Industrial Drives and Applications-BEE702

Module-5

Synchronous Motors cntd
Stepper Motor Drives
Industrial Drives

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Synchronous Motor Drives (continued):

Self-controlled synchronous motor drive employing load commutated thryrister inverter,

Starting Large Synchronous Machines,

Permanent Magnet ac (PMAC) Motor Drives,

Sinusoidal PMAC Motor Drives, Brushless dc Motor Drives.

Stepper Motor Drives:

Variable Reluctance

Permanent Magnet

Important Features of Stepper Motors,

Torque Versus Stepping rate Characteristics,

Drive Circuits for Stepper Motor.

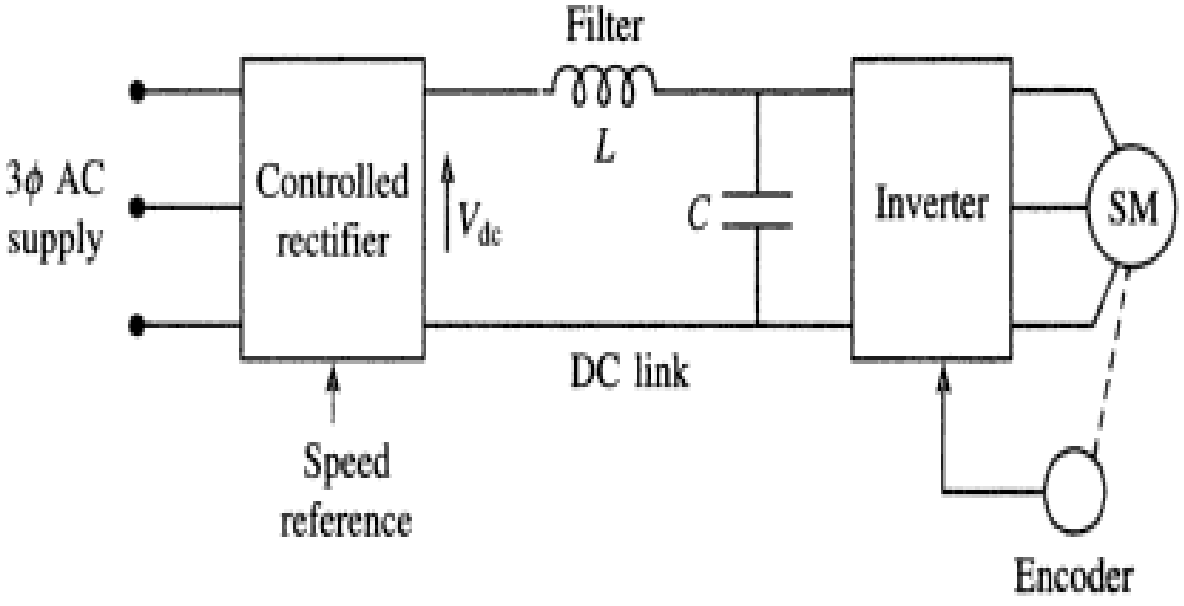
Industrial Drives:

Textile Mills, Steel Rolling Mills, Cranes and Hoists, Machine Tools

- https://www.youtube.com/watch?v=if-9_XzANYw&t=361s
- https://www.youtube.com/watch?v=RELKvoKkIvE&t=672s

Self Controlled Synchronous Motor

- The block diagram of a self controlled motor fed from a 3 phase inverter is shown in below Fig.
- The inverter may be a CSI or VSI. Depending on the type of inverter, the input dc source may be a controllable current source or controllable voltage source
  - The inverter output frequency is determined by the rotor speed.
  - The accurate speed of the rotor is tracked by using rotor position sensors, where the switching devices operate to turn the stator windings ON and OFF. The switches are fired at a frequency proportional to the motor speed.



Self Controlled Synchronous Motor

- With the increase of load if the rotor slows down, then the stator supply frequency automatically changes so that the rotor remains synchronized with the rotating field.
- When the motor starts from rest, the motor current will be large at first and then will decrease with increase of speed.
- The speed of the motor is controlled by varying the dc link voltage to the inverter, by varying the firing pulses of the controlled rectifier.
- Four quadrant operation is possible if the inverter is fed from a full converter.

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Self-controlled synchronous motor drive employing load commutated thyristor inverter

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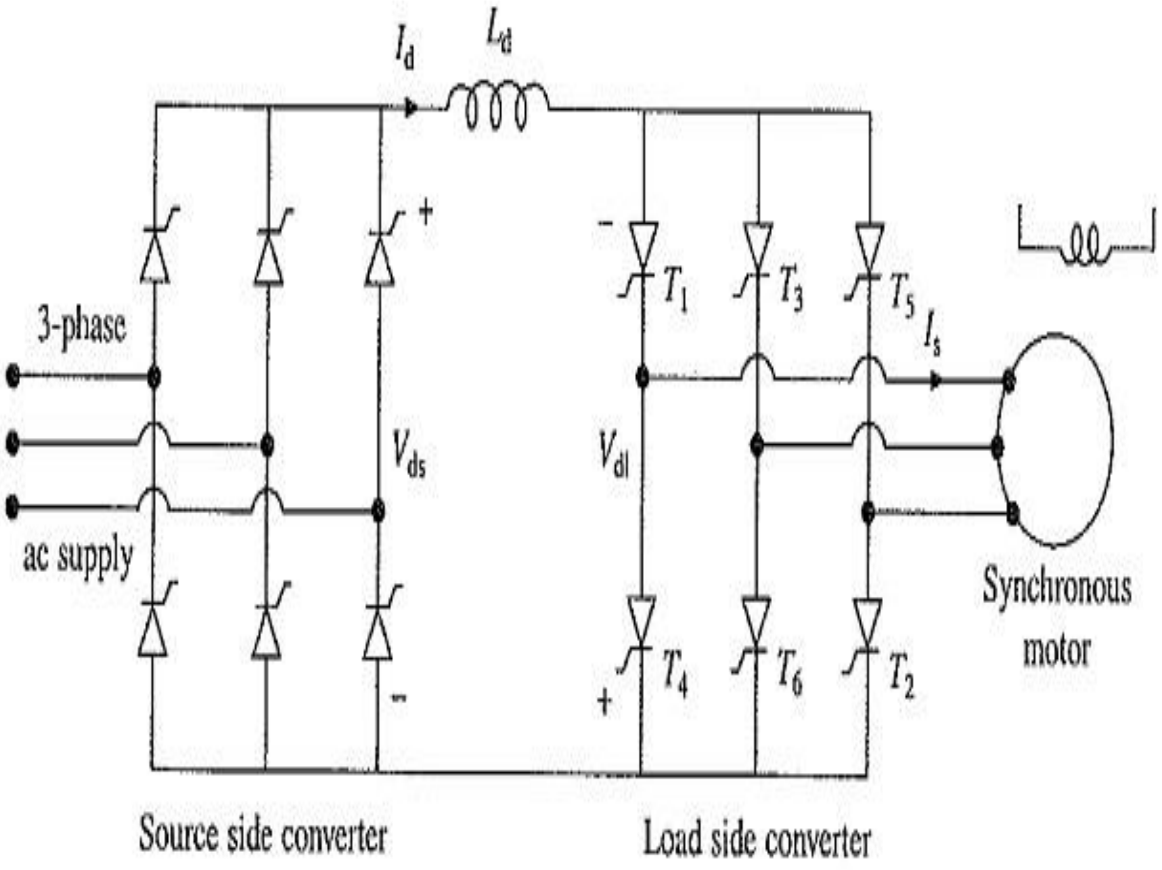
A Self Controlled Synchronous Motor Drive employing a load commutated thyristor inverter is shown in Fig.

The drive employs two converters.

1. **Source side converter**
2. **Load side converter**

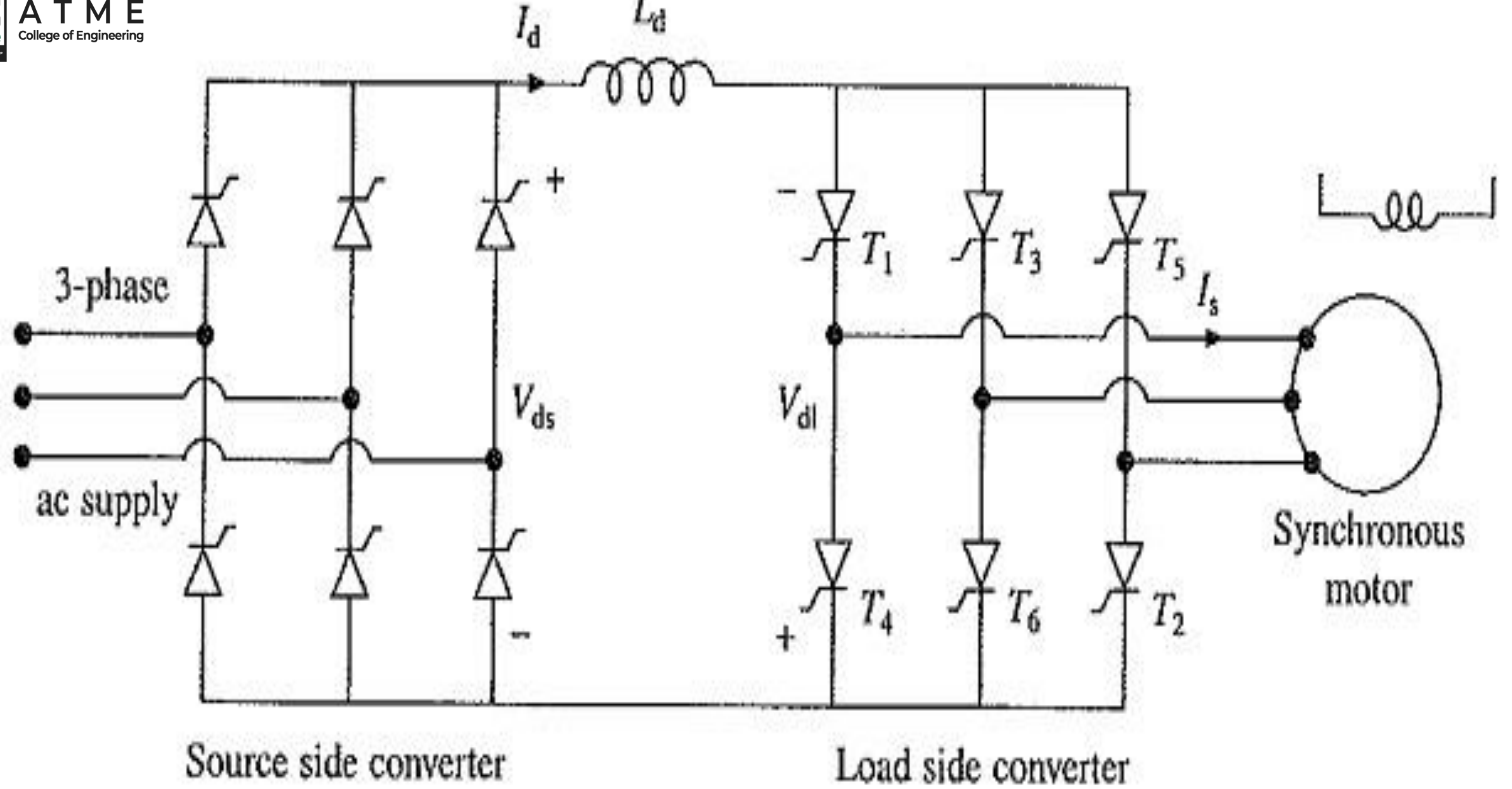
1. Source side converter

- The source side converter-is a 6-pulse line-commutated thyristor converter.
- For a firing angle range $0 \leq \alpha_s \leq 90°$, it works as a line-commutated fully controlled rectifier delivering positive V_{ds} and positive I_d,
- For firing angle range $90° \leq \alpha_s \leq 180°$, it works as a line-commutated inverter delivering negative V_{ds} and positive I_d.
- Commutation of thyristors by induced voltages of load (here load is a motor) is known as load commutation.



Self-controlled synchronous motor drive employing load commutated inverter

- Firing angle is measured by comparison of induced voltages in the same way as by the comparison of line voltages in a line commutated converter



Self-controlled synchronous motor drive employing load commutated inverter

2. Load Side Converter

- For $0 \leq \alpha_l \leq 90°$ it works as a rectifier giving positive V_{dl}.
- For, $90° \leq \alpha_l \leq 180°$, Converter operates as an inverter producing negative V_{dl} and carrying positive I_d

$0 \leq \alpha_s \leq 90°$, $90° \leq \alpha_l \leq 180°$ and with $V_{ds} > V_{dl}$	source side converter works as a rectifier and load side converter as an inverter	power flow from ac source to the motor, thus giving motoring operation
$90° \leq \alpha_s \leq 180°$ and $0° \leq \alpha_l \leq 90°$,	the load side converter operates as a rectifier and the source side as an inverter.	power flow reverses and machine operates in regenerative braking.

- The magnitude of torque depends on (V_{ds} — V_{dl}). Speed can be changed by control of line side converter firing angles.
- Commutation lead angle for load side converter as $\beta_l = 180° - \alpha_l$
- Converter working as an inverter with Fixed value of commutation lead angle= β_{lc}
- When working as a rectifier: $\beta_l = 180°$ (or $\alpha_l = 0°$)

- To minimize converter rating, with good power factor , the load side converter when working as an inverter is operated with **Constant Margin Angle Control**.
- The duration for thyristor under commutation is subjected to reverse bias after current through it has fallen to zero is given by

$$\gamma = \beta_l - u$$

Where, u-commutation overlap of the thyristor under commutation

- For successful commutation of thyristor:

$$\gamma > \omega t_q$$

where t_q is the turn-off time of thyristors and ω the frequency of motor voltage in radians/sec.

- Since u α I_d ; βl can be calculated such that the thyristor under commutation is reverse biased for a duration γ_{min} for commutation.
- This in turn minimizes βl and maximizes motor power factor. Since γ is kept constant at its minimum value γ_{min}, the control scheme is called **constant margin angle control.**
- The dc link inductor L_d reduces the ripple in the dc link current I_d - prevents the two converters from interfering with each other's operation.
- Fundamental component of motor phase current I_s is:

$$I_s = \frac{\sqrt{6}}{\pi} I_d$$

Load commutation has a number of advantages over forced commutation:

- ✓ **it does not require commutation circuits**
- ✓ **frequency of operation can be higher and**
- ✓ **it can operate at power levels beyond the capability of forced commutation.**

- Load side converter performs somewhat similar function as commutator in a dc machine.
- The load side converter and Self Controlled Synchronous Motor Drive combination functions similar to a dc machine.
- The drive consisting of load side converter and synchronous motor is known as **Commutator Less DC Motor.**

Closed-loop speed control scheme of load commutated inverter synchronous motor drive

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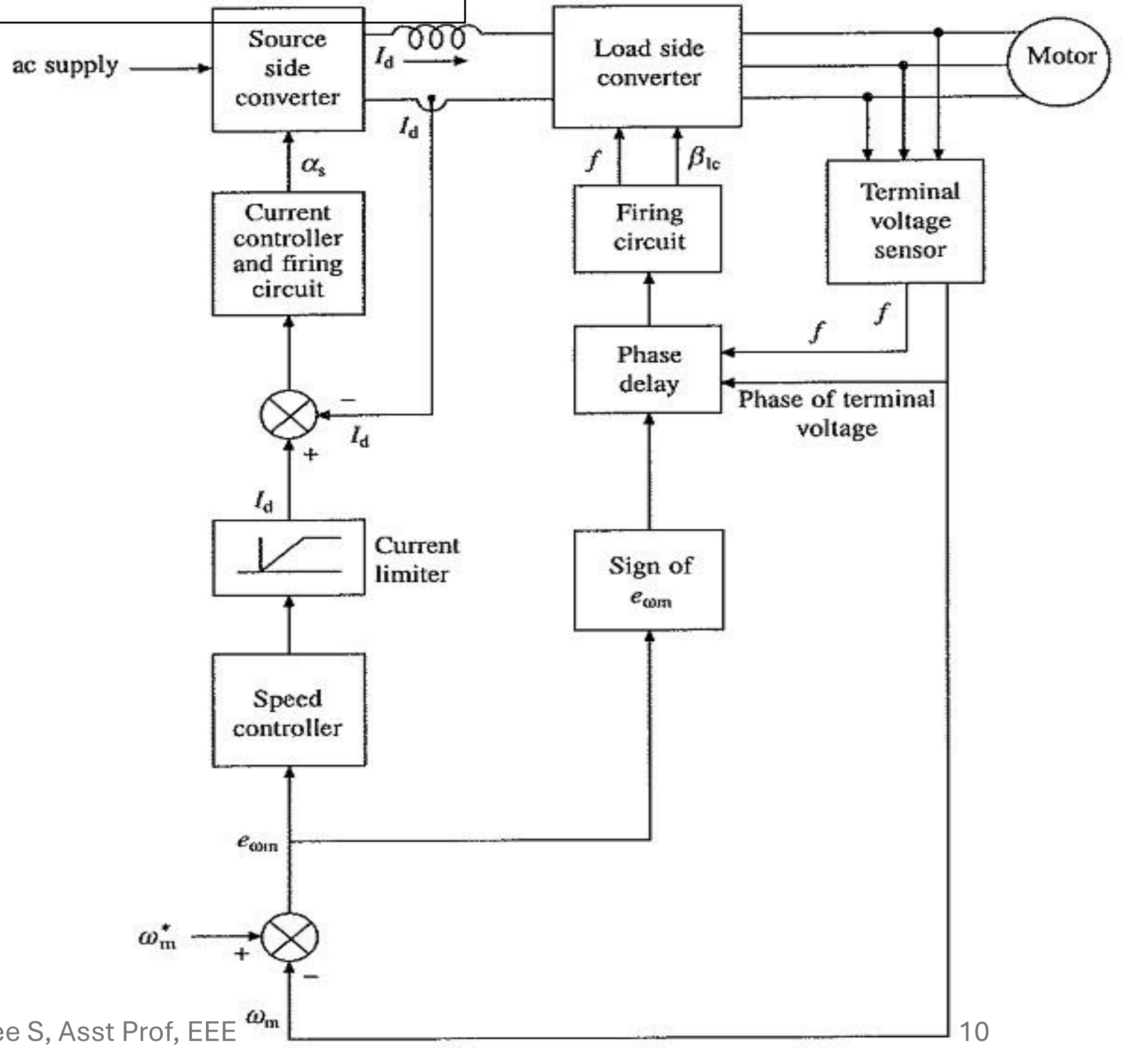
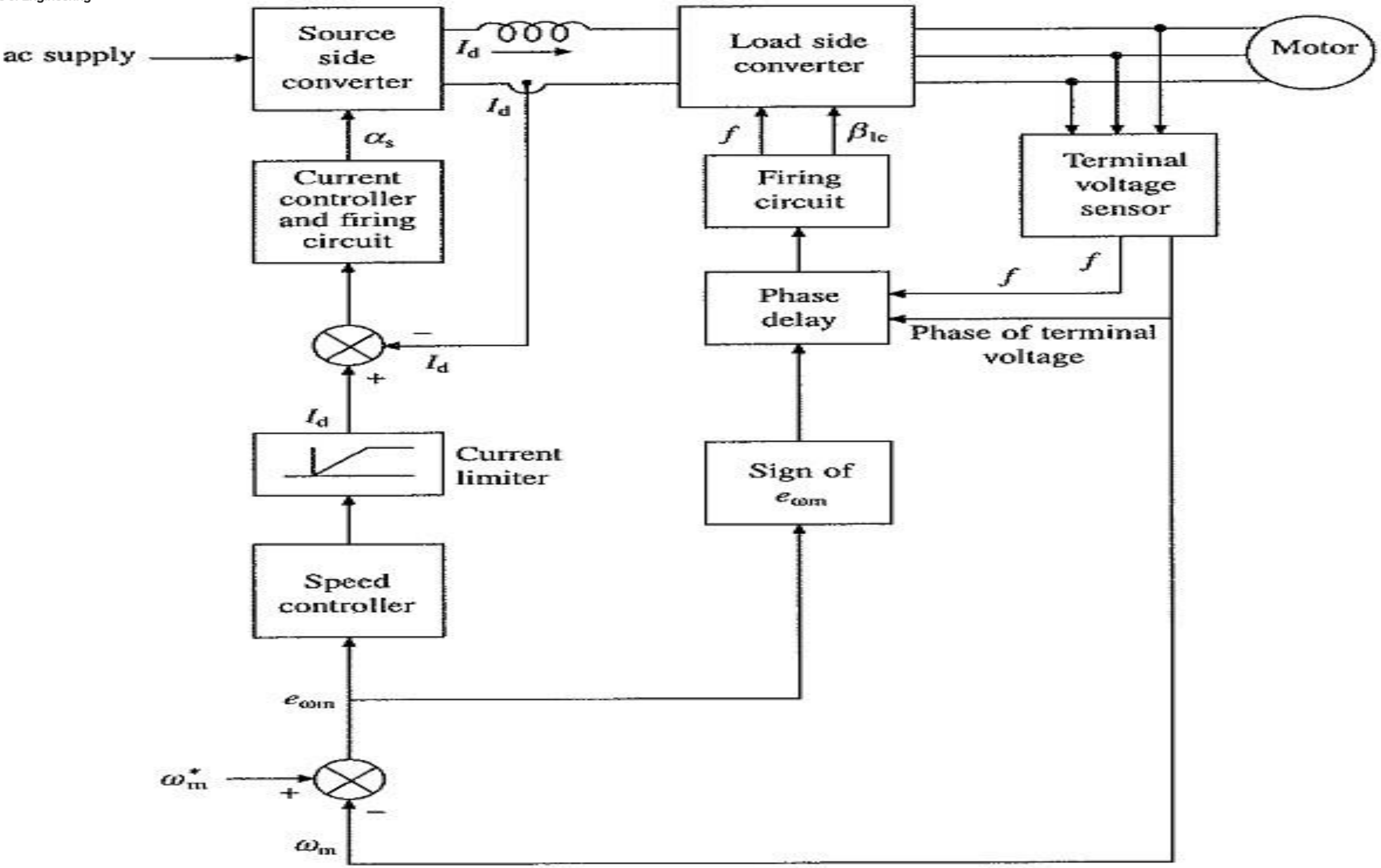
- It employs outer speed control loop and inner current control loop with a limiter, like a dc motor .
- The terminal voltage sensor generates reference pulses of the same frequency as the machine-induced voltages.
- The phase delay circuit shifts the reference pulses to obtain control at a constant commutation lead angle β_{lc}.
- Depending on the sign of speed error, β_{lc} is set to provide motoring or braking operation.
- Speed ω_m can be sensed either from the terminal voltage sensor or from a separate tachometer.
- An increase in reference speed ω_m produces a positive speed error. β_{lc} value is set for motoring operation.

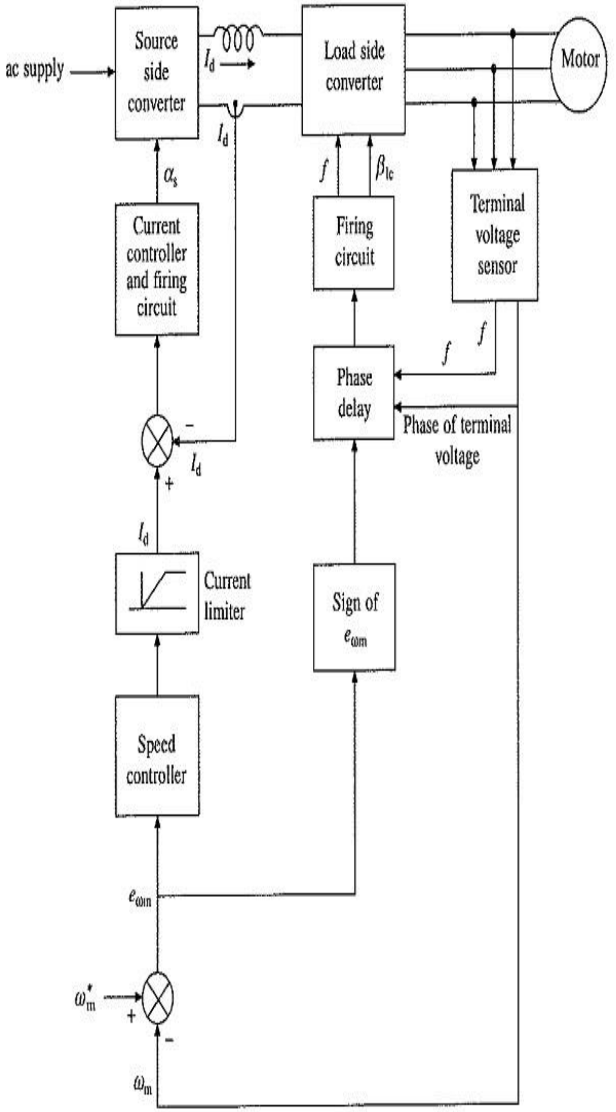


Closed-loop speed control of load commutated inverter synchronous motor drive



Closed-loop speed control of load commutated inverter synchronous motor drive

- The speed controller and current limiter set the dc link current reference at the maximum permissible value. The machine accelerates fast.
- When close to the desired speed, the current limiter desaturates, which balances motor and load torques.
- Similarly a reduction in reference speed produces a negative speed error.
- This sets β_{lc} for regenerative braking operation (i.e. 180°) and the motor decelerates.



Closed-loop speed control of load commutated inverter synchronous motor drive

Advantages of the drive:

- ✓ High efficiency
- ✓ four-quadrant operation with regenerative braking,
- ✓ high power ratings (up to 100 MW)
- ✓ ability to run at high speeds (6000 rpm)

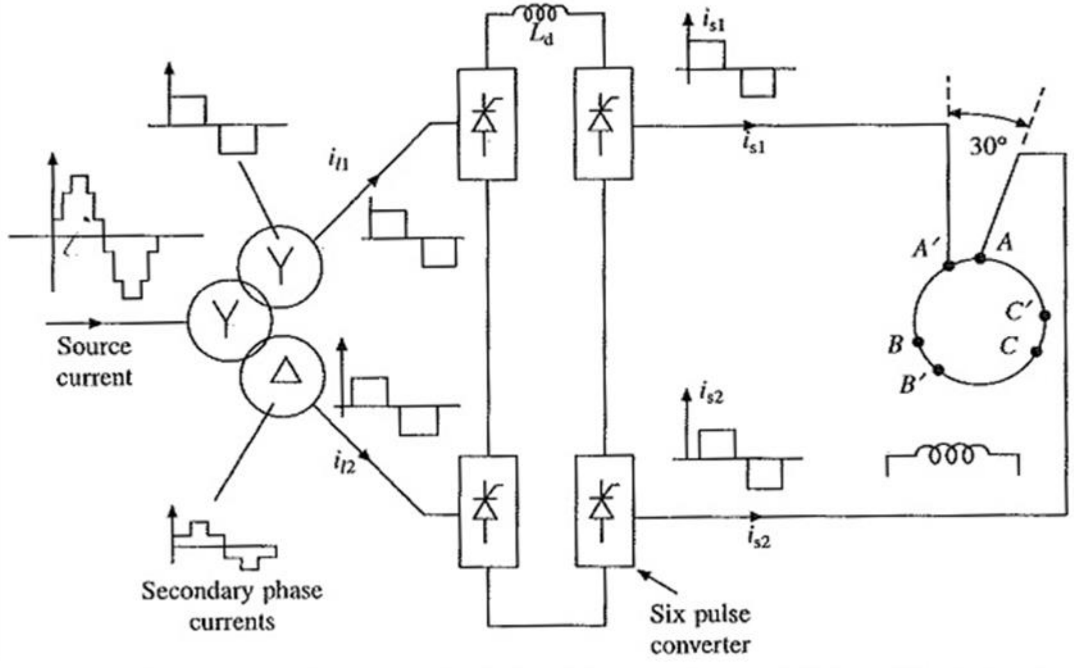
Applications

High speed and high power drives for compressors, blowers, fans, pumps, conveyers, steel rolling mills, main line traction, ship propulsion and aircraft test facilities.

Single line diagram of a high power drive

At very high power levels, **harmonics** generated at the source and motor terminals require special attention. Single line diagram of a high power drive is shown in Fig.

- The source side harmonics are reduced by using a 12-pulse converter.
- For this two six-pulse converters are connected in series.
- The supply for the converters is obtained through a transformer with primary-star and two secondary windings- one star connected feeds one six pulse converter and another delta connected feeds another six pulse converter.
- This way 30° phase shift is provided between the input voltages of two six-pulse converters.
- The input current waveforms of two converters and source current are shown in Fig.
- The source current is more close to sinusoidal compared to six-pulse converter.



High power synchronous motor drive with series connections of 6-pulse converters to obtain 12-pulse configurations

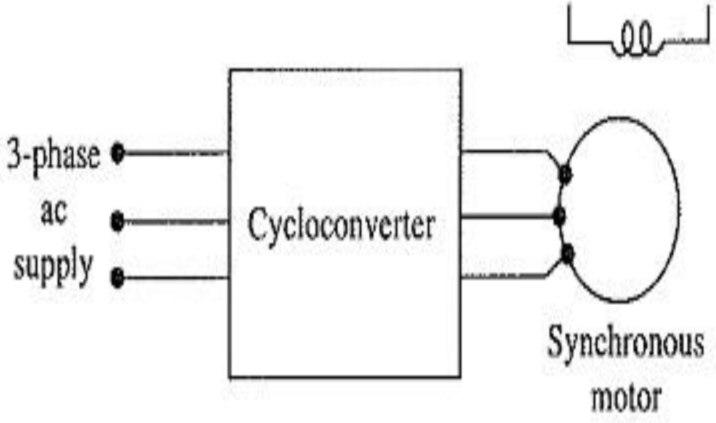
- The harmonics in motor current produce torque pulsations and losses in rotor and damper windings
- These effects are minimized by using a Self Controlled Synchronous Motor Drive
- The resultant stator mmf has twelve pulse waveform.
- Therefore, torque pulsations and rotor and damper winding losses are reduced.

Starting large Synchronous Motor

- When operating with self control, the starting current is low & starting torque is high compared to DOL starting as in case of IM.
- To start large synchronous motor in gas turbines and pumped storage power plants, self-control is employed.
- From standstill to 10% base speed, inverter operate in pulse mode and above 10% speed synchronous speed the inverted operated with load commutation.

Self Controlled Synchronous Motor Drive Employing a Cycloconverter

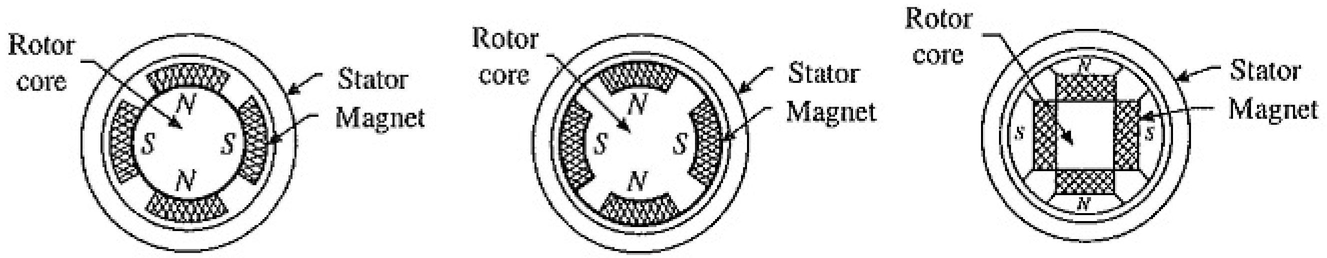
- Self Controlled Synchronous Motor Drive Employing a Cycloconverter as shown in Fig.
- Firing pulses are generated either by comparison of the motor terminal voltages or by rotor position sensors as in the case of drive.
- Cycloconverter control has the advantages of smooth low speed operation, four-quadrant operation with regenerative braking and good dynamic response.



Self-controlled synchronous motor drive employing a cycloconverter

- A synchronous motor without the damper winding is used, because the damper winding reduces the inductance of the machine, and therefore, its ability to filter out harmonics in the output voltage of cycloconverter.
- The drive operates in self-controlled mode, the damper winding is not needed for its conventional roles.
- The drive is employed in low speed gearless drives for ball mills in cement plants, mine hoists, reversing rolling mills requiring fast dynamic response and in ships equipped with diesel generator fed Self Controlled Synchronous Motor Drive Employing a Cycloconverter.
- At such high power levels, considerable saving in cycloconverter cost is obtained by operating the motor at unity power factor by adjusting the field current.
- A cycloconverter is ideally suitable for such a low frequency supply. Earlier gears were employed to get low speed operation

Permanent Magnet AC Motor Drives



(a) Projecting surface mounting (b) Inset magnet (a) Interior magnet

- Permanent magnet synchronous motors are now commonly known as permanent magnet ac (PMAC) motors.
- Classified based on the nature of voltage induced in the stator as
  - ✓ **Sinusoidally Excited-** induced voltage has a sinusoidal waveform- Known as **Sinusoidal PMAC** Motors
  - ✓ **Trapezoidally Excited-** induced voltage has trapezoidal waveform-known as **Trapezoidal PMAC** motors.

Sinusoidal PMAC motor

✓has distributed winding in the stator.

✓rotor geometries includes inset or interior shown in Fig.

✓Rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform.

Trapezoidal PMAC motors.

✓The stator has concentrated windings

✓rotor with a wide pole arc.

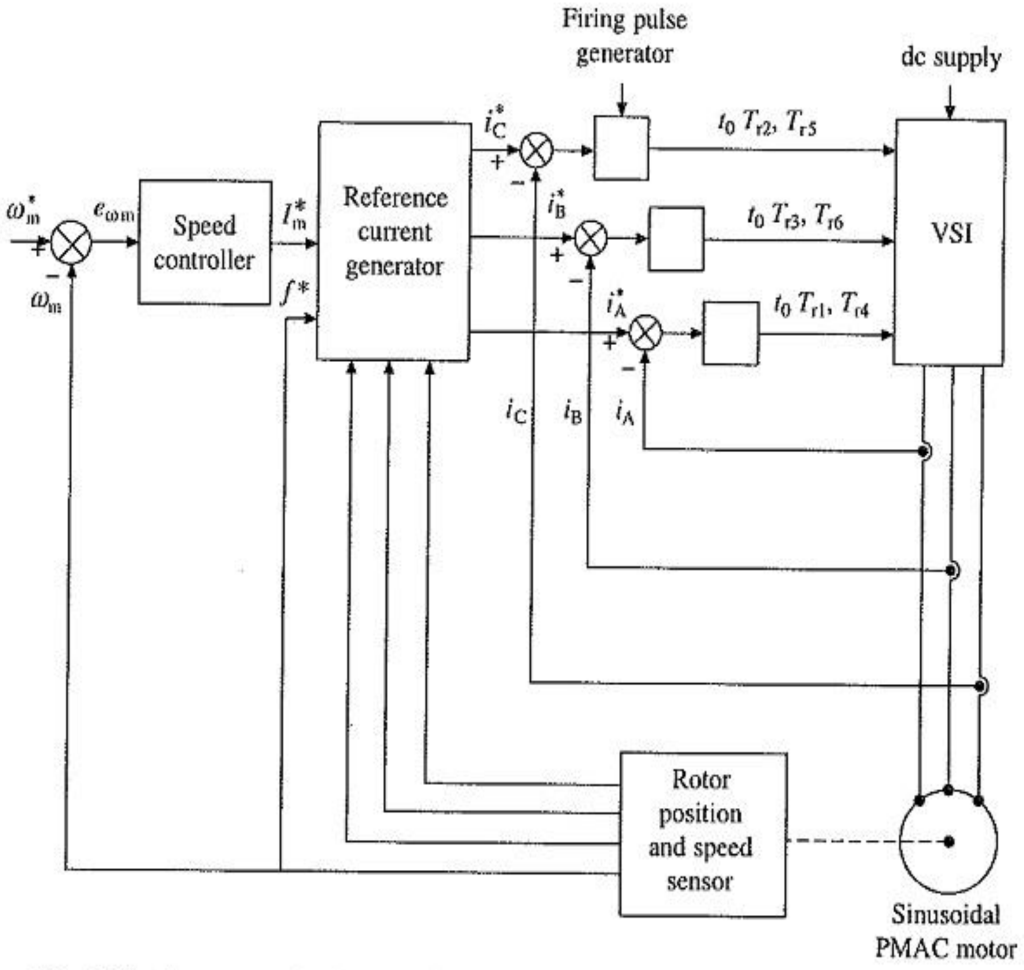
✓The voltage induced in the stator phase has a trapezoidal waveform.

✓The self-controlled variable frequency drives employing a trapezoidal PMAC motor are now called brushless dc motor drives

- The speed of PMAC motors is controlled by feeding them from variable frequency voltage/currents.
- They are operated in self-controlled mode. Rotor position sensors are employed for operation in self-control mode.

Servo Drive Employing Sinusoidal PMAC Motor Fed from a Current Regulated Voltage Source Inverter

- Reference currents i^*_A, i^*_B and i^*_C - generated by a reference current generator.
- The actual speed ω_m is compared with reference speed ω^*_m.
- The speed error is processed through the speed controller.
- The output of the speed controller sets a reference for the amplitude and polarity of the stator current I^*_s.
- The stator current templates for the three phases are generated by the rotor position sensors in such a way that $\delta' = \pi/2$.
- When speed error is positive the machine will work as a motor and the drive will accelerate to reference speed ω^*_m.
- If speed error is negative, braking will decelerate the motor to reference speed ω^*_m.



Brushless DC Motor Drives (Trapezoidal PMAC)

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- The cross section of a 3-phase 2 pole Brushless DC Motor Drives is shown in Fig.1.
- An inverter fed trapezoidal PMAC motor drive operating in self-controlled mode is called a brushless dc motor
- It has permanent magnet rotor with wide pole arc.

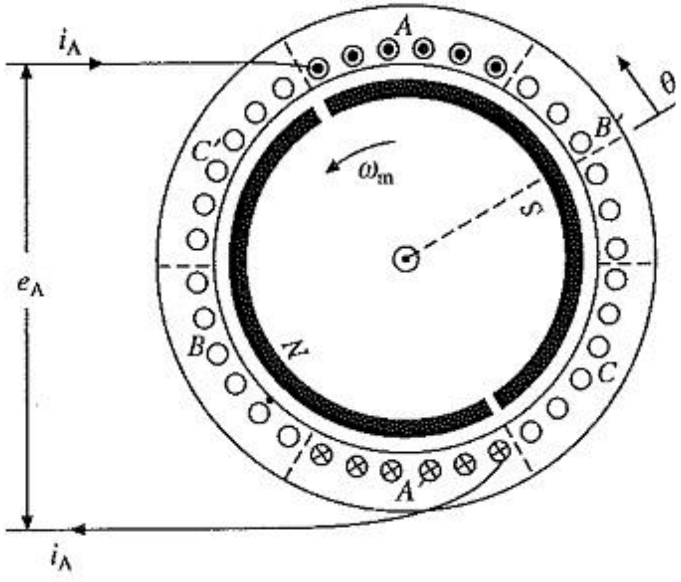


Fig 1 Cross Section of Trapezoidal PMAC Motor

- The stator has three concentrated phase windings, which are displaced by 120° and each phase winding spans 60° on each side.
- The voltages induced in three phases are shown in Fig. 2

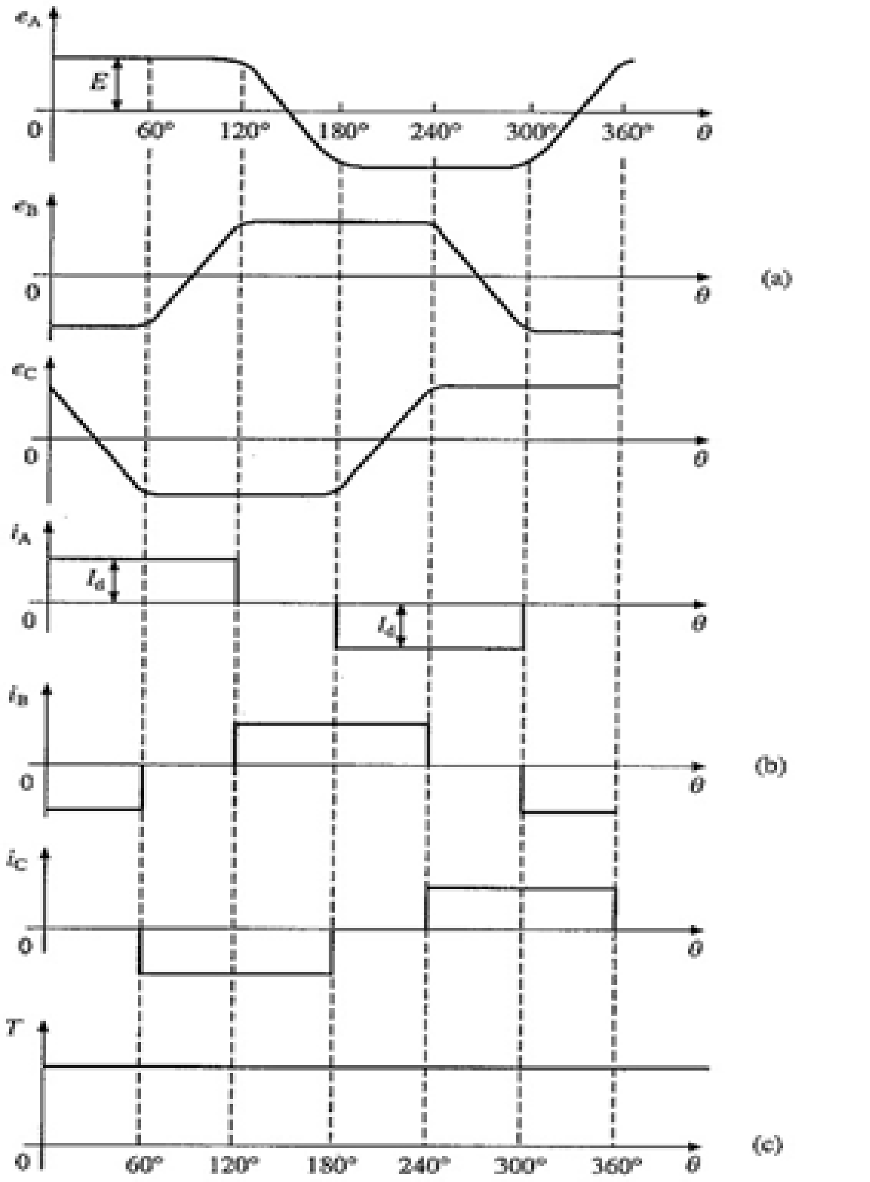
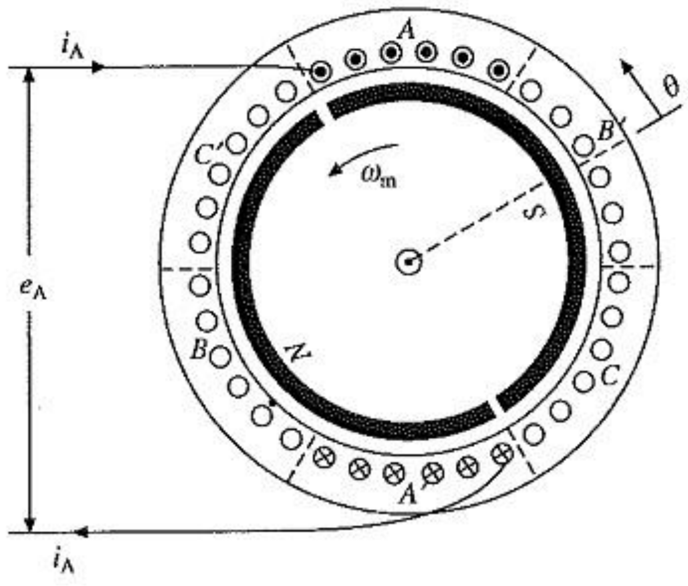


Fig. 2 Induced voltage, phase current and torque wavefors of a brushless dc motor

Brushless DC Motor Drives (Trapezoidal PMAC)



Reason for getting trapezoidal waveform

- When revolving in the counter-clockwise direction, up to 120^0 rotation from the position shown in Fig. 1, all top conductors of phase A will be linking the south pole and all bottom conductors of phase A will be linking the north pole.
- Hence the voltage induced in phase A will be the same during 120^0 rotation as in fig2.
- Beyond 120^0, some conductors in the top, link north pole and others the south pole. Same happens with the bottom conductors.
- Hence, the voltage induced in phase A linearly reverses in next 60^0 rotation.
- Rest of the waveform of phase A and waveforms of phases B and C can be similarly explained.

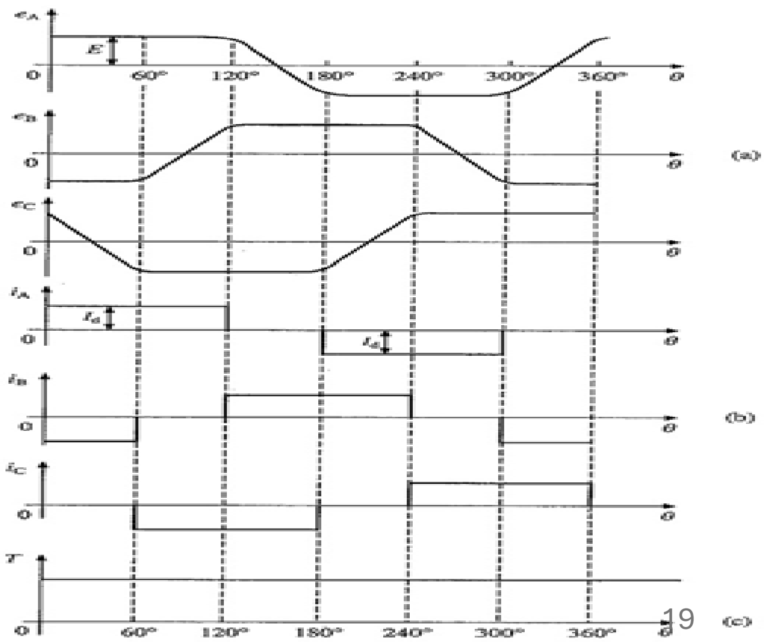


Fig. 2 Induced voltage, phase current and torque wavefors of a brushless dc motor

Brushless DC Motor Drive for Servo Applications

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- A Brushless DC Motor Drives employing a voltage source inverter (VSI) and a trapezoidal PMAC motor is shown in Fig. 3(a) the stator windings be fed with current pulses shown in Fig. 3(b)

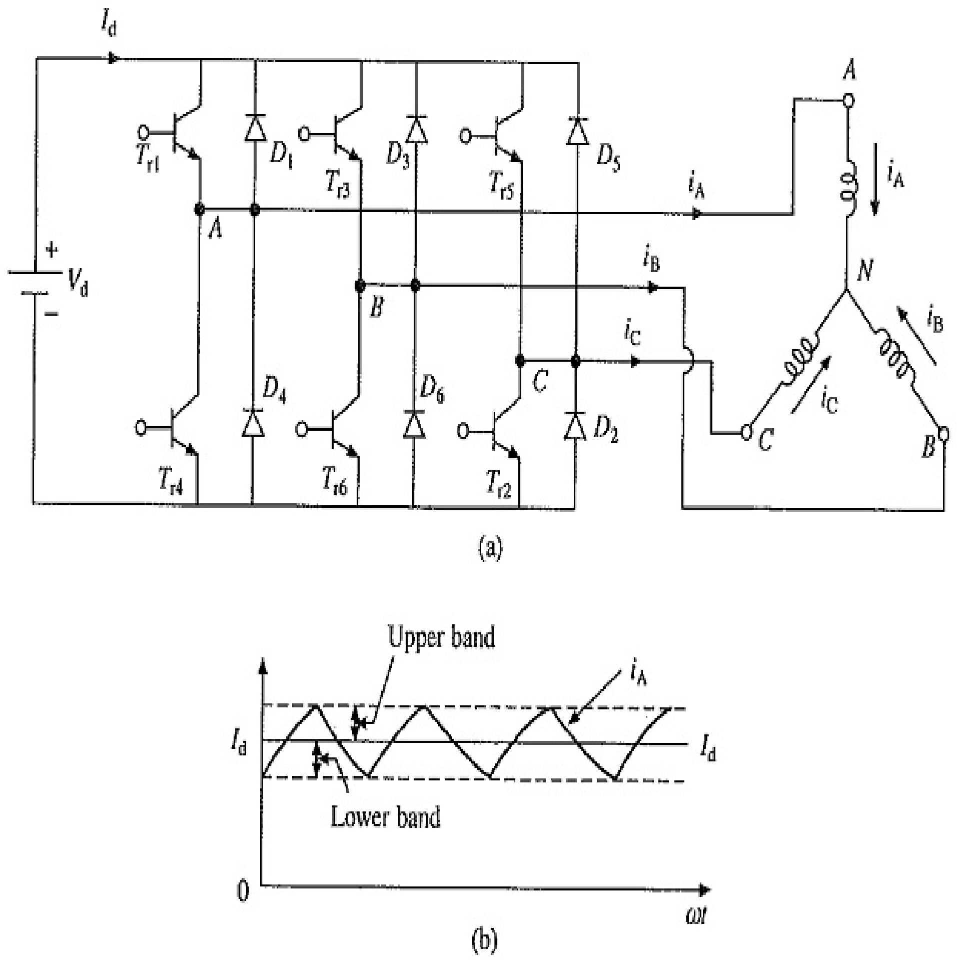


Fig. 3 Trapezoidal PMAC motor fed from a current regulated voltage source inverter

- The current pulses are each of 120° duration and are located in the region where induced voltage is constant and maximum.
- Further, the polarity of current pulses is the same as that of induced voltage.
- Since the air-gap flux is constant, the voltage induced is proportional to speed of rotor.

$$E = K_e \omega_m$$

- During each 60° interval in Fig.4, current enters one phase and comes out of another phase, therefore, power supplied to the motor in each such interval

$$P = EI_d + (-E)(-I_d) = 2EI_d = 2K_e\omega_m I_d$$

Brushless DC Motor Drive for Servo Applications cntd.

The waveform of torque is shown in fig.4

Torque developed by the motor $$T = \frac{P}{\omega_m} = 2K_e I_d = K_T I_d$$

- During the period 0° to 60° , $i_A = I_d$ and $i_B = -I_d$. The current i_A enters through the phase A and leaves through the phase B.
- When transistors T_{r1} and T_{r6} are ON, terminals A and B are respectively connected to positive and negative terminals of the dc source V_d.
- A current will flow through the path consisting of V_d, T_{r1}, phase A, phase B and T_{r6} and rate of change of current i_A will be positive.
- When T_{r1} and T_{r6} are turned OFF, this current will flow through a path consisting of phase A, phase B, diode D_3, V_d and diode D_4. Rate of change of i_A will be negative.

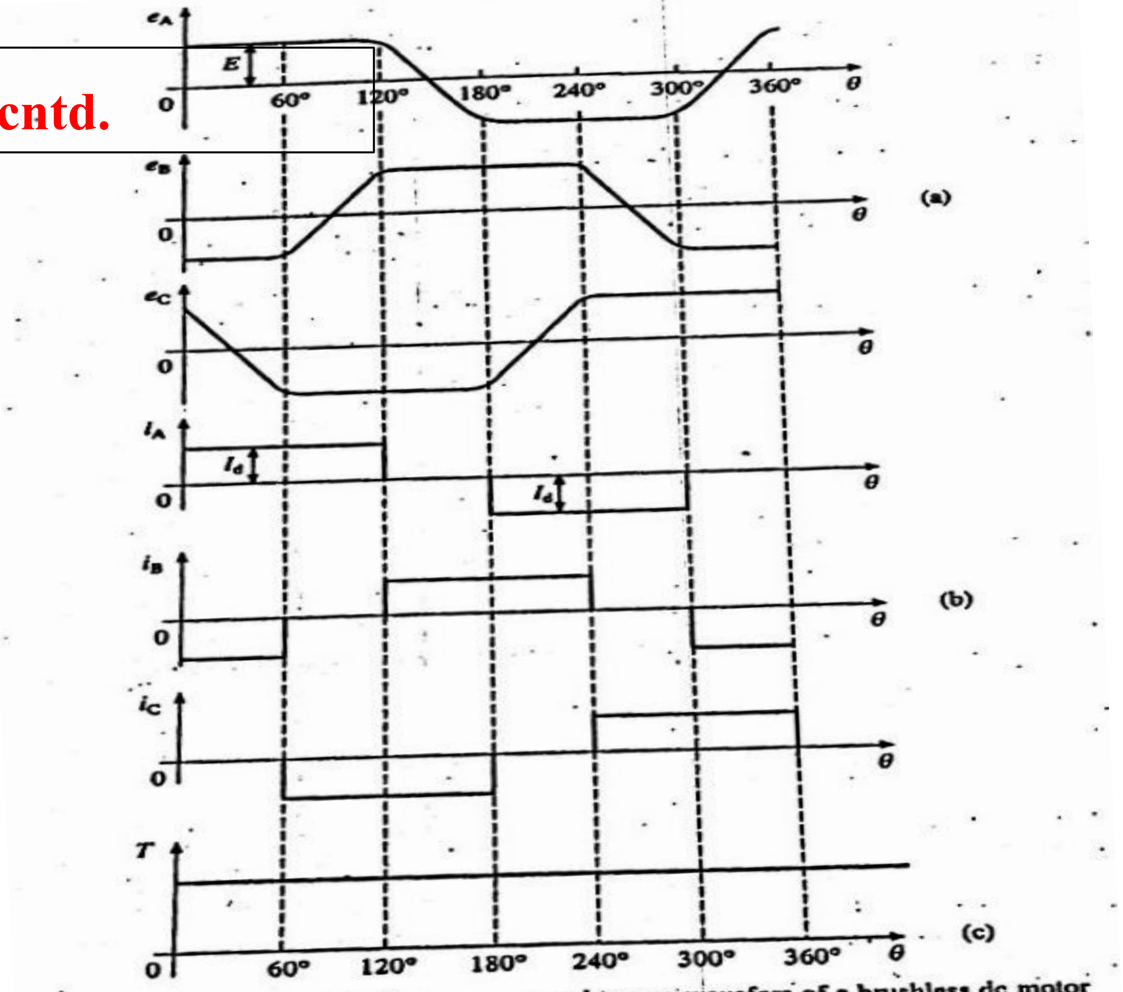
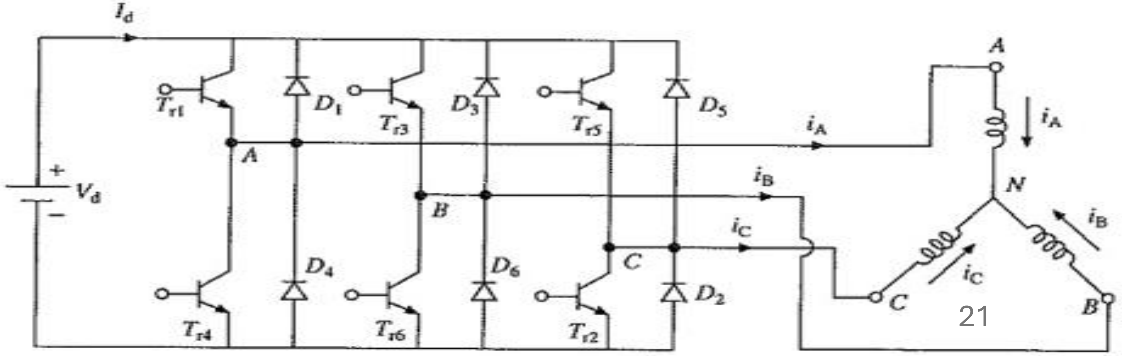
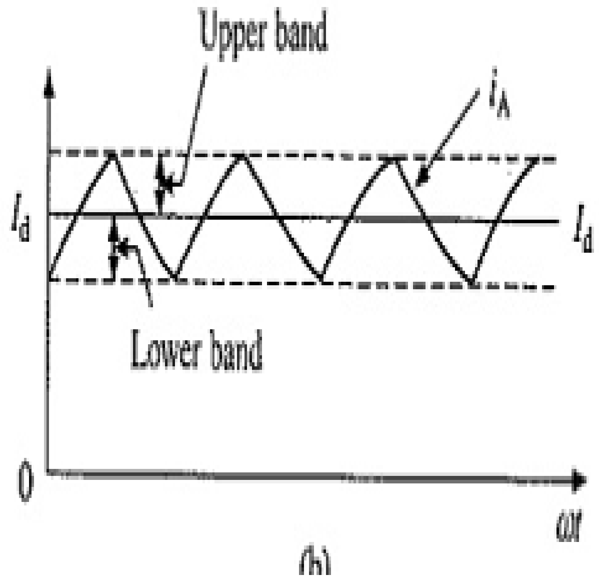


Fig. 7.17 Induced voltage, phase current and torque wavefors of a brushless dc motor



Brushless DC Motor Drive for Servo Applications cntd.

- A current can be made to follow the reference current I_d within a hysteresis band as shown in Fig. 3(b).
- By reducing the band sufficiently nearly a dc current of desired value can be produced.
- The sensors are mounted at 60^0 interval and aligned suitably with the stator winding,
- Sensors used with trapezoidal PMAC motor are cheaper compared to those required with sinusoid PMAC motor. Hence the drive has much lower cost.



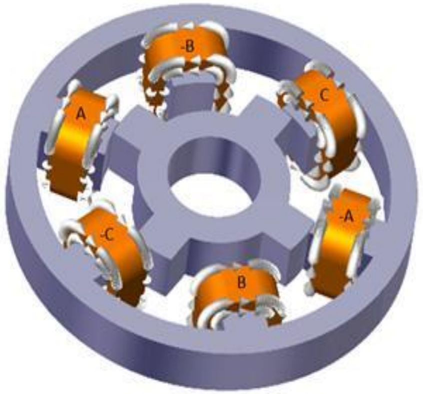
Self study

Important Features and Applications

- Due to the absence of brushes and commutator, Brushless DC Motor Drives have a number of advantages compared to conventional dc motors.
- They require practically no maintenance, have long life, high reliability, low inertia and friction, and low radio frequency interference and noise.
- Due to low inertia and friction, they have a faster acceleration and can be run at much higher speeds – up to 100,000 rpm and higher are common.
- Because armature windings are on the stator, cooling is much better, i.e. higher specific outputs can be obtained.
- These motors have high efficiency, exceeding 75% whereas wound field motors of low power ratings have much lower efficiency.
- The disadvantages compared to conventional dc motors are high cost and low starting torque.
- The size of a brushless dc motor is nearly the same as of conventional dc motor.
- The Brushless DC Motor Drives finds applications in turn table drives in record players, tape drive for video recorders, spindle drives in hard disk drives for computers, and low cost and low power drives in computer peripherals, instruments and control systems.
- They also have applications in the fields of aerospace, e.g. gyroscope motors, and biomedical like cryogenic coolers and artificial heart pumps.
- They are also used for driving cooling fans for electronic circuits and heat sinks.

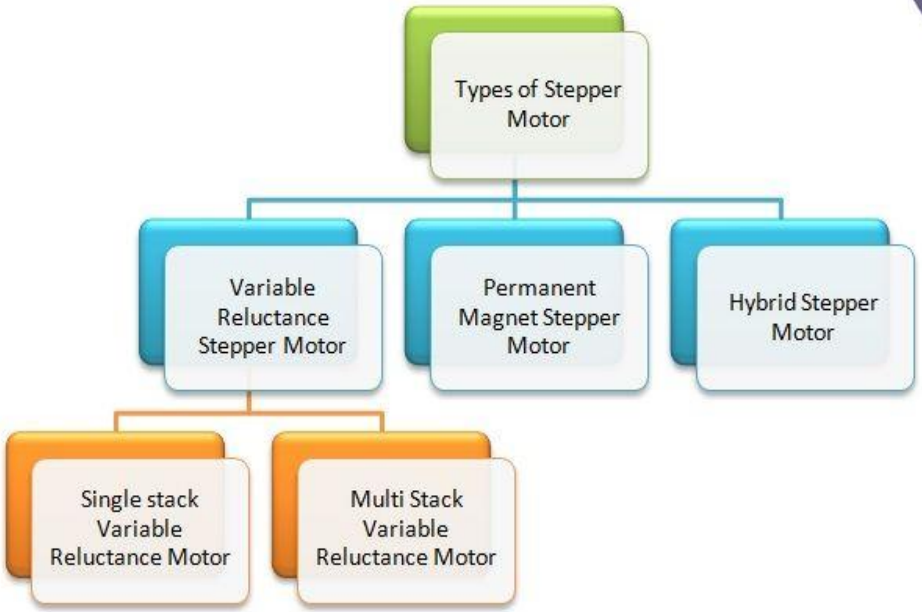
Stepper Motor

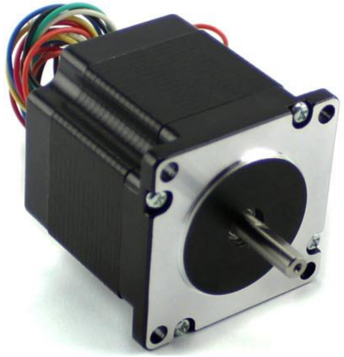
- **Stepper Motor** is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation.
- The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input



Large Varieties of Stepper Motor can be divide into three categories based on the rotor arrangements. They are as follows

1. Variable Reluctance (VR) Stepper Motor : It is of two types.
   i. Single stack variable reluctance motor
   ii. Multi-stack variable reluctance motor.
2. Permanent Magnet (PM) Stepper Motor
3. Hybrid Stepper Motor (combination of VR and PM type)





Important Features of Stepper Motors

Stepper motors have following advantages and disadvantages: V.Impt

Disadvantages of Stepper Motor

- Proper Matching between Load, motor and its drive is required.
- At the higher speed, the value of torque reduces.
- Lower efficiency.
- The Resonance condition arises and requires micro stepping.
- At the high speed, the control is not possible

Advantages of stepper Motor

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- Compatibility with digital systems and do not require digital to analog conversion at the input.
  - While simple open-loop control is good enough for the control of Position and speed, it can also be used in closed loop position and speed control system.
  - A wide range of step angles is available in the range of 1.8 to 90º. The range of torque is from 1µNm(tiny wrist watch) to 50Nm(Machine Tool applications)
  - Bidirectional control is available
  - Maximum Torque occurs at low pulse rates. The stepper motor can accelerate its load easily.
  - Low Speed are possible without reduction gear.
  - Moment of Inertia is usually Low.
  - Multiple stepper motors driven from the same source can maintain perfect synchronization.
  - The starting current is Low
  - Low Cost, Compact Size

Applications of stepper Motor

- Machine tools
- Process Control system
- X-Y Recorder
- Robotics
- Textile industry
- Integrated circuit fabrication
- Electric Watches

Step Angle in Stepper Motor

- **Definition: Step angle** is defined as the angle which the rotor of a stepper motor moves when one pulse is applied to the input of the stator.
- The positioning of a motor is decided by the step angle and is expressed in degrees.
- The resolution or the step number of a motor is the number of steps it makes in one revolution of the rotor.
- Smaller the step angle higher the resolution of the positioning of the stepper motor.

$$\text{Resolution} = \frac{\text{number of steps}}{\text{number of revolutions of the rotor}}$$

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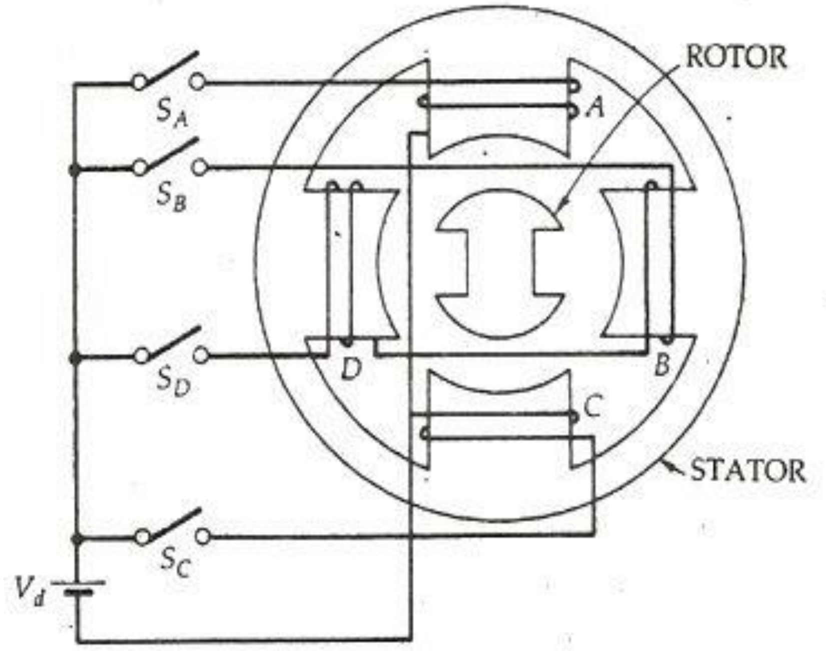
Variable reluctance stepper motor

Single stack variable reluctance stepper motor

- A variable reluctance stepper motor has salient pole (or tooth) stator and rotor.
- Rotor has no windings, stator has concentrated coils placed over the stator poles (teeth).
- Number of phases in Stator winding depends on the connection of stator coils.
- A four phase, 4/2 pole (4 stator poles & 2 rotor poles), single stack variable reluctance stepper motor is shown in fig.



Fig(a). Four phase or (4/2 pole), single stack variable reluctance stepper motor

- The four phases A, B, C and D are connected to the DC source with the help of a semiconductor, switches SA, SB, SC and SD respectively as shown in the above figure (a).
- The phase windings of the stator are energized in the sequence A, B, C, D, A.
- The rotor aligns itself with the axis of phase A as the winding A is energized. The rotor is stable in this position and cannot move until phase A is de-energized.
- Now, the phase B is excited and phase A is disconnected.
- The rotor moves 90 degrees in the clockwise direction to align itself with the axis of the phase.

Variable reluctance stepper motor

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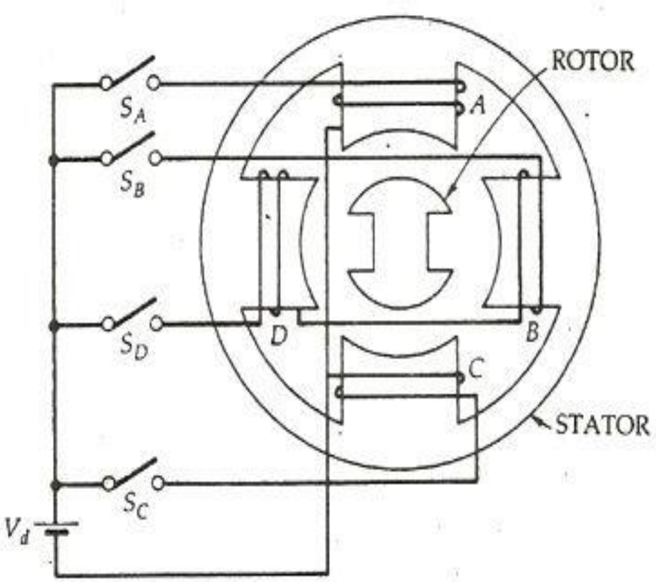
Single stack variable reluctance stepper motor cntd.

- Similarly the phase C is energized, and the phase B is disconnected, and the rotor moves again in 90 degrees to align itself with the axis of the phase.
- Thus, as the Phases are excited in the order as A, B, C, D, A, the rotor moves 90 degrees at each transition step in the clockwise direction.
- Direction of rotation can be reversed by reversing the sequence of switching the phases, that is A, D, C, B, A.

- The step-angle can be reduced from 90 to 45^0 by exciting phases in sequence A, A + B, B, B + C, C, C + D, D, D +A, A.
- When phase A is excited, the rotor aligns with the axis of A.
- When, both phases A and B are excited, the resultant air-gap field axis, and therefore, rotor turns by 45^0 in the clockwise direction.
- Rotor can be turned in anticlockwise direction with a step of 45^0 by switching phases in sequence of A, A + D, D, D + C, C, C + B, B, B + A, A.
- This technique of gradually shifting excitation from one phase to another (e.g. from A to B with an intermediate step of A + B) is known as **microstepping** and is used to realise smaller steps.



Single stack variable reluctance stepper motor cntd.

- A four-phase, 8/6 pole, single-stack variable reluctance motor is shown in Fig. 8.2.
- The rotor turns with a step angle of 15^0
- For clockwise rotation, phases are switched in the sequence of A, B, C, D, A
- For anticlockwise rotation, they are switched in the reverse sequence of A, D, C. B, A.

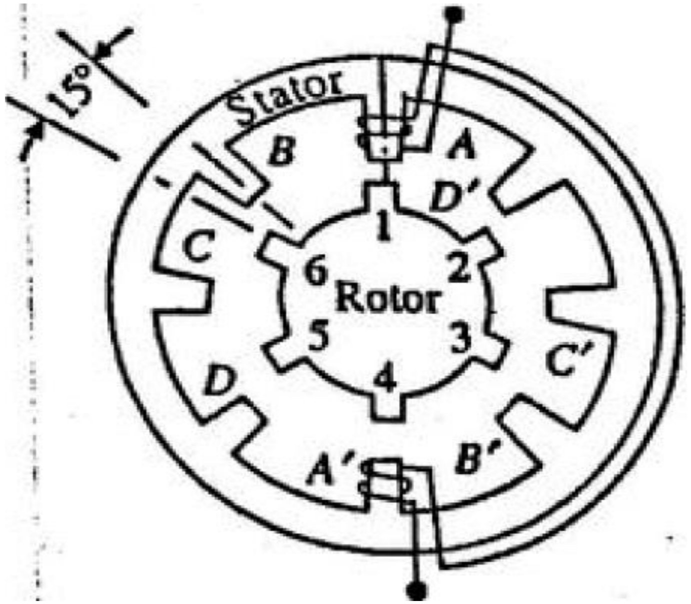


Fig. 8.2 Four-phase 8/6-pole variable reluctance motor

- When phase A is energised, the rotor turns until a pair of its poles (1 and 4 here) align with the axis of phase A (Fig. 8.2).
- If B is excited, the rotor turns by 15^0 in the clockwise direction until rotor poles 3 and 6 are aligned with the; axis of phase B. Here also, the microsteeping can be adapted to reduce the step size.
- For clockwise rotation with a Step size of 7.5^0 the sequence A, A + B, B, B + C, C, C+D,D, D +A, A can be used.
- In order to have self starting capability and bidirectional rotation, the stator and rotor pole numbers have to be different.

Multi Stack or m stack variable reluctance stepper motor

V. Impt

- A Multi Stack or m stack variable reluctance stepper motor is made up of m identical single stack variable reluctance motor.
- These are used to obtain smaller step sizes of range of 2 to 15^0.
- The rotor is mounted on the single shaft.
- Here stator and rotor, have the same number of poles and hence, the same pole pitch.
- All the stator poles are aligned in a Multi-Stack motor. But the rotor poles are displaced by 1/m of the pole pitch angle from each other.
- The stator windings of each stack forms one phase as the stator pole windings are excited simultaneously.
- Thus, the number of phases and the number of stacks are same.
- There are 12 stator and rotor poles in each stack.
- The pole pitch for the 12 pole rotor is 30 degrees and the step angle or the rotor pole teeth are displaced by 10 degrees from each other.

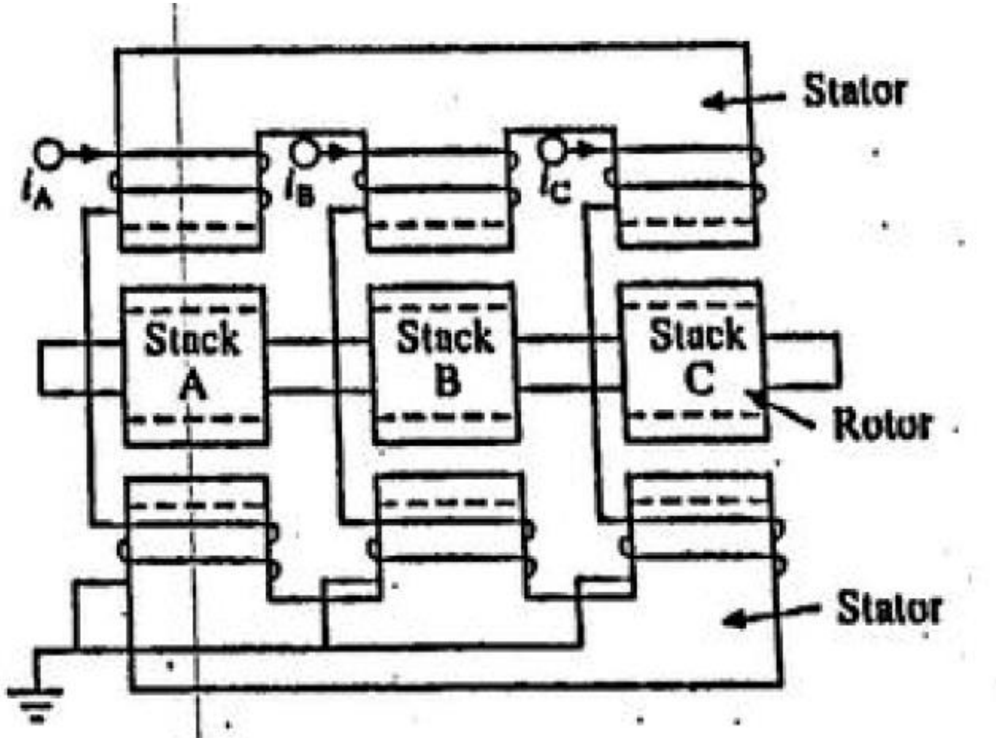


Fig. 8.3 Cross section of a three stack variable reluctance motor parallel to the shaft.

- Rotor poles of stack A are aligned with the stator poles.
- If phase A is de-excited and B excited, rotor poles of stack B will get aligned with the stator poles.
- Thus, rotor will move by 1/3rd of the pole pitch in anticlockwise direction as shown in fig b)
- If phase B is de-excited and C excited, rotor will move by another 1/3rd of pole pitch in the anticlockwise direction.
- If phase C is de-excited and A excited, rotor will have moved by one pole pitch compared to its position in Fig. 8.4(a).

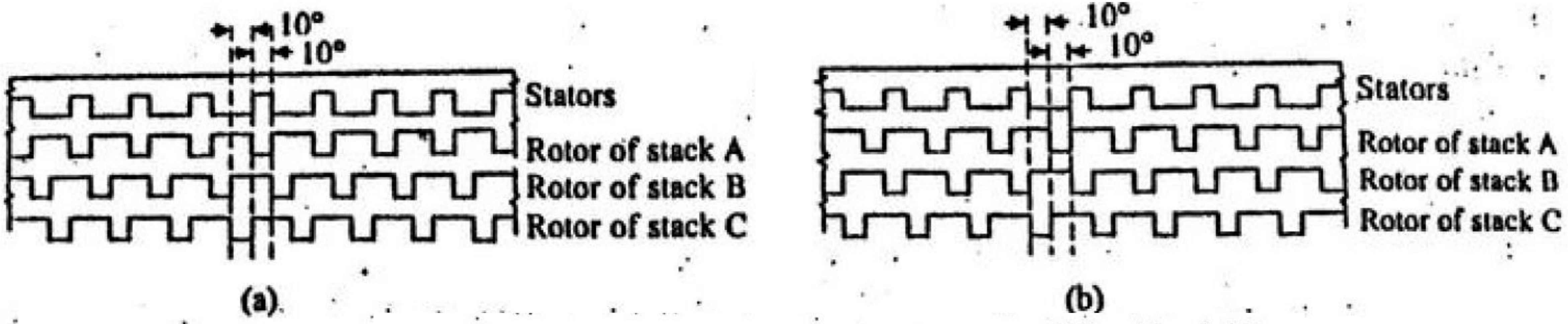


Fig. 8.4 Position of stator and rotor poles in a 3-stack variable reluctance motor: (a) Phase A is excited. Stator and rotor poles in stack A are aligned, (b) Phase B is excited. Stator and rotor poles in stack B are aligned.

Let,
N -number of rotor poles (or teeth)
m-number of stacks or phases.

$$\text{Pole (or tooth) pitch} = \frac{360^\circ}{N}$$

$$\text{Step angle} = \frac{360^\circ}{m \times N}$$

- The variable reluctance motors, both single and m- stack types. have high torque to inertia ratio, giving high rates of acceleration and fast response.

Permanent Magnet Stepper Motor

V. Impt

- The stator of a permanent magnet stepper motor is simitar to that of a single-stack variable reluctance motor.
- Rotor is cylindrical and consists of radially magnetised permanent magnets.
- Fig. shows a two-pole permanent magnet stepper motor.
- When phase A is exited with the direction of current i_A as shown, north pole of rotor aligns with the phase A pole on the left.
- The rotor turns through 90^0 when excitation is switched from phase A to B.
- The direction of rotation depends on the direction of current in phase B.
- When i_B is positive, the rotor turns clockwise
- when i_B is negative, rotor turns anticlockwise.
- Thus, polarities of winding currents determine the direction of rotation and for bidirectional operation, provision has to be made for supply of current in either direction.

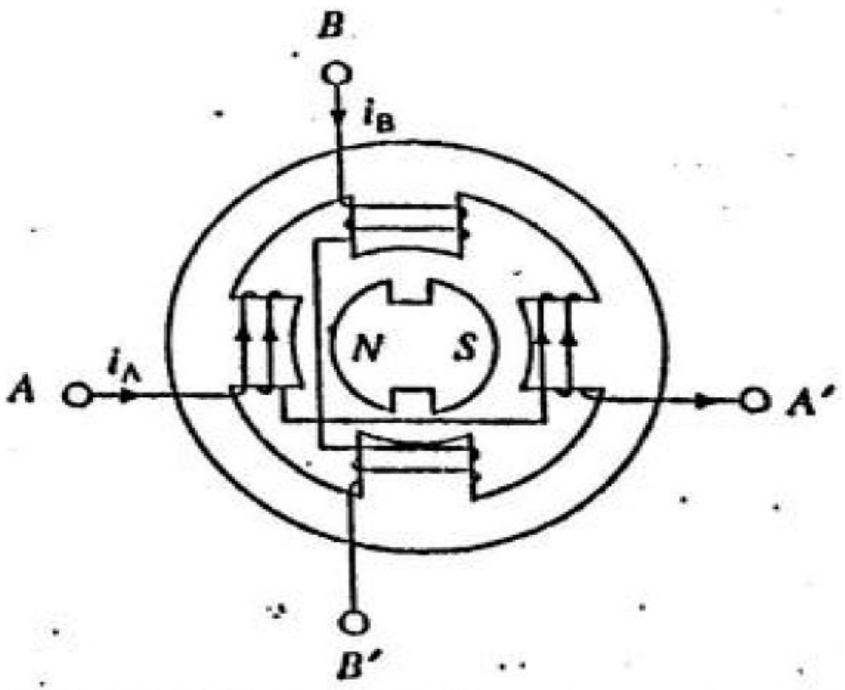


Fig. 8.5 Two-phase 4/2-pole permanent magnet stepper motor.

Comparison with Variable Reluctance Motor

- Due to permanent magnet rotor, the motor has:
  - ✓ high Detent (residual) torque
  - ✓ produces higher torque per ampere of stator current
  - ✓ because of higher rotor volume it has higher inertia
  - ✓ lower torque-to-inertia ratio.
  - ✓ Slower acceleration and response.
- The maximum stepping rate for permanent magnet stepper motors is around 300 pulses/sec. It can be as high as 1200 pulses/sec for variable reluctance motors.
- Due to manufacturing difficulty of small permanent magnet rotor with large number of poles, the permanent magnet stepper motor are restricted to larger step sizes in the range of 30-90^0.
- Disk-type of permanent magnet stepper motor has overcome the above limitations.

Disk-type of permanent magnet stepper motor

- The disk is magnetised with alternating north and south poles.
- Due to thin disk, it can be magnetised up to around 100 individual tiny magnets.
- Simple C shaped two stationary field-poles, offset by half a rotor pole pitch form two phases.
- When one of the phase is energised, the rotor will align itself with its field-pole.
- When excitation is shifted to another phase, the rotor will turn by half the rotor pole pitch, to align with field-pole of the second phase.
- To keep the rotor turning in the same direction, second phase is turned-off and first phase turned-on with its direction reversed.

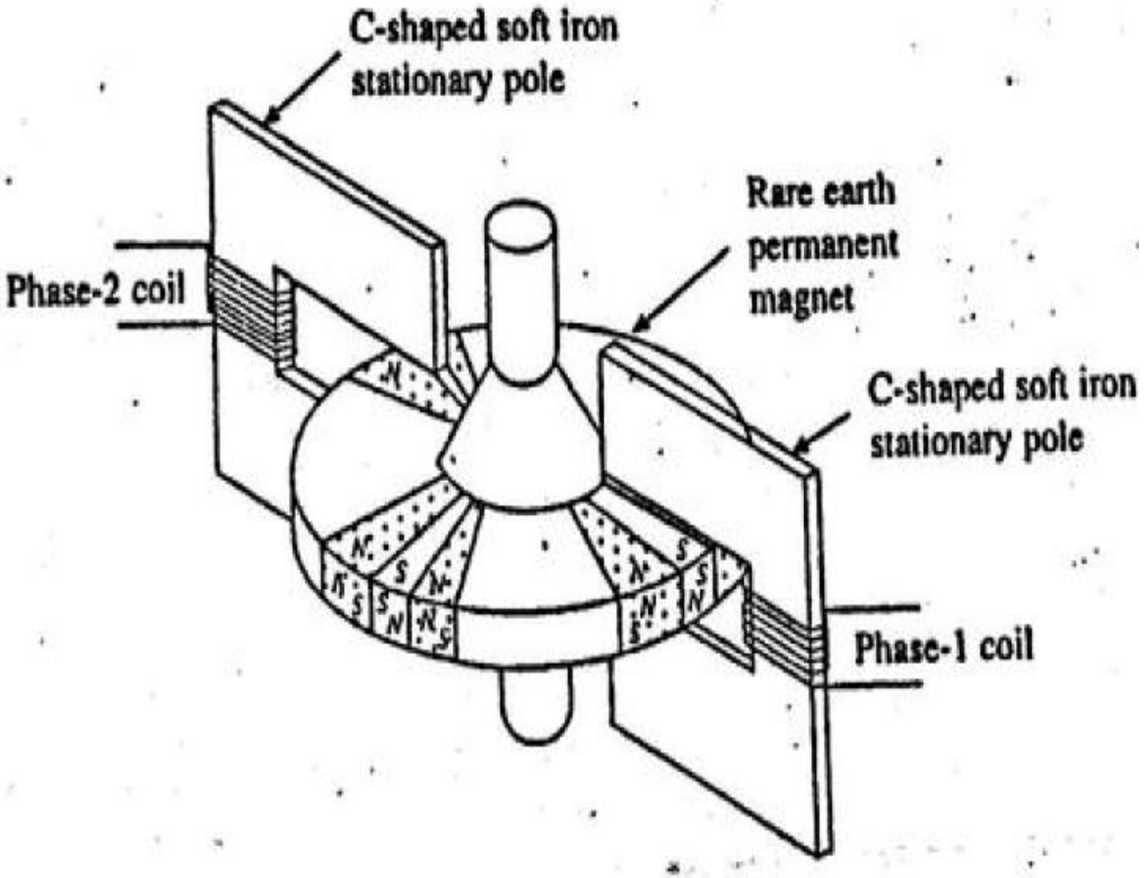


Fig. 8.6 Disk-type permanent magnet stepper motor.

Hybrid Stepper Motor

It combines the important features Of variable reluctance and permanent magnet motors. This is achieved by incorporating an axial permanent magnet in the middle of the rotor, whose construction is somewhat similar to the rotor of a variable reluctance motor.

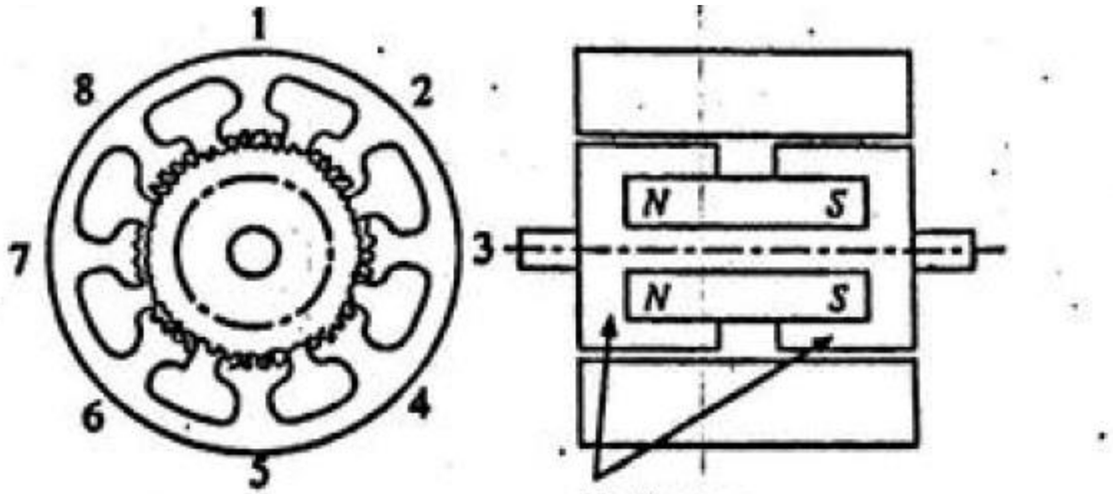


Fig. 8.7 Hybrid stepping motor with 200 steps per revolution

Advantages of Hybrid Stepper Motor

- The length of the step is smaller.
- It has greater torque.
- Provides Detent Torque with the de-energized windings.
- Higher efficiency at lower speed.
- Lower stepping rate.

Disadvantages of Hybrid Stepper Motor

- Higher inertia.
- The weight of the motor is more because of the presence of the rotor magnet.
- If the magnetic strength is varied, the performance of the motor is effected.
- The cost of the Hybrid motor is more as compared to the Variable Reluctance Motor.

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Torque Vs Stepping(or Pulsing) rate Characteristics of a Stepper Motor

Impt

- The **Torque pulse rate Characteristics** of a Stepper Motor gives the variation of an electromagnetic torque as a function of stepping rate in pulse per second (PPS).
- There are two characteristic curves 1 and 2 shown in the figure below.
- **Curve 1** is (blue colour line is)- known as the **Pull-in torque**.
- It shows the maximum stepping rate for the various values of the load torque at which the motor can start, synchronise, stop or reverse.
- **Curve 2** (Red colour line) - is known as **pullout torque characteristics.**

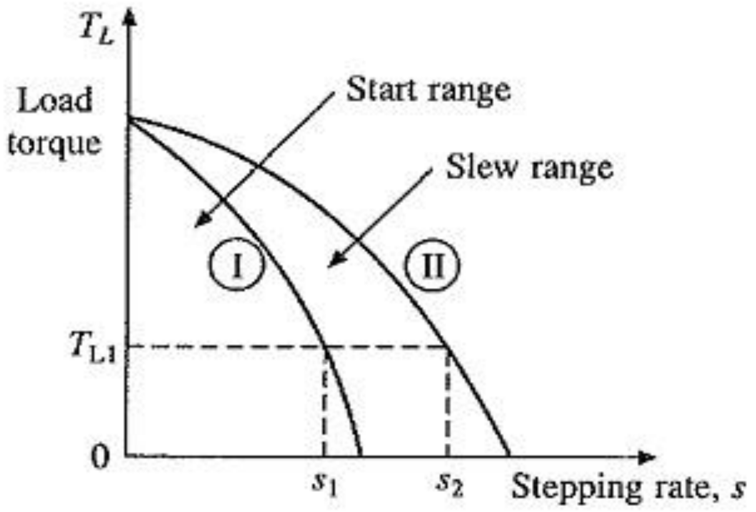


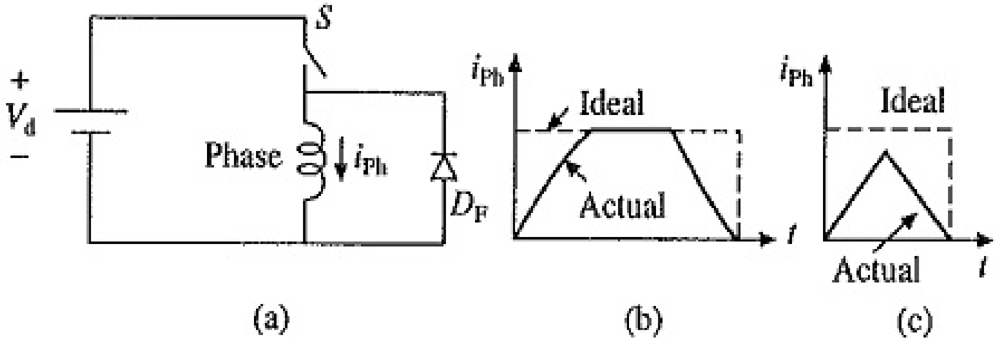
Fig. 8.8 Torque-stepping rate characteristics

- If the pulse rate is less than S_1: The motor can start, synchronise and stop or reverse for the load torque TL1
- The stepping rate can be increased for the same load as the rotor started the rotation and synchronized.
- The stepping rate can be increased up to S2: synchronising, without losing the synchronism, for the load TL1.
- If the stepping rate is increased beyond S2: the motor will lose synchronism.
- Thus, the area between curves 1 and 2 represents the various torque values, the range of stepping rate, which the motors follow without losing the synchronism.
- This is known as **Slew Range** and motor operate in slewing mode.

Drive Circuits for Stepper Motor

Impt

- A Drive Circuits for Stepper Motor is usually driven from a low voltage dc source.
- When a phase is to be energised, the dc source is connected to the phase by a semiconductor switch S
- The phase current builds up at the rate decided by the phase winding's electrical time constant.



Drive circuit requirement

- When the phase is to be de-energised, switch is turned off, which transfers the current to freewheeling diode D_F.
- The current drops to zero, again at the rate decided by the time constant of the phase winding.
- Motor torque, which is a function of i_{ph}, builds up and decays in the same manner.
- In order to maximize torque capability of a stepper motor, current builds up and decay as fast as possible, ideally as shown by dotted lines in Fig. (b).
- This is specially important when high stepping rates are required, as demonstrated in Fig. (c). The Drive Circuits for Stepper Motor are designed to incorporate this requirement.

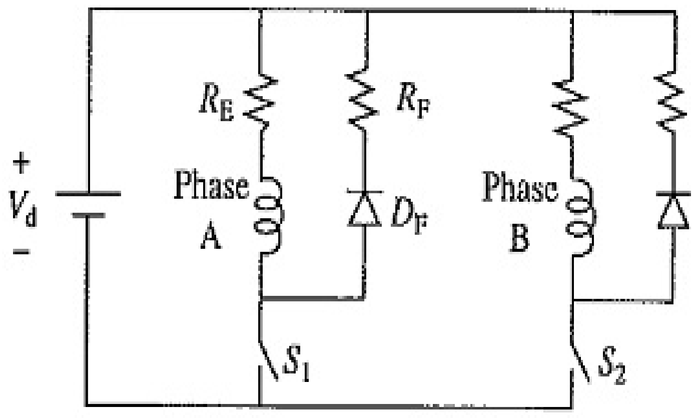
Unipolar Drive for Variable Reluctance Motors

Impt

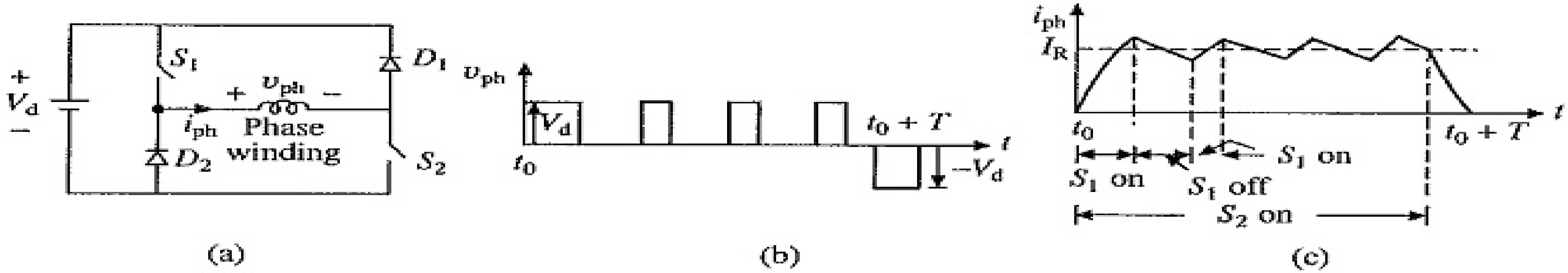
- In case of variable reluctance motors, phase currents need only be switched on or off and the current polarity does not matter.
- Unipolar drive, which is capable of supplying current only in one direction, is sufficient.
- Unipolar drive circuit for low power two phase variable reluctance motor is shown in Fig.
- When switch S_1 is closed, phase A winding is connected to the dc source V_d and the phase current builds up
- When S1 is opened, the phase current decays in the freewheeling path consisting of phase A, D_F and R_F.
- The external resistor R_E reduces the electrical time constant, speeding up the current build-up.

$$V_d = I_R(R_E + R_P)$$

- During on period of the switch, phase current also flows through the external resistor R_E, energy dissipated in R_E.
- Further, energy stored in the phase winding inductance during the on period of the switch is all dissipated in free-wheeling circuit resistances when the switch is turned off.



Unipolar drive circuit for a low power variable reluctance motor



Efficient unipolar drive for variable reluctance motor

(a) (b) and (c) show drive circuit, phase voltage and current waveforms respectively

- An efficient unipolar drive circuit is shown in Fig. It uses chopper principle.
- To energise the phase, semiconductor switches S1 and S2 are closed at t = to.
- This connects phase winding to the dc source voltage Vd and phase current iph builds up fast.
- When it crosses the rated current $I_{R,}$ S1 is switched off.
- The phase current freewheels through S2 and D2 and decreases below I_R.
- After a fixed interval, S1 is turned on. Phase current iph increases.
- When it exceeds the rated current IR, again S1 is turned off.

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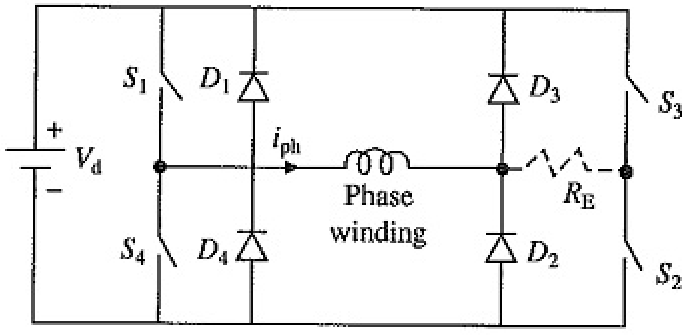
Bipolar Drive for Permanent Magnet and Hybrid Motors

- The phase winding carries a positive current when semiconductor switches S1 and S2 conduct and it carries a negative current when S3 and S4 conduct.
- The phase winding is energised with a positive current when S1 and S2 are turned on.
- The external resistance RE reduces the electrical time constant allowing rapid build-up of phase current.
- The phase is de-energised by turning off S1 and S2. Winding current now flows through the path consisting of D3, source Vd and D4.
- The major proportion of energy stored in phase winding inductance is fed back to the source and phase current decays rapidly to zero.



Bipolar drive circuit

Theory- Self Study portions

Industrial Drives:

Textile Mills, Steel Rolling Mills, Cranes and Hoists, Machine Tools

Sinusoidal PMAC Motor

- Since the voltages induced in the stator phases of a sinusoidal PMAC motor are sinusoidal, ideally, the three stator phases must be supplied with variable frequency sinusoidal voltages or currents with a phase difference of 120° between them.
- Consider the behavior of drive fed from a variable frequency current source.

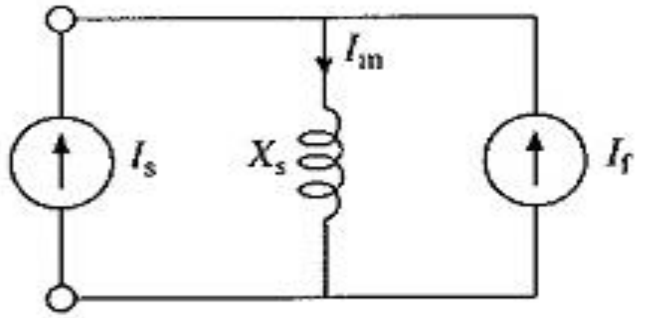


Fig. is the Norton's equivalent of the synchronous motor.

$$\bar{I}_f = \frac{\bar{E}}{jX_s} = \frac{E}{X_s} \angle -(\delta + \pi/2)$$

$$\bar{I}_m = \bar{I}_s + \bar{I}_f$$

The phasor diagram of the motor with I_s as a reference phasor is shown in Fig. The mechanical power developed is

$$P_m = 3EI_s \cos(\delta' - \pi/2)$$

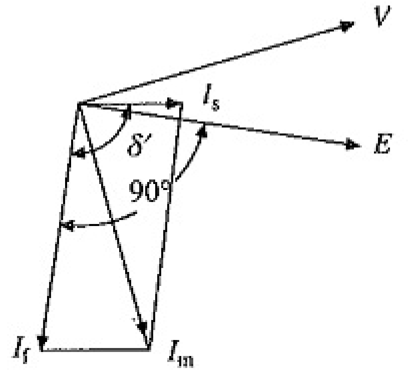
$$P_m = 3X_s I_s I_f \sin \delta'$$

$$T = \frac{P_m}{\omega_{ms}} = K I_s I_f \sin \delta'$$

where $K = 3X_s / \omega_{ms}$ = constant.

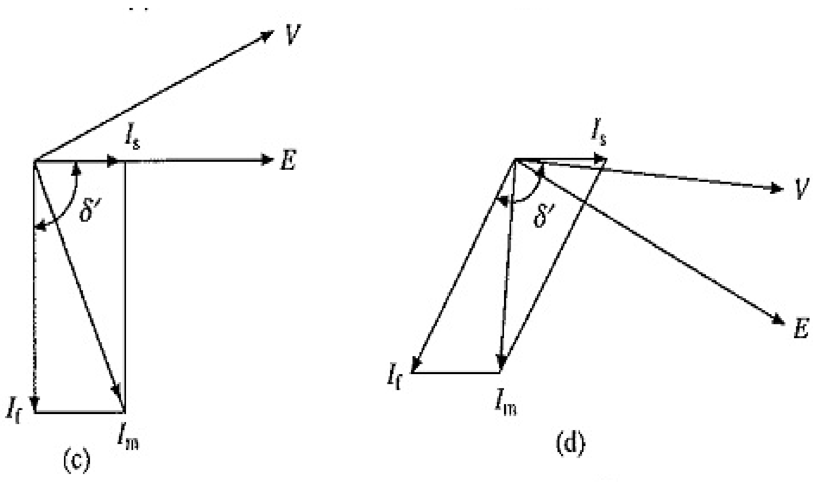
$$\delta' = \pm 90°$$

$$T = \pm K I_f I_s = \pm K_T I_s$$



For a given value of I_s, maximum torque is obtained when $\delta' = \pi/2$. Phasor diagram for $\delta' = \pi/2$ is shown in Fig.

- In this condition, the motor is said to operate with unity internal power factor because I_s is in phase with E.
- The motor itself has a lagging power factor. It is desirable to obtain maximum torque, which is the preferred operating condition



- Similarly in braking operation, maximum torque per unity of stator current is obtained when $\delta' = \pi/2$, hence this is the preferred operating condition for braking operation.
- In wound field motors, the operation up to the base speed is obtained by varying both voltage and frequency.
- The speed control above the base speed is obtained by reducing the air-gap flux so that rated motor terminal voltage is maintained by increasing frequency.
- Fig. (d); At $\delta = 90°$, Is is in quadrature with I_f
- For $\delta' > 90°$, Is can be resolved into two components, one in quadrature with I_f and another in phase opposition to I_f, which causes reduction in I_m and air-gap flux.

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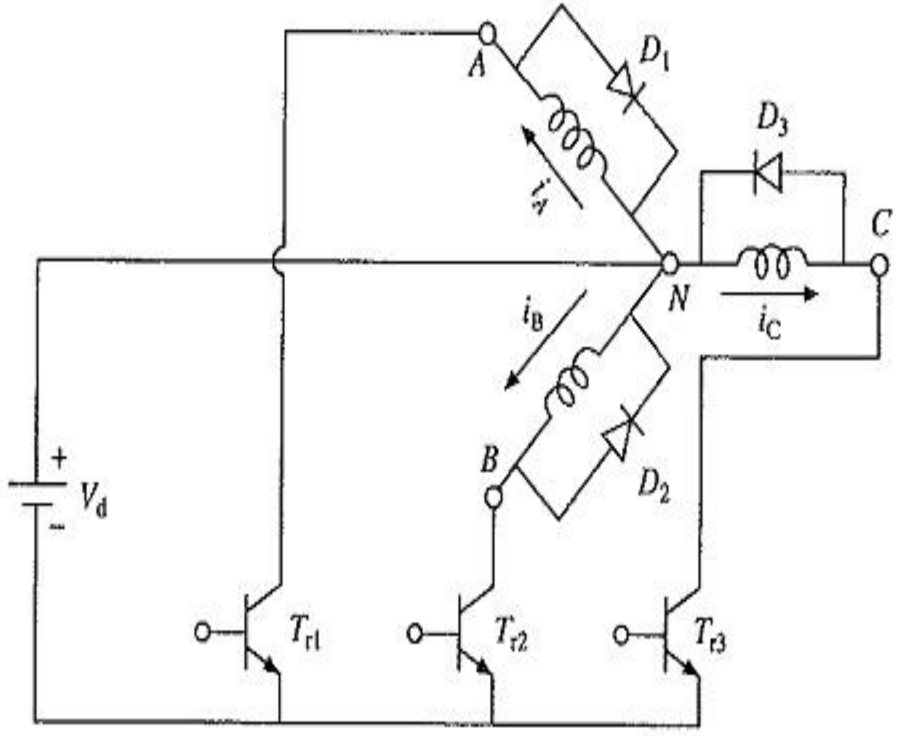
Self study

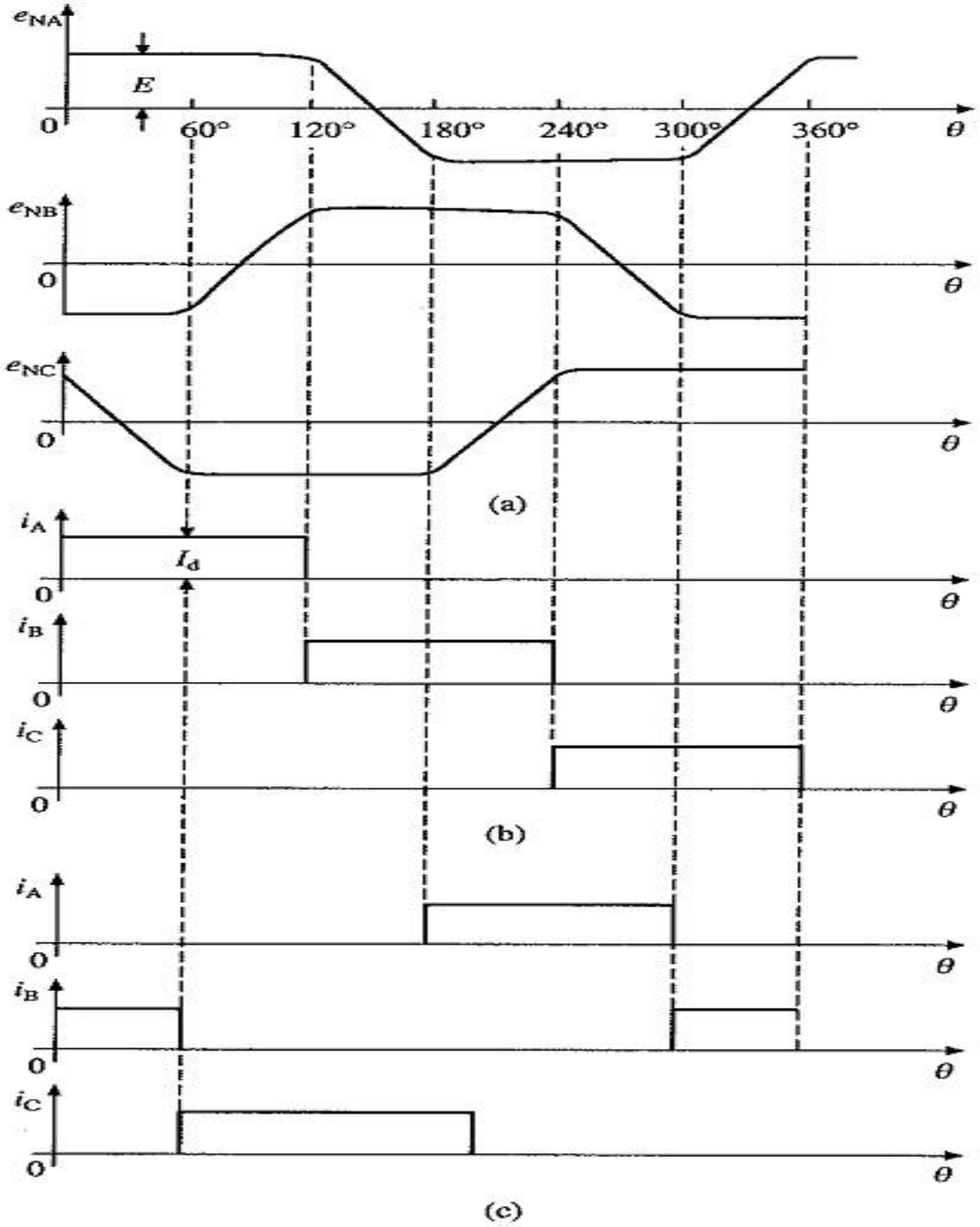
Low Cost Brushless DC Motor Drives

- The drive is simplified substantially, resulting in simpler control and substantial reduction in cost.
- While three phase machines are used in majority applications, single phase and four phase machines are also employed.
- Similarly wide variety of converters/inverters is used.
- The motors are fed by current pulses and also by voltage pulses with a current limit only to make sure that the current does not exceed ratings of converter and motor.
- A low cost drive employing a 3-phase trapezoidal PMAC motor is shown in Fig.
- It employs only three transistor and three diode converter, which can supply only positive currents or voltages to three motor phases.



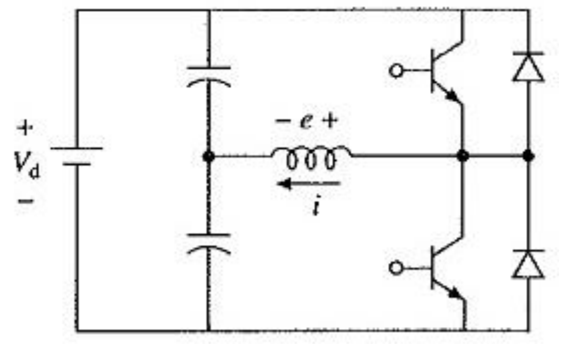
A low cost-three phase brushless dc motor drive

- Induced voltages and current supplied for motoring and braking operations are shown in Fig.
- When 120° positive current pulses as shown in Fig. (b) are supplied to the motor, motoring operation is obtained in counter clockwise direction.
- When these pulses are shifted by 180°, as shown in Fig.(c), braking operation is obtained.
- Motoring and braking operations for clockwise rotation is obtained by timing the pulses as shown in Fig. (c) and (b), respectively.
- Each phase is essentially supplied by a chopper.
- The phase NA current is controlled by Tr1 and D1.
- When Tr1 is on source Vd is connected across winding NA and rate of change of iA is positive.



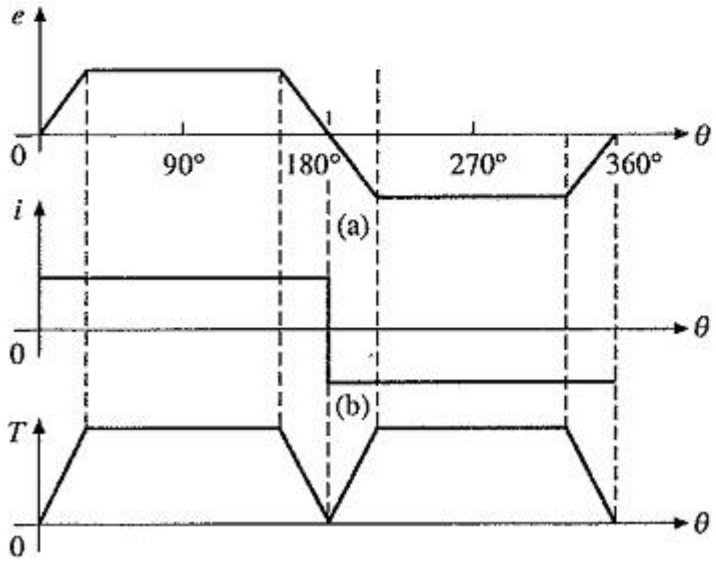
A low cost three-phase brushless dc motor drive

- When Tr1 is turned off, current iA freewheels through diode D1 and rate of change of iA is negative.
- Thus during the period for 0° to 120°, Tr1 can be alternately turned on and off so that current iA is made to follow a rectangular reference current i*A within a hysteresis band.
- A single concentrated phase winding with a spread of 60° on either side.
- Let θ be measured from the instant when the axis of phase coincides with the axis of the rotor pole, then the voltage induced in the phase winding will have waveform as shown in Fig.
- Let the motor be supplied from a half bridge single phase converter shown in Fig. (d)



(d)

- with a rectangular current waveforms shown in Fig.
- Then the torque produced by the motor will have waveform shown in Fig. (c).
- Although the torque has a large ripple, when running at high speeds the torque ripple will be filtered out by the inertia of motor load system, giving a uniform speed.



(c)

End of Module-5