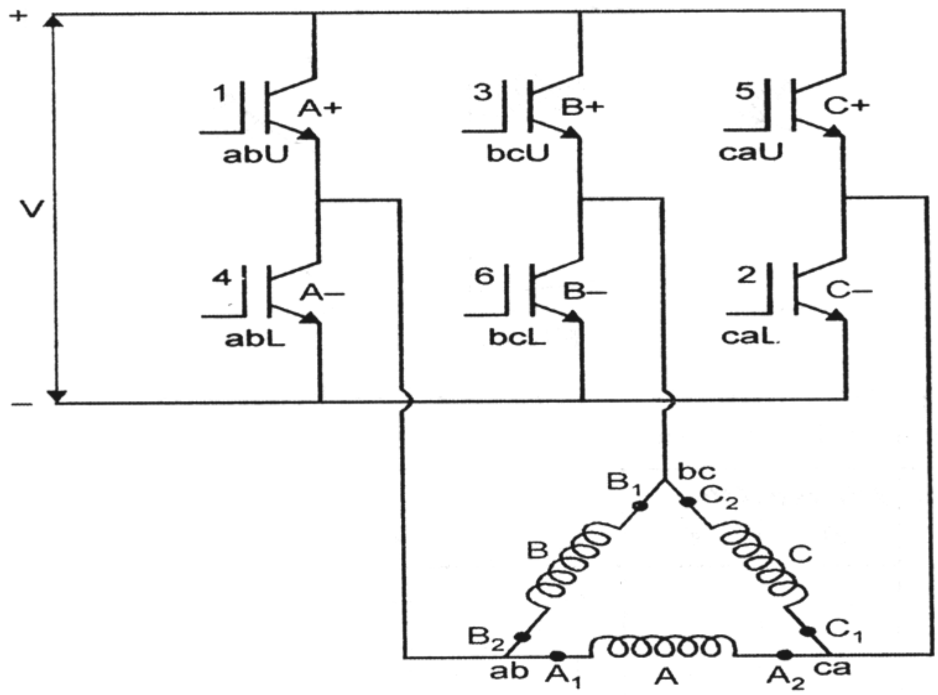


Fig. Converter with delta connected phase winding

- A+ - current flows from A_1 to A_2 A- - current flows from A_2 to A_1
- Same applicable for B and C windings.
- U – upper leg L – Lower leg

Table: Commutation logic table

Rotor position	Phase A	Phase B	Phase C	ab U 1	ab L 4	bc U 3	bc L 6	ca U 5	ca L 2
0° – 60°	+	+	–	0	0	1	0	0	1
60° – 120°	+	–	–	1	0	0	0	0	1
120° – 180°	+	–	+	1	0	0	1	0	0
180° – 240°	–	–	+	0	0	0	1	1	0
240° – 300°	–	+	+	0	1	0	0	1	0
300° – 360°	–	+	–	0	1	1	0	0	0

Rotor position 0° - 60° :

- A+, B+ , C- windings are energized.
- IGBT-3, IGBT-2 are conducting.

Rotor position 60° - 120° :

- A+, B- , C- windings are energized.
- IGBT-1, IGBT-2 are conducting.

Rotor position 120° - 180° :

- A+, B- , C+ windings are energized.
- IGBT-1, IGBT-6 are conducting.

Rotor position 180° - 240° :

- A-, B- , C+ windings are energized.
- IGBT-6, IGBT-5 are conducting.

Rotor position 240° - 300° :

- A-, B+ , C+ windings are energized.
- IGBT-4, IGBT-5 are conducting.

Rotor position 300° - 360° :

- A-, B+ , C- windings are energized.
- IGBT-4, IGBT-3 are conducting.

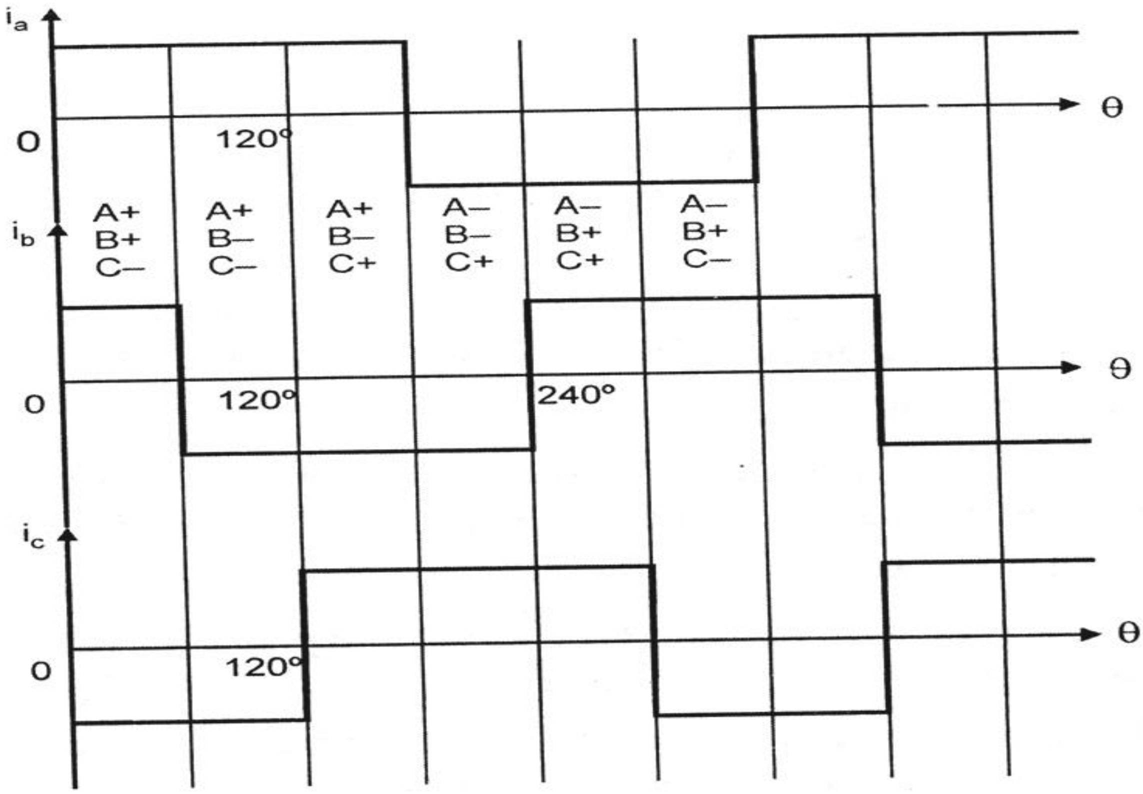


Fig. Phase current waveforms for 120° pole arc magnet

(b) 180° magnetic arc BLDC motor:

- 180˚ magnetic arc, 120˚ square wave phase current.
- Phase windings are star connected.

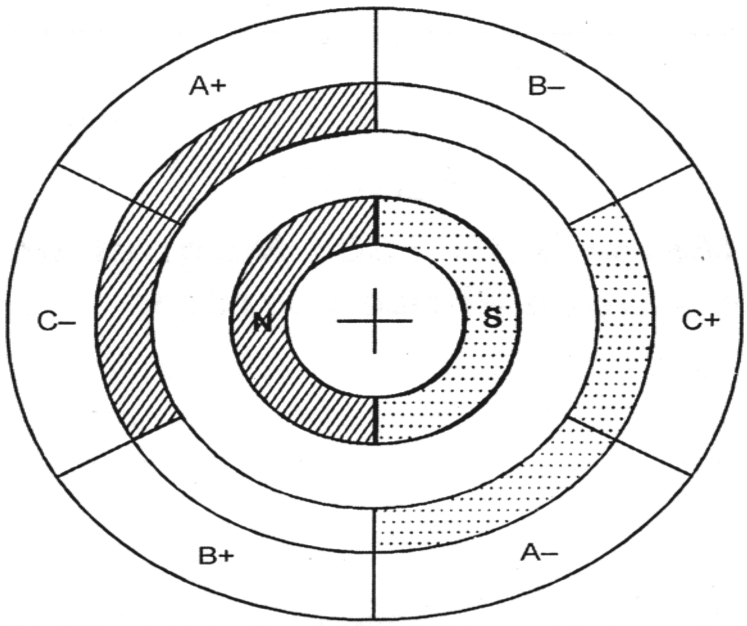


Fig. BLDC motor with 180˚ magnetic pole arc

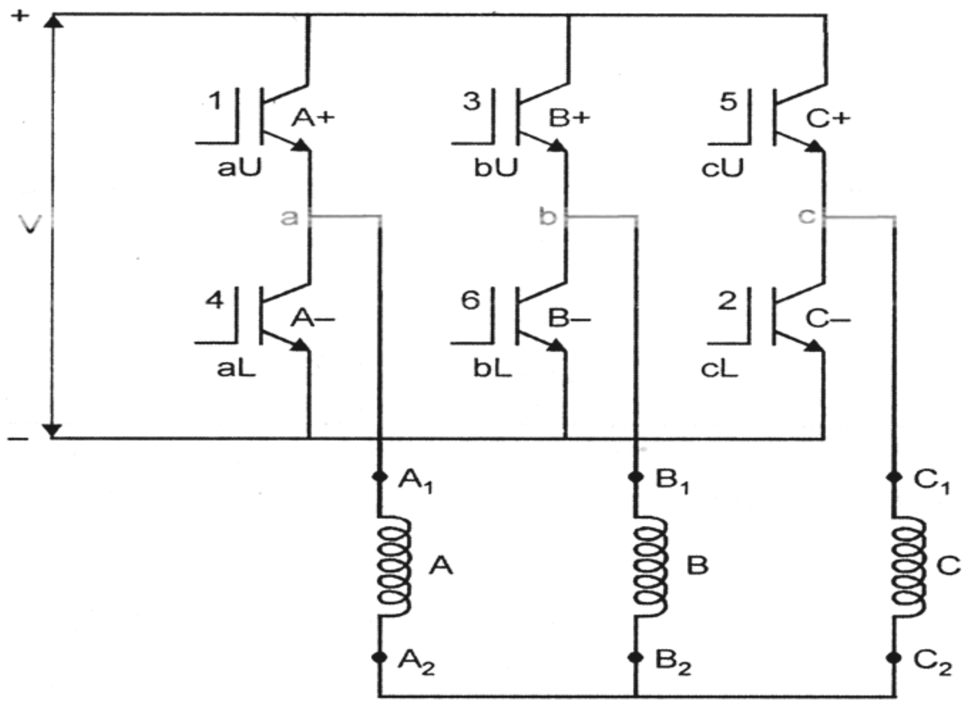


Fig. Converter with star connected phase winding

Table: Commutation logic table

Rotor position	Phase A	Phase B	Phase C	a U 1	a L 4	b U 3	b L 6	c U 5	c L 2
0° – 60°	+	0	–	1	0	0	0	0	1
60° – 120°	+	–	0	1	0	0	1	0	0
120° – 180°	0	–	+	0	0	0	1	1	0
180° – 240°	–	0	+	0	1	0	0	1	0
240° – 300°	–	+	0	0	1	1	0	0	0
300° – 360°	0	+	–	0	0	1	0	0	1

Rotor position 0° - 60° :

- A+, C- windings are energized.
- IGBT-1, IGBT-2 are conducting.

Rotor position 60° - 120° :

- A+, B- windings are energized.
- IGBT-1, IGBT-6 are conducting.

Rotor position 120° - 180° :

- B- , C+ windings are energized.
- IGBT-6, IGBT-5 are conducting.

Rotor position 180° - 240° :

- A-, C+ windings are energized.
- IGBT-4, IGBT-5 are conducting.

Rotor position 240° - 300° :

- A-, B+ windings are energized.
- IGBT-4, IGBT-3 are conducting.

Rotor position 300° - 360° :

- B+ , C- windings are energized.
- IGBT-3, IGBT-2 are conducting.

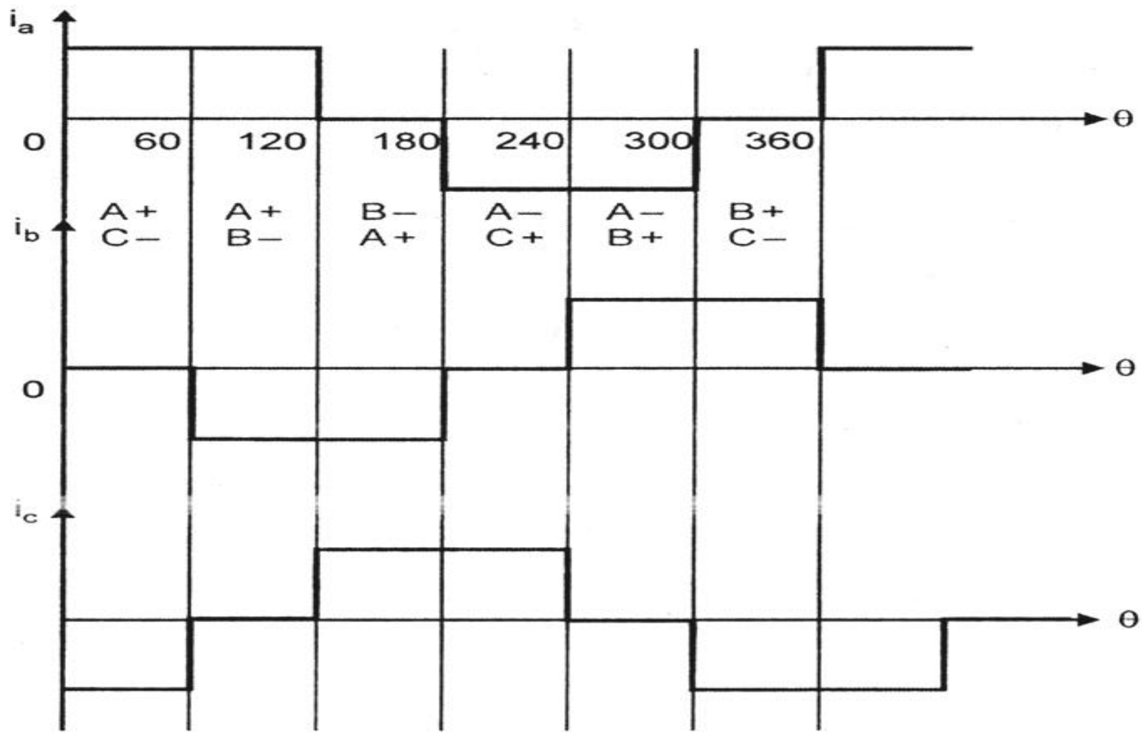


Fig. Phase current waveforms for 180° pole arc magnet

EMF equation:

6. Derive the expression of EMF equation of PMBLDC Motor.

Dec-2017, 2015, May–2018, 2017, 2014, 2012

l	-	length of armature, m
r	-	radius of airgap, m
B_g	-	flux density in airgap, wb/m^2
T_c	-	no. of turns per coil
p	-	no. of poles

Assume, the axis of permanent magnet rotor is along the x-axis. Stator has 12 slots and 3-phase winding.

$\therefore$ 2 slots / pole / phase.

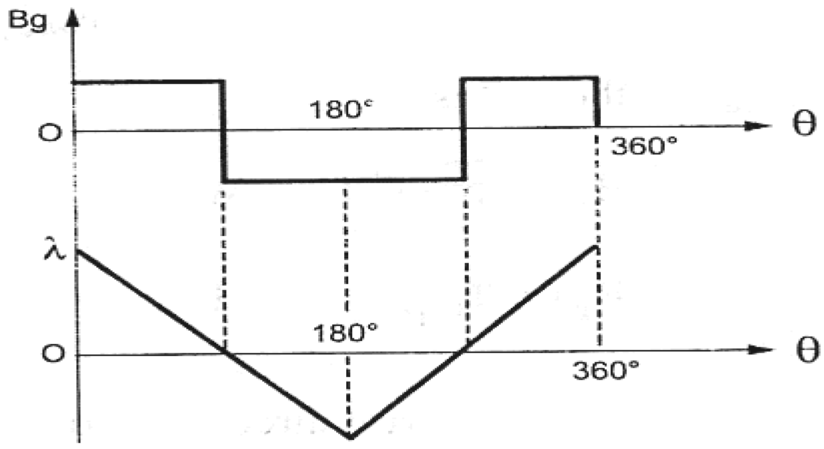


Fig. Magnetic flux density around the airgap

At θ = 0, center of N pole gets aligned with x-axis.

Flux enclosed with coil is,

$$\varphi_{max} = B_g \frac{2\,\pi\, r}{p}\, l$$

Flux linkage of coil is,

$$\lambda_{max} = \left(B_g \frac{2\,\pi\, r}{p}\, l\right) T_c \quad wb - T$$

λ varies with θ.

$$At\ \theta = 0^\circ\ or\ t = 0, \qquad \lambda = \frac{2\, B_g\, \pi\, r\, l\, T_c}{p}$$

$$At\ \theta = 90^\circ\ or\ t = \frac{\pi}{p\,\omega_m}, \qquad \lambda = 0$$

$$\therefore \frac{\Delta\lambda}{\Delta t} = \frac{final\ flux\ linkage - initial\ flux\ linkage}{final\ time - initial\ time}$$

$$= \frac{0 - \dfrac{2\, B_g\, \pi\, r\, l\, T_c}{p}}{\dfrac{\pi}{p\,\omega_m} - 0}$$

$$= \frac{- \dfrac{2\, B_g\, \pi\, r\, l\, T_c}{p}}{\dfrac{\pi}{p\,\omega_m}}$$

$$\frac{\Delta\lambda}{\Delta t} = -2\, B_g\, r\, l\, T_c\, \omega_m$$

$$e_c = -\frac{d\lambda}{dt} = -\left(-\,2\, B_g\, r\, l\, T_c\, \omega_m\right)$$

$$e_c = 2\, B_g\, r\, l\, T_c\, \omega_m \quad volts$$

Emf waveform is rectangular, changes between + e_c to $-e_c$.

Consider two coils, a_1A_1 & a_2A_2. Coils a_2A_2 is adjacent to a_1A_1 & connected in series, displaced by angle 30˚.

Emf induced in coil a_1A_1 is,

$$e_{c1} = 2\, B_g\, r\, l\, T_c\, \omega_m \quad volts$$

Emf induced in coil a_2A_2 is,

$$e_{c2} = 2\, B_g\, r\, l\, T_c\, \omega_m \quad volts$$

Two coils are connected in series,

$$e_{c1} + e_{c2} = 4\, B_g\, r\, l\, T_c\, \omega_m \quad volts$$

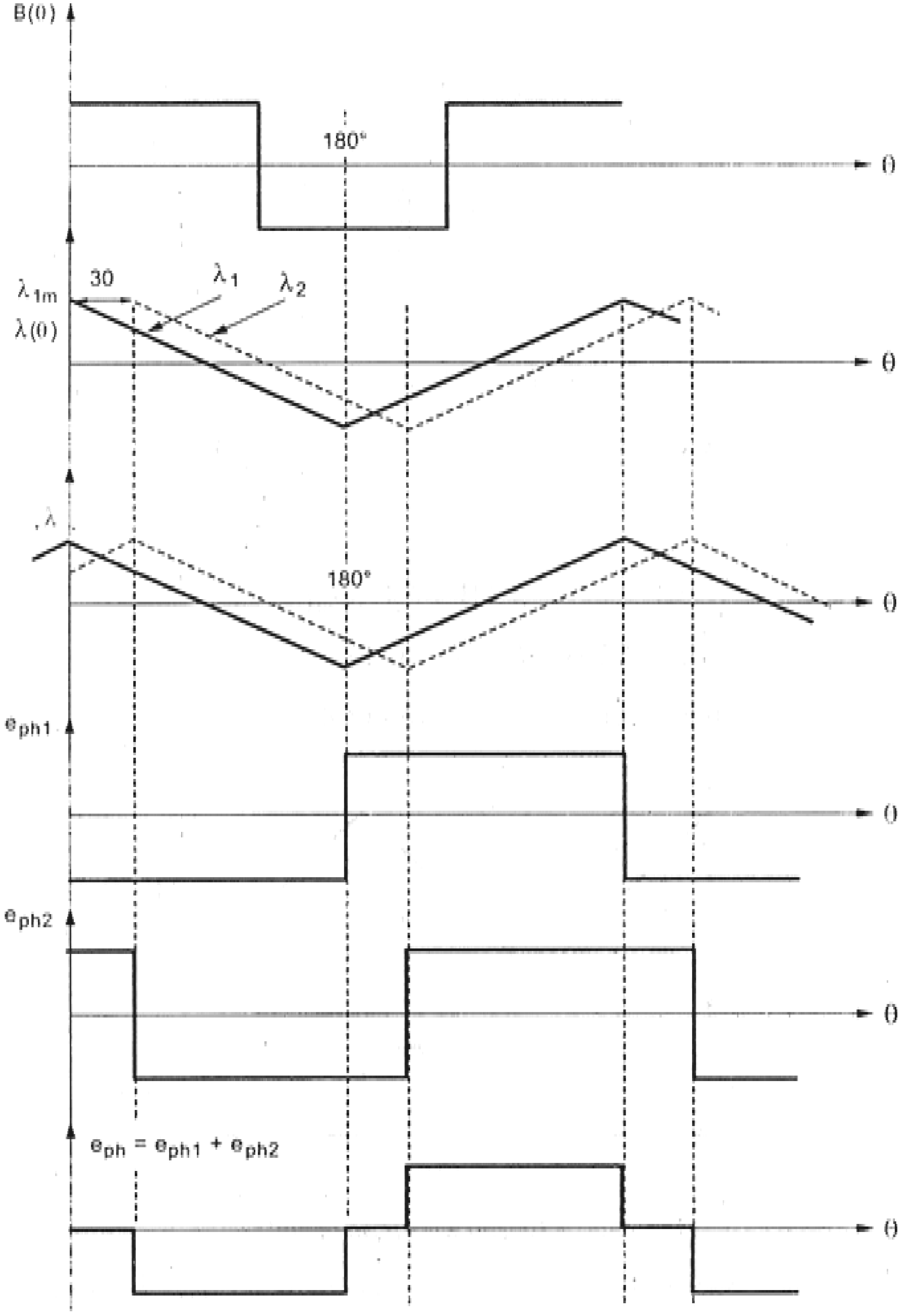


Fig. Waveform of flux density and flux linkage

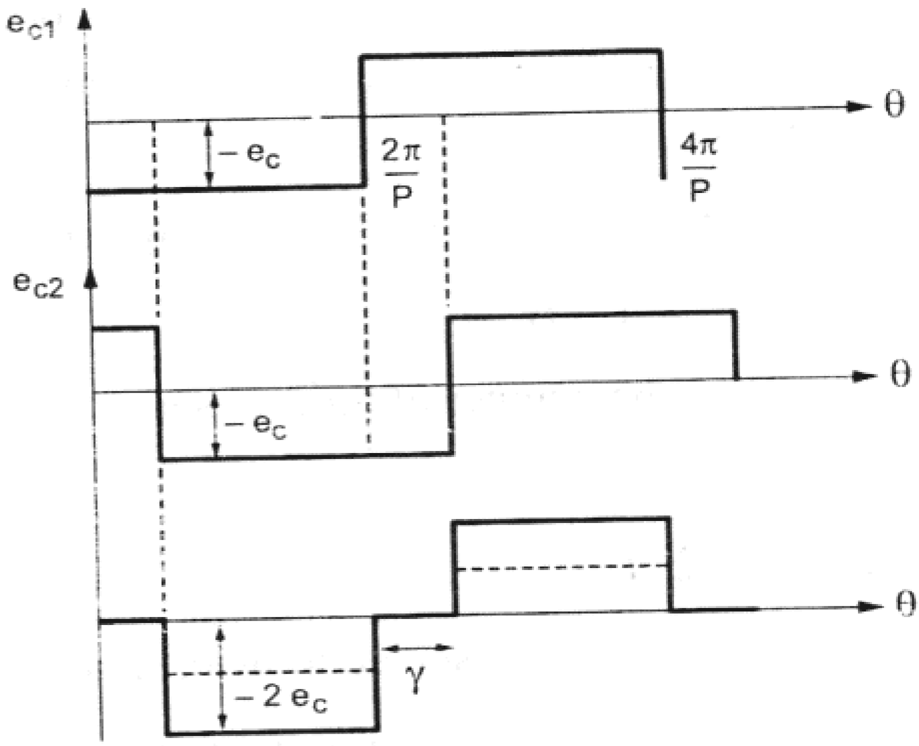


Fig. phase ‘a’emf waveform

If there are ‘ n_c ‘ no. of coils connected in series per phase,
Emf per phase,

$$e_{ph} = 2\,B_g\,r\,l\,T_c\,\omega_m\,n_c \qquad (n_c\,T_c = T_{ph})$$

$$\boxed{\boldsymbol{e_{ph} = 2\,B_g\,r\,l\;\omega_m\,T_{ph}\;volts}}$$

Torque equation:

7. Derive the torque equation of PMBLDC motor. Dec-2017, 2015, May-2017, 2014, 2012

$$e_{ph} = 2\,B_g\,r\,l\;\omega_m\,T_{ph}\;\;volts$$

$$Mechanical\;power, \quad P = \omega_m\,T_e$$

$$Also, \quad P = 2\,e_{ph}\,I$$

$$\omega_m\,T_e = 2\,e_{ph}\,I$$

$$T_e = \frac{2\,e_{ph}\,I}{\omega_m}$$

$$= \frac{2\;x\;\;2\,B_g\,r\,l\;\;\omega_m\,T_{ph}\;\;x\;\;I}{\omega_m}$$

$$\boxed{\boldsymbol{T_e = 4\;B_g\,r\,l\;\;T_{ph}\,I \qquad N-m}}$$

Commutation:

Mechanical Commutator:

8. Explain briefly about the mechanical commutator in conventional DC motor and Electronic Commutator in BLPMDC motor. Dec - 2012

- Function of the commutator is to facilitate the collection of current from the armature conductors.
- Converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit.
- Aim of commutator is to sets up a mmf whose axis is in quadrature with the main field axis irrespective of the speed of the armature.

Mechanical commutator:

- Consists of special wedge - shaped segments made up of copper.
- These segments are insulated from each other by thin layer of mica.
- These segments are tapered to form a cylinder.

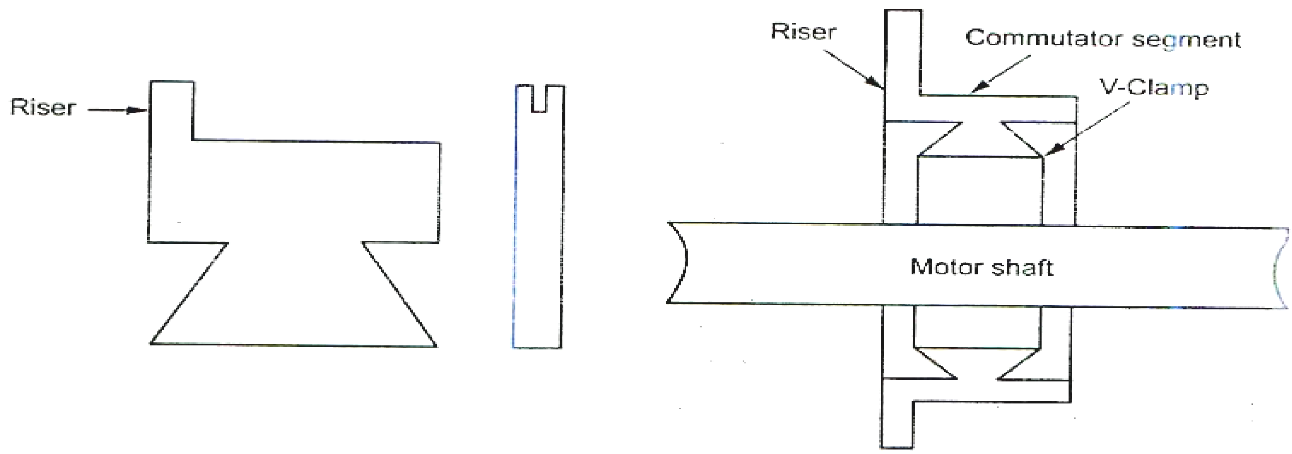


Fig. Commutator segment

- Commutator segments are mechanically fixed to the shaft using V-shaped circular steel clamps, isolated electrically from the shaft.
- Schematic of a two pole machine with 12 commutator segments.
- Brushes of the two pole machine are X and Y.

Arrangement of mechanical Commutator:

- Brush X contacts with CS1 and Y contacts with CS7.
- The brushes X and Y are connected across the dc supply.
- A dc current is passing through the brush X, CS1, tapping 1, tapping 7, CS7 and brush Y.
- There are two armature parallel paths between the tappings1and 7.
  - ✓ 1-2-3-4-5-6-7
  - ✓ 1-12-11-10-9-8-7

- Current passing through the armature conductors sets up an mmf along the axis of the tappings 7 and 1 (ie), along the axis of Y and X.

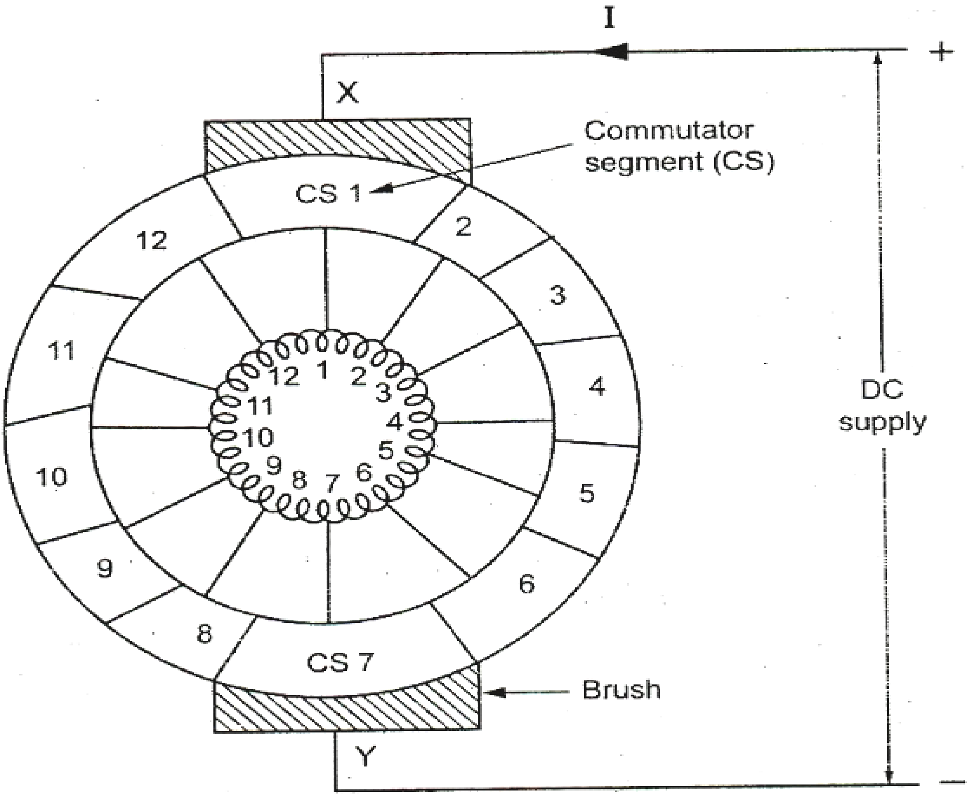


Fig. Mechanical commutator and brushes arrangement

- Commutator rotates along the anti-clockwise direction.
- Now the brush X contacts with CS2, & brush Y contacts with CS8.
- Hence the current passes through the tappings 2 and 8.
- There are two parallel paths,
  - ✓ 2-3-4-5-6-7-8
  - ✓ 2-1-12-11-10-9-8
- The mmf set up by the armature winding is from tapping 8 to 2 (ie), along the brush axis Y and X.
- Armature mmf direction is always along the brush axis Y and X.
- Function of the commutator and brushes arrangement in a conventional dc machine is to set up an armature mmf whose axis is always in quadrature with the main field irrespective of the speed of the rotation of the motor.

Electronic commutator:

9. Analyze the operation of electronic commutator in PMBLDC motor with neat diagram.
May-2015, Dec-2016, 2011

- Armature winding in the stator has 12 tappings.

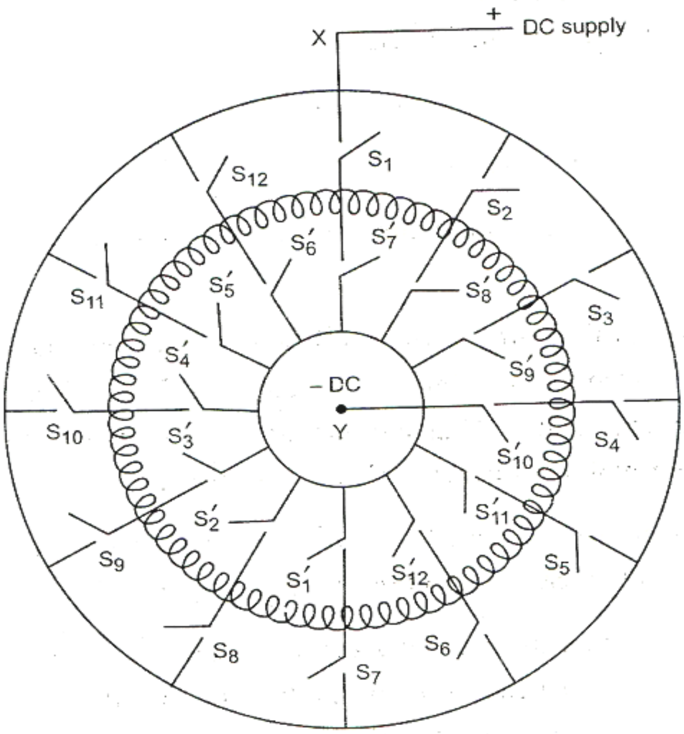


Fig. Electronic Commutator

- Each tapping is connected to the positive of the dc supply (ie) X through the switches S_1 , S_2 , S_3……..S_{12}
- Connected to the negative of the supply (ie) Y through the switches S_1', S_2' , S_3' …… S_{12}'.
- When the switches S1 and S_1' are closed, the dc supply is given to the tappings1 and 7.
- The current which is passing through the armature winding has two parallel paths.
  - ✓ 1-2-3-4-5-6-7
  - ✓ 1-12-11-10-9-8-7
- This current sets up an armature mmf, whose axis is along the axis of the tappings 1 &7.
- After a small interval of time, Switches S_1 and S_1' are kept open and S_2 and S_2' are closed.
- Current passes through the tappings 2, 8 and sets up an mmf along the axis of the tapping 2 &8.
- By operating the switches in sequential manner, it is possible to get revolving magnetic field in the airgap.

- These switches S_1 to S_{12} and S_1' and S_{12}' can be replaced by power electronic switching devices such as SCR, MOSFET, IGBT etc.

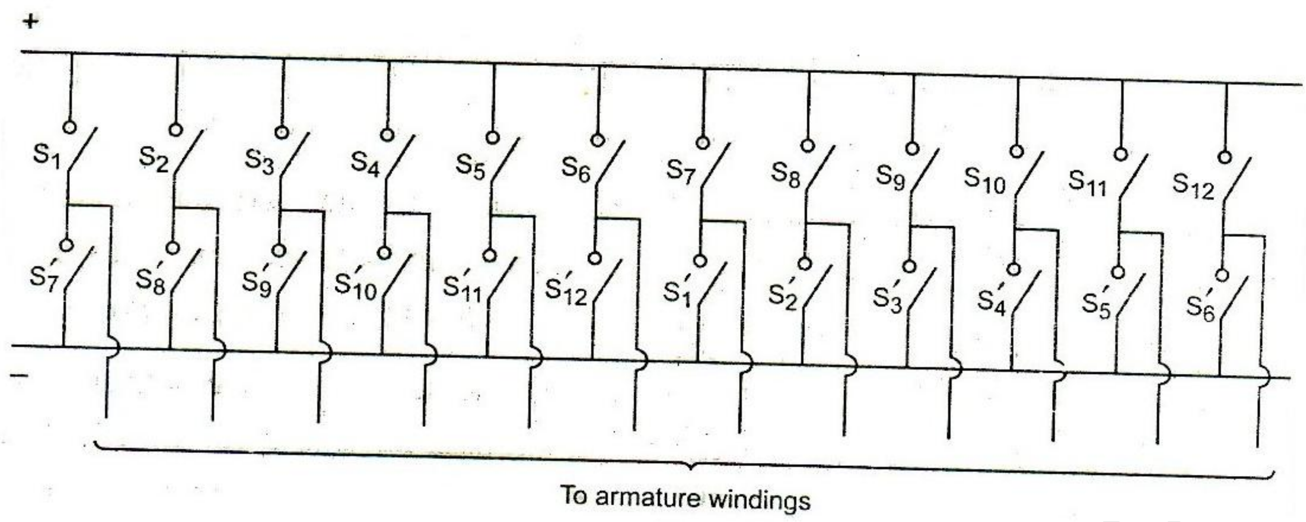


Fig. Switching circuit of electronic commutator

- More number of devices are employed, the circuit becomes complex.
- In normal electronic commutator, usually six switching devices are used. Hence, the armature should have three tappings, which can be connected either in star or delta.

Power converter circuits and their controllers:

10. Explain briefly driver circuits of PMBLDC motor?

(OR)

Describe the different types of PMBLDC motor based on drive circuits?

- For 3-φ, 6 pulse BLDC motors, 6 Hall effect sensors are used.
- Displaced by 60°.
- Placed in stator.
- Connected with controller to turn ON the devices for electronic commutation.

Classification of drive circuits:

- Classified based on the no. of phase windings and the no. of pulses given to the devices.
  - ✓ One phase winding and one pulse BLDC motor
  - ✓ One phase winding and two pulse BLDC motor
  - ✓ Two phase winding and two pulse BLDC motor
  - ✓ Three-phase winding and three pulse BLDC motor
  - ✓ Three-phase winding and six pulse BLDC motor

(a) One phase winding and one pulse BLDC motor

- Stator has one phase winding.
- Connected to the supply through a semi conductor switch.
- When rotor position sensor is influenced by north pole, it turns ON the switch.
- Current flows through the stator winding and develops torque.
- The current & torque are approximated as sinusoidally varying.

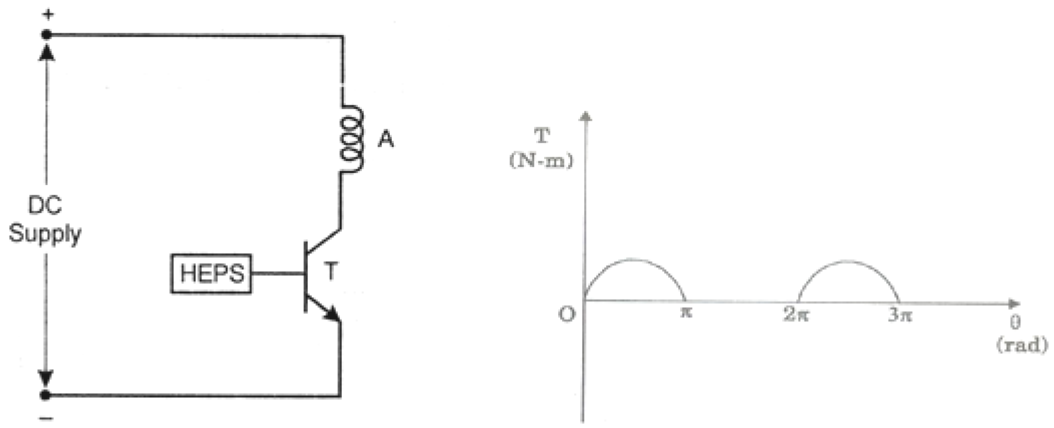


Fig. Stator with one phase winding

Advantages:

- Consists of the one transistor and one position sensor is sufficient.

De-merits:

- Inertia should be high, such that rotor rotates continuously.
- Utilization of Transistor & winding are less.

(b) One phase winding and two pulse BLDC motor

- Stator has only one winding.
- Connected to the 3 wire dc supply through, two semi-conductor switches.
- Only one position sensor.

When the position sensor is under the influence of North pole:

T_1 is turned ON, phase winding carries current from A to B.

When the position sensor is under the influence of South pole:

T_2 is turned ON, phase winding carries a current from B to A.

- The polarity of flux is altered depending upon the position of rotor.

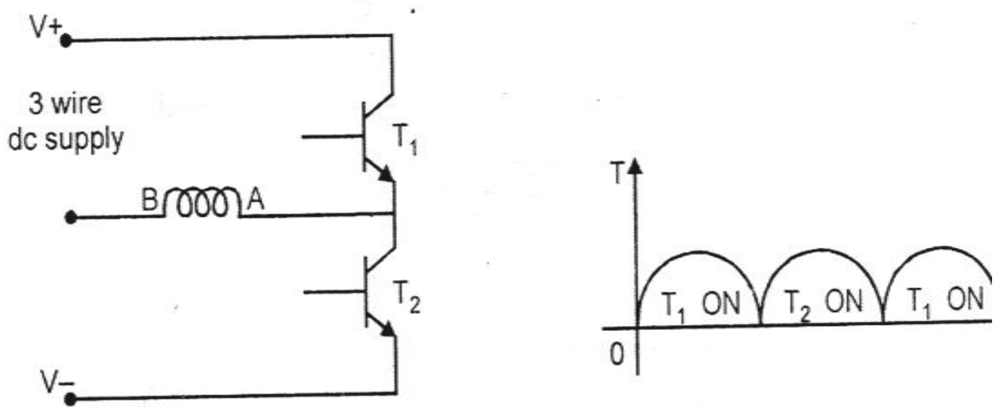


Fig. One phase winding and two pulse BLDC motor

Features:

- Winding utilization is better, however transistor utilization is less.
- Torque developed is more uniform.

Disadvantages:

- Requires three wire DC supply.

(c) Two phase winding and two pulse BLDC motor:

- Stator has two phase windings.
- Each phase winding is controlled by a switch depending on position of rotor.

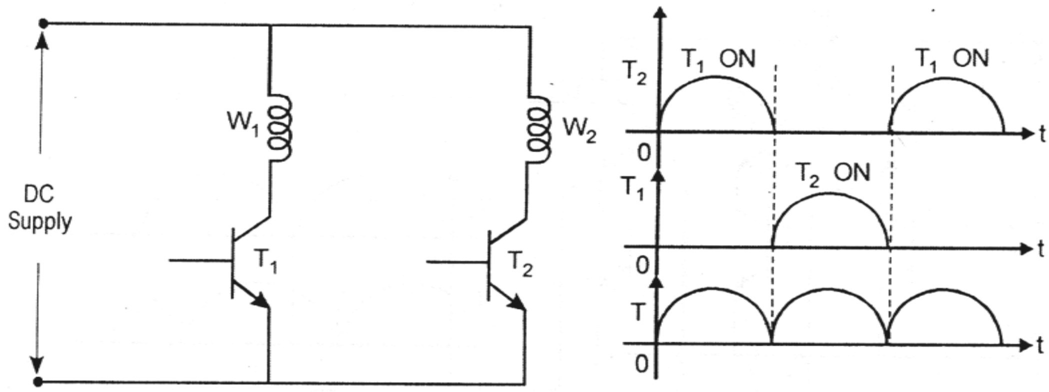


Fig. Two phase winding and two pulse BLDC motor

Features:

- Windings utilization is only 50% which is less.
- It provides better torque waveforms.

(d) Three phase winding and three pulse BLDC motor:

- The stator has three phase winding.
- Each phase winding is controlled by semi conductor switch, depending on position of rotor.

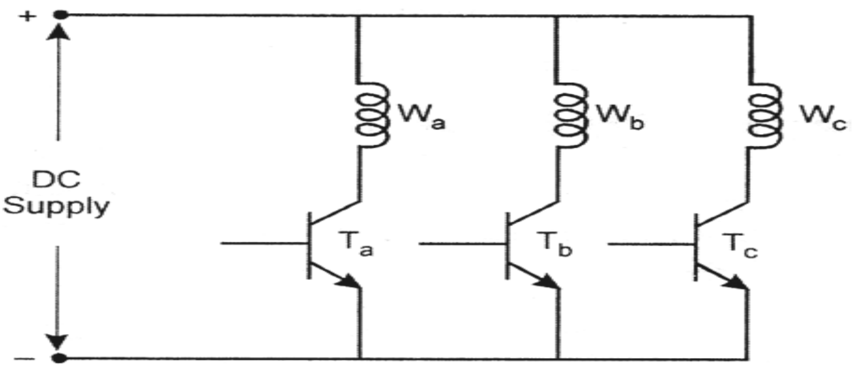


Fig. Three phase winding and three pulse BLDC motor

Disadvantage:

- 3 position sensors are required.

(e) Three phase windings and six pulse BLDC motor:

- Uses three phases and six switching devices.
- Usually 120 degree (or) 180 degree conduction is adopted.

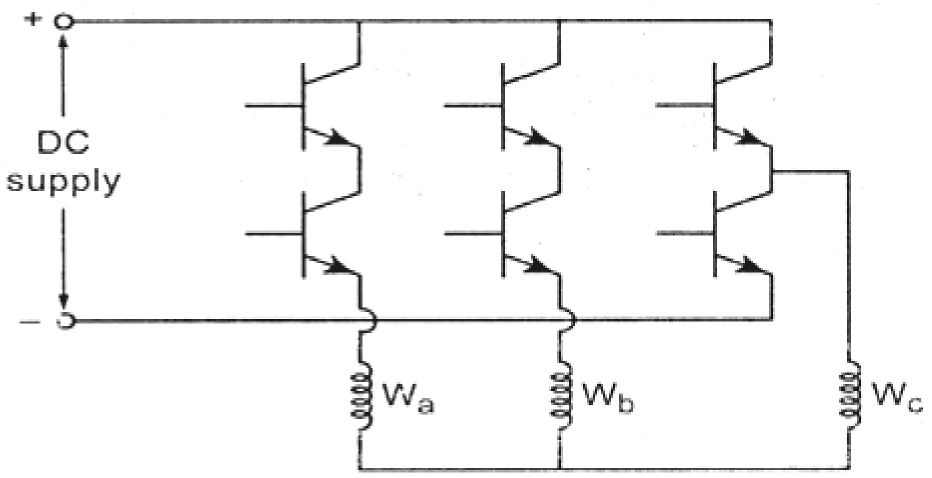


Fig. Three phase windings and six pulse BLDC motor

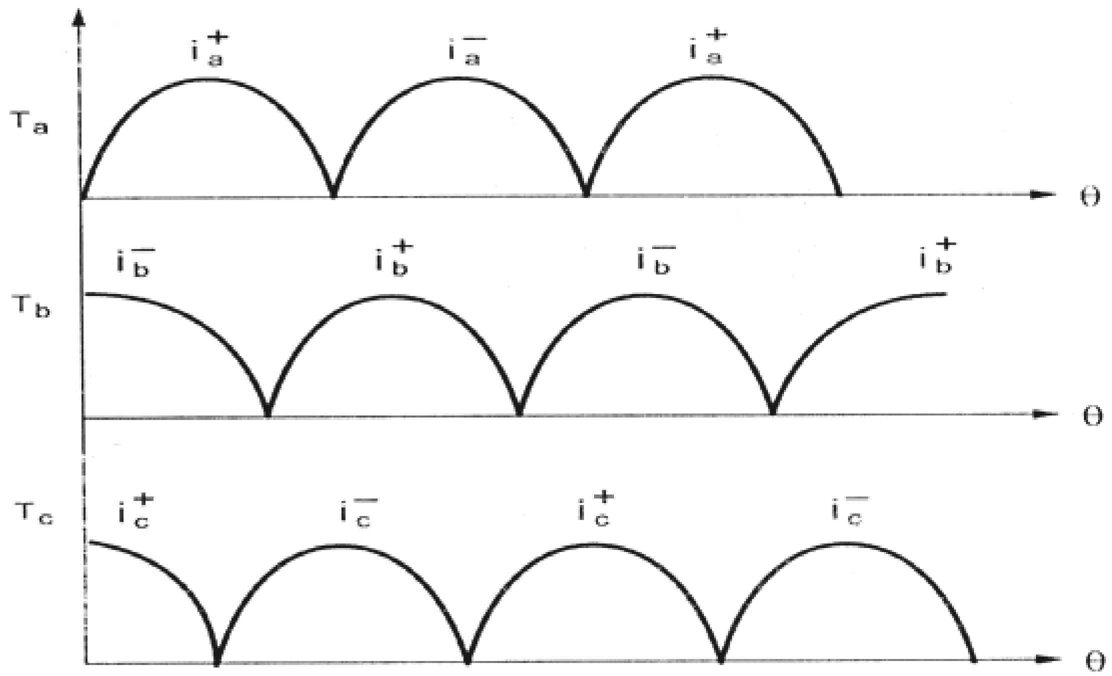


Fig. Torque waveforms

Features:

- Utilization factor of winding is better.
- Torque pulse and ripple frequency components are less.

Power controllers:

11. Sketch the structure of power controllers for PMBLDC motor and explain the function of various blocks. **May–2014, 2013, Dec-2011**

Explain in detail, the power controllers for PMBLDC. **Dec-2016**

Draw and explain the general structure of a controller for a permanent magnet brushless DC motor. **May-2018**

Power circuit:

- Consists of six power switching devices.
- Connected in bridge configuration across the DC supply.
- A shunt resistance 'R' is connected in series to get the current feedback signal.
- Feedback diodes are connected across the main devices.
- Armature winding is assumed to be star connected.
- Rotor carries rotor position sensor and shaft is coupled with tacho generator to get speed feedback signal.

Control circuit:

- Consists of commutation logic circuit which gets information about the rotor position
- Decides which devices are to be turned ON and OFF.

Commutation logic circuit:

- Provides six output signals out of which three signals are used as the base drive for the upper leg devices.
- Other three output signals are logically ANDed with high frequency pulses (PWM).
- The resultant signals are used to drive the lower leg devices.

Speed Comparator:

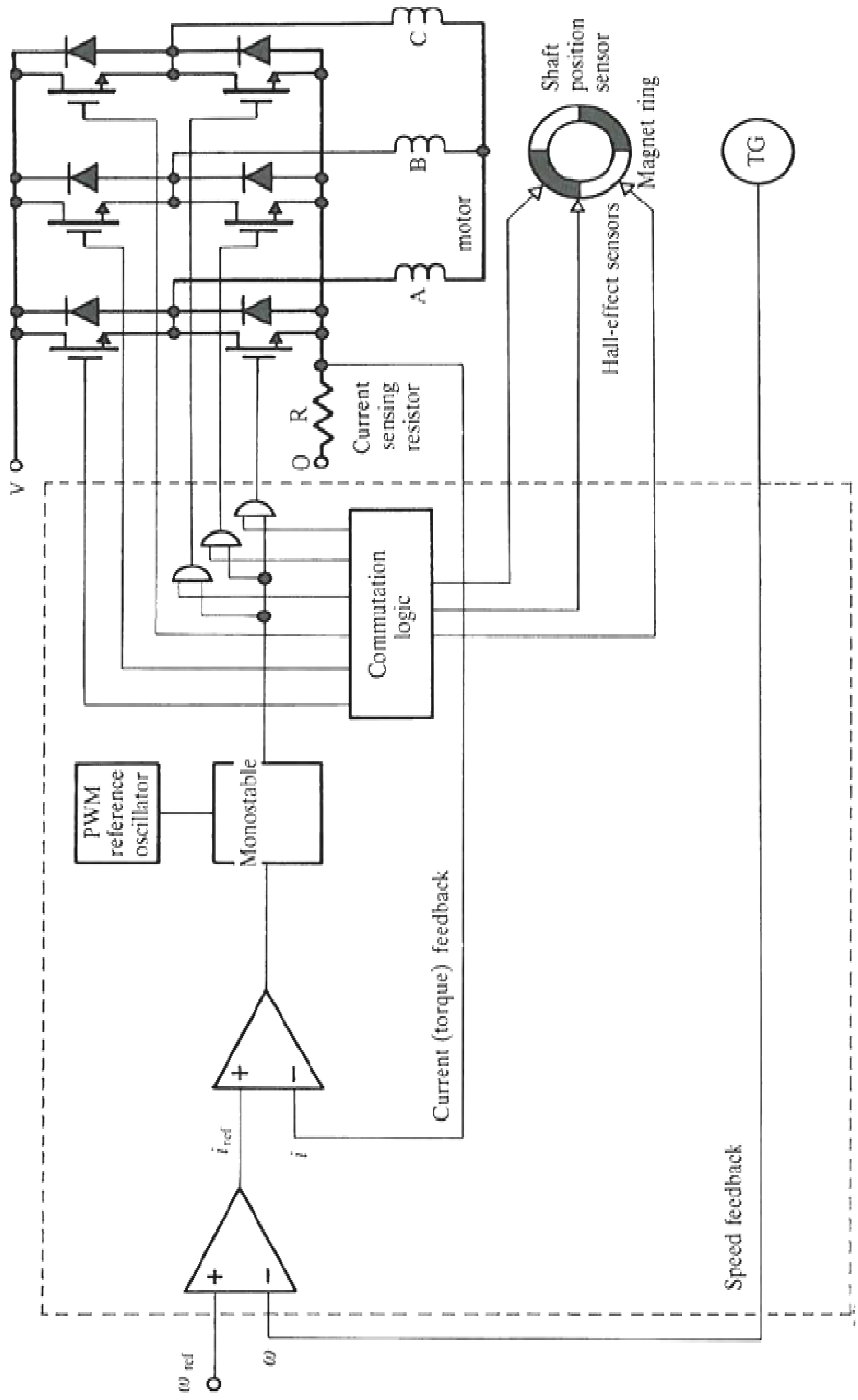
- Speed comparator compares the reference speed (W_{ref}) with the speed feed back signal (ω_m) obtained from the tachogenerator.
- Output of the speed comparator (ie) the speed error signal serves as the current reference for the current comparator.

Current Comparator:

- Compares the reference current (i_{ref}) with the actual current signal (i_{actual}) obtained from the current transducer.
- Resulting error signal is fed to the monostable circuit.

Monostable Circuit:

- The monostable circuit is excited by high frequency pulse signals.
- The duty cycle of the output of monostable multivibrator circuit is controlled by error signal.



V
C
B
A
motor
R
Current sensing resistor
Shaft position sensor
Magnet ring
Hall-effect sensors
TG
Commutation logic
PWM reference oscillator
Monostable
Current (torque) feedback
i_{ref}
i
Speed feedback
ω_{ref}
ω

Rotor Position Sensor:

- Rotor position sensor converts information of rotor shaft position into a suitable electrical signal.
- Signal from rotor position sensor is fed to the commutation logic circuit.
- It gives necessary output signals to switch ON and switch OFF the semiconductor devices of electronic switching and commutation circuit.
- Sensors : Optical position sensor & Hall effect position sensor.

Function of the controller:

- The rotor position is sensed by a hall effect sensor.
- These signals are decoded by commutation logic circuit to give the firing signals for 120˚ conduction.
- It has six outputs which control the upper and lower phase leg transistors.

- The PWM signal is applied only to the lower leg transistors.
- Reduces current ripple.
- The upper leg transistors need not be the same type as the lower leg transistor.
- The use of AND gate is a simple way of combining commutation signal and chopping signals.

- The monostable circuit is controlled by the error signal obtained from the comparator.
- The output of the monostable circuit and signal from the commutation logic circuit influences the conduction period and duty cycle of lower leg devices.
- Desired current for desired speed is obtained.

Motor Characteristics:

12. Explain the speed – Torque characteristics of PMBLDC motor.

May-2018, 2017, 2016, 2014, Dec–2013

- Assume Commutation is perfect, phase current waveform is ideal, converter is supplied form a ideal voltage source, V, then,

$$V = E + R I$$

- If phase resistance is small, the characteristics is similar to DC shunt motor. By varying voltage, V, Speed can be controlled.
- Voltage is controlled by chopping or PWM.
- There are boundaries for the continuous and intermittent operation.
- Continuous limit - heat transfer, temp rise
- Intermittent limit – max. rating of semiconductor switch, temp rise.

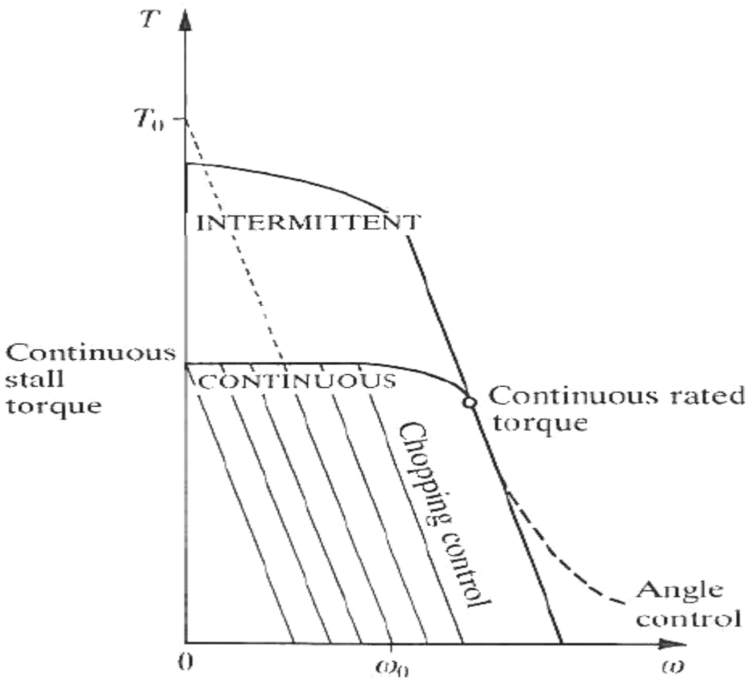


Fig. Speed-Torque characteristics of BLDC motors

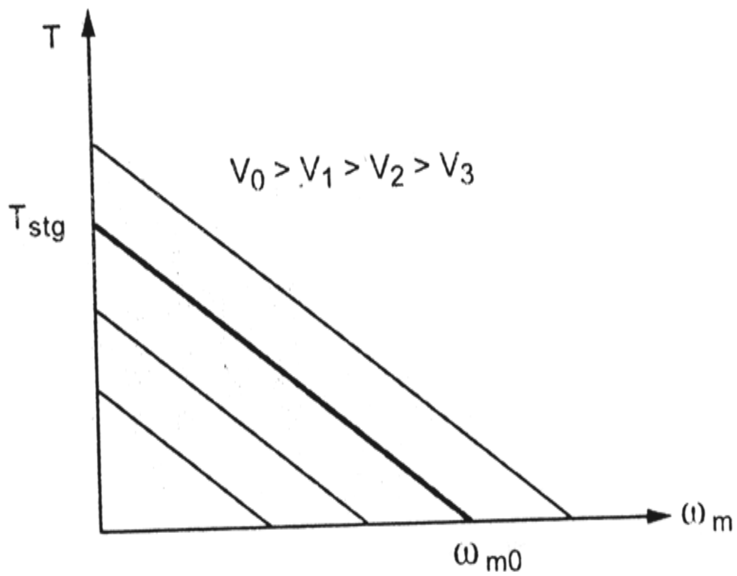
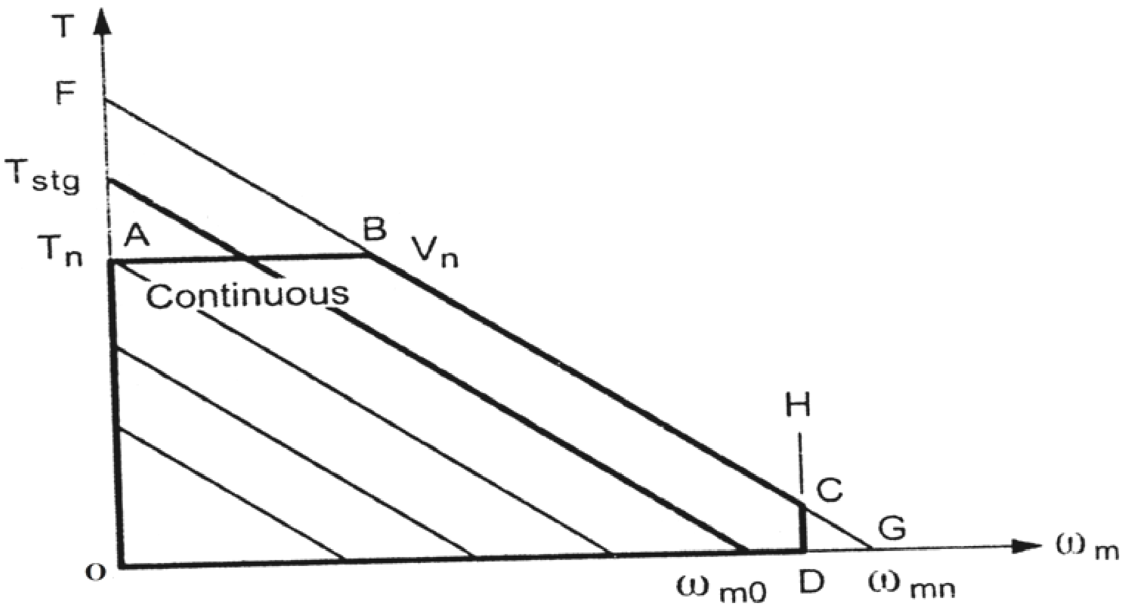


Fig. Family of T-N characteristics for various constant supply voltages.

Permissible region of operation:

- Current, torque, supply voltage, speed should be within limits.



Line AB:

- ✓ Parallel to x-axis
- ✓ Max. torque developed

Line FG:

- ✓ N-T characteristics for max. permissible voltage

Line DH:

- ✓ Perpendicular to x-axis
- ✓ Max. permissible speed

OABCDO – permissible region of operation

Applications:

13. Discuss the applications of PMBLDC motors.

Industry:

- ✓ Industrial drives (fans, pumps, blowers, handling systems)
- ✓ Machine tools
- ✓ Servo drives
- ✓ Automation process
- ✓ Internal transportation systems
- ✓ Robots

Public life:

- ✓ Air conditioning systems
- ✓ Catering equipment
- ✓ Ticketing machines
- ✓ Clocks
- ✓ Coin laundry machines

Domestic life:

- ✓ Kitchen equipment
- ✓ Washing machines
- ✓ Vacuum cleaners

- ✓ Lawn mowers
- ✓ Toys
- ✓ Security systems

Information & office equipment:

- ✓ Computers
- ✓ Printers
- ✓ Plotters
- ✓ Photo copiers

Automobiles & Transportation:

- ✓ Elevators
- ✓ Light railways
- ✓ street cars
- ✓ Electric road vehicles
- ✓ Air craft flight control
- ✓ boats

Defense:

- ✓ Tanks
- ✓ Missiles
- ✓ Radar systems
- ✓ Sub marines

Aerospace:

- ✓ Rockets
- ✓ Space shuttles
- ✓ Satellites

Medical & health care:

- ✓ Dentist drills
- ✓ Electric wheel chairs

Power tools:

- ✓ Drills
- ✓ Screw drivers
- ✓ Polishers
- ✓ Saws
- ✓ Sheep shearing hand pieces

Rotor position sensors:

14. Explain briefly the operation of rotor position sensors in BLPM motors.

- BLDC motor needs rotor position sensor (RPS) for its operation.
- RPS converts the information about the rotor shaft position into a suitable electrical signal.
- This electrical signal is used to turn ON or OFF the power electronic switching circuit in BLDC.

Methods of sensing rotor position:

- Explicit position sensor – use external devices
- Implicit position sensor – use motor phase voltage & currents.

Explicit position sensors:

- Optical position sensor
- Hall effect position sensor
- Encoders
- Resolvers

(a) Optical position sensor:

- Uses photo transistors.
- Device is turned ON, when light rays fall on it.
- Fixed at the end shield cover of the motor.
- Mutually displaced by certain angle based on number of photo transistors used.
- Shaft carries a circular disc and rotates along with shaft.
- Suitable slots are punched in the disc so as to excite the photo transistors.

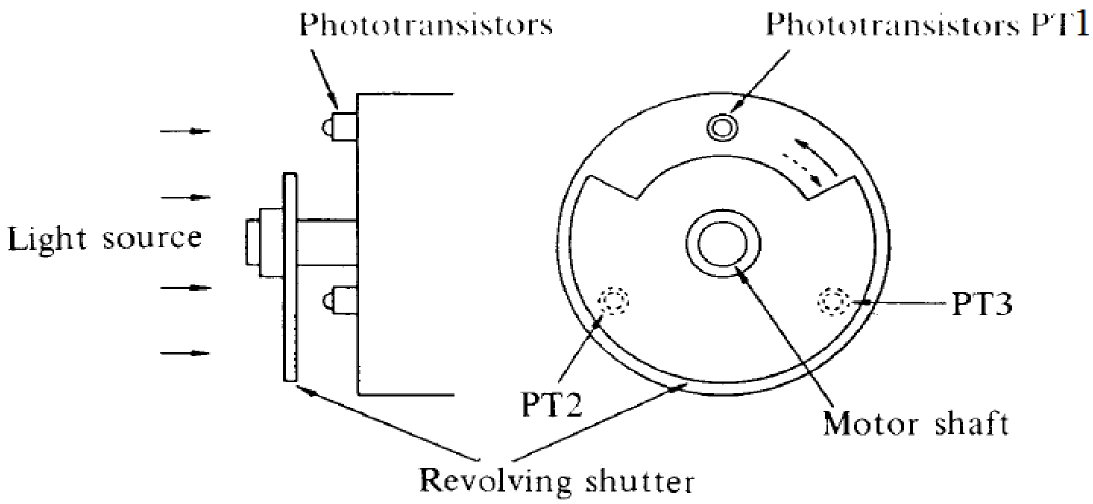


Fig. Optical position sensor

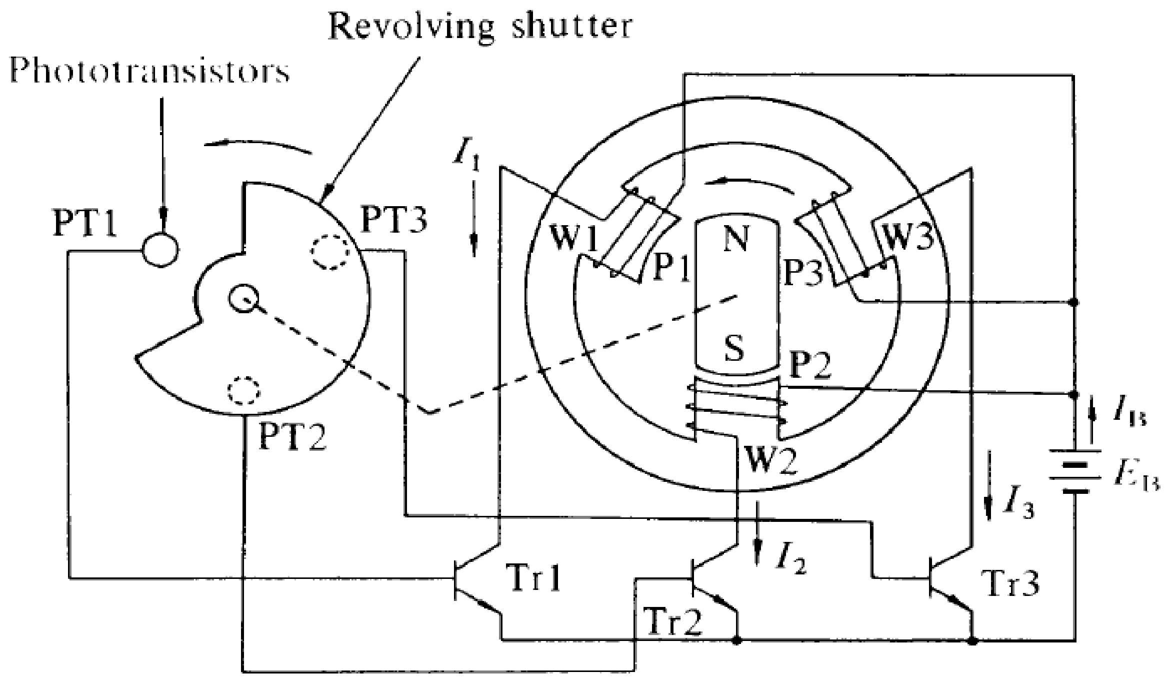


Fig. Three – phase unipolar driven BLDC motor

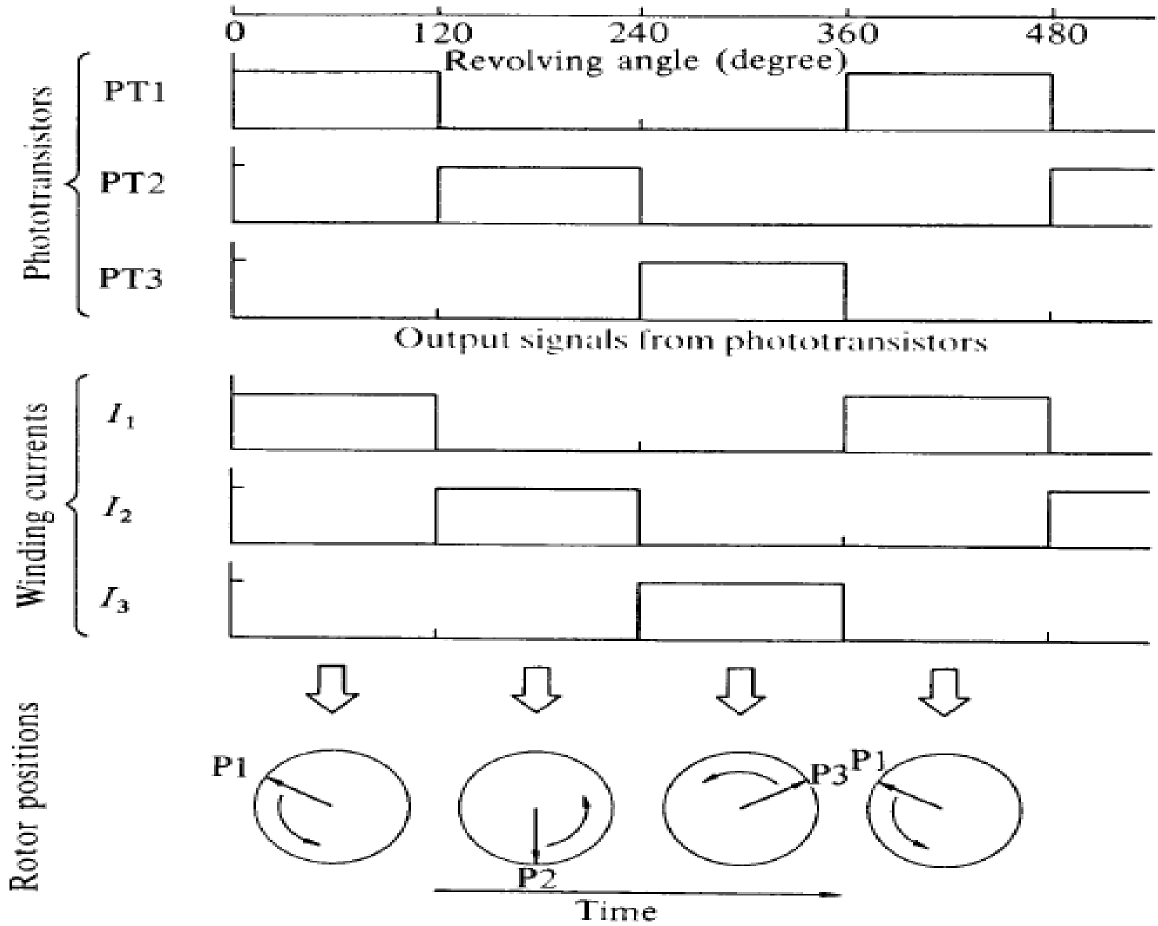


Fig. Switching sequence

Reversing the direction of BLDC Motor:

For Anticlockwise direction:	*For clockwise direction:*
PT1 – Tr1	PT1 – Tr3
PT2 – Tr2	PT2 – Tr1
PT3 – Tr3	PT3 – Tr2

Revolving direction Switching sequence		CCW 1	CCW 2	CCW 3	CCW 4	CW 1	CW 2	CW 3	CW 4
Phototransistors	PT1	1	0	0	1	1	0	0	1
	PT2	0	1	0	0	0	0	1	0
	PT3	0	0	1	0	0	1	0	0
Transistors	Tr1	1	0	0	1	0	0	1	0
	Tr2	0	1	0	0	0	1	0	0
	Tr3	0	0	1	0	1	0	0	1

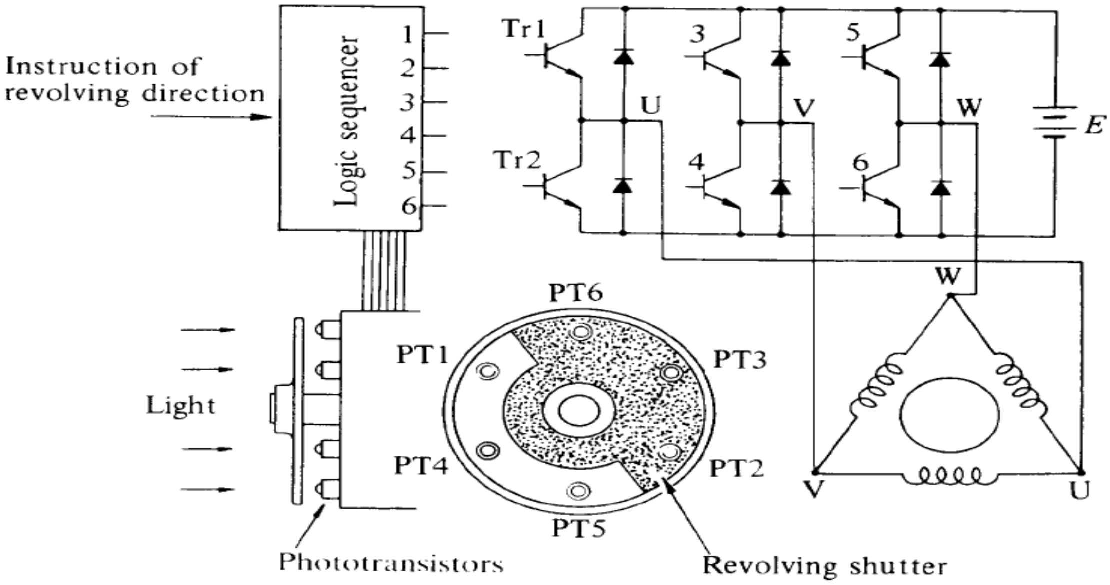


Fig. Three-phase bipolar driven BLDC motor

ON-OFF sequence	1	2	3	4	5	6
Tr 1	1	1	1	0	0	0
2	0	0	0	1	1	1
3	0	0	1	1	1	0
4	1	1	0	0	0	1
5	1	0	0	0	1	1
6	0	1	1	1	0	0

Fig. Clockwise rotation

ON-OFF sequence	1	2	3	4	5	6
Tr 1	0	1	1	1	0	0
2	1	0	0	0	1	1
3	1	1	0	0	0	1
4	0	0	1	1	1	0
5	0	0	0	1	1	1
6	1	1	1	0	0	0

Fig. Anticlockwise rotation

(b) Hall effect position sensor:

Hall Effect:

- When current I_C flows downwards in a semiconductor pellet placed in a magnetic field (B) perpendicular to pellet surface, an emf V_H (Hall emf) is created perpendicular to direction of current & magnetic field.
- According to fleming's left hand rule, charged particles are biased on the left side of the pellet.
- Polarity depends on p or n – type semiconductor.

$$V_H = \frac{1}{d} B I_C R_H$$

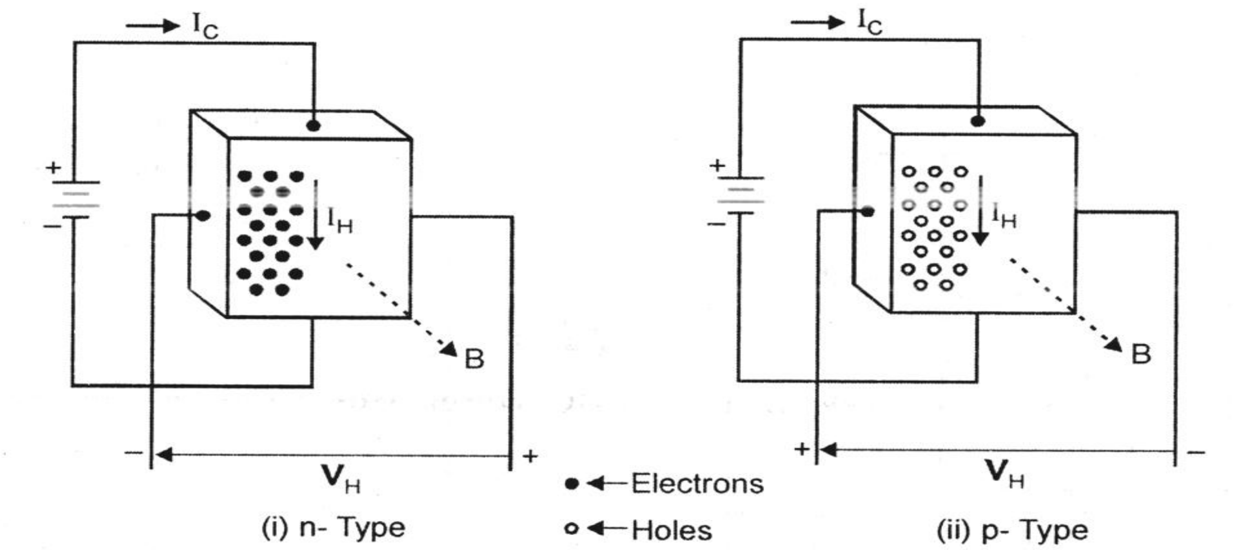
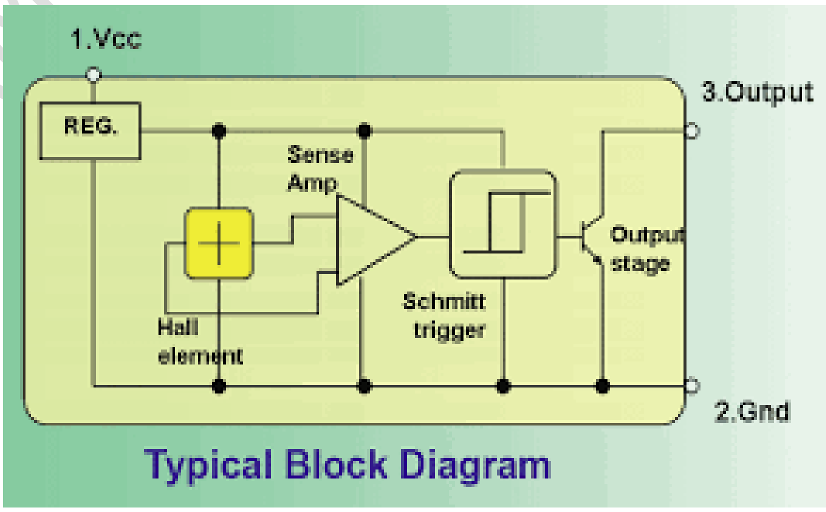


Fig. Operation of Hall Effect Sensor

- In modern BLDC motors, InSb (indium-antimony), GaAs (gallium-arsenide) n-type semiconductors are used.
- Also Hall ICs are available.

Hall ICs:



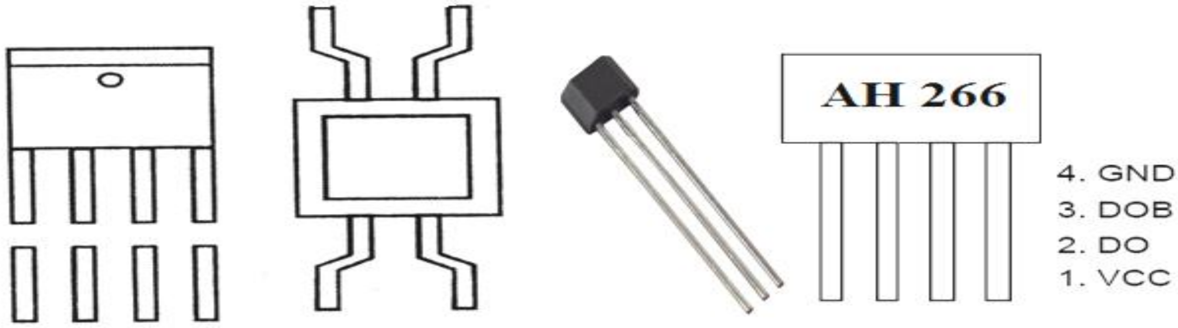
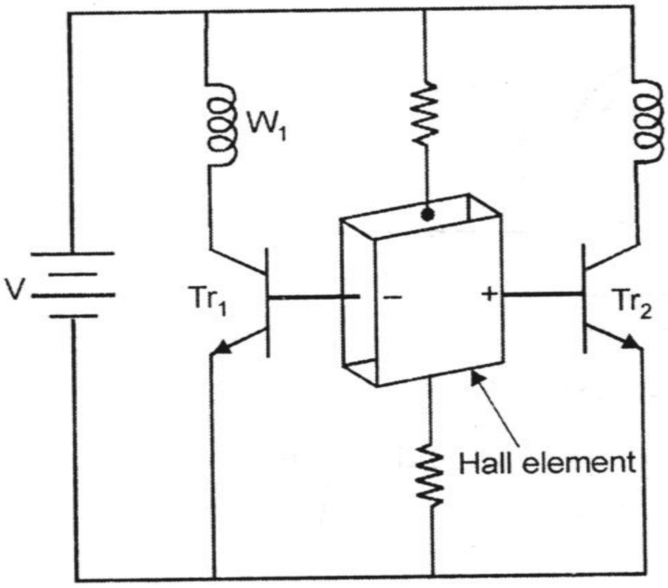
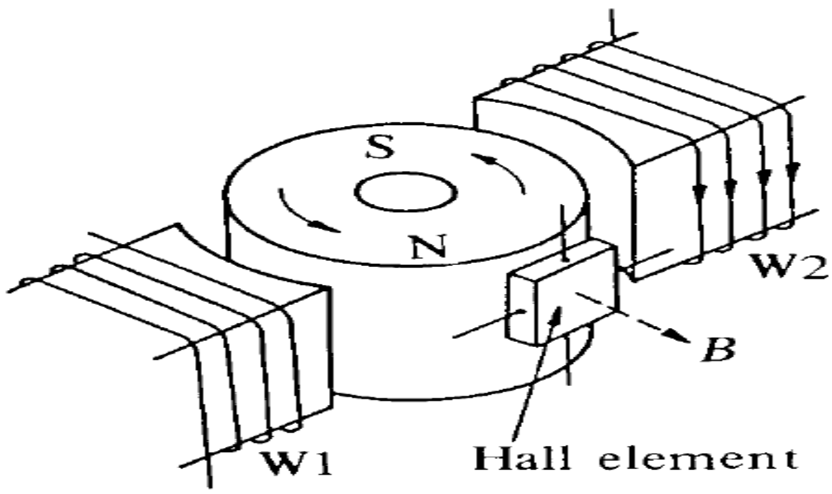


Fig. Hall ICs

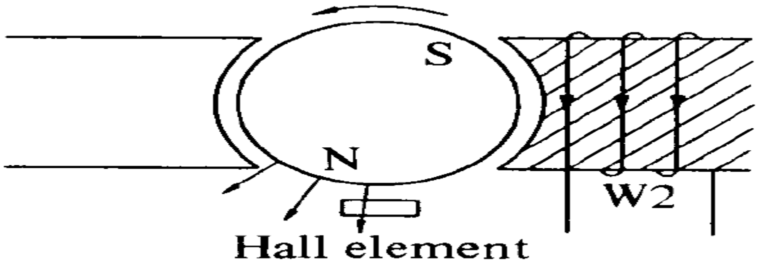
Position detection using Hall sensors:

- Output signals from Hall element operate two transistors, Tr1& Tr2, to control current in the two stator windings W_1, W_2.

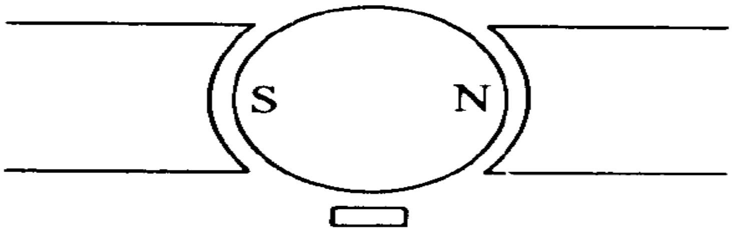




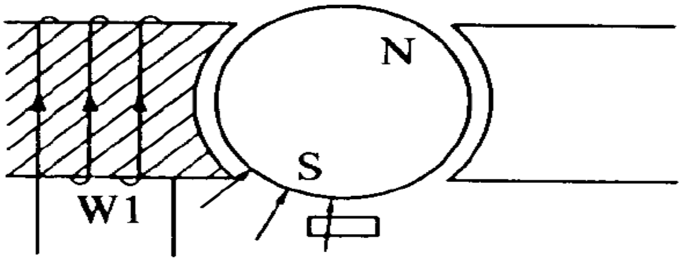
(a) Hall element detect the North pole of rotor magnet, energizes winding W_2 to produce south pole which attracts north pole of rotor by rotating in CCW direction.



(b) Hall element detect none of the rotor poles, so winding W_1 & W_2 are OFF. Rotor rotates due to inertia.



(c) Hall element detect the South pole of rotor magnet, energizes winding W_1 to produce south pole which attracts north pole of rotor by rotating in CCW direction.



Implicit position sensors:

- Reduces the cost
- Increases reliability
- Increases lifetime of the drive

Methods:

There are three implicit methods by which the rotor position can be sensed.

- detecting saturation of phase inductance.
- detecting backward emf.
- detecting harmonics of induced motor voltages.

Magnetic Circuit Analysis :

15. Discuss the magnetic circuit analysis relevant to PMBLDC motor in detail. Also draw its characteristics. May – 2017, 2013, 2012

From the magnetic circuit analysis of permanent magnet brushless DC motor derive the expression for permeance coefficient. Dec-2015

Explain in detail about magnetic circuit analysis of PMBLDC motor. Also draw its characteristics. Dec-2017

Explain the magnetic circuit analysis of permanent magnet brushless DC motor on open circuit. May-2018

- First step in analyzing magnet circuit is to identify the main flux path and assign reluctance and permeance to them.
- Stator is shown without slots or windings.
- The magnetic flux leaving north pole at airgap crosses over to the stator and splits into two equal sections, each travelling in opposite direction and crossing the airgap towards south poles at airgap.
- Consider the cross section of 2 pole BLDC motor having high energy rare earth magnets on the rotor.

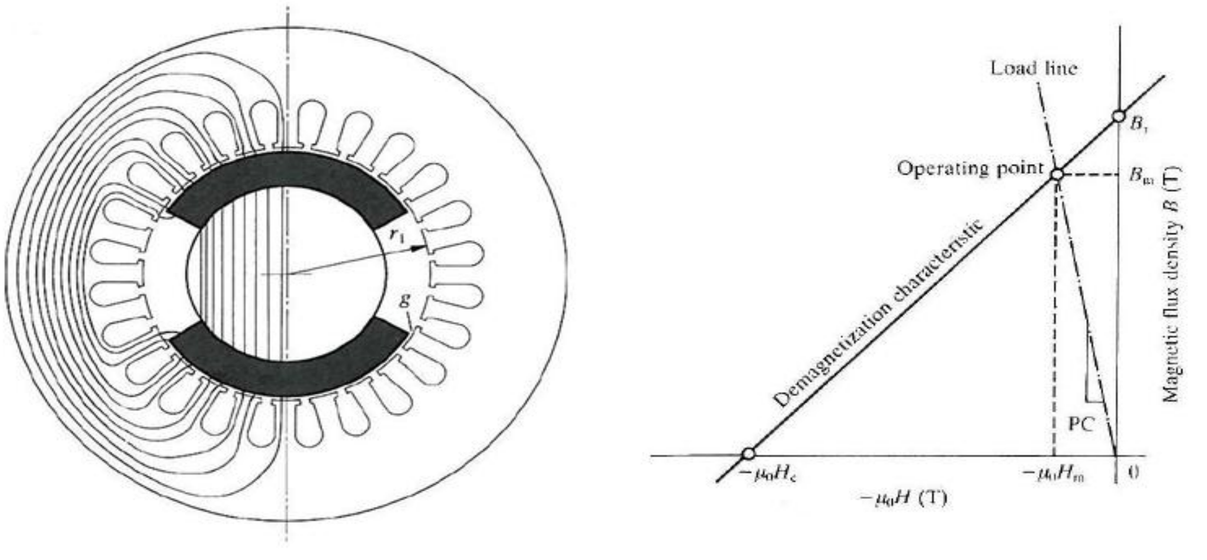


Fig. (a) Cross section and flux pattern of 2 pole BLDC motor
(b) Demagnetization curve

- Only half of the equivalent circuit is shown and the lower half is the mirror image of upper half about the horizontal axis.

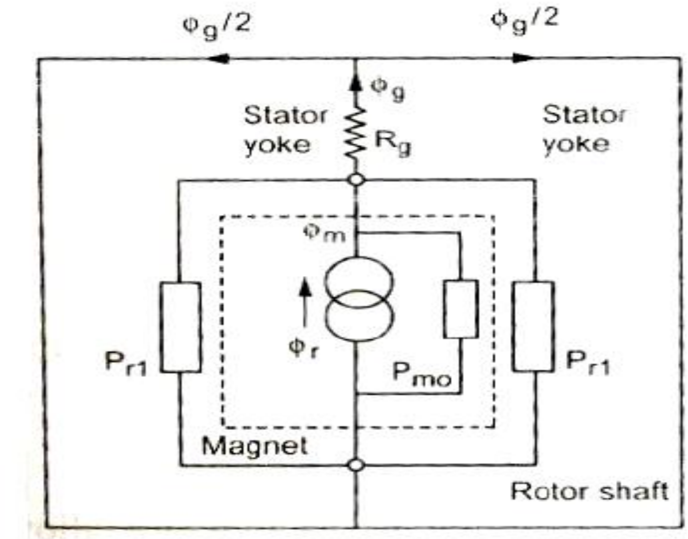


Fig. Magnetic equivalent circuit

$$\varphi_r = B_r A_m$$

$$P_{m0} = \frac{\mu_0 \mu_{rec} A_m}{l_m}$$

A_m – pole area of magnet

B_r – Remanent flux density

l_m – magnet length in the direction of magnetization

μ_{rec} – relative recoil permeability

120° magnet arc is considered.

$$A_m = \frac{2}{3} \pi \left[r_1 - g - \frac{l_m}{2} \right] l$$

$$R_g = \frac{g'}{\mu_0 A_g} \qquad where, \quad g' = k_c g$$

By allowing fringing,

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

$$P_m = P_{m0} + P_{r1}$$

$$P_m = P_{m0} (1 + P_{r1})$$

By solving magnetic circuit,

$$F_m = \frac{\varphi_r - \varphi_g}{P_m} = \varphi_g R_g$$

$$\frac{\varphi_r - \varphi_g}{P_m} = \varphi_g R_g$$

$$\frac{\varphi_r}{P_m} - \frac{\varphi_g}{P_m} = \varphi_g R_g$$

$$\frac{\varphi_r}{P_m} = \varphi_g R_g + \frac{\varphi_g}{P_m} = \varphi_g \left(\frac{1}{P_m} + R_g \right) = \varphi_g \left(\frac{1 + R_g P_m}{P_m} \right)$$

$$\varphi_r = \varphi_g \left(1 + R_g P_m\right)$$

$$\varphi_g = \frac{\varphi_r}{1 + R_g P_m}$$

$$\left.\begin{matrix} Flux\ concenteration\ factor\ or \\ flux\ focusing\ factor \end{matrix}\right\} C_\varphi = \frac{magnet\ pole\ area}{airgap\ area} = \frac{A_m}{A_g}$$

$$airgap\ flux\ density, \quad B_g = \frac{C_\varphi}{1 + R_g P_m} B_r$$

$$magnetic\ flux\ density, \quad B_m = \frac{1 + P_{r1} R_g}{1 + P_m R_g} B_g$$

Magnetizing force H_m is solved using demagnetization characteristics.

$$-H_m = \frac{B_r - B_m}{\mu_0 \mu_{rec}} \quad A/m$$

- ve sign indicates demagnetizing force and magnet operates in second quadrant of B-H curve.

The line drawn from the origin through the operating point is called load line and absoluete value of its slope normalized to μ_0 is called Permeance Co-efficient (PC).

$$\boxed{\boldsymbol{PC = \mu_{rec} \left[\frac{1 + P_{r1} R_g}{P_{m0} R_g}\right]}}$$

---

16. Explain about the various types of magnetic materials.

PERMANENT-MAGNET TYPES

The main features of the three types of permanent-magnet materials used in small rotating machines are briefly summarized below.

__(a) Ceramic-ferrite magnets__

These have a relatively linear demagnetization characteristic, a low remanence of about 0.4T, a moderately high coercive force of up to 250kAm^{-1}, a maximum energy product of around 30kjm^{-3} and an extremely high electrical resistivity of about 10^{10} µΩm.

Ceramic magnets are relatively cheap and are used widely in small dc motors.

__(b) Alnico magnet__

This is a more expensive material than ceramic-ferrite. It has a non-linear demagnetization characteristic, a very high remanence of up to 1.2T, a low coercive force of below l20kAm^{-1} , a maximum energy product of around 60kjm^{-3}and a low electrical resistivity of about 0.5 µΩm.

__(c) Samarium-cobalt rare-earth magnet__

This material has an almost linear demagnetization characteristics, a high remanence (up to 0.9T), a very high coercive force (up to 750 kAm^{-1}) and a maximum energy product of round 400 kJm^{-3}.

It has a maximum energy product greater than that of other materials, which is a great advantage on a volumetric basis.

The disadvantage of the material is its high cost, and it was consequently first used only for aerospace and military equipment and for computer memory disks.

Samarium-cobalt rare-earth magnets are now becoming increasingly used, as the availability of the material becomes widespread and its cost falls.

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17. Explain about the magnetic characteristics in detail.

PERMANENT-MAGNET CHARACTERISTICS:

A typical hysteresis loop for a permanent-magnet material is shown in fig.

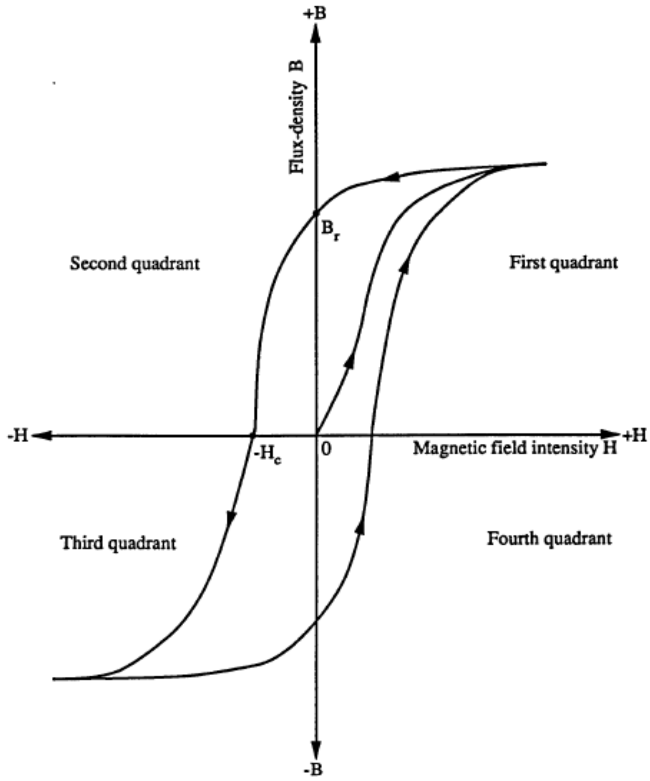


Fig. Hysteresis loop for a typical permanent-magnet material

In most permanent-magnet devices the material operates in the second quadrant of its hysteresis loop, in which the magnetic field H and the flux-density B are opposed. That portion of the hysteresis loop which lies in the second quadrant is called the demagnetization characteristic.

In the typical B-H loop shown in Fig. and known as the normal hysteresis loop, the B-value includes the contributions from both the intrinsic flux-density of the material B_i and the flux-density $\mu_0 H$ resulting from the applied field H.

If only B_i is plotted against H, the resultant loop represents the intrinsic hysteresis loop.

The intrinsic loop represents that proportion of the flux-density which is intrinsic to the magnetic material itself for a particular magnetic field H, and it is of use in the design of a permanent-magnet machine.

The intrinsic flux-density B_i, the normal flux-density B and the magnetizing field intensity H are related by the equation

$$B = \mu_0 H + B_i$$

Several terms used in permanent-magnet studies are defined below.

(i) Magnetic Remanence

(ii) Normal Coercivity

(iii) Wrinsic Coercivity

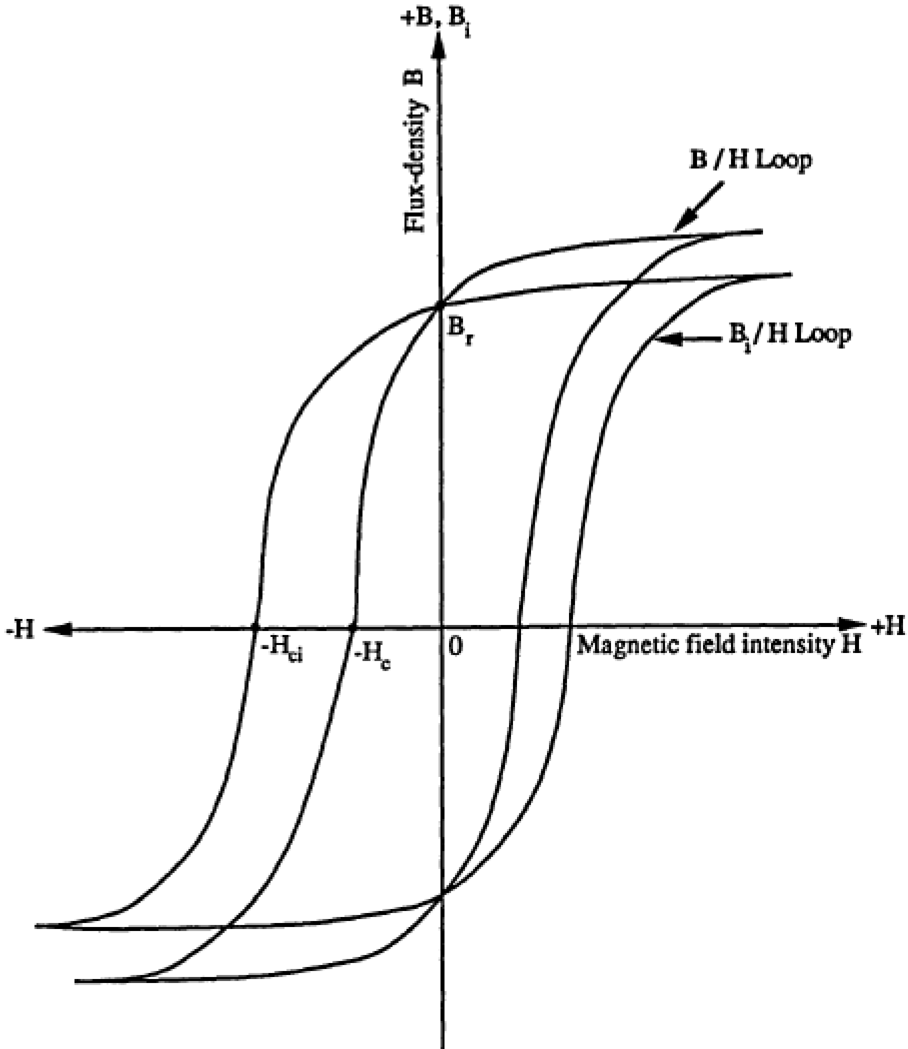


Fig. Normal and intrinsic hysteresis loops for a typical permanent-magnet material

<u>MAGNETIC REMANENCE, B_r</u>

If a magnetizing force is applied to an unmagnetized magnet and then removed, there remains a residual flux-density or remanence B_r due to the non-elastic displacement of the boundary walls between the magnetic domains.

The remanence is the same for both the B and B_i curves, since at this point H is zero.

NORMAL COERCIVITY, H_C

Increasing the negative magnetic field intensity H eventually reduces the normal flux-density B to zero. The value of the magnetic field intensity for this situation is termed the coercivity or coercive force H_c.

INTRINSIC COERCIVITY, H_{ci}

The intrinsic coercivity H_{ci} is the value of the magnetic field intensity at which the intrinsic flux-density B_i is zero.

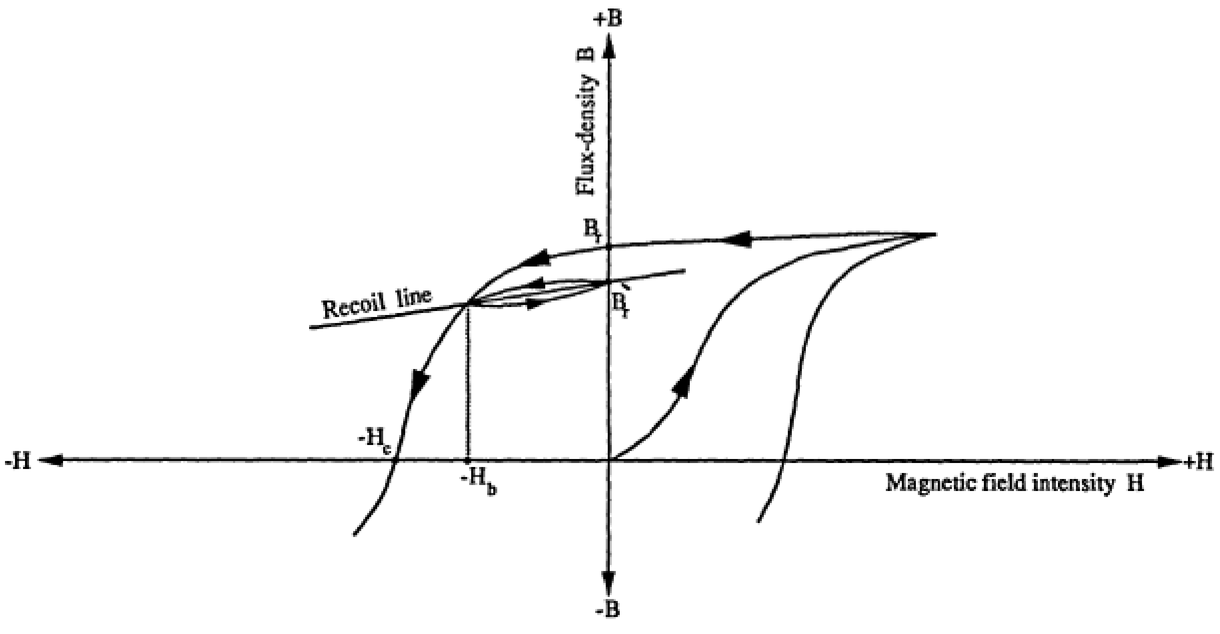
It is a measure of the ability of the magnetic material to withstand demagnetizing forces without permanent changes in its magnetization. The magnitude of H_{ci} may be several times greater than that of H_c

---

18. Discuss about the recoil line in magnetism.

If the demagnetization field is reduced to the value H_b and then returned to zero, the B/H characteristic does not return along the original demagnetizing curve but rather along the lower half of a minor hysteresis loop.

When H_b is re-applied the characteristic follows the upper half of the minor loop. This loop is very narrow and may be replaced by a straight line, termed the recoil line. The slope of this line is specified as the recoil or permanent permeability of the material.



Permanent Magnet recoil line

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19. A Permanent Magnet DC commutator has a no-load speed of 6000 rpm when connected to a 120 V supply. The armature resistance is 2.5 and rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60V and the torque is 0.5 Nm.

May-2016, Dec–2016, 2013, 2012

Given:

V_s = 120 V R_a = 2.5 Ω T = 0.5 N m

To find:

N = ? at 60 V.

Solution:

$$E_b = K_m \ \omega_m$$

$$V = K_m \ \omega_{m0}$$

$$T = K_m \ I_a$$

$$K_m = \frac{V}{\omega_{m0}} = \frac{120}{\frac{2\pi N}{60}} = \frac{120 \ x \ 60}{2\pi \ x \ 6000} = 0.19$$

$$I_a = \frac{T}{K_m} = \frac{0.5}{0.19} = 2.631 \ A$$

$$E_b = V - I_a R_a$$

$$= 60 - 2.631 \ x \ 2.5 = 281.15 \ rad/sec$$

$$\omega_m = \frac{2 \pi N}{60}$$

$$N = \frac{281.5 \ x \ 60}{2\pi} = 2684.78 \, rpm$$

20. A PMBLDC motor has torque constant 0.12 Nm / A referred to DC supply. Find the motors no-load speed when connected to 48 V DC supply. Find the stall current and stall torque if armature resistance is 0.15 Ω/phase and drop in controller transistor is 2 V.

May-2016, Dec – 2013, 2012

Given data :

K_m = 0.1 Nm / A V = 48 V

Solution:

(a) No load Speed:

$$\omega_{mo} = \frac{V}{K_m} = \frac{48}{0.12} = 400 \frac{rad}{sec}$$

$$\omega_m = \frac{2\pi N_0}{60}$$

$$N_0 = \frac{480 \times 60}{2\pi}$$

$$N_0 = 3819.71 \, rpm$$

$$R_{ph} = 0.15\Omega$$

$$V_{dd} = 2 \, V$$

$$Starting \ current \ or \ stall \ current, I_{st} = \frac{V - V_{dd}}{2R_{ph}} = \frac{48 - 2}{2 \times 0.15} = 153.33 \ A$$

$$Starting \ torque \ orstall \ torque, \quad T_{st} = K_e I_{st} = 0.12 \times 153.33 = \mathbf{18.4 \ N - m}$$

Anna University Questions

Part – A

1. Compare conventional DC motor and PMBLDC motor? Dec - 2012
2. What are the advantages of BLPM dc motor over conventional DC motor? Dec-2015
   What are the merits of brushless dc motor drives? Dec-2016
3. State the principle of operation of PM brushless DC motor. Dec-2017, 2014
4. What is an electronic commutator? May-2017, Dec - 2011
5. Write down the EMF equation of PM brushless DC motor. May-2017
6. Write the torque equation of PMBLDC motor. Dec-2017
7. List any four permanent magnet materials. May-2018, 2014
8. Compare PMBLDC motor and switched reluctance motor? May–2014, 2013
9. List out some applications of BLPMDC motor? May-2018, 2016, Dec-2017, 2015
10. What is permeance co-efficient? Dec-2016, May - 2012
11. Comparison between mechanical and electronic commutator. May-2017, Dec–2016, 2013
12. Name the power controllers used in the PMBLDC. Dec-2016, May - 2012
13. Draw the magnetic equivalent circuit of PMBLDC motor. May-2017, 2014, Dec-2013
14. What is commutation? May–2013
15. How are the directions of rotations reversed in case of PMBLDC motor? Dec–2011
16. Classify the types of BLDC motor. May-2015
17. What is meant by demagnetization in PMBLDC motor? Dec-2014
18. How the demagnetization occurs in PMBLDC motor? May-2015
19. Why Brushless permanent magnet DC motor is called as electronically commutated motor? May-2016, Dec-2017, 2015

Part – B

1. Comparison between conventional DC motor and PMBLDC motor. May-2017
   What are the advantages of BLPM over conventional DC motor. Dec-2017, 2015
2. Comparison between mechanical and electronic commutator. Dec–2013, 2011, May-2017
3. Explain briefly constructional and working principle of PMBLDC motors. May-2014, Dec-2016, 2013
   Discuss the construction of permanent magnet dc motor. May-2016
4. Explain the operation of PMBLDC motor. Dec-2016
5. Explain the operation of different types of BLPM DC motor. May-2014, Dec-2012

6. Derive the expression of EMF equation of PMBLDC Motor.
Dec-2017, 2015, May–2018, 2017, 2014, 2012

7. Derive the torque equation of PMBLDC motor. Dec-2017, 2015, May-2017, 2014

8. Explain briefly about the mechanical commutator in conventional DC motor and Electronic Commutator in BLPMDC motor. Dec - 2012

9. Analyze the operation of electronic commutator in PMBLDC motor with neat diagram.
May-2015, Dec-2016, 2011

10. Sketch the structure of power controllers for PMBLDC motor and explain the function of various blocks. May–2014, 2013, Dec-2011

Explain in detail, the power controllers for PMBLDC. Dec-2016

Draw and explain the general structure of a controller for a permanent magnet brushless DC motor. May-2018

11. Explain the speed – Torque characteristics of PMBLDC motor.
May-2018, 2017, 2016, 2014, Dec - 2013

12. Discuss the magnetic circuit analysis relevant to PMBLDC motor in detail. Also draw its characteristics. May – 2017, 2013, 2012

From the magnetic circuit analysis of permanent magnet brushless DC motor derive the expression for permeance coefficient. Dec-2015

Explain in detail about magnetic circuit analysis of PMBLDC motor. Also draw its characteristics. Dec-2017

Explain the magnetic circuit analysis of permanent magnet brushless DC motor on open circuit. May-2018

13. A Permanent Magnet DC commutator has a no-load speed of 6000 rpm when connected to a 120 V supply. The armature resistance is 2.5 and rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60V and the torque is 0.5 Nm. May-2016, Dec–2016, 2013, 2012

14. A PMBLDC motor has torque constant 0.12 Nm / A referred to DC supply. Find the motors no-load speed when connected to 48 V DC supply. Find the stall current and stall torque if armature resistance is 0.15 Ω/phase and drop in controller transistor is 2 V.
May-2016, Dec – 2013, 2012

MAILAM ENGINEERING COLLEGE

Department of Electrical and Electronics Engineering

SUB CODE: EE 6703 **SUB NAME: SPECIAL ELECTRICAL MACHINES**

UNIT – 05
PERMANENT MAGNET SYNCHRONOUS MOTOR

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

PART – A

1. What is brushless AC motor?

- The ***sinusoidal current***-fed motor, which has ***distributed winding*** on the stator inducing ***sinusoidal voltage*** is known as brushless AC motor.
- Used in ***high power drives***.
- The brushless AC motor is also known as permanent magnet synchronous motor (PMSM).

2. What is a permanent magnet synchronous motor (PMSM)?

An AC motor which is having a ***poly phase distributed winding*** on the stator, ***permanent magnets on the rotor*** and the nature of voltage induced in the stator is ***sinusoidal*** is known as permanent magnet synchronous motor.

3. State the important features of permanent magnet synchronous motor. **May-2018**

- The construction is ***robust, compact***.
- There is ***no field current*** or rotor current.
- The ***weight*** of the whole machine assembly is ***less***.
- The ***copper loss*** due to current flow which is the largest loss in motors is about half that of induction motor.
- ***Efficiency*** of the machine is ***high***.

4. State the principle of operation of permanent magnet synchronous motor.

The brushless permanent magnet synchronous motor is a classical salient-pole synchronous AC motor with approximately sine distributed windings, and it can therefore run from a sine wave supply without electronic commutation.

When AC supply is given, based on the rotor-position information from the shaft position sensor, the motor phase windings are excited sequentially in such a fashion as to produce the desired torque and speed.

5. What are the types of materials used in permanent magnet motor? **May-2017**

- Alinco magnet
- Cobalt- Samarium magnet
- Barium and Strontium ferrites
- Neodymium – Iron - Boron (NdFeB) magnet

6. What are the differences between conventional synchronous motor and PM synchronous motor?

S. No	Conventional synchronous motor	PM synchronous motor
1	The ***rotor has field winding***, which is supplied from a DC source through slip-rings and brushes.	The ***rotor has permanent magnets***.
2	***Maintenance*** requirement is ***high*** because of the presence of slip-rings and brushes.	***Low maintenance.***
3	When the wound field synchronous motor is started as an induction motor, DC field is kept off.	The field cannot be 'turned off'
4	***No rotor position sensor.***	***Rotor shaft position*** can be detected by using sensor.

7. What are the types of PM synchronous motor? **Dec-2017**

Classify the different types of PMSM. **Dec-2016**

(a) General classification

In general, there are two types of p.m. synchronous motor,

1. Surface mounted motor
2. Interior (or buried) motor

The surface mounted motor is further classified as,

Projected type → magnets are projected from the surface of rotor

Insert type → magnets are inserted into the rotor.

(b) Classification based on rotor configuration

According to the rotor configurations, permanent magnet synchronous motor is classified as,

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

8. When does a PM synchronous motor operate as synchronous reluctance motor?

The permanent magnet synchronous motor operators as a synchronous reluctance motor if the ***magnets are left out or demagnetized***.

9. List out the differences between the PM brushless DC motors and PM synchronous motors. **Dec-2015, May-2017**

Differentiate square wave and sine wave motor. **Dec-2016**

S. No	PM brushless DC motor (Square wave)	PM synchronous motor (Sine wave)
1	It has ***concentrated winding*** on the stator.	It has ***distributed winding*** on the stator.
2	Induces ***square*** or trapezoidal ***voltage.***	Induces ***sinusoidal voltage***.
3	Known as brushless DC motor.	Known as brushless AC motor.
4	Used as ***low power*** drive.	Used as ***high power*** drive.

10. Write down the emf equation of PMSM. **Dec-2017, 2016, 2013**

The rms value of induced emf per phase of the armature winding of an ideal BLPM sine wave (PMSM) motor is expressed as,

$$E_{ph} = 4.44\, f\, \varphi_m\, T_{ph} \quad volts$$

Where, f - frequency (Hz)
φ_m – sinusoidal distributed flux/pole (wb)
T_{ph} – number of turns per phase

11. Write down the torque equation of PMSM. **Dec-2017, 2016, 2013**

The torque equation of BLPM sine wave (PMSM) motor is expressed as,

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

Where, I – The rms value of current (A)
r_1– Stator bore radius (m)
l_1- Stack length (m)
B – Distributed magnetic flux density (wb/m^2)
N_s- Number of series turns per phase of sine – distributed winding
β – Torque angle (deg or rad)

Another expression can be written in terms of the total torque experienced by the armature conductors. It is given by,

$$T = \pi\, \hat{A}\, \hat{B}\, r\, l \sin\alpha \quad N-m$$

Where, $\hat{A}$ – Ampere conductor density
$\hat{B}$ – distributed magnetic flux density ($\frac{wb}{m^2}$)
r – radial distance of the conductors from the axis of the shaft (m)
l – Length of the armature (m)
α – Phase angle (deg or rad)

12. What is meant by synchronous reactance? **May-2016, 2014, 2013**

The synchronous reactance is the ***fictitious reactance*** employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and the change in the airgap flux caused by armature reaction.

$$X_s = \frac{3\,\pi\,\mu_0\, {N_s}^2\, l\, r_1\, \omega}{8\, p^2\, g''}$$

Where, μ_0- Permeability of free space
r_1- Stator bore radius (m)
l – Stack length (m)
ω – Angular velocity in mech.rad/sec.
p – Pole pairs
g" – Effective airgap length allowing for magnet

13. Mention the objective of self control. **May-2017, Dec-2012**

The objective of self-control is to make the armature (stator) and rotor fields of brushless synchronous motor drive to ***move in synchronism*** for all operating points.

The stator of permanent magnet synchronous motor has distributed armature winding and the rotor has surface mounted permanent magnets. In self-control, as the ***rotor speed changes***, the ***armature supply frequency*** is also ***changed*** proportionately, so the armature field always moves at the same speed as the rotor.

14. State the objective of vector control.

Briefly explain the vector control of PMSM. **Dec-2014**

The objective of vector control in brushless permanent magnet synchronous motor is to make the motor to have ***better steady state and dynamic performance***.

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

15. What is meant by slotless motor? **May-2014**

If the stator teeth of permanent magnet synchronous motor are removed and resulting space is partially filled with additional copper, then the structure is known as slotless motor.

In this slotless motor, the maximum useable magnet energy is higher than in a conventional slotted motor.

The slotless construction permits an increase in rotor diameter within the same frame size, or alternatively and increase in electric loading without a corresponding increase in current density.

16. What is the magnitude of stator current in PMSM to achieve demagnetization?

The magnitude of stator current PMSM to achieve partial demagnetization of the magnets is given by,

$$I = \frac{E_q}{X_s} \quad A$$

Which is many times greater than the normal continuous rating of the motor windings or the converter.

Where, E_q - Open circuit emf due to magnet

X_s - synchronous reactance

17. Synchronous machines with surface - mount magnets have very little differences between direct axis and quadrature – axis inductances. Why?

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.

18. State the types of power controllers for PMSM. **May-2018, Dec-2017**

Types of power controllers for PM synchronous motor are,

1. PWM inverter using power MOSFETS with microprocessor control.
2. PWM inverter using BJT's with microprocessor control (upto 100kw)
3. Self control
4. Vector control

19. State the advantages of PM synchronous motor over other A.C. motors.

1. Higher efficiency due to the elimination of brushes, slip rings and field copper losses.
2. It has superior power density.
3. High torque to inertia ratio is its additional merit.
4. Normally, for small drives applications [from few KW to 10KW], the PMSM is quite advantageous than other AC motors.

20. What are the uses of optical sensor?

The optical sensor is used as position sensor in P.M. synchronous motor.

These sensors detect the position of the rotating magnets (because in this motor, permanent magnet is in rotor) and send logic codes to communication decoder, which after processing this code, activates the semiconductor switches of firing circuits.

In optical sensors, a light source shines through a patterned disc attached to the rotor shaft and a photodiode detects the presence or absence of light.

21. State the advantages and disadvantages of optical sensors.

Advantages of optical sensor

- Quite suitable for sinusoidal type (PMSM) motor as it is a high resolution sensor.
- 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.

Disadvantages of optical sensor

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

22. State the applications of PMSM. **May-2014, Dec-2011**

- Low integral – hp industrial drives
- Fiber spinning mills
- Applied as direct drive traction motor.
- Used as high speed drives for compressors, blowers, conveyors, fans, pumps, steel rolling mills and aircraft test facilities.

23. Write the significance of power controllers of permanent magnet synchronous motors.

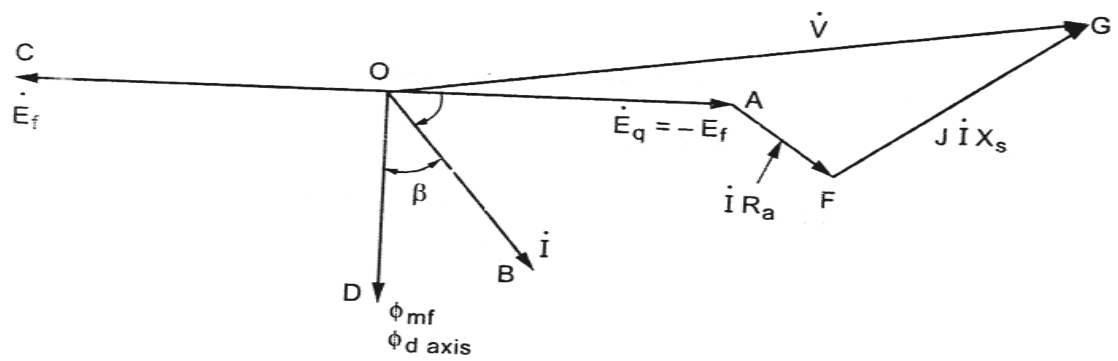
Dec-2017, 2016, 2013

Power controllers are the power semiconducting switching circuits. All the power conducting switching devices such as transistors, MOSFET, IGBT and SCR can be used.

24. Brief-up the advantages of load commutation in PMSM. **Dec-2012**

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

25. Draw the output phasor diagram of PMSM. **May-2016, 2014, 2013**



26. Write down the expression for the self and synchronous reactance of PMSM. **Dec-2011**

The expression for synchronous reactance is,

$$X_s = \frac{3\,\pi\,\mu_0\,N_s{}^2\,l\,r_1\,\omega}{8\,p^2\,g''}$$

The expression for self reactance is,

$$L_g = \frac{\pi\,\mu_0\,N_s{}^2\,l\,r_1}{4\,p^2\,g''}$$

27. What are the merits of 3-phase Brushless Permanent Magnet Synchronous Motor? **Dec-2013**

(i) The Permanent magnet synchronous motor (PMSM) has ***higher efficiency*** due to elimination of brushes, slip rings and field copper losses.

(ii) It has ***superior power density***.

(iii) High torque to inertia ratio is its additional merit.

28. Write the drawbacks in PMSM. **May-2015**

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

29. Mention the various assumptions in deriving the EMF equation of PMSM. **Dec-2014**

- Ideal sine wave brushless motor with ***pure sine distributed phase winding*** and permanent magnet rotor with ***sine distributed flux***.
- Rotor rotates with an ***uniform angular velocity*** of ω_m.

30. Define the term load angle. **May-2015**

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

31. Explain the distribution factor for PMSM. **May-2017, Dec-2015**

Distribution factor or spread factor is

$$k_{d1} = \frac{\sin\frac{q\gamma}{2}}{q\sin\frac{\gamma}{2}}$$

Where, γ – slot pitch

q – number of slots per pole per phase.

PART-B

Other names:

- Permanent Magnet Brushless Sinewave motors (PMBL SNW motors)
- PMAC motors
- Permanent Magnet Synchronous Motors (PMSM)

Construction:

1. With neat sketch, explain the constructional features of Permanent Magnet Synchronous Motor (PMSM). May-2014, Dec-2013

Enumerate the construction and performance of a permanent magnet synchronous motor with diagrams. Dec-2016, 2014

Describe the construction and performance of PMSM with neat diagram. May-2017

Explain the construction and performance of a permanent magnet synchronous motor with neat diagram. Dec-2017

- Constructionally similar to BLDC motors.
- The armature winding and the shape of the permanent magnet are so designed so that flux density distribution of the air gap is sinusoidal.
- Magnetic field set up by the permanent magnet in the air gap is sinusoidal.
- Because of the presence of permanent magnet, slip rings and field windings are absent.

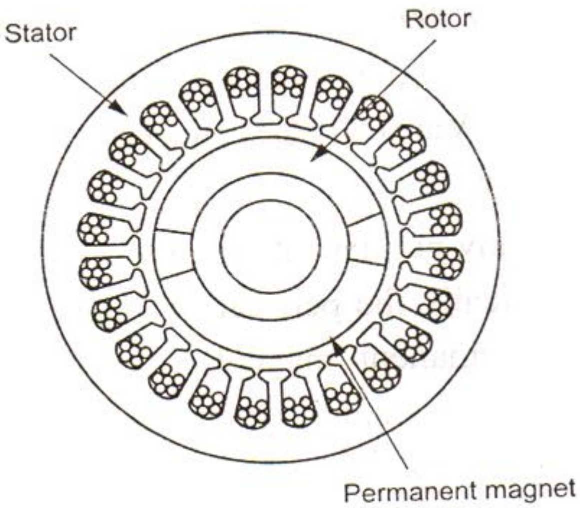


Fig. Construction of PMSM

Stator:

- Stationary member.
- Contains double layer, lap wound distributed armature winding.
- Star or delta connections are possible.
- Coils are insulated from each other
- Dielectric strength of the insulation depend on voltage rating of the machine.
- By making continuous strips of soft steel, the stator laminations for axial machines are formed.
- Thickness of the lamination depends upon the frequency of the armature source voltage.

Rotor:

- Rotor poles shaped to produce sinusoidal waveform.
- Rotor is made of permanent magnet.
- Usually ferrite magnets are employed.
- Rare earth (cobalt-samarium) magnets are used.

- Four types of rotor geometries. They are,
  - ✓ Peripheral type
  - ✓ Interior type
  - ✓ Claw-pole type
  - ✓ Transverse type

Peripheral type rotor:

- Permanent magnet is located on the rotor periphery.
- Flux pattern of permanent magnet is radial.

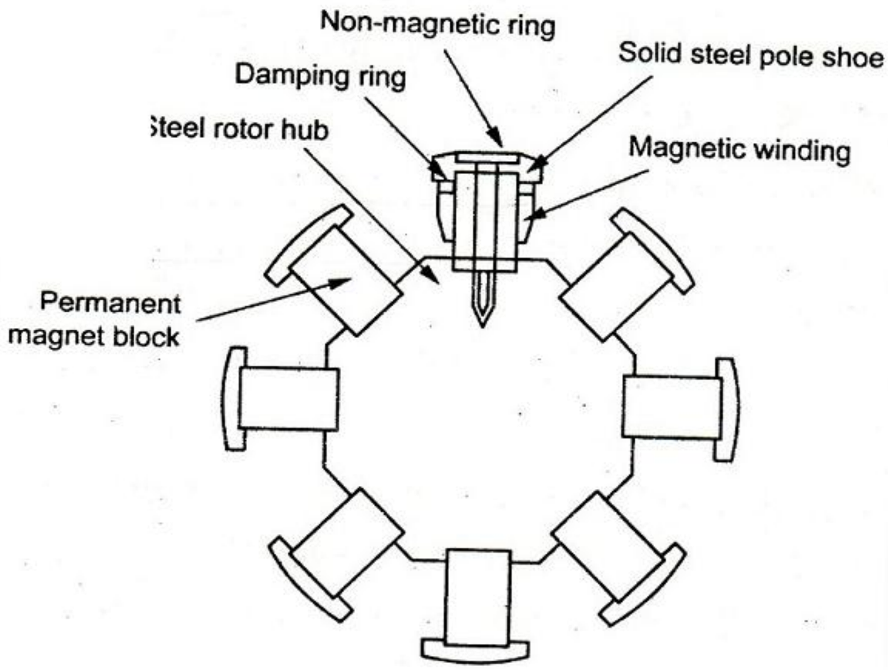


Fig. Peripheral type rotor

Interior type rotor:

- Permanent magnet is located in the interior of the rotor
- Pattern of flux is generally radial.
- More robust, not easier to construct compared to peripheral type.
- Suitable for high speed applications.

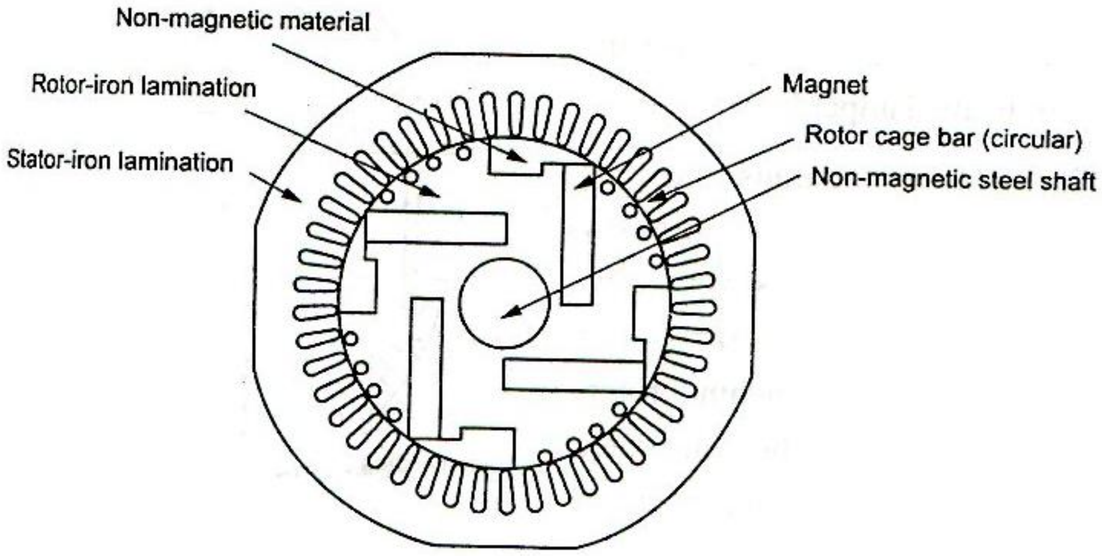


Fig. Interior type rotor

Claw-pole type rotor:

- Permanent magnets are generally disc-shaped.
- Magnetized axially.
- The long, soft-extensions of the construction comes out axially from the periphery of the discs like Claws.
- called as claw-pole type or Lundell type rotor.
- Set of equally-space alternate claws on each disc forming alternate north and south poles.

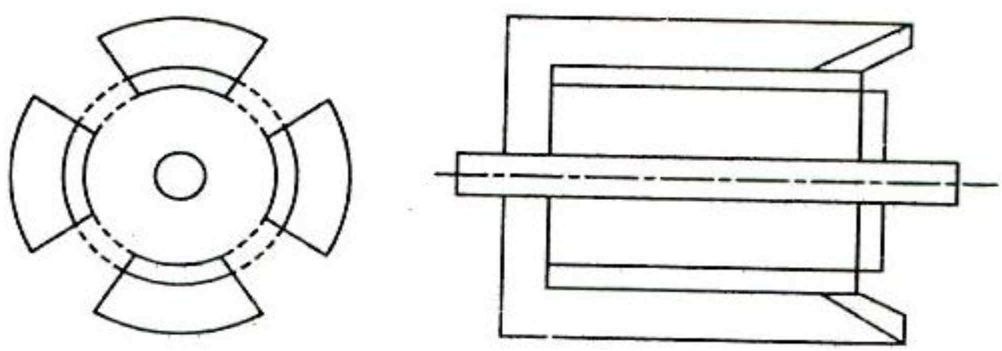


Fig. Claw pole type

Transverse type rotor:

- Permanent magnet in the rotor is generally between soft-iron poles
- Flux pattern is circumferential.
- Rectangles in the soft-iron poles indicate damper bars.
- Permeability of the permanent magnet is very low.
- Similar to a reluctance machine rotor.
- there exists both the reluctance torque and torque resulting from the flux of permanent magnet.

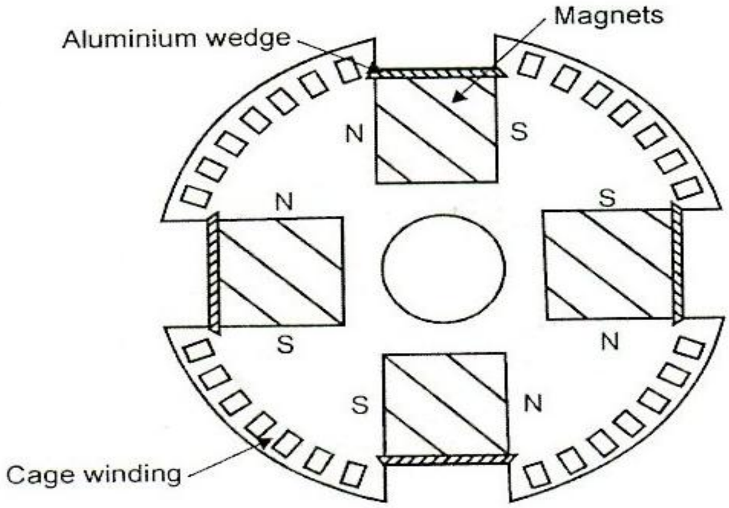


Fig. Transverse type rotor

Principle of operation:

2. Explain the operation of PMSM. **Dec-2017**
Discuss the current control scheme of PMSM in detail. **Dec-2014**

- PMSM is fed directly from a three phase supply.
- When the armature winding draws a current, the current distribution in the stator winding depends on rotor position and turning on process of the devices in control circuit.
- For maximum torque, angle between the stator flux and rotor flux is kept close to 90°.
- Hence motor requires electronic control for proper operation.

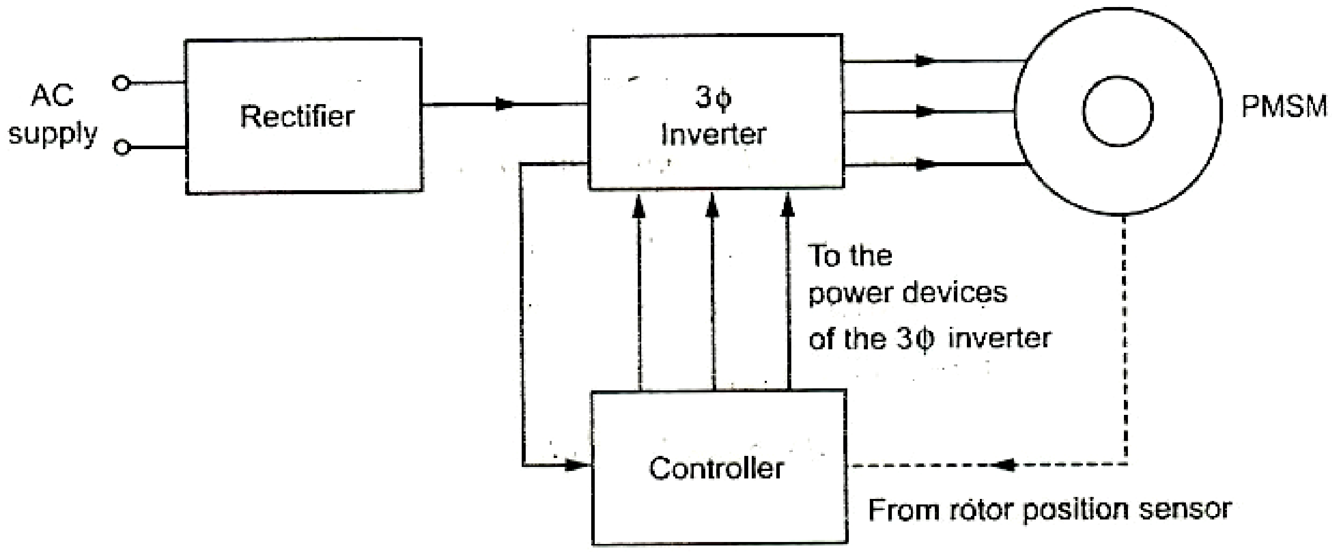


Fig. Operation of PMSM

- The armature supply frequency is changed in proportion to the changes in rotor speed.
- So, stator field always moves at the same speed as the rotor.
- Rotor position sensor is required for accurate tracking of the speed.

EMF equation:

3. Derive the EMF equation of an ideal sine wave PM motor.

Dec-2017, 2016, 2015, 2013, May-2018, 2017, 2016, 2014, 2013

$Flux\ density, B = \hat{B} \sin p\theta$

Consider a small strip dθ from a distance θ from the reference.

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

$Incremental\ flux\ in\ strip, \quad d\varphi = B\ x\ area\ swept\ by\ conductor$

$$d\varphi = B\, l\, r\, d\theta$$

$$= \hat{B} \sin p\theta\ \ l\, r\, d\theta$$

$$= \hat{B}\, l\, r\ \sin p\theta\ \ d\theta$$

$$\varphi = \int_{\omega_m t}^{\omega_m t + \frac{\pi}{p}} \hat{B}\, l\, r\ \sin p\theta\ \ d\theta$$

$$\varphi = \hat{B}\, l\, r \int_{\omega_m t}^{\omega_m t + \frac{\pi}{p}} \sin p\theta\ \ d\theta$$

$$= \hat{B}\, l\, r\ \left[-\frac{\cos p\theta}{p}\right]_{\omega_m t}^{\omega_m t + \frac{\pi}{p}}$$

$$= \frac{\hat{B}\, l\, r}{p}\ [-\cos\ (p\,\omega_m t + \pi) + \cos\ p\omega_m t\,]$$

$$= \frac{\hat{B}\, l\, r}{p}\ [2\ \cos\ p\omega_m t\,]$$

$$\boxed{\boldsymbol{\varphi = \frac{2\,\hat{B}\, l\, r}{p}\ \cos\ p\omega_m t}}$$

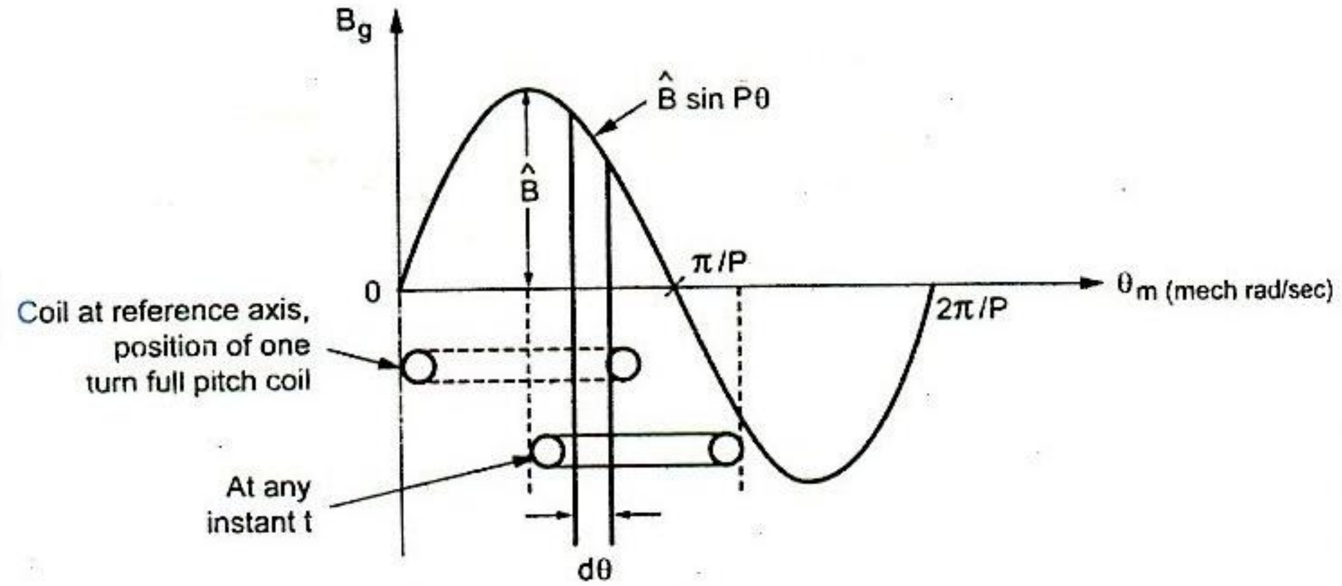


Fig. Flux density distribution of PMSM

By faradays law,

For single turn coil,

$$e = -N\frac{d\varphi}{dt}$$

$$e = -\frac{d\varphi}{dt} \qquad (\because N = 1)$$

$$e = -\frac{d}{dt}\left[\frac{2\,\hat{B}\,l\,r}{p}\ \cos\ p\omega_m t\right]$$

$$= \frac{2\,\hat{B}\,l\,r}{p}\ \sin p\omega_m t\quad p\omega_m$$

$$e = 2\,\hat{B}\,l\,r\,\omega_m\ \sin p\omega_m t$$

Induced emf per phase,

$$e_{ph} = \left(2\,\hat{B}\,l\,r\,\omega_m\ \sin p\omega_m t\right) T_{ph}$$

$$e_{ph} = \widehat{E_{ph}}\ \sin p\omega_m t \qquad\qquad (\ p\omega_m = \omega_e\ )$$

$$e_{ph} = \widehat{E_{ph}}\ \sin \omega_e t$$

$where, \qquad \widehat{E_{ph}} = 2\,\hat{B}\,l\,r\,\omega_m\,T_{ph}$

$RMS\ value\ of\ induced\ emf, \qquad E_{ph} = \frac{\widehat{E_{ph}}}{\sqrt{2}}$

$$E_{ph} = \frac{2\,\hat{B}\,l\,r\,\omega_m\,T_{ph}}{\sqrt{2}}$$

$$E_{ph} = \sqrt{2}\,\hat{B}\,l\,r\,\omega_m\,T_{ph} \qquad ----\ (1)$$

$$\varphi_m = B_{av}\ \tau\ l$$

$$\varphi_m = B_{av}\ \frac{2\,\pi\, r}{2\,p}\ l = B_{av}\ \frac{\pi\, r}{p}\ l$$

$$But,\ \ B_{av} = \frac{2}{\pi}\ \hat{B}$$

$$\varphi_m = \frac{2}{\pi}\ \hat{B}\ \frac{\pi\, r}{p}\ l$$

$$\varphi_m = \frac{2\,\hat{B}\,l\,r}{p}$$

$$\hat{B}\ l\ r = \frac{\varphi_m\ p}{2}$$

$$(1) => \ E_{ph} = \sqrt{2}\ \frac{\varphi_m\ p}{2}\ \omega_m\ T_{ph}$$

$$= \sqrt{2}\ \frac{\varphi_m\ p}{2}\ \frac{\omega}{p}\ T_{ph} = \sqrt{2}\ \frac{\varphi_m\ p}{2}\ \frac{2\pi f}{p}\ T_{ph}$$

$$= \sqrt{2}\ \pi f \varphi_m\ T_{ph}$$

$$\boxed{E_{ph} = 4.44\ f\ \varphi_m\ T_{ph}}$$

For practical PMBL sinewave motor,

$$\boxed{\boldsymbol{E_{ph} = 4.44\ f\ \varphi_m\, T_{ph}\, K_{w1}\quad volts}}$$

$$where, K_{w1} = k_{s1}\ k_{p1}\ k_{b1}$$

Ampere conductor density distribution:

$$Ampere\ conductor\ density,\ \ A = \hat{A}\ \sin p\theta$$

Consider a strip dθ at an angle θ from reference.

$$Ampere\ conductors\ in\ strip\ d\theta = A\ d\theta$$

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

$$ampere\ conductors\ per\ pole = \int_0^{\frac{\pi}{p}} \hat{A} \sin p\theta\ d\theta$$

$$= \hat{A} \int_0^{\frac{\pi}{p}} \sin p\theta\ d\theta$$

$$= \hat{A}\left[-\frac{\cos p\theta}{p}\right]_0^{\frac{\pi}{p}} = \frac{\hat{A}}{p}\left[-\cos\pi + \cos 0\right]$$

$$ampere\ conductors\ per\ pole = \frac{2\,\hat{A}}{p} \qquad ----(1)$$

Also,

$$ampere\ conductors\ per\ pole = \frac{2\,i\,T_{ph}}{2\,p} \qquad ------(2)$$

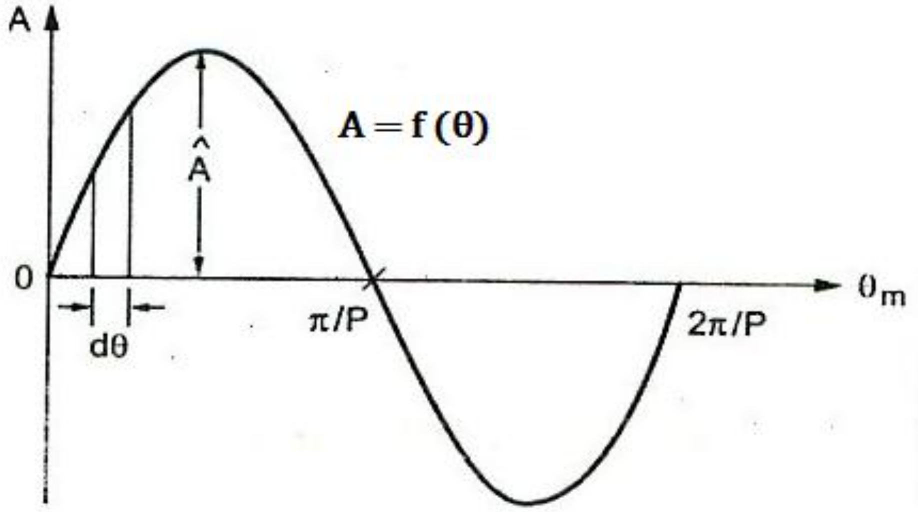


Fig. Ampere conductor density distribution

From (1) & (2),

$$\frac{2\,\hat{A}}{p} = \frac{2\,i\,T_{ph}}{2\,p}$$

$$\boxed{\hat{A} = \frac{i\,T_{ph}}{2}}$$

<u>Torque equation:</u>

4. Derive the torque equation of an ideal sine wave PM motor.

Dec-2017, 2016, 2015, 2013, 2012, May-2018, 2017, 2016, 2014, 2013

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

$$Flux\ density\ distribution\ is\ displaced\ by\ \left(\frac{\pi}{2} - \alpha\right)$$

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

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

$B = \hat{B} \cos (p\theta - \alpha)$

Consider a small strip dθ at an angle θ from reference.

$$B = \hat{B} \cos (p\theta - \alpha)$$

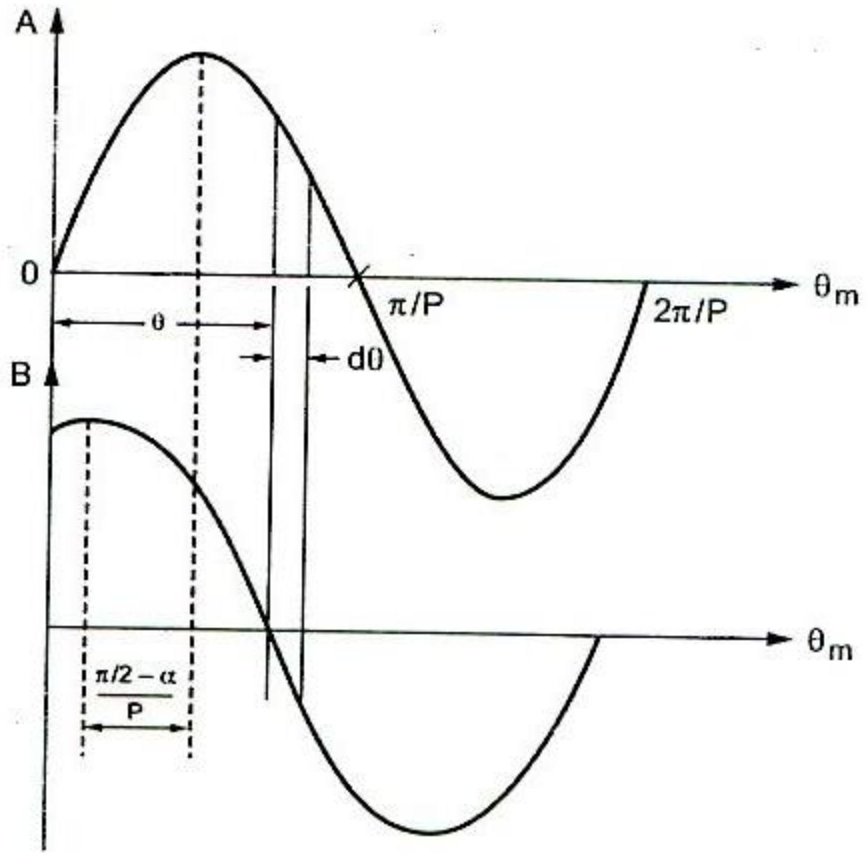


Fig. Ampere conductor and flux density distribution

$$Ampere\ conductors\ in\ strip = A\ d\theta$$

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

$$Force\ experienced\ by\ armature\ conductors\ in\ strip\ d\theta = B\ l\ A\ d\theta$$

$$dF = \hat{B} \cos(p\theta - \alpha)\ l\ \hat{A} \sin p\theta\ \ d\theta$$

$$= \hat{A}\ \hat{B}\ l\ \sin p\theta\ \cos(p\theta - \alpha)\ d\theta$$

$$Torque\ experienced\ by\ strip = dF\ x\ r$$

$$dT = \hat{A}\ \hat{B}\ l\ r\ \sin p\theta\ \cos(p\theta - \alpha)\ d\theta$$

$$Torque\ per\ pole = \int_0^{\frac{\pi}{p}} dT$$

$$= \int_0^{\frac{\pi}{p}} \hat{A}\ \hat{B}\ l\ r\ \sin p\theta\ \cos(p\theta - \alpha)\ d\theta$$

$$= \frac{\hat{A}\,\hat{B}\,l\,r}{2}\;\frac{\pi \sin\alpha}{p} \quad N-m$$

$$T = 2p\,x\,torque/pole$$

$$= 2p\,x\,\frac{\hat{A}\,\hat{B}\,l\,r}{2}\;\frac{\pi \sin\alpha}{p}$$

$$T = \pi\ \hat{A}\,\hat{B}\,l\,r \sin\alpha \ \ N-m$$

This is the torque experienced by the armature conductors in stator.

$Torque\ experienced\ by\ rotor\ = -\pi\,\hat{A}\,\hat{B}\,l\,r \sin\alpha$

$$\boldsymbol{T = \pi\,\hat{A}\,\hat{B}\,l\,r \sin\beta}$$

For a practical motor,

$$\boldsymbol{T = \frac{3\,E_{ph}\,I_{ph}}{\omega_m}\sin\beta}$$

Armature reaction MMF:

5. Write short notes on armature reaction in PMSM. **May-2017, 2015**

- Flux is produced by current in stator winding
- Magnet is unmagnetized.
- MMF is concentrated across the two airgap.

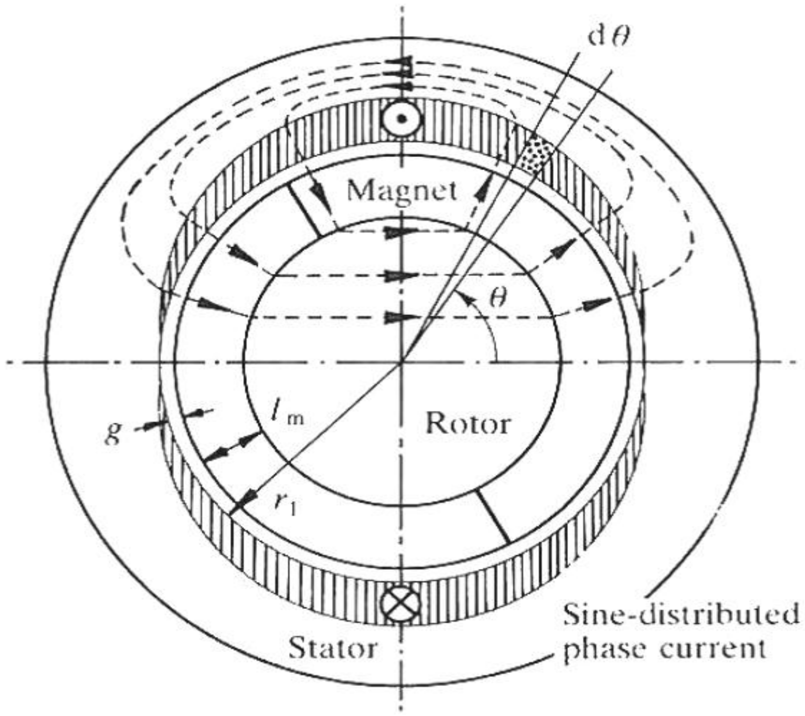


Fig. Armature reaction mmf of sine wave winding

F_g - mmf across airgap
H_g - field strength at airgap
l_m - length of magnet
g" - effective airgap length for magnet

$$F_g = H_g\, g'' = \frac{1}{2}\int_{\theta}^{\frac{\pi}{p}-\theta} \frac{i\,N_s}{2}\sin p\theta\; d\theta$$

$$F_g = \frac{N_s\; i}{2\,p}\cos p\theta$$

$$\Rightarrow\; H_g = \frac{N_s\; i}{2\,p\,g''}\cos p\theta$$

$$B(\theta) = \mu_0\, H_g$$

$$= \mu_0\; x\, \frac{N_s\; i}{2\,p\,g''}\cos p\theta$$

$$B(\theta) = \frac{\mu_0\; N_s\; i}{2\,p\,g''}\cos p\theta = \widehat{B_a}\;\cos p\theta$$

Armature reaction flux per pole,

$$\varphi_a = \frac{\widehat{B_a}\,D\,l}{p}$$

$$Flux\ linkage,\qquad \Psi_a = \frac{\pi}{4}\,N_s\;\varphi_a$$

$$self\ inductance,\qquad \boxed{\boldsymbol{L_a = \frac{\pi\,\mu_0\,N_s{}^2\,l\,r_1}{4\;p^2\;g''}}\ \ Henry}$$

<u>***Synchronous reactance:***</u>

6. Write short notes on synchronous reactance in PMSM. May-2017, 2015
Derive an expression for synchronous reactance of PMSM. Dec-2015

- 3-phase sine distributed windings carry 3-phase balanced sinusoidal current.

$$ampere\ conductor\ distribution, \quad = \frac{3}{2}\;I\sqrt{2}\;\frac{N_s}{2}\sin(p\theta - \omega t)$$

$$rotating\ flux = \widehat{B_a}\;\sin(p\theta - \omega t)$$

$$where, \qquad \widehat{B_a} = \frac{\mu_0\;N_s}{2\,p\,g''}\;x\;\frac{3}{2}\;I\sqrt{2}$$

$synchronous\ reactance,\qquad \boxed{X_s = \dfrac{3\,\pi\,\mu_0\,N_s^{\,2}\,l\,r_1\,\omega}{8\;p^2\;g''}\quad ohms}$

Sinewave motor with practical windings:

7. Discuss about the sinewave motor with practical windings.

- Expressions developed for torque, emf, inductance and reactance can be modified for practical windings by means of fourier analysis and harmonic winding factors.
- For AC machines, operation is dominated by the fundamental space-harmonic components of the conductor and flux distributions.
- Consider the concentrated two-pole full-pitched coil with one slot per pole per phase and N conductors in each slot.

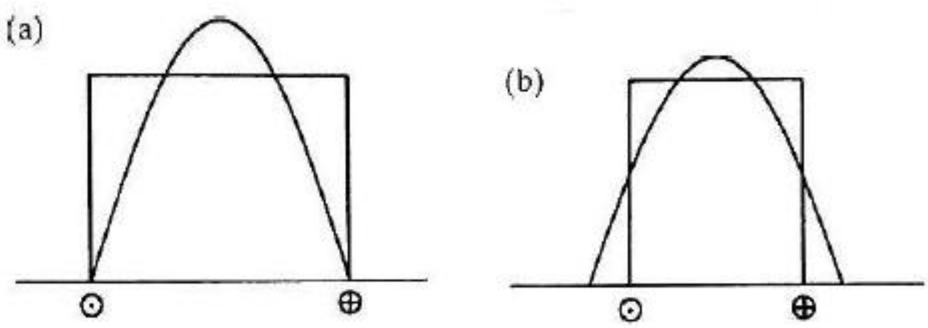


Fig. Distribution and fundamental harmonic component of single full-pitched coil

Winding is considered to have N/2 turns per pole.

For rectangular mmf wave,

$$Fundamental\ harmonic\ component\ =\ \frac{4}{\pi}\ peak\ flat\ topped\ value$$

$$Effective\ number\ of\ sine-distributed\ turns\ per\ pole\ ,$$

$$N_s\ =\ \frac{4}{\pi}\ N$$

There are p pole-pairs in series.

$$turns\ per\ phase,\qquad N_{ph}\ =\ 2\,p\,N$$

$$N_s\ =\ \frac{4}{\pi}\ N_{ph}$$

For a distributed full-pitch winding with q slots per pole per phase,

$$N_s = \frac{4}{\pi} k_{d1} \ N_{ph}$$

k_{d1} – distribution factor or spread factor

$$k_{d1} = \frac{\sin \frac{q\gamma}{2}}{q \sin \frac{\gamma}{2}}$$

Where, γ – slot pitch

q – number of slots per pole per phase.

For chorded or short pitched coils,

k_{p1} – pitch factor or chording factor

$$k_{p1} = \cos \frac{\varepsilon}{2}$$

For skewed windings,

k_{s1} – skew factor

$$k_{s1} = \frac{\sin \sigma}{\sigma}$$

When coil is distributed, chorded and skewed,

$$fundamental\ winding\ factor, \quad k_{w1} = k_{d1}\, k_{p1}\, k_{p1}$$

Number of effective sine-distributed turns per phase,

$$N_s = \frac{4}{\pi} k_{w1} N_{ph}$$

$$open\ circuit\ phase\ emf\ , \quad E_{ph} = \frac{2\,\pi}{\sqrt{2}} \ k_{w1} N_{ph}\, \varphi_{m1} \ f \ V_{rms}$$

$$T = \frac{3\,p}{\omega} E_q \, I \sin\beta \qquad N\,m$$

$$X_{sg} = \frac{6\,\mu_0\, D\, l\, f}{p^2\, g''} \left(k_{w1}\, N_{ph}\right)^2 \ \ ohms$$

$$X_s = X_{sg} + X_\sigma$$

Phasor diagram:

8. Draw and explain about the phasor diagram of PMSM.

With the help of phasor diagram derive an expression for torque in a permanent magnet synchronous motor.

Derive the torque equation of PMSM along with phasor diagram. Dec-2016

Describe the construction of phasor diagram of surface-magnet sine wave motor. May-2018

Derive the expression for power input and torque of a PMSM. Dec-2017

$\vec{V}$ – supply voltage per phase across each phase winding

$\overrightarrow{E_f}$ – emf induced in armature winding per phase due to field flux

$\overrightarrow{E_a}$ – emf induced in armature winding due to resultant armature mmf

$\overrightarrow{E_{al}}$ – emf induced in armature winding due to armature leakage flux

$$\overrightarrow{E_a} = -j\, I_a\, X_a$$

$$\overrightarrow{E_{al}} = -j\, I_a\, X_{al}$$

$$\vec{V} = -\overrightarrow{E_f} + \overrightarrow{I_a}\, R_a - j\,\overrightarrow{I_a}\, X_{al} - j\,\overrightarrow{I_a}\, X_a$$

$$= \overrightarrow{E_q} + \overrightarrow{I_a}\, R_a - j\,\overrightarrow{I_a}\,(X_a + X_{al})$$

$$= \overrightarrow{E_q} + \overrightarrow{I_a}\, R_a - j\,\overrightarrow{I_a}\, X_s \qquad (\because\ X_a + X_{al} = X_s)$$

$$= \overrightarrow{E_q} + \overrightarrow{I_a}\,(R_a - jX_s)$$

$$\boxed{\vec{V} = \overrightarrow{E_q} + \overrightarrow{I_a}\, Z_s}$$

$$P_{in} = 3\,\vec{V}\,\overrightarrow{I_a}$$

$$= 3\left(\overrightarrow{E_q} + \overrightarrow{I_a}\, Z_s\right)\overrightarrow{I_a}$$

$$= 3\left(\overrightarrow{E_q} + \overrightarrow{I_a}\, R_a + j\,\overrightarrow{I_a}\, X_s\right)\overrightarrow{I_a}$$

$$= 3\,\overrightarrow{E_q}\,\overrightarrow{I_a} + 3\,\overrightarrow{I_a}^2\, R_a$$

$$P_{in} = P_m + cu\ loss$$

$$P_m = 3\,\overrightarrow{E_q}\,\overrightarrow{I_a}$$

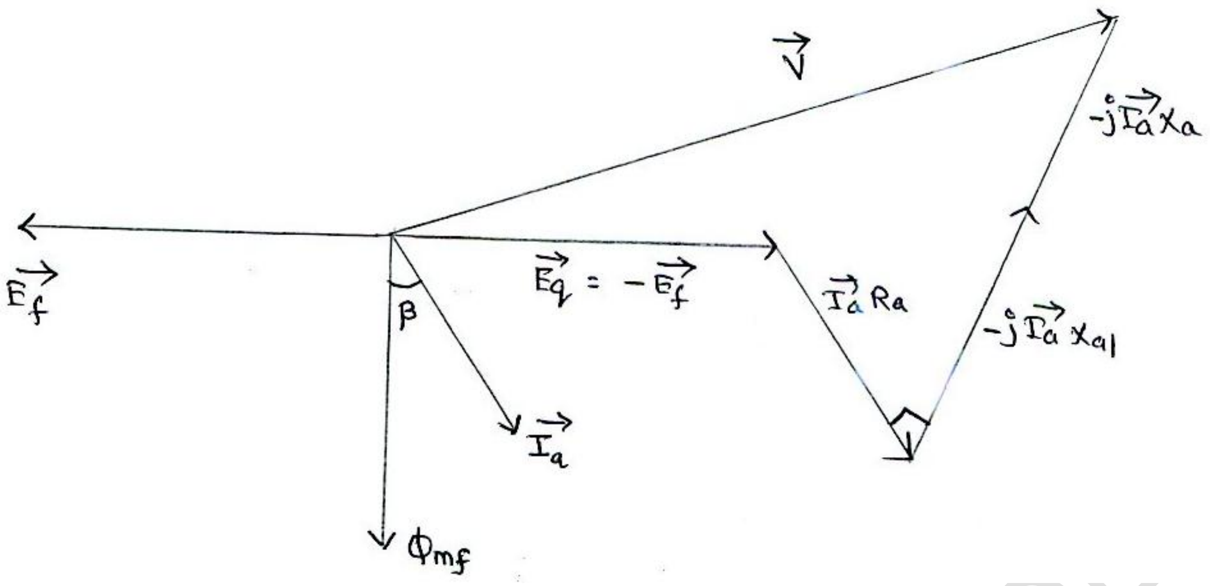


Fig. Phasor diagram for PMSM

$$P_m = 3\left|E_q\right| \; I_a \; \cos(90-\beta)$$

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

$$P_m = 3\left|E_f\right| I\sin\beta$$

$$P_m = \omega_m\,T$$

$$T = \frac{P_m}{\omega_m}$$

$$\boldsymbol{T = \frac{3\,E_q\,I\sin\beta}{\omega_m}\;N\,m}$$

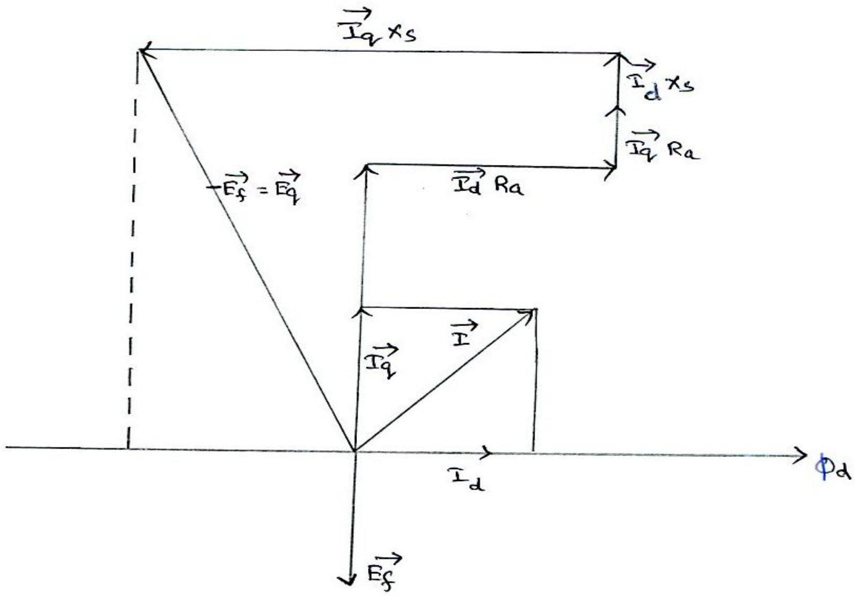


Fig. Phasor diagram with φ_d as reference axis

Torque - Speed Characteristics:

9. Explain the torque- speed characteristics of PMBL SNW or PMSM motor.
May-2018, 2016, 2014, 2013, 2012, Dec-2017, 2016, 2014, 2011

- For given V_C, I_C (maximum permissible voltage and current) torque remains constant from low frequency to corner frequency f_0.
- Above corner frequency f_0 , torque decreases.

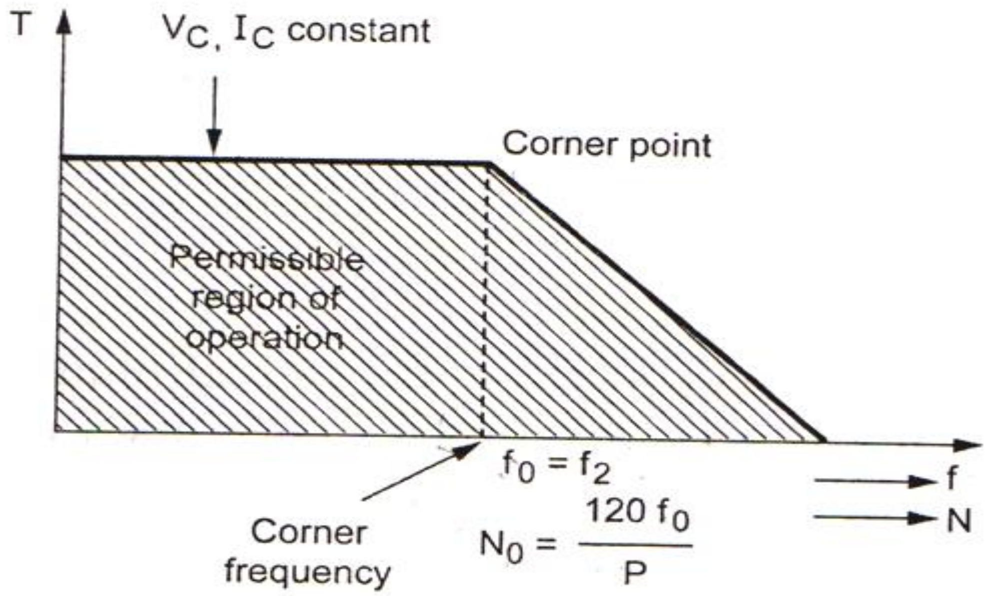


Fig. Torque-speed characteristics

Controllers for PMSM:

- Used in variable speed drives.
- Low and medium power applications.
- Speed depends on frequency of inverter.
- Different control schemes used are:
    - ❖ Vector control
    - ❖ Self control
    - ❖ Microprocessor based control
    - ❖ Power controller (or) current control scheme

Vector control:

10. Explain about the vector control of permanent magnet synchronous motor with a neat diagram.
Dec-2012, 2011

- Based on decoupling theory.
- Flux and torque are decoupled.
- Armature mmf and field mmf are made quadrature in all operating conditions.

From low speed to corner point speed:

- Direct axis component, I_d =0.
- Quadrature axis component, I_q exists.
- Control is achieved by inverter output voltage by adjusting the frequency.
- PWM is used usually.

Above corner point speed:

- I_d is minimum and voltage constraint is satisfied.

Principle of vector control:

- Balanced three-phase voltage obtained from inverter is fed to the stator of PMSM.
- Armature phase currents are given by,

$$i_{Rs} = i_s \sin(\omega_r t + \beta)$$

$$i_{Ys} = i_s \sin\left(\omega_r t + \beta - \frac{2\pi}{3}\right)$$

$$i_{Bs} = i_s \sin\left(\omega_r t + \beta - \frac{4\pi}{3}\right)$$

- Stator current in rotor reference frame is,

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t - \frac{2\pi}{3}\right) & \cos\left(\omega_r t - \frac{4\pi}{3}\right) \\ \sin\omega_r t & \sin\left(\omega_r t - \frac{2\pi}{3}\right) & \sin\left(\omega_r t - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{Rs} \\ i_{Ys} \\ i_{Bs} \end{bmatrix}$$

- Substituting the armature phase currents in the above equations, rotor reference currents are obtained as,

$$i_{qs}^r = i_s \sin\beta$$

$$i_{ds}^r = i_s \cos\beta$$

- Current i_{qs}^r - equivalent to armature current of separately excited DC motor.
- Current i_{ds}^r - equivalent to part of field current.
- Current i_{fm} - another part of field current produced by permanent magnet.

Flux linkage of the stator in the rotor reference frame is,

$$\Psi_{qs}^r = L_{qs}\, i_{qs}^r$$
$$\Psi_{ds}^r = L_{ds}\, i_{ds}^r + L_m\, i_{fm}$$

$$Electromagnetic\ torque\ , \quad \boxed{T = \frac{3}{2}\frac{P}{2}\left[\Psi_{ds}^r\, i_{qs}^r - \Psi_{qs}^r\, i_{ds}^r\right]}$$

Or

$$T = \frac{3}{2}\frac{P}{2}\left[\left(L_d - L_q\right) i_{qs}^r \; i_{ds}^r + L_m \, i_{fm}\right]$$

For operating point on q-axis,

$$i_{ds}^r = 0, \qquad \beta = 90°$$

$$T = \frac{3}{2}\frac{P}{2} \; L_m \, i_{fm} \, i_s$$

$$T = k_1 \, L_m \, i_{fm} \, i_s$$

Torque producing component is $i_T = i_{qs}^r$

Flux producing component is $i_f = i_{ds}^r$

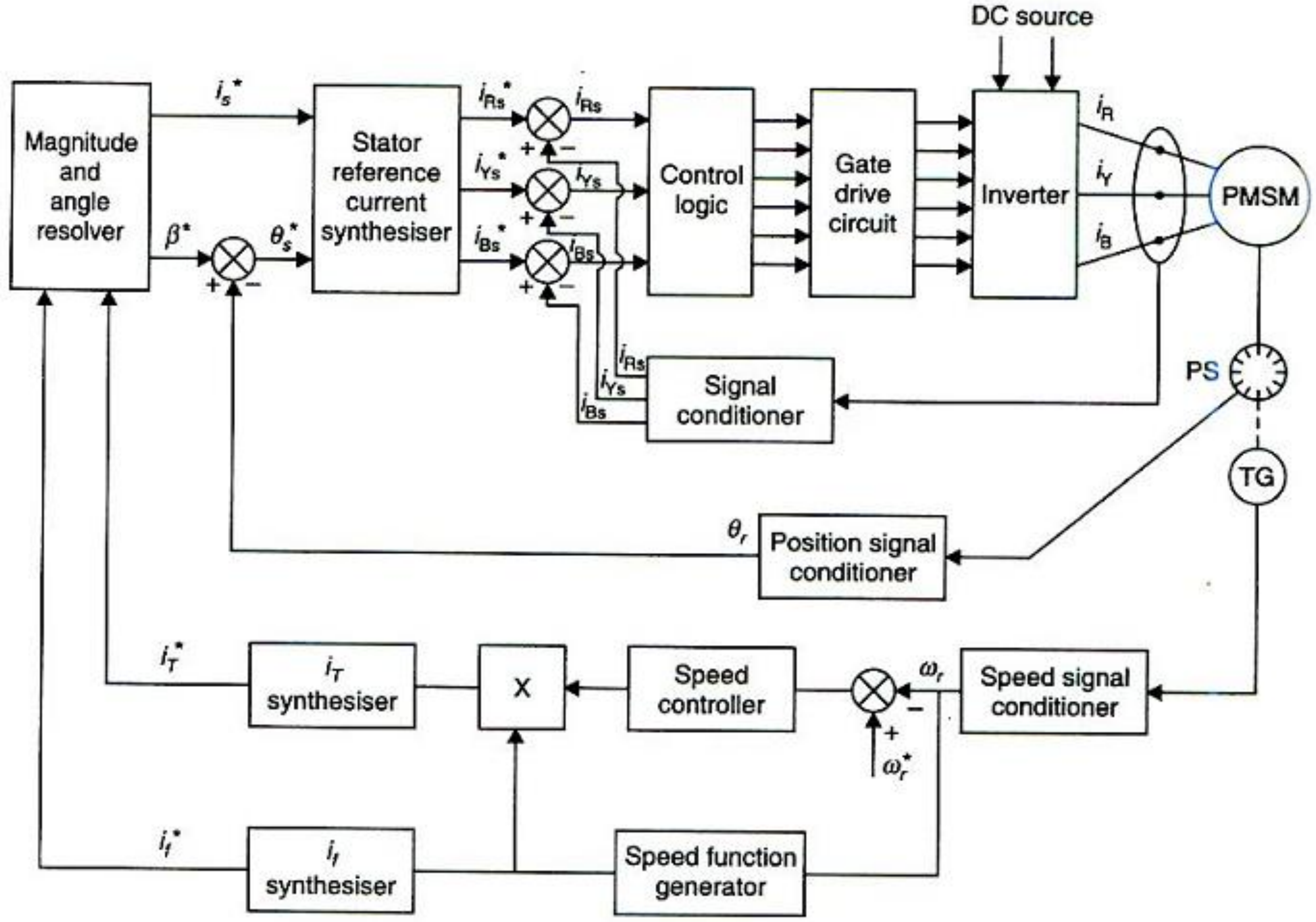


Fig. Vector control of PMSM

- Rotor position is sensed by an optical sensor.
- Speed feedback is obtained by tacho generator.
- Actual speed and reference speed are compared.
- Speed controller is used to get fast speed response.
- **Below corner speed point:**
  - ✓ Output of speed controller is used as reference torque, T*.
  - ✓ T* divided by $k_1 \, i_{fm} \, L_m$ gives i_T*.

- **Above corner speed point:**
  - ✓ Function of speed error and actual speed is used as reference torque, T*.
  - ✓ Field weakening block is needed for finding i_T*.
- Using i_T* and i_f*, reference stator current i_s* and torque angle signal β* are generated.
- Form, the above signals, reference stator current is obtained.
- Comparing the reference and actual stator current signals, gating signals for the inverter are produced.

Self control:

11. Explain about the self control of permanent magnet synchronous motor with a neat diagram.

Principle of self control:

- Uses two converters namely source side converter and load side converter.
- **Source side converter:**
  - ✓ Firing angle – α_s.
  - ✓ $0 \leq \alpha_s \leq 90^\circ$ - line commutated rectifier, + V_{ds}, + I_d
  - ✓ $90^\circ \leq \alpha_s \leq 180^\circ$ - line commutated inverter, - V_{ds}, + I_d
- **Load side converter:**
  - ✓ Firing angle – α_l.
  - ✓ $90^\circ \leq \alpha_l \leq 180^\circ$ - line commutated inverter, - V_{dl}, + I_d
  - ✓ $0 \leq \alpha_l \leq 90^\circ$ - line commutated rectifier, + V_{dl}, + I_d
- **For $0 \leq \alpha_s \leq 90^\circ$ & $90^\circ \leq \alpha_l \leq 180^\circ$, $V_{ds} > V_{dl}$,**
  - ✓ Source side converter – rectifier
  - ✓ Load side converter – inverter
  - ✓ Power flow from AC source to motor.
  - ✓ Motoring action takes place.
- **For $90^\circ \leq \alpha_s \leq 180^\circ$ & $0 \leq \alpha_l \leq 90^\circ$,**
  - ✓ Source side converter – inverter
  - ✓ Load side converter – rectifier
  - ✓ Power flow from motor to AC source.
  - ✓ Regenerative braking action takes place.
- Speed can be changed by controlling the line side converter firing angles.
- At all operating points, armature and rotor fields move at the same speed.

- Consists of outer speed loop & inner current loop.
- Rotor position is sensed by rotor position sensor.
- Speed feedback is obtained by tacho generator.
- Using the rotor position signal, firing pulses for the load side converter is generated.

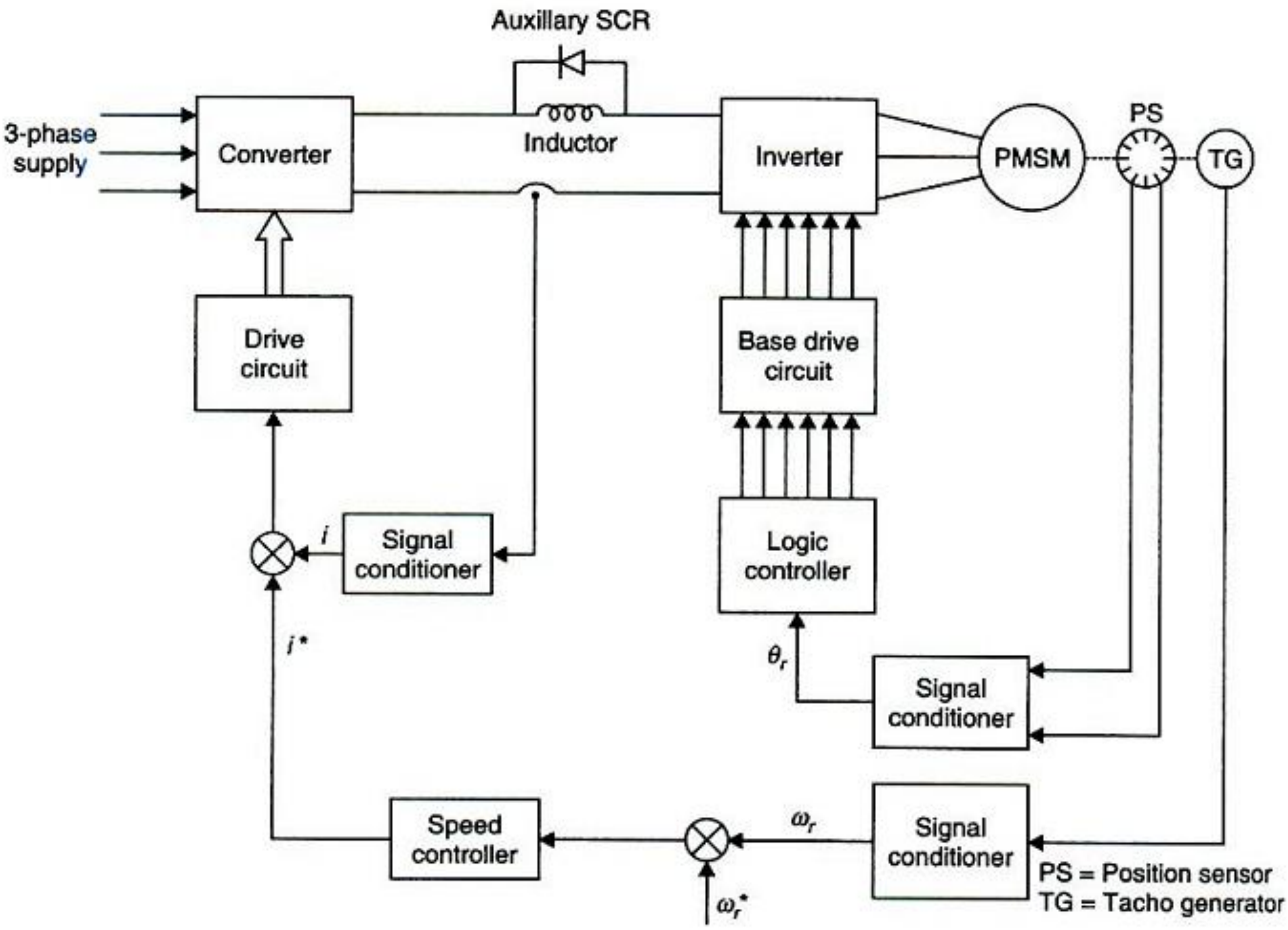


Fig. Self control of PMSM

- From the reference speed and actual speed, speed error is generated.
- Speed error signal is fed to speed controller which produces reference current.
- Actual current and reference current are compared to produce the gating signals for the source side converter.
- Based on the speed error value, converters are operated as rectifier or inverter.
- By operating the converter in proper operating region (rectifier or inverter) self control mode is achieved.
- Self control mode can also be achieved using induced emf.

<u>Microprocessor based control:</u>

12. Explain the Microprocessor based control of Permanent Magnet Synchronous Motor.

May-2014, Dec-2012

- Replaces the conventional hardware control.
- Control algorithm can easily be alerted or improved without changing the hardware.
- Simplification of hardware saves control electronic cost and improves the system reliability.

- Uses controlled rectifier and inverter.
- Balanced three-phase voltage is converted to DC voltage by thyristor converter.
- DC voltage is converted to AC by using inverter.
- Motor operation is made self synchronous by the addition of a rotor position sensor.

- Position sensor controls the firing signals of solid state inverters.

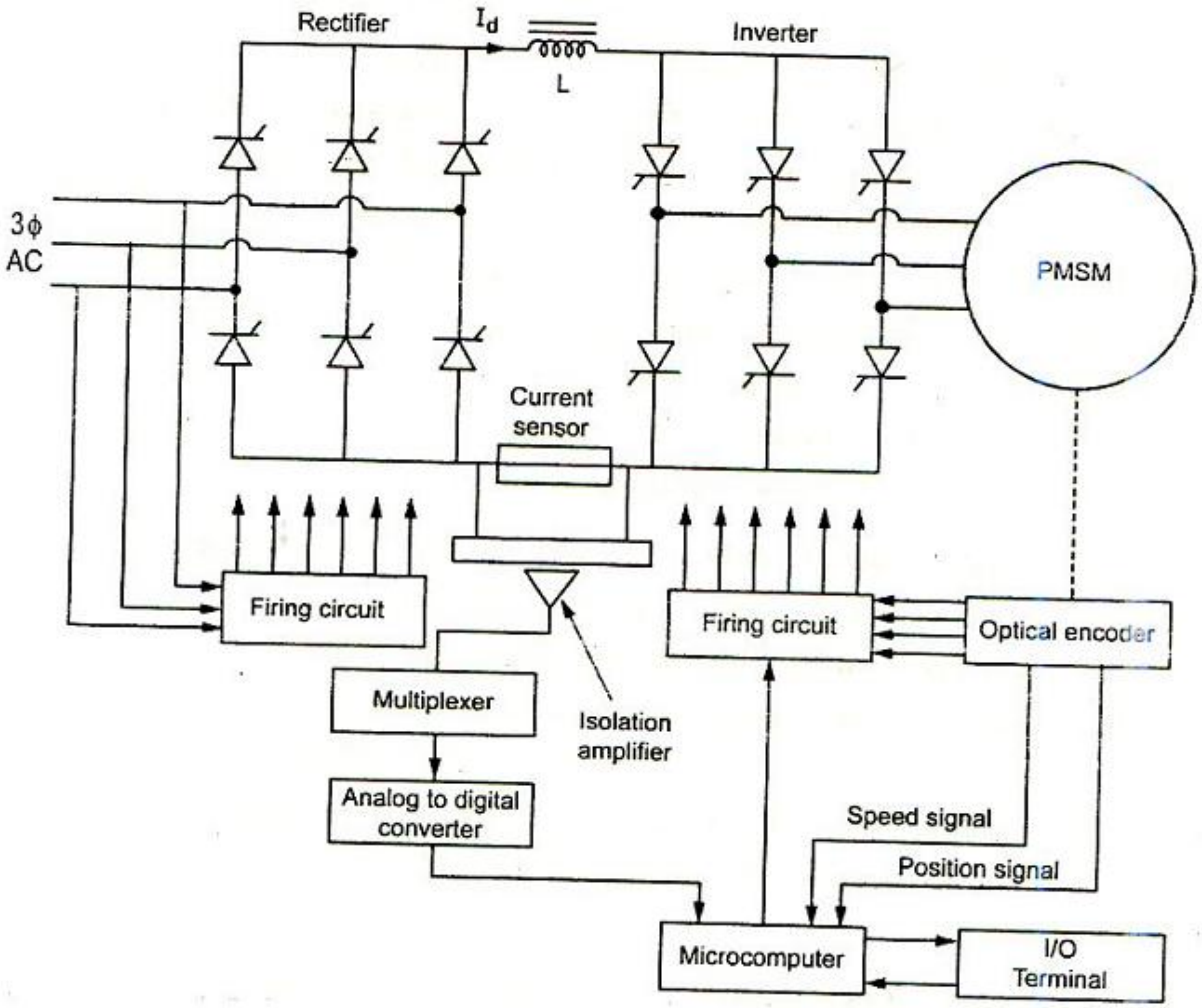


Fig. Microprocessor based control of PMSM

- Phase current is sinusoidal function of rotor position.
- So, absolute encoder or resolver or other high resolution sensor is necessary to obtain position information with the required resolution.
- Rotor position information requires at least 9 or 10 bit resolution.
- Microprocessor gets speed, position, actual current signals and the signal from I/O terminal.
- Based on the various control signals, microprocessor gives control signal to the rectifier and inverters to get the desired motor performance.

Power controllers:

13. Explain briefly power controller of PMSM.

Draw and discuss the various power controllers used in PMSM with neat diagram. **May-2017, 2015**

Explain the power controllers used in PMSM. **Dec-2015**

- PMSM is fed directly from a three-phase supply.
- When the armature winding draws a current, the current distribution in the stator winding depends on,
  - ✓ Rotor position
  - ✓ Turning on process of the devices in control circuit.
- For maximum torque, angle between the stator flux and rotor flux is kept close to 90°.
- Hence motor requires electronic control for proper operation.

- The armature supply frequency is changed in proportion to the changes in rotor speed.
- So, stator field always moves at the same speed as the rotor.
- Rotor position sensor is required for accurate tracking of the speed.

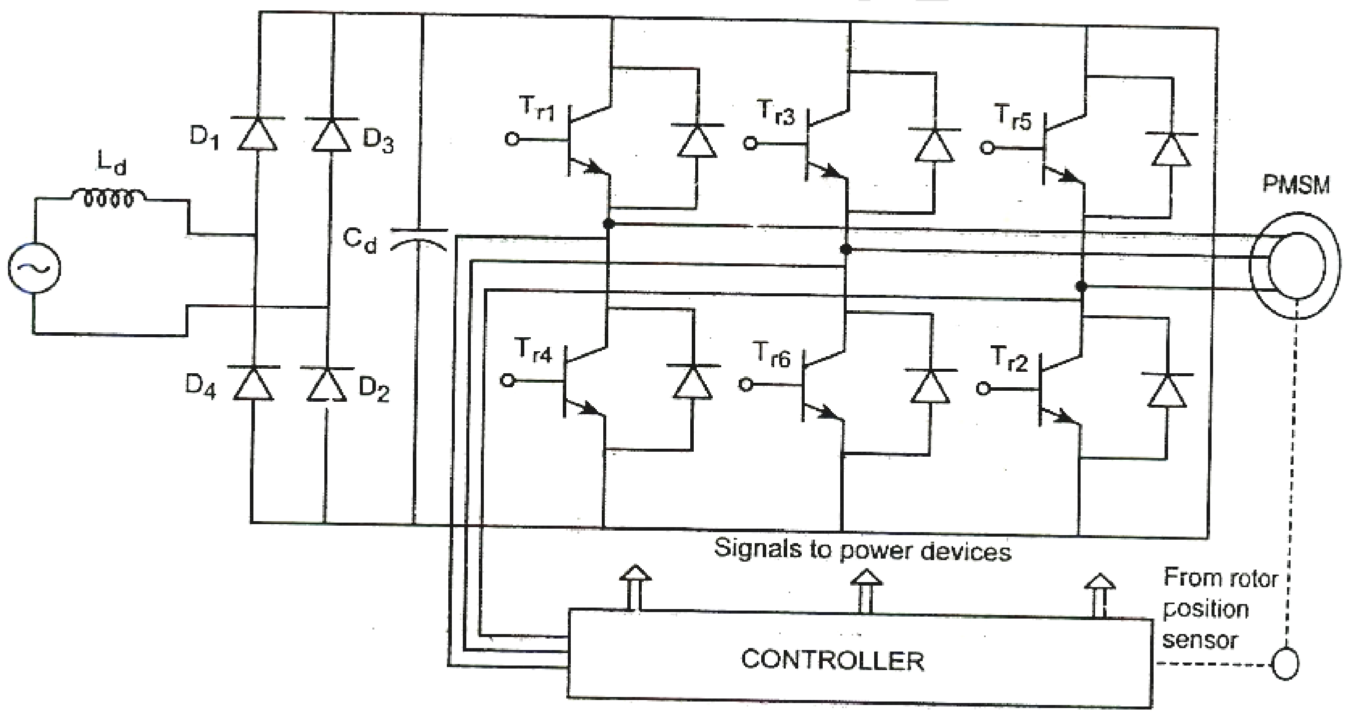


Fig. Power controller for PMSM

- Torque is related with the d-axis & q-axis currents.
- To achieve the maximum torque/current ratio, I_d = 0, so torque is proportional only to the q-axis current.
- Drive system consists of PMSM, power electronic devices, converter, sensors & controller.

- PWM current control is used to regulate the actual machine current.
- Hysteresis current controller or PI controller with sinusoidal triangle or SVPWM strategies is employed.

Converter Volt-Ampere requirement:

14. Write short notes on converter Volt-ampere requirements in PMSM motor.

May-2016, 2014, 2013, 2012

- Volt-amperes per watt of shaft power are sinewave values and represent the total apparent power at the motor terminals.
- Volt-amperes per watt can also be represented in terms of the volt-ampere product required in the ratings of the semiconductor devices in the converter.

Example:

- Consider a two-phase motor and it assume that each phase was supplied by a full bridge circuit, requiring a total of eight transistors.
- The nominal converter volt-amperes, based on rms current in each device times peak voltage times the number of devices.

$$V\sqrt{2}\ x\ 8\ x\left(\frac{I}{\sqrt{2}}\right) = 8\,VI$$

- Same results are obtained, if a single full bridge was used to supply both windings connected in a centre-tap arrangement.
- With a three-phase bridge converter the number of devices per phase is only two.
- Consequently the total device volt-ampere requirement is only 6 VI.

- With a nominal AC supply, apparent power requirement of about 1.1 VA/W, is raised to 1.2 to allow for core losses and friction.
- With respect to RMS current in each switch, if ‘q’ is the phase number,

rms KVA / KW = 2q x I_s x V_s

I_s - rms current in each switch

V_s - peak voltage across each switch.

For a sinewave motor,

$$Peak\ line - line\ voltage\ of\ motor = V = \sqrt{3}\ \widehat{V_{ph}}$$

$$rms\ switch\ VA = 6\,V\,x\ \frac{I}{\sqrt{2}}$$

$$peak\ switch\ VA = 6\,V\ \hat{I}$$

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

Applications:

- Direct drive traction
- Compressors and blowers
- Steel rolling mills
- Ship propulsion
- Fans and pumps

Anna University Questions

Part – A

1. State the important features of permanent magnet synchronous motor. May-2018
2. What are the types of materials used in permanent magnet motor? May-2017
3. What are the types of PM synchronous motor? Dec-2017

    Classify the different types of PMSM. Dec-2016
4. List out the differences between the PM brushless DC motors and PM synchronous motors. Dec-2015, May-2017

    Differentiate square wave and sine wave motor. Dec-2016
5. Write down the emf equation of PMSM. Dec-2017, 2016, 2013
6. Write down the torque equation of PMSM. Dec-2017, 2016, 2013
7. What is meant by synchronous reactance? May-2016, 2014, 2013
8. Mention the objective of self control. May-2017, Dec-2012
9. Briefly explain the vector control of PMSM. Dec-2014
10. What is meant by slotless motor? May-2014
11. State the types of power controllers for PMSM. May-2018, Dec-2017
12. State the applications of PMSM. May-2014, Dec-2011
13. Write the significance of power controllers of permanent magnet synchronous motors. Dec-2017, 2016, 2013
14. Brief-up the advantages of load commutation in PMSM. Dec-2012
15. Draw the output phasor diagram of PMSM. May-2016, 2014, 2013
16. Write down the expression for the self and synchronous reactance of PMSM. Dec-2011
17. What are the merits of 3-phase Brushless Permanent Magnet Synchronous Motor? Dec-2013
18. Write the drawbacks in PMSM. May-2015
19. Mention the various assumptions in deriving the EMF equation of PMSM. Dec-2014
20. Define the term load angle. May-2015
21. Explain the distribution factor for PMSM. May-2017, Dec-2015

Part – B

1. With neat sketch, explain the constructional features of Permanent Magnet Synchronous Motor (PMSM). May-2014, Dec-2013

    Enumerate the construction and performance of a permanent magnet synchronous motor with diagrams. Dec-2016, 2014

    Describe the construction and performance of PMSM with neat diagram. May-2017

    Explain the construction and performance of a permanent magnet synchronous motor with neat diagram. Dec-2017

2. Explain the operation of PMSM. Dec-2017
   Discuss the current control scheme of PMSM in detail. Dec-2014

3. Derive the EMF equation of an ideal sine wave PM motor.
   Dec-2017, 2016, 2015, 2013, May-2018, 2017, 2016, 2014, 2013

4. Derive the torque equation of an ideal sine wave PM motor.
   Dec-2017, 2016, 2015, 2013, 2012, May-2018, 2017, 2016, 2014, 2013

5. Write short notes on armature reaction in PMSM. May-2017, 2015

6. Write short notes on synchronous reactance in PMSM. May-2017, 2015
   Derive an expression for synchronous reactance of PMSM. Dec-2015

7. Derive the torque equation of PMSM along with phasor diagram. Dec-2016
   Describe the construction of phasor diagram of surface-magnet sine wave motor. May-2018
   Derive the expression for power input and torque of a PMSM. Dec-2017

8. Explain the torque- speed characteristics of PMBL SNW or PMSM motor.
   May-2018, 2016, 2014, 2013, 2012, Dec-2017, 2016, 2014, 2011

9. Explain about the vector control of permanent magnet synchronous motor with a neat diagram. Dec-2012, 2011

10. Explain the Microprocessor based control of Permanent Magnet Synchronous Motor.
    May-2014, Dec-2012

11. Draw and discuss the various power controllers used in PMSM with neat diagram.
    May-2017, 2015
    Explain the power controllers used in PMSM. Dec-2015

12. Write short notes on converter Volt-ampere requirements in PMSM motor.
    May-2016, 2014, 2013, 2012

Reg. No. :

Question Paper Code : 41013

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2018

Seventh Semester

Electrical and Electronics Engineering

EE6703 – SPECIAL ELECTRICAL MACHINES

(Regulations 2013)

Time : Three Hours Maximum : 100 Marks

Answer ALL questions

PART – A (10×2=20 Marks)

1. Mention any two advantages of synchronous reluctance motors.
2. Define 'Reluctance Torque' with reference to synchronous reluctance motor.
3. What are the different modes of excitation in a stepper motor ?
4. What is meant by Lead angle in stepper motors ?
5. What is the need for shaft position sensor for Switched Reluctance Motor ?
6. Draw the speed-torque characteristics of Switched Reluctance Motor.
7. List any four permanent magnet materials.
8. State some important applications of Permanent Magnet Brushless DC Motors.
9. Write the important features of Permanent Magnet Synchronous Motor.
10. State the types of power controllers for Permanent Magnet Synchronous Motor.

PART – B (5×16=80 Marks)

11. a) Explain the constructional details and working principle of synchronous reluctance motor with neat diagrams. (10+6)

(OR)

b) Explain the phasor diagram and characteristics of synchronous reluctance motor. (10+6)

12. a) i) Describe the principle of operation of hybrid stepper motor. (8)

ii) Explain briefly a closed-loop operation system using a microprocessor for a hybrid stepping motor. (8)

(OR)

b) i) Explain the mechanism of static torque production in a variable reluctance stepping motor. (10)

ii) Describe the dynamic characteristics of a variable reluctance stepper motor. (6)

13. a) Draw the cross sectional view of switched reluctance motor and explain the principle of operation. State the advantages of switched reluctance motor. (10+6)

(OR)

b) Draw and explain four converter topologies for a 3-phase SRM. Write the merits and demerits of each topology. (16)

14. a) i) Explain the magnetic circuit analysis of permanent magnet brushless DC motor on open-circuit. (10)

ii) Derive the EMF equation of permanent magnet brush less DC motor. (6)

(OR)

b) i) Draw and explain the general structure of a controller for a permanent magnet brush less DC motor. (8)

ii) Describe the torque/speed curve of the ideal burshless DC motor. (8)

15. a) For an ideal sine wave permanent magnet motor, derive the EMF and Torque equations. (8+8)

(OR)

b) i) Describe the construction of phasor diagram of surface-magnet sine wave motor. (8)

ii) Explain the torque/speed characteristic of sine wave motor. (8)

Reg. No. :

Question Paper Code : 50495

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2017

Seventh Semester

Electrical and Electronics Engineering

EE 6703 – SPECIAL ELECTRICAL MACHINES

(Regulations 2013)

Time : Three Hours Maximum : 100 Marks

Answer ALL questions

PART – A (10×2=20 Marks)

1. Compare synchronous reluctance motor and induction motor.
2. Classify the different types of synchronous reluctance motor.
3. Name the various modes of excitation in stepper motor.
4. Distinguish the half step and full step operations of a stepper motor.
5. Illustrate the different modes of operation of switched reluctance motor.
6. Give the advantages of sensorless operation of switched reluctance motor.
7. What is the principle of operation of PMBLDC motor.
8. Write down the torque equation of PMBLDC motor.
9. What are the types of PMSM ?
10. State the power controllers for PM synchronous machines.

PART – B (5×16=80 Marks)

11. a) i) Discuss in detail about the construction and working of synchronous reluctance motor with neat diagrams. (8)

ii) Draw and explain phasor diagram with characteristics of synchronous reluctance motor. (8)

(OR)

b) Describe the constructional features and operation of variable reluctance synchronous reluctance motor. (16)

12. a) Draw and explain the drive circuits and their performance characteristics for stepper motor. (16)

(OR)

b) With a neat block diagram explain microprocessor control of stepper motor. (16)

13. a) Explain with a neat circuit any two configuration of power converters used for the control of switched reluctance motor. (16)

(OR)

b) Explain with a neat diagram the constructional details and working of rotary switched reluctance motor. (16)

14. a) Discuss in detail about magnetic circuit analysis of PMBLDC motor. Also draw its characteristics. (16)

(OR)

b) Prove that the torque equation in BLDC motor is similar to that of conventional DC motor. (16)

15. a) Derive the expression for power input and torque of a PMSM. Explain how its torque speed characteristics is obtained. (16)

(OR)

b) Explain the construction and working principle of operation of PMSM. (16)

Reg. No. :

Question Paper Code : 52509

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2017
Seventh Semester
Electrical and Electronics Engineering
EE2403 – SPECIAL ELECTRICAL MACHINES
(Regulations 2008)

Time : Three Hours | Maximum : 100 Marks

Answer ALL questions

PART – A (10×2=20 Marks)

1. Give some potential applications of synchronous reluctance machine.
2. Write the various design parameters of a synchronous reluctance motor.
3. Compare single stack and multistack configurations in stepping motors.
4. List the different modes of excitations in stepping motors.
5. Write the torque equation of switched reluctance motor.
6. What is the significance of position sensors used in switched reluctance motor ?
7. Why Brushless Permanent Magnet (BLPM) DC motor is called as electronically commutated motor ?
8. List down some important applications of BLPM DC motor.
9. Write torque and EMF equation of PM synchronous motor.
10. Write the significance of power controllers of permanent magnet synchronous motors.

PART – B (5×16=80 Marks)

11. a) Describe in detail, the speed-torque and torque-angle characteristics of synchronous reluctance motors with phasor diagrams. (16)

(OR)

b) Explain in detail with a neat diagram, the construction and working principle of synchronous reluctance motor. (16)

12. a) Explain with a neat diagram the microprocessor control of stepper motor. (16)

(OR)

b) Explain the working of drive circuits used to drive the stepping motor. (16)

13. a) Describe the construction and working of rotary and linear switched reluctance motor. (16)

(OR)

b) Discuss the following in switched reluctance motor.

i) Methods of Rotor position sensing. (8)

ii) Sensorless operation. (8)

14. a) i) What are the advantages of BLPM DC motor over conventional dc motor ? (4)

ii) Derive the expression for permeance coefficient from the magnetic circuit analysis of permanent magnet brushless DC motor. (12)

(OR)

b) Derive the emf equation and torque equation of PMBL DC motor. (16)

15. a) Explain the construction and performance of a permanent magnet synchronous motor with neat diagram. (16)

(OR)

b) Derive the emf and torque equation of permanent magnet synchronous motor. (16)

Reg. No. : | | | | | | | | | | | | |

Question Paper Code : 73513

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2017.

Seventh Semester

Electrical and Electronics Engineering

EE 2403/EE 73/10133 EEE 25 — SPECIAL ELECTRICAL MACHINES

(Regulations 2008/2010)

(Common to PTEE 2403 – Special Electrical Machines for B.E. (Part-Time) Sixth Semester – EEE – Regulations 2009)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. Give the difference between synchronous reluctance motor and switched reluctance motor.

2. Write the operating principle of radial flux motor.

3. Mention the function of drive circuit in stepping motor.

4. Define step angle in stepping motor.

5. State the reluctance principle.

6. List the characteristics of switched reluctance motor.

7. Distinguish between electronic and mechanical commutators.

8. Draw the magnetic equivalent circuit of PMBLDC motor.

9. Write the distribution factor for PMSM.

10. Compare PM synchronous motor with BLPM DC motor.

PART B — (5 × 16 = 80 marks)

11. (a) Discuss in detail the principle of operation and constructional features of different types of synchronous reluctance motor. (16)

Or

(b) Explain the torque speed characteristics of synchronous reluctance motor in detail. (16)

12. (a) (i) Explain microprocessor based control of stepper motor with an example. (12)

(ii) What are the advantages of closed loop control of stepper motor? (4)

Or

(b) Describe the operation of a variable reluctance type stepper motor with different modes of operation. (16)

13. (a) Describe the construction and working of rotary and linear switched reluctance motors. (16)

Or

(b) Discuss the following in switched reluctance motor.

(i) Methods of Rotor position sensing (8)

(ii) Seasorless operation. (8)

14. (a) Explain the characteristics and control of permanent magnet brushless D.C. Motor. (16)

Or

(b) Describe the magnetic circuit analysis and derive the EMF and torque equations of permanent magnet brushless D.C. motor. (8 + 8)

15. (a) Write short technical note on :

(i) Armature reaction in PMSM (8)

(ii) Synchronous Reactance. (8)

Or

(b) Draw and discuss the various power controllers used in PMSM with neat diagram. (16)

Reg. No. : | | | | | | | | | | | | |

Question Paper Code : 71786

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2017.

Seventh Semester

Electrical and Electronics Engineering

EE 6703 — SPECIAL ELECTRICAL MACHINES

(Regulations 2013)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. What are the types of rotor available in synchronous reluctance motor?

2. What are the applications of synchronous reluctance motor?

3. Draw the equivalent circuit of winding in stepper motor.

4. What are the applications of stepper motor?

5. Define energy ratio.

6. Draw the Torque — Speed characteristics of SRM.

7. What is electronic commutator?

8. Write the EMF equation of a P.M. Brushless D.C Motor?

9. What are the types of materials used in permanent magnet motor?

10. What is self control in PMSM?

PART B — (5 × 16 = 80 marks)

11. (a) Explain the working principle and construction details of different types of Synchronous reluctance motor. (16)

Or

(b) (i) Derive the torque equation of a Synchronous Reluctance motor and draw the Torque- Angle characteristic. (8)

(ii) Derive the expression for d-axis synchronous reactance of a permanent magnet Synchronous reluctance motor. (8)

12. (a) Describe construction and working of variable reluctance stepper motor with neat diagram. (16)

Or

(b) (i) Explain in detail the power driver circuits of stepper motor. (10)

(ii) Write in detail the microprocessor based closed loop operation of stepper motor. (6)

13. (a) (i) Explain in detail the power controllers for switched reluctance motor. (10)

(ii) Explain the role of microprocessors in control of switched reluctance motor.

Or

(b) (i) Describe the construction and working principle of SRM. (12)

(ii) What are the applications and advantages of SRM? (4)

14. (a) Derive the emf and torque equation of a Brushless permanent magnet square wave motor. (16)

Or

(b) Explain the construction of PMBLDC motor also compare conventional dc motor and PMBLDC motor. (16)

15. (a) Describe the construction and performance of PMSM with neat diagram. (16)

Or

(b) Derive the emf and torque equation of a Brushless permanent magnet since wave DC motor. (16)

Reg. No. : [ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ]

Question Paper Code : 80387

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2016.

Seventh Semester

Electrical and Electronics Engineering

EE 6703 — SPECIAL ELECTRICAL MACHINES

(Regulations 2013)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. What is meant by reluctance torque in synchronous reluctance motor?

2. Write down the applications of synchronous reluctance motor.

3. Define lead angle.

4. What is the need of suppressor circuits in stepper motor?

5. What is the need of a rotor positioning sensor in Switched Reluctance Motor?

6. Write any four applications of SRM.

7. What are the merits of the brushless dc motor drives?

8. Write the difference between electronic and mechanical commutator.

9. Classify the different types of PMSM.

10. Differentiate square wave and sine wave motor.

PART B — ($5 \times 16 = 80$ marks)

11. (a) Explain with neat diagram, the construction, working principle and types of synchronous reluctance motor. (16)

Or

(b) Draw the steady state phasor diagram of synchronous reluctance motor and derive the expression for torque of synchronous reluctance motor. (16)

12. (a) (i) Explain in detail the multi stack construction of stepper motor. (8)

(ii) Explain the modes of excitation of a stepper motor with neat diagram. (8)

Or

(b) (i) A stepper motor has resolution of 180 steps/rev. Find the pulse rate required in order to obtain a rotor speed of 2400 rpm. (8)

(ii) Explain in detail, the static and dynamic characteristics of a stepper motor. (8)

13. (a) (i) Explain with neat diagram, the microprocessor based control of Switched reluctance motor. (10)

(ii) Derive the expression for static torque in SRM. (6)

Or

(b) (i) Explain with the neat diagram any two converter topologies for SRM. (8)

(ii) Explain the torque speed characteristics of SRM in detail. (8)

14. (a) Explain the construction and principle of operation of PMBLDC motor. (16)

Or

(b) (i) Explain in detail, the power controllers for PMBLDC. (8)

(ii) A BLPM motor has a no load speed of 6000 rpm when connected to a 120 V DC supply. The armature resistance is 2 Ω. Rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60 V and the torque is 0.5 N-m. (8)

15. (a) Derive the Torque equation of PMSM along with the phasor diagram. (16)

Or

(b) (i) Derive the EMF equation of PMSM. (10)

(ii) Explain the torque speed characteristics of PMSM. (6)

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Reg. No. : | | | | | | | | | | | | |

Question Paper Code : 60517

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2016.

Seventh Semester

Electrical and Electronics Engineering

EE 2403/EE 73/10133 EEE 25 — SPECIAL ELECTRICAL MACHINES

(Regulations 2008/2010)

(Common to PTEE 2403 – Special Electrical Machines for B.E. (Part-Time) Sixth Semester – EEE – Regulations 2009)

Time : Three hours — Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. List the types of synchronous reluctance motors.

2. Give the difference between synchronous reluctance motor and switched reluctance motor.

3. Define the micro stepping mode of Stepper motor.

4. Name the various driver circuits used in stepper motor.

5. Enumerate the different power controllers used for the control of SRM.

6. Mention the different modes of operation of switched reluctance motor.

7. What is permeance coefficient?

8. Name the power controllers used in permanent magnet brushless D.C. motor.

9. Write torque and EMF equation of PM synchronous motor.

10. Write the significance of power controllers of permanent magnet synchronous motors.

PART B — (5 × 16 = 80 marks)

11. (a) (i) Draw the phasor diagram of synchronous reluctance motor. (4)

(ii) Explain the construction of radial and axial flux machines. Discuss the advantages and disadvantages of each construction. (12)

Or

(b) Explain in detail, the operating principle and construction of synchronous reluctance motor with neat diagram. Derive the torque equation of synchronous reluctance motor. (16)

12. (a) With a neat block diagram, explain the microprocessor control of stepping motor. (16)

Or

(b) Explain the working of single and multistack configured stepping motors. (16)

13. (a) Describe the constructional features of Rotary and Linear switched reluctance motors. (16)

Or

(b) Explain the closed loop control of SRM using sensorless operation. (16)

14. (a) Discuss the hysteresis type current regulation of PMBLDC motor with neat diagram. (16)

Or

(b) Analyze the operation of electronic commutator in PMBLDC motor with neat diagram. (16)

15. (a) Explain the construction and performance of a permanent magnet synchronous motor with neat diagram. (16)

Or

(b) Derive the emf and torque equation of permanent magnet synchronous motor. (16)

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Reg. No. | | | | | | | | | | | | |

Question Paper Code : 51517

B.E./ B.Tech. DEGREE EXAMINATION, MAY/JUNE 2016

Seventh Semester

Electrical and Electronics Engineering

EE 2403/EE 73/10133 EEE 25– SPECIAL ELECTRICAL MACHINES

(Regulations 2008/2010)

(Common to PTEE 2403/10133 EEE 25 – Special Electrical Machines for B.E (Part-Time) Sixth/Seventh Semester- EEE-Regulations 2009/2010)

Time : Three Hours **Maximum : 100 Marks**

Answer ALL questions.

PART – A (10 × 2 = 20 Marks)

1. List the applications of synchronous reluctance motors.
2. Draw the voltage and torque characteristics of Synchronous reluctance motor.
3. Name the various driver circuits used in stepped motor.
4. Define : Stepping angle
5. What is the significance of closed loop control in switched reluctance motor ?
6. List out the advantages of switched reluctance motors.
7. Why Brushless Permanent Magnet (BLPM) DC motor is called as electronically commutated motor ?
8. List down some important applications of BLPM DC motor.
9. Define synchronous reactance in PMSM.
10. Draw the output phasor diagram of PMSM

PART – B (5 × 16 = 80 Marks)

11. (a) Explain the construction and operation of Axial and Radial flux motors with neat diagram. **(16)**

OR

(b) (i) Derive the expression for the torque equation for the synchronous reluctance motor. **(8)**

(ii) Investigate the performance of the synchronous reluctance motor with neat phasor diagram. **(8)**

12. (a) Construct and evaluate the operation of single stack and multi-stack stepper motor with a neat diagram. **(16)**

OR

(b) Compare the static and dynamic characteristics of stepper motor with necessary diagrams. **(16)**

13. (a) Explain with a neat diagram the constructional details and operation of rotary switched reluctance motors. **(16)**

OR

(b) (i) Explain with a neat circuit any two configurations of power converters used for the control of switched reluctance motor. **(12)**

(ii) State the advantages of sensorless operation. **(4)**

14. (a) (i) Discuss the construction of a permanent magnet dc motor. **(8)**

(ii) A permanent magnet DC commutator motor has a no-load speed of 600 rpm when connected to a 120 C Supply. The armature resistance is 2.5 Ω and rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60 V and the torque is 0.5 Nm. **(8)**

OR

(b) (i) Explain the speed torque characteristics of PMDC motor. **(8)**

(ii) A PMBLDC motor has torque constant 0.12 Nm/A referred to DC supply. Find the motor's no-load speed when connected to 48 V DC supply. Find the stall current and stall torque if armature resistance is 0.15 Ω/ phase and drop in controller transistor is 2 V. **(8)**

15. (a) Write short notes on :

(i) Volt-ampere requirements in PMSM Motor. **(8)**

(ii) Torque/speed characteristics in PMSM Motor. **(8)**

OR

(b) Derive EMF and torque equations of permanent magnet synchronous motor. **(16)**