Module 5

Synchronous Motors cntd
Stepper Motor Drives
Industrial Drives

Syllabus:

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,

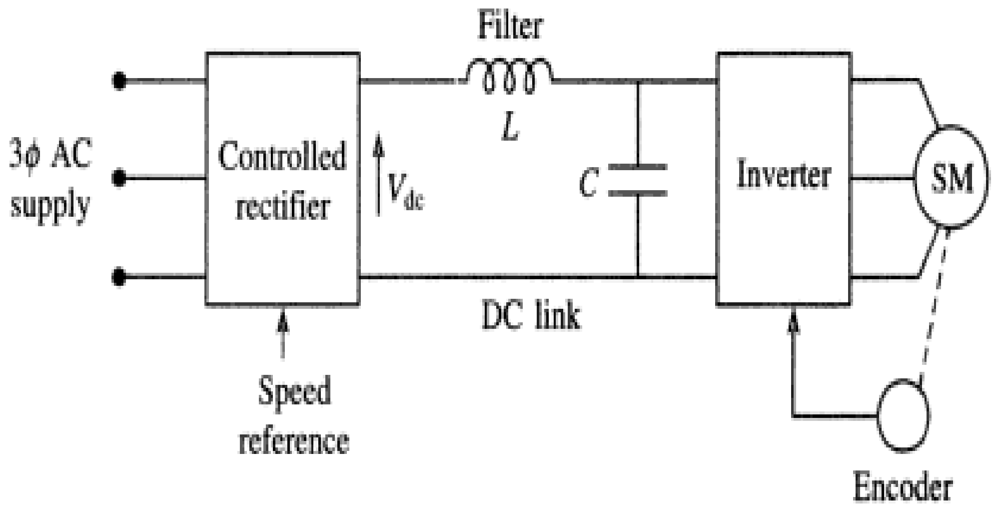
Torque Versus Stepping rate Characteristics,

Drive Circuits for Stepper Motor.

Industrial Drives:

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

Self Controlled Synchronous Motor



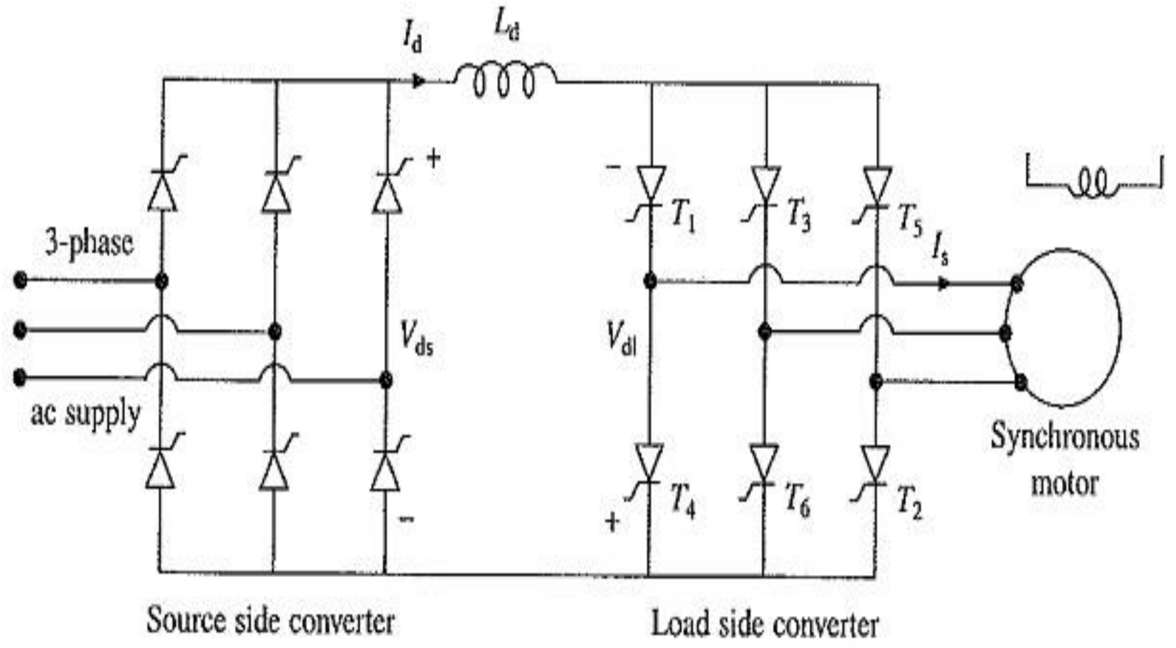
- The block diagram of a self controlled motor fed from a 3 phase inverter is shown in below Fig.
- The inverter may be a CSI or VSI. Depending on the type of inverter, the input dc source may be a controllable current source or controllable voltage source
- The inverter output frequency is determined 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.
- 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.

Self-controlled synchronous motor drive employing load commutated thyristor inverter

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**



Self-controlled synchronous motor drive employing load commutated inverter

1. Source side converter

- The source side converter-is a 6-pulse line-commutated thyristor converter.
- For a firing angle range $0 \leq \alpha_s \leq 90^\circ$, it works as a line-commutated fully controlled rectifier delivering positive V_{ds} and positive I_d,
- For firing angle range $90^\circ \leq \alpha_s \leq 180^\circ$, 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.
- 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

2. Load Side Converter

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

$0 \leq \alpha_s \leq 90^\circ$, $90^\circ \leq \alpha_l \leq 180^\circ$ 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
$90^\circ \leq \alpha_s \leq 180^\circ$ and $0^\circ \leq \alpha_l \leq 90^\circ$,	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 $\alpha_l = 0°$)

Constant Margin Angle Control:

- 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 $\gamma = \beta_l - u$

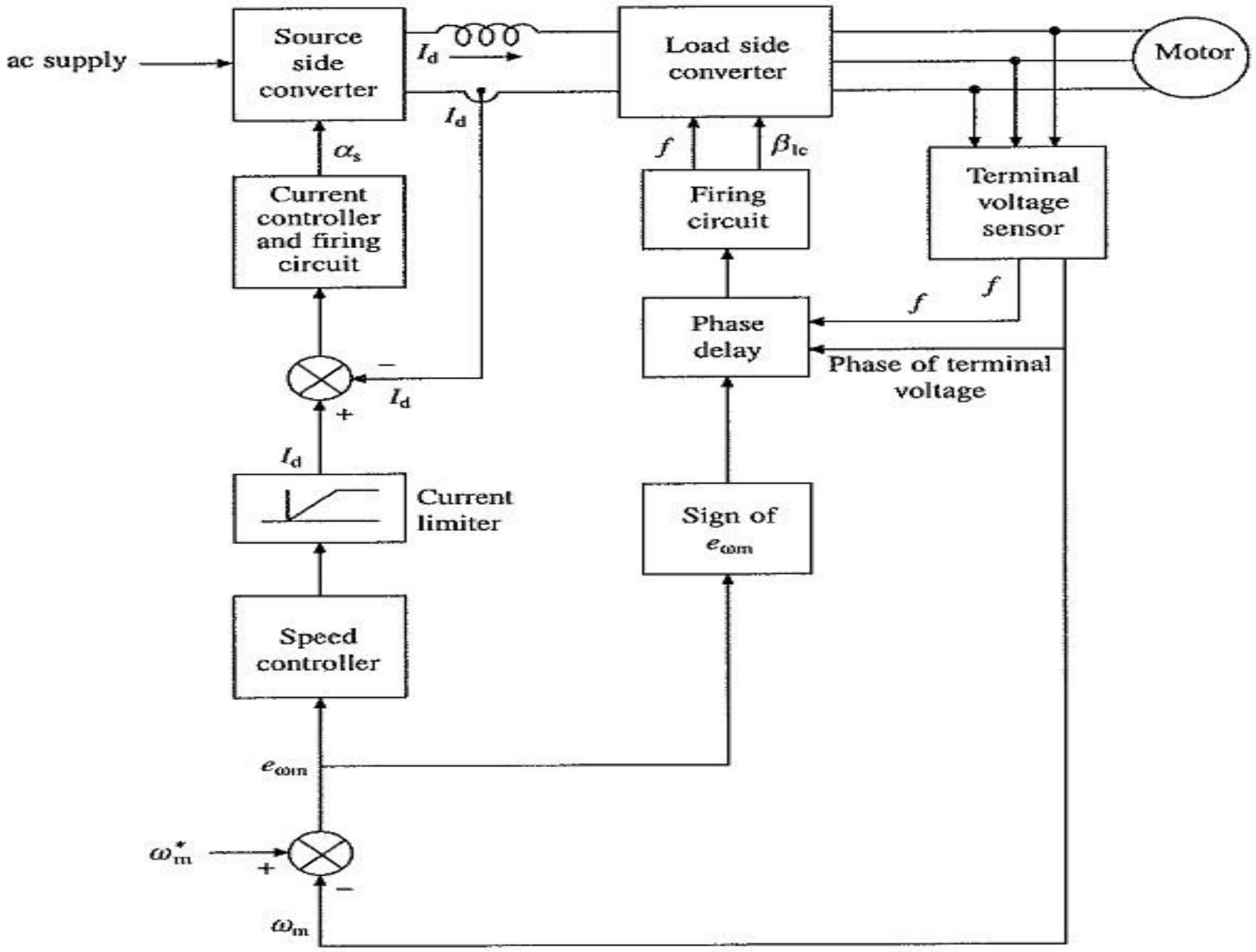
  Where, u-commutation overlap of the thyristor under commutation
- For successful commutation of thyristor: $\gamma > \omega t_q$

  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



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

- 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.
- 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.

Advantages of the drive:

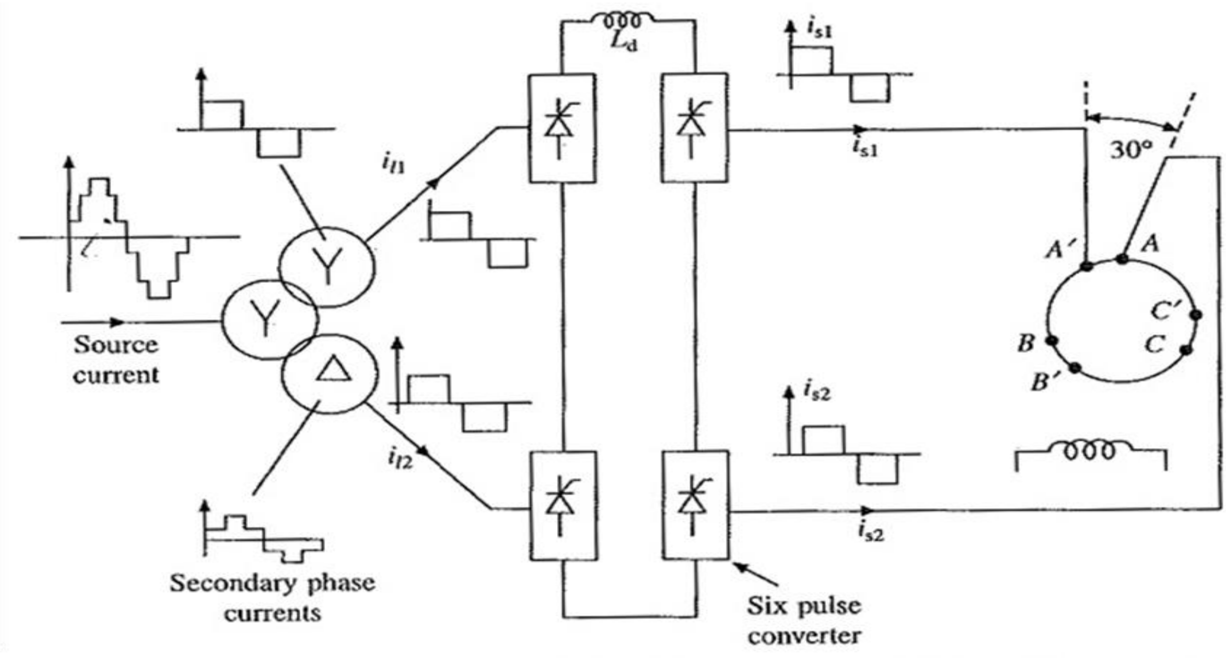
- ✓ High efficiency
- ✓ four-quadrant operation with regenerative braking,
- ✓ high power ratings (up to 100 MW)
- ✓ ability to run at high speeds (6000 rpm)

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.



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

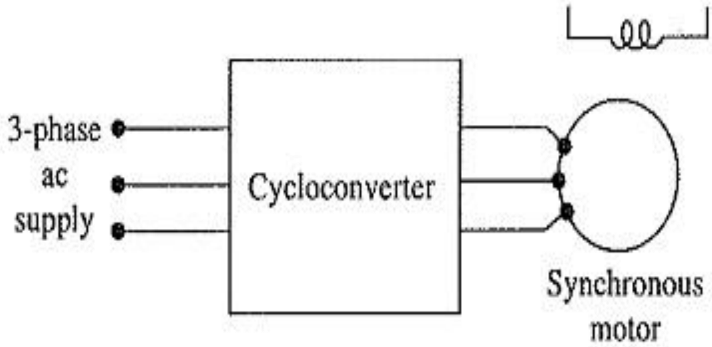
- The source side harmonics are reduced by using a 12-pulse converter.
- For this two six-pulse converters are connected in series.
- The supply for the converters is obtained through a transformer with primary-star and two secondary windings- one star connected feeds one six pulse converter and another 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.
- 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 Synchronous Motor Drive Employing a Cycloconverter

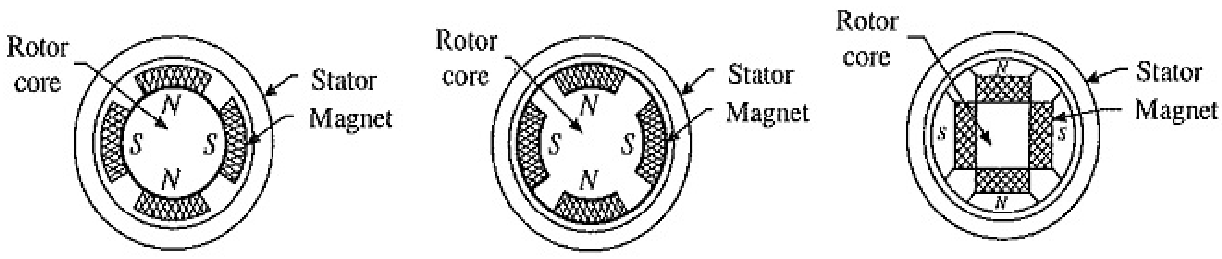


Self-controlled synchronous motor drive employing a cycloconverter

- 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.
- 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

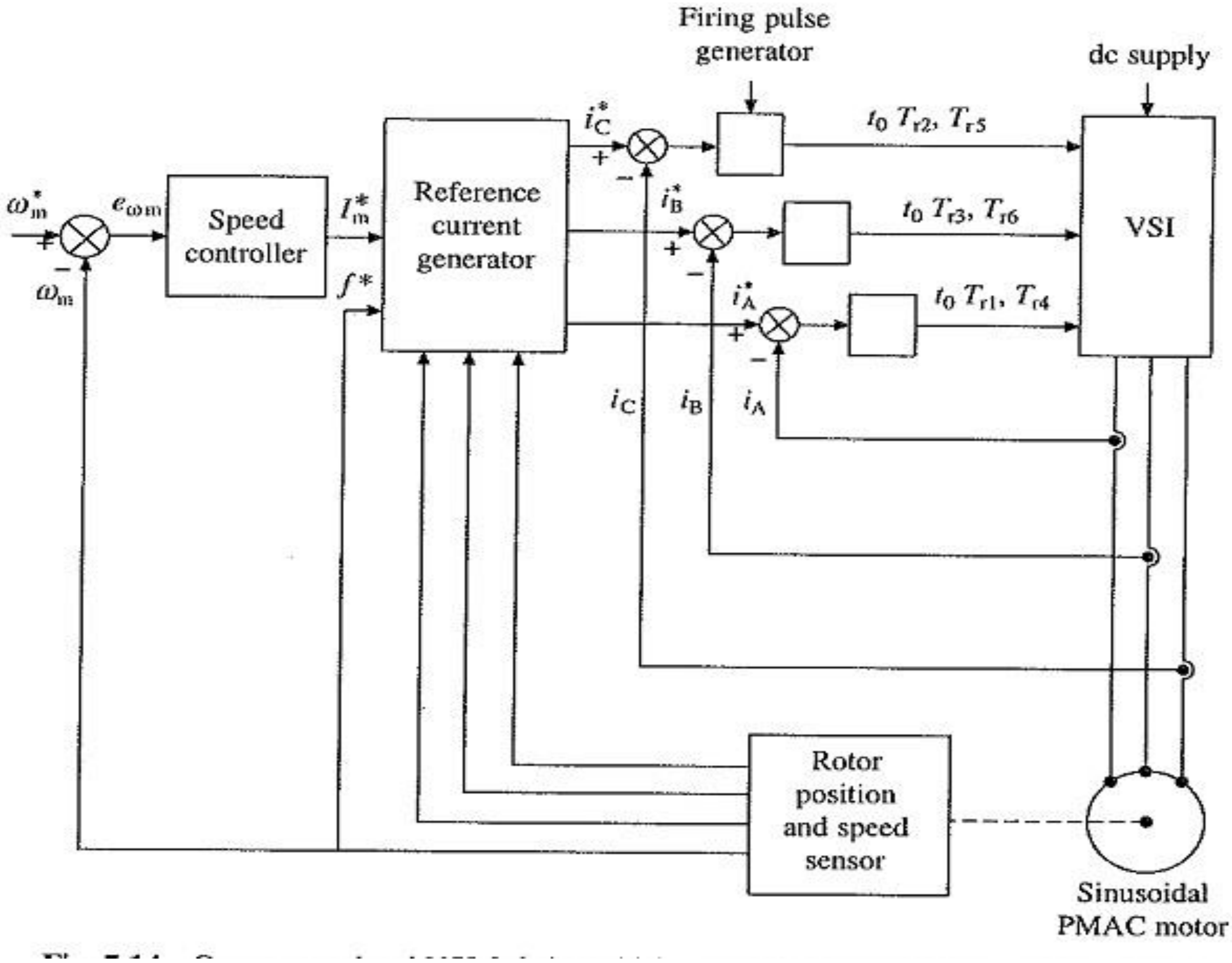
✓ has distributed winding in the stator.
✓ rotor geometries includes inset or interior shown in Fig.
✓ Rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform.

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)

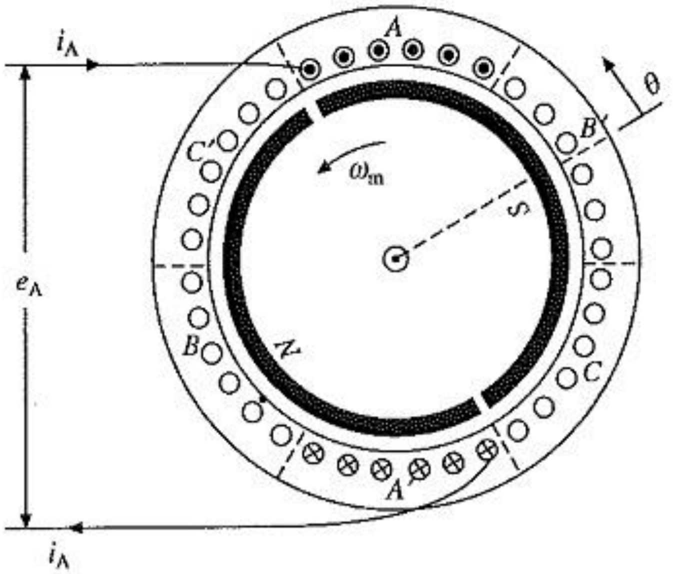


Fig 1 Cross Section of Trapezoidal PMAC Motor

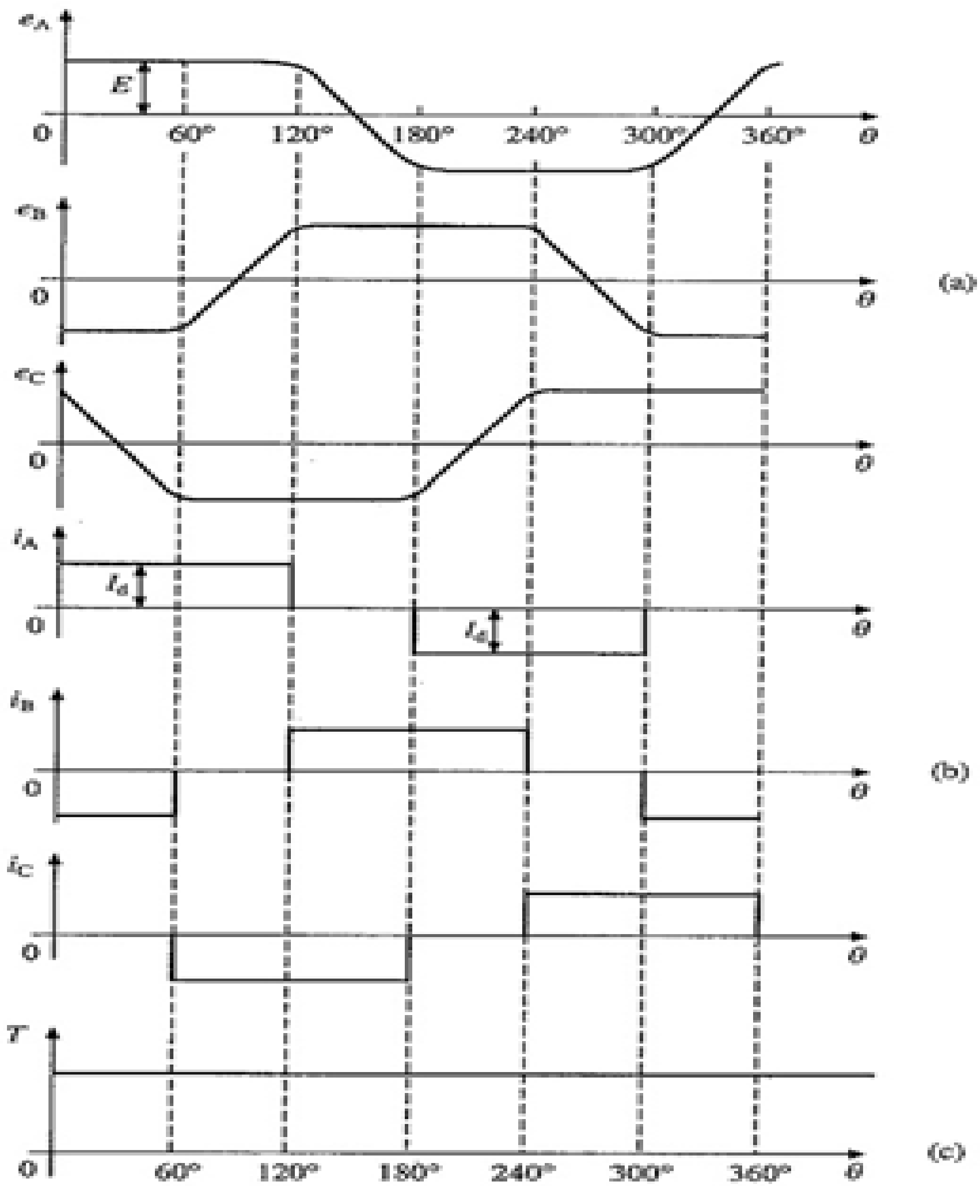


Fig. 2 Induced voltage, phase current and torque wavefors of a brushless dc motor

- 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.
- 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

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.

Brushless DC Motor Drive for Servo Applications

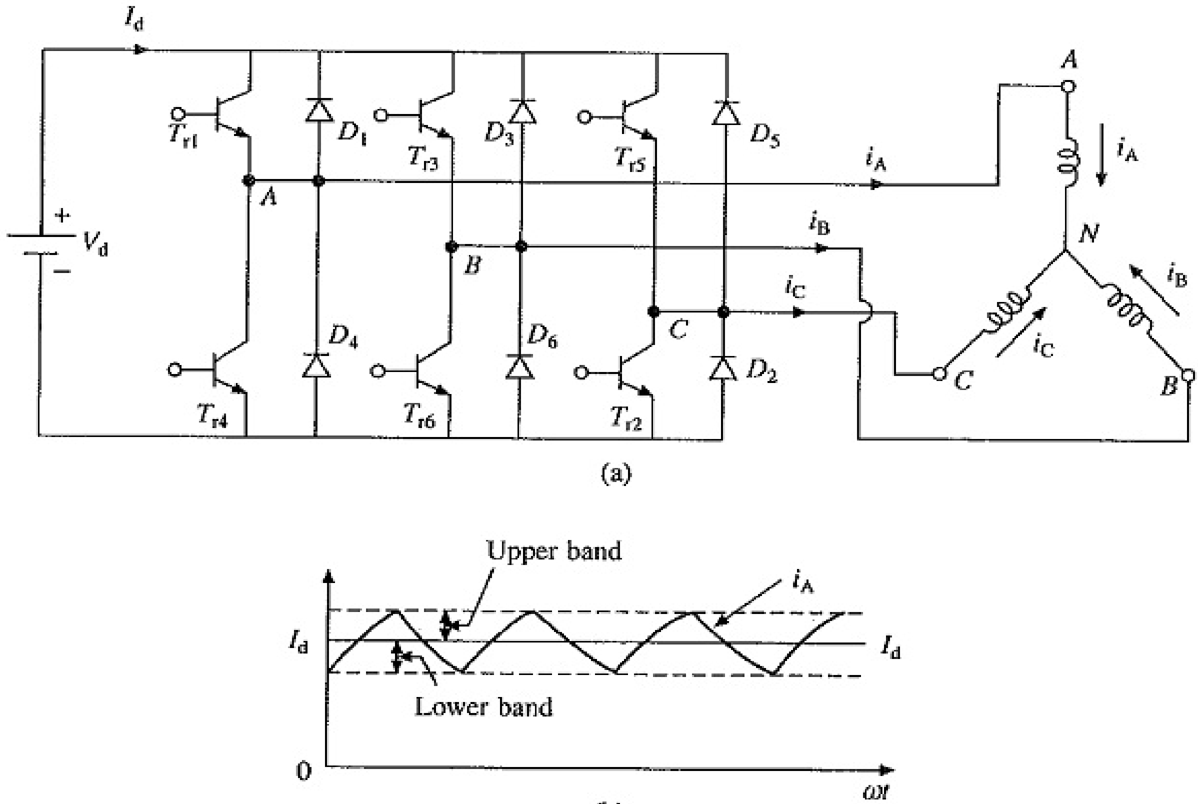


Fig. 3 Trapezoidal PMAC motor fed from a current regulated voltage source inverter

- 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)
- 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

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

The waveform of torque is shown in fig.below

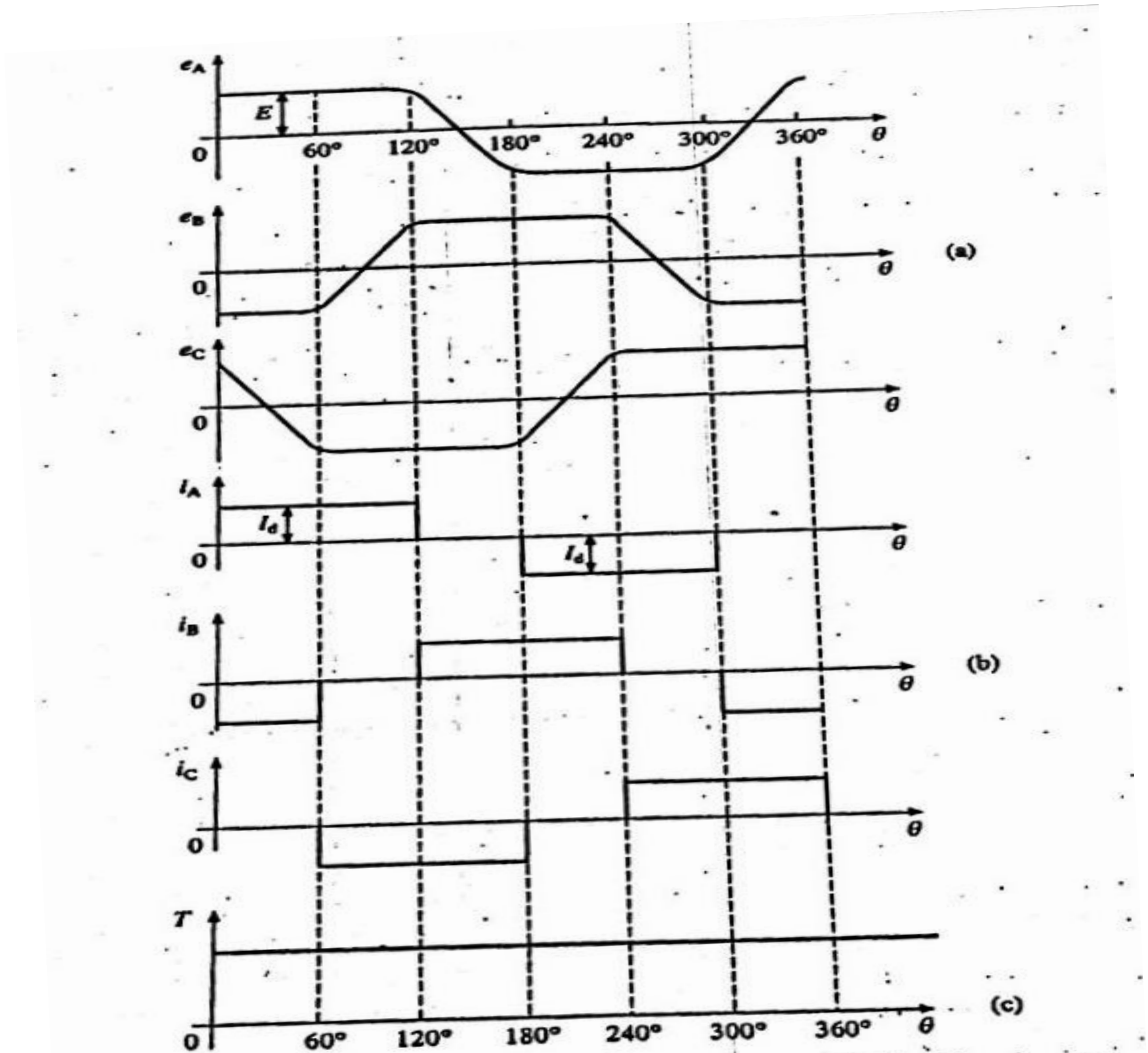


Fig. 7.17 Induced voltage, phase current and torque wavefors of a brushless dc motor

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.
- 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.

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

Defn: 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:

Advantages of stepper Motor

- 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

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

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

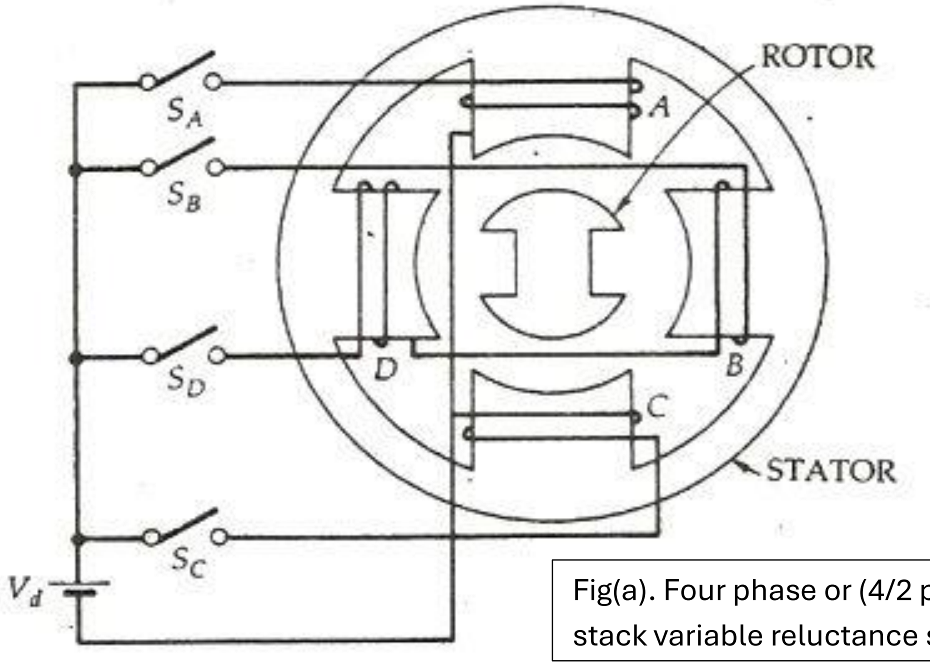
- **Definition: Step angle** is defined as the angle which the rotor of a stepper motor moves when one pulse is applied to the input of the stator.
- The positioning of a motor is decided by the step angle and is expressed in degrees.
- The resolution or the step number of a motor is the number of steps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

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

Variable reluctance stepper motor

1. 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

- 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.
- 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.

Example: A four-phase, 8/6 pole, single-stack variable reluctance motor

- 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.

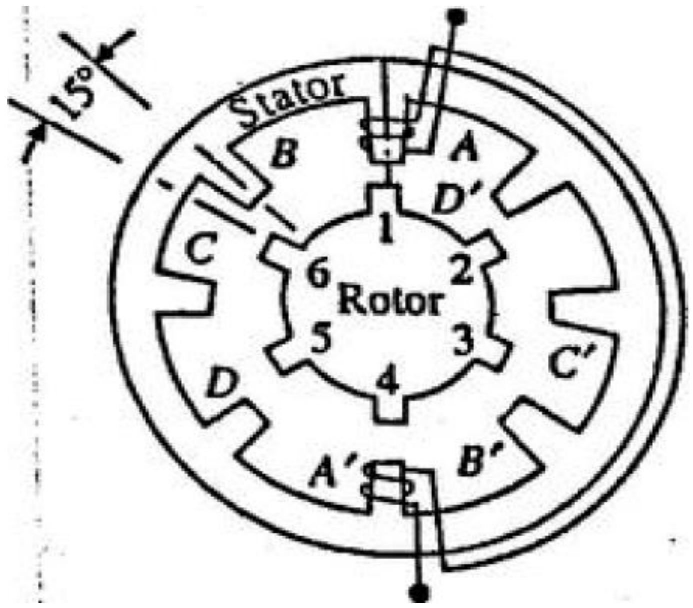


Fig. 8.2 Four-phase 8/6-pole variable reluctance motor

- 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.

2. Multi Stack or m stack variable reluctance stepper motor

- 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.

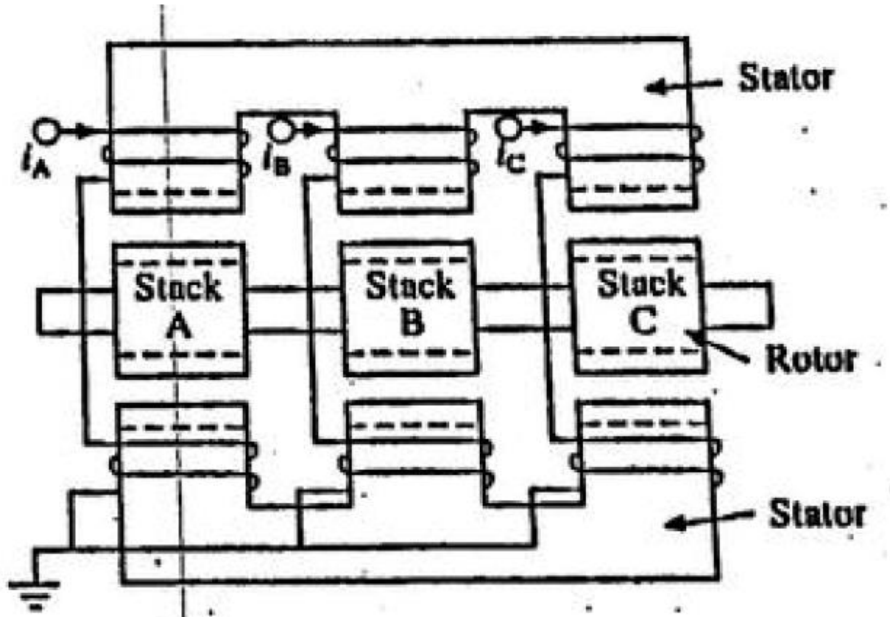


Fig. 8.3 Cross section of a three stack variable reluctance motor parallel to the shaft.

- 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).

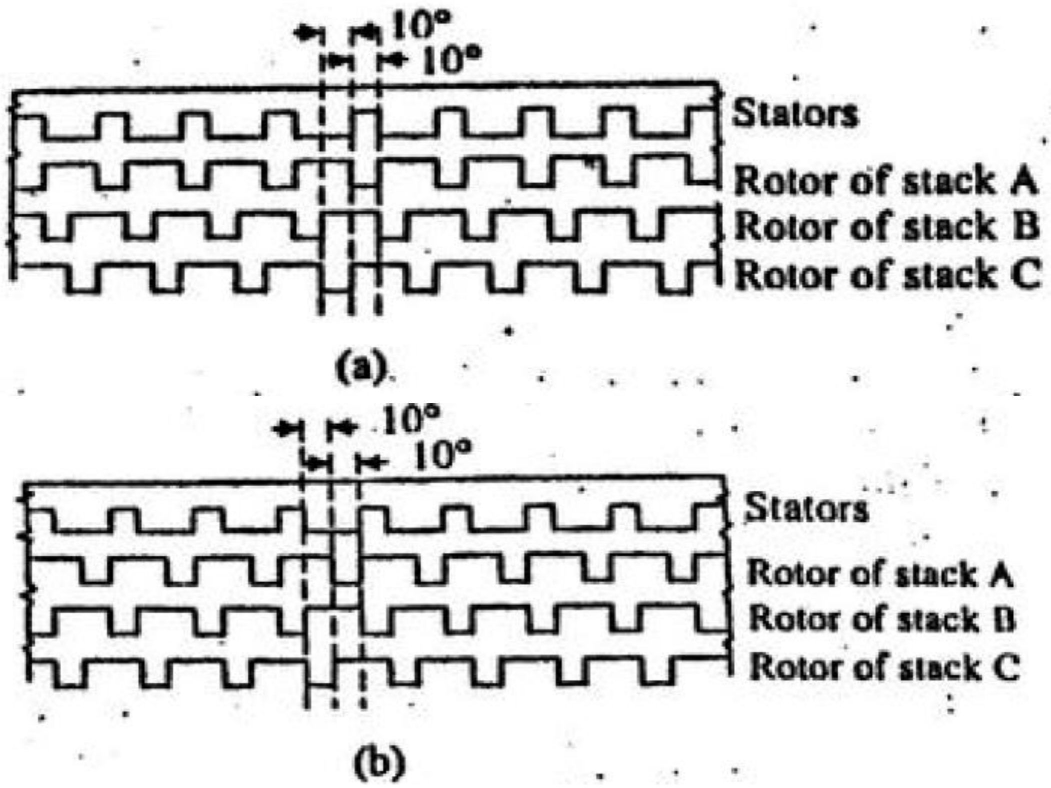


Fig. 8.4 Position of stator and rotor poles in a 3-stack variable reluctance motor: (a) Phase A is excited. Stator and rotor poles in stack A are aligned, (b) Phase B is excited. Stator and rotor poles in stack B are aligned.

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

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

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

- 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

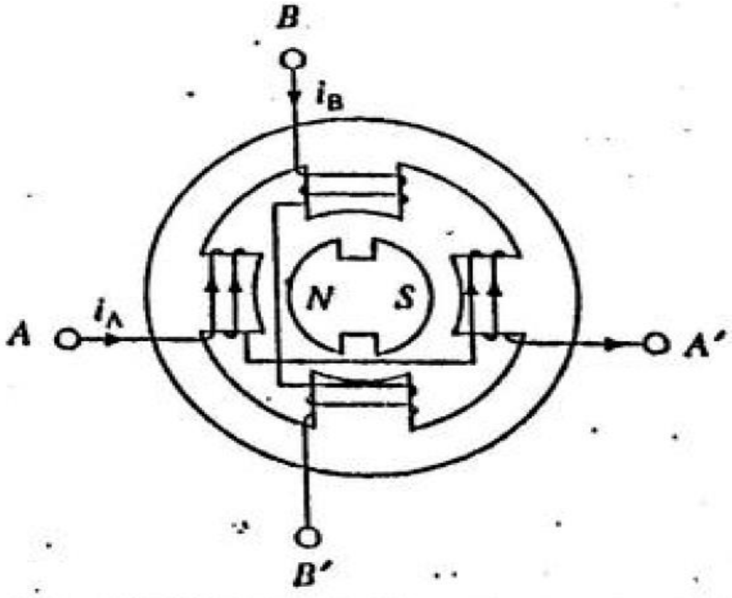


Fig. 8.5 Two-phase 4/2-pole permanent magnet stepper motor.

- 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.

i. 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.

ii. Disk-type of permanent magnet stepper motor

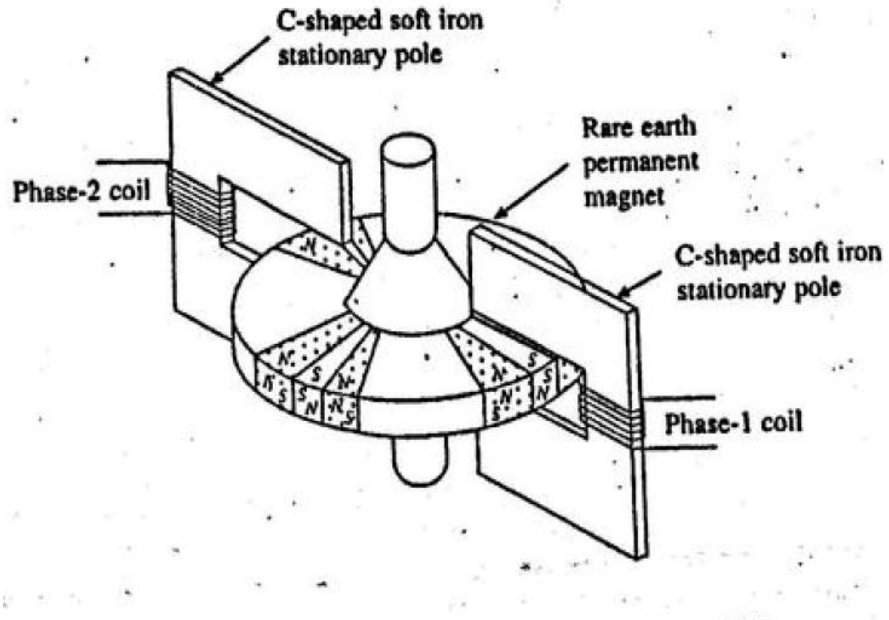


Fig. 8.6 Disk-type permanent magnet stepper motor.

- 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

iii. 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.

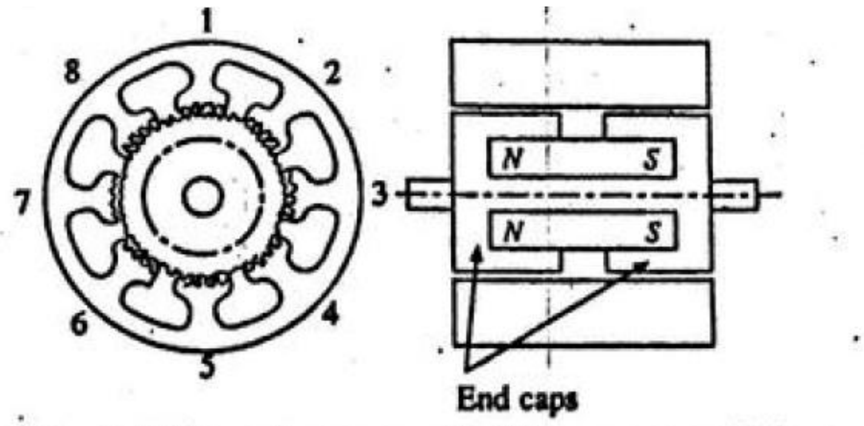


Fig. 8.7 Hybrid stepping motor with 200 steps per revolution

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.

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

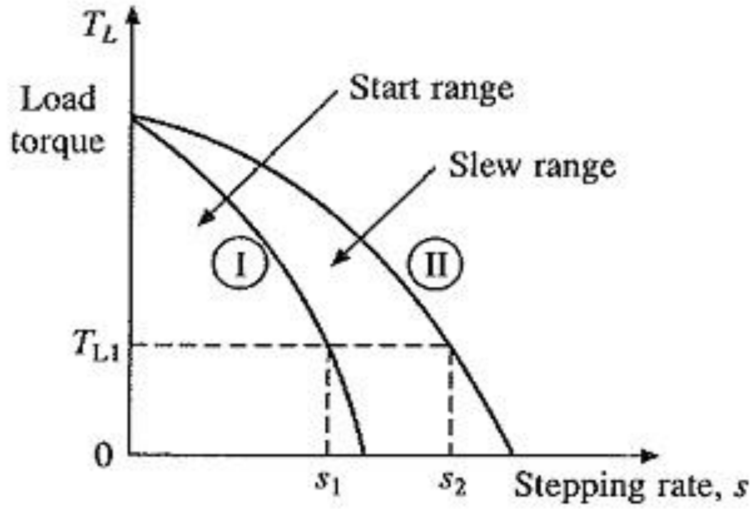


Fig. 8.8 Torque-stepping rate characteristics

- 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 I -** 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 II-** known as **pullout torque 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

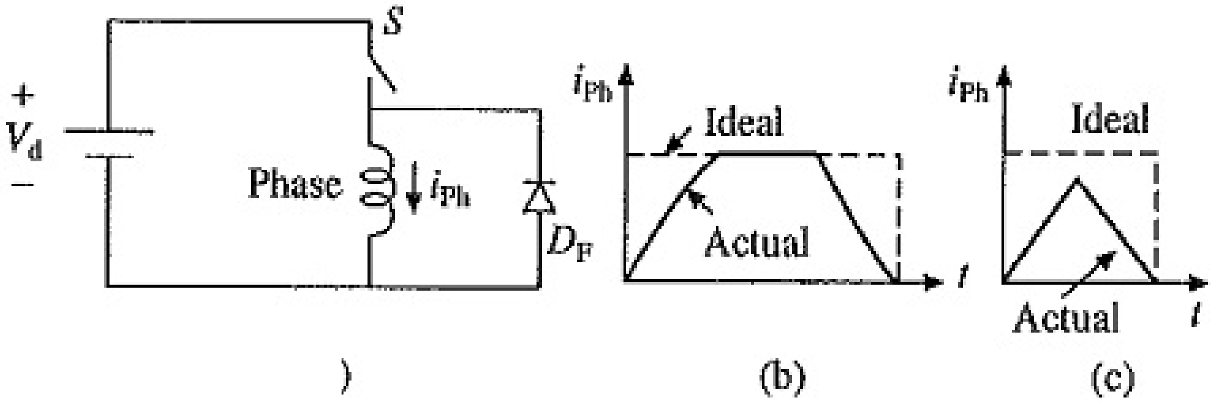


Fig. 8.9 Drive circuit requirement

- 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.
- 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.

i. Unipolar Drive for Variable Reluctance Motors

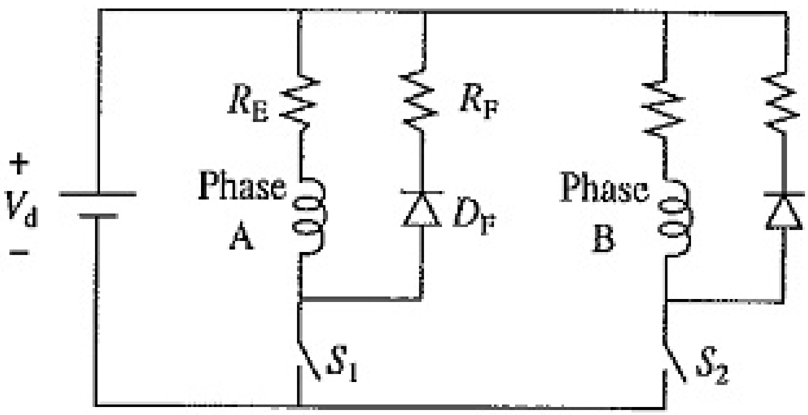
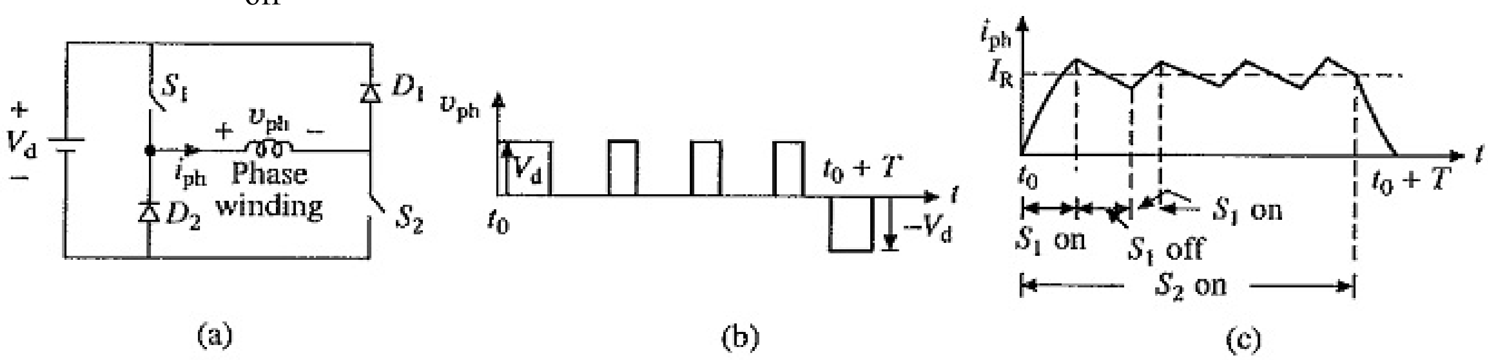


Fig. 8.10 Unipolar drive circuit for a low power variable reluctance motor

- 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

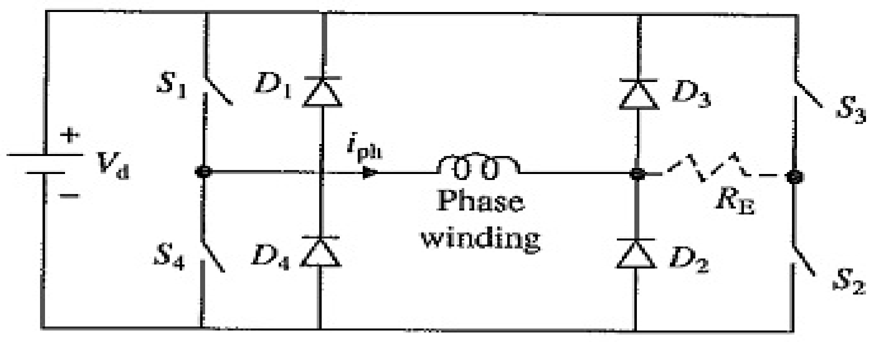


Efficient unipolar drive for variable reluctance motor

(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.

ii. Bipolar Drive for Permanent Magnet and Hybrid Motors



Bipolar drive circuit

- 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.

Industrial Drives for Applications

Drives requirement for Industrial Applications

1. The torque-speed curve of the industrial load is required. This fixes up the type of motor required to drive the load.

2. The environmental conditions in the industry where the motor is located. This also decides the ambient temperature at which the motor operates.

3. Duty cycle of the load, and the frequency of starting and braking.

4 The speed control needed also decides the type of motor.

5. The necessary information is required to decide between the individual and group drive.

6. To meet certain specific duties in a particular application special designs of the motors may be required.

Drive Considerations for Textile Mills

Ginning (separating): The process of separating seeds from the raw cotton picked from the field is called ginning.

Blowing: The ginned cotton in the form of bales is opened up and is cleaned up very well in a blowing room.

Cording -The process of converting cleaned cotton into laps (sheet form of definite width and length) is done by lap machines which are normal three-phase standard squirrel cage motors.

Control of ac Motors to have Torque Control

It is clear that the motors used for textile applications must have

i. high starting torque
ii. torque control providing uniform acceleration so that the breakage of the yam is minimum and the quality of the product is improved.

	Starting torque	Overload capacity	Acceleration	Speed range	Speed control method	Type of motor
1. Textile mills ginning	Standard	Standard		Operating speed range 200 to 1500 rpm. The operation is however at constant speed.	No speed control is required as the operation is at constant speed and load.	Standard TEFC squirrel cage motor.
Cording	High starting torque. 2.75 to 3.5 times rated value.	High overload capacity 3.75 to 3.00 times rated value.	Should be capable of prolonged acceleration as the starting period is large proper rating must be there for the motor due to losses at starting.	Operating speed is 600 rpm or 700 rpm. Constant speed operation.	No speed control.	Slip ring rotor with rotor resistance starting. High torque motors with DOL starting.
Spinning	150–200% of rated value	200– 275% of rated value.	Acceleration must be constant or uniform so that there is no breakage of thread.	Constant speed operation.	Two speed motors are preferred.	Ring frame motors.
Looms	2 to 2.3 times the rated torque.	2.3 to 2.7 times rated torque.	Frequent starts and stops.	Constant speed of operation.	No speed control.	Totally enclosed high torque squirrel cage motors 0.3 to 2.2 kW.

Table: Summary of requirements of motors for different industrial drives

Drives for Steel Rolling Mills

- Steel rolling mills are either hot rolled or cold rolled.
- These may be either reversing type or continuous type.
- The motors used for reversing mills need operation in both the directions of rotation.
- A four quadrant operation of the motor may be required.
- In the continuous type the motor rotates only in one direction.

i. <u>Reversing Hot Rolling Mills</u>:

- A wide range of speeds of operation is required.
- The direction of rotation must be reversible without causing serious disturbances to power handling circuits.
- High Reliability and accuracy.
- Ward Leonard control of dc motors is very much suitable here.
- Ac motors employing a variable frequency supply for speed control may be employed.
- The Cyclo-converter have advantages at very low speeds over the dc link converters.
- So, Cyclo-converter fed synchronous motors are used very commonly for driving steel mills, The converters facilitate four quadrant operation.

ii. <u>Continuous Hot Rolling Mills</u>

- When a mill has to produce billets of different sizes the gap between working rolls of the mill-stand must be adjustable.

- To be able to reduce the thickness of the metal gradually the motors of consecutive mill-stands must have differing speeds.
- The sag of the metal between two stands must be avoided.
- The dc motors controlled by Ward Leonard control, ac commutator motors and ac motors fed from thyristor converters may be advantageously employed here.

iii. Reversing Cold Rolled Mills

- The drive must be capable of reverse rotation. A four quadrant operation must be possible.
- One or two individually driven motors may be used.
- The coiling motors besides the driving coilers ensure the desired tension of the strip between the coilers and mill-stand.
- The gap adjustment must he made simultaneously with the reversing.
- The inertia of the motor must be kept low and lower than that of the rollers.
- Torque control as well as speed control must be possible to maintain constant tension
- of the strip.
- It is also limited by stability conditions of the motor. The armature current control may be employed beyond this limit.
- The acceleration of the drive must be uniform to avoid breaking.
- The motor selected for this purpose must have its torque developed, causing a smooth acceleration.
- It should be capable of four quadrant operation with smooth speed reversal. Torque control at different speeds must be possible.

iv. Continuous Cold Rolling Mills

- These work only in the forward direction and no reversing is required.
- The metal passes in one direction only in different stands till the product has the required thickness.
- The mill may be two high or four high.
- The coiler roller requires accurate torque and speed control.
- The strip tension must be constant and large.
- Low speed operation is required while threading the steel into the rolls.
- Immediately after the threading the speed of the motor must be increased.
- The thyristor power converters provide a variable frequency supply which can be used for speed control of ac motors. Both torque control and speed control are possible.
- For low speeds, cycloconverters can be used to give a smooth speed control.
- Thyristorized dc drives can be used in the place of Ward Leonard dc drives

Drive Considerations for Machine Tools

- The motors must be reliable and low cost, requiring less maintenance.
- They must be capable of speed control. Some applications may require operation at fixed speeds.
- Starting torque may vary from about 10% to 250% of full load torque depending upon the type of machine tool.

- The acceleration of the motor should be sufficiently fast to avoid motor heating during starting.
- The duty cycles are specified for the machine tool operations. The design of the machine tool depends upon the duty cycle.
- Peak loads of short duration may alternate with light load in certain operations. A smaller size motor may be selected if a flywheel is used.
- The motor should have sufficient speed regulation to make use of flywheel. High slip induction motors or cumulatively compound motors are used.
- Variable speed operation with constant torque at all speeds may be required in machine tools, such as grinder, planer, polishing, rapid reversing, etc. Variable speed operation with constant power also finds application.
- Some machine tools require very high speeds of operation. These are high speed grinders.
- Numerically controlled machine tools are being preferred to conventional machine tools.
- The requirements of the drive motor are fast response, wide range of speed control, low vibrations, better thermal capacity, low maintenance, etc. To have fast.
- Due to the simple, economical and robust construction, reliability and less maintenance, squirrel cage motors are suitable for driving machine tools.
- Till the advent of thyristor power converters which are capable of providing variable voltage, variable frequency supply, the speed control of these motors was a problem.
- Pole change multi speed motors are available when definite stepped speed operation is allowed.
- These connections are available for constant torque as well as constant power operation. They provide high and low speeds.

The motors for duty cycles S1-S6 are listed:

S1 -Hydraulic pump motors, lubrication pump motor, coolant pump motor.

S2 -Rapid transverse motor.

S3- Main motor for gear shaper, and for drilling machine.

S4- Main drive motor in lathes without clutch in the drive, work head motor in grinding machine, main drive motor in gear nobbing machine, coolant pump motor with frequent starting and stopping.

S5- Work head motor in grinding machine with electric braking.

S6- Main and feed drive motors with clutch in the drive.

Drive Considerations for Cranes & Hoist

- The motion of the crane hook is in all three dimensions.
- In crane drives, the acceleration and retardation must be uniform. This is more important than the speed control.
- For exact positioning of the load creep speeds must be possible.
- When the motion is in the horizontal direction braking is not a problem.
- The speed must be constant while lowering the loads. The steady braking of the motor against overhauling must be possible.

- The drive must have high speeds in both the directions. The motor must have high speeds at light loads.
- Mechanical braking must be available under emergency conditions.
- Power lowering may be used when an empty cage or light hooks are lowered.

The duty cycle of cranes depends upon some requirements. These are:

- it must be able to perform strenuous duty
- it must withstand high ambient temperature
- it must be able to work in a dusty atmosphere
- it must provide trouble free operation
- it should have rigid safety measures.
-

DC drive	*AC drive*
1. Fast acceleration and smooth speed control	All ac motors are not self starting
2. Speed-torque curve can be modified to suit the purpose in a simple manner with resistance in the armature or field circuit.	Induction motors are self starting. Squirrel cage motors require special designs for improved starting performance. Slip ring induction motors can be made to have improved starting performance by means of rotor resistance control.
They reduce the time cycle.	They have large time cycle.
3. Dc series motors have very high torque at low speeds particularly at zero speed, which is more attractive for crane operation.	
4. Frequent maintenance of the motor is required due to commutator	Less maintenance.
5. The drive motor and its control are costly	Squirrel cage motors are cheaper, simple in construction and robust.
6. Dc source is required. A rectifier may be used to convert ac to dc	
7. Inertia of the motor is high.	Inertia of cage motors is less.

Stages in Cement Production

The raw materials of cement are lime and silica. Alumina and ferric oxide are used as fluxing agents.

i. Collection of raw materials such as lime stone. This is transported to the mill site and crushed there if the quarry is far off. If the quarry is nearer it is crushed at the quarry itself and transported to the mill site.
ii. Grinding of this crushed lime stone after the addition with bauxite, iron ore, etc. By passing air through bottom the lime powder is homogenised
iii. This is fed to the cement kilns where the cement clinker is made at high temperature. The process where dry powder is used is called dry process.

iv. Wet processes of cement making are also popular. Here the slurry is made by crushing or grinding the lime stone, bauxite with water. This is then fed to the kiln through the kiln feed tank.

v. Dry process is preferred to wet process due to the reduced quantity of fuel required. However the latter becomes economical if the materials are already wet and drying them may not be economical.

vi. The hot clinker is then air cooled in special types of coolers and made ready for storage.

vii. After storing for a few days gypsum is added in required quantities and ground to the required fineness. Every stage has its own drive. Several drives in cement making are raw mill drives, cement mill drives, kiln drives, crusher drives, waste gas fan drives and compressor drives.

Requirement of Mill Motors

a. They should have high starting torque. The starting current must be limited to a maximum of two times full load value to minimise voltage dips. The breakdown torque should also be high so that sufficient overload capacity is available.
b. An overload capacity of 50% for one minute may be necessary, occurring for four times in an hour.
c. Three starts from cold conditions and two consecutive starts from hot conditions per hour against full load.

These are very well met by a three-phase slip ring induction motor. Suitable starting torques may be accomplished at reduced starting currents by means of rotor resistance. The motor must have sufficient thermal rating to have frequent starts both under cold as well as hot conditions. The power factor may be improved by capacitor bank.

Paper Mills

Process:

Paper making involves two main processes: pulp production and paper conversion.

Pulp is made either by a purely mechanical process or a combination of chemical and mechanical processes.

Purely mechanical pulp production involves grinding wood logs in large machines at a constant speed (200-300 rpm), often using synchronous motors with geared drives or cycloconverters.

Chemical and mechanical pulp production begins with chopping wood into smaller pieces, treating them with chemicals, and beating them into pulp using beaters. Suitable motors include slip ring induction motors for beaters and synchronous motors for processes like chipping and refining.

The paper conversion process includes several stages: wire (couch) section, pressing section, dryer, calender, and reel section.

Each section contributes to removing water from the pulp and forming it into sheets of paper, which are then wound up on a mandrel.

Paper making machine should satisfy the following requirements.

i. The speed of the paper machine must be constant in view of economy while forming the sheets of paper.
ii. A speed control range of 10:1 is required so that it is suitable for performing several jobs.
iii. The speeds of individual sections should be varied independently to allow an elongation of 5% of the web on the wet end of the paper. The quality of the paper is decided by this elongation. To allow free hanging of the web between sections, at the dry end of the paper a definite amount of tension is required and it must be regulated. The successive sections must be run at speeds with a definite difference. This relative speed between the sections also affects the pull on the paper. It must be regulated so that there is no tearing of the paper.
iv. The arrangement should be capable of taking up sag.
v. Even with correct speeds in the last two sections, uneven drying of the paper may cause variations in tension, which must be taken care of by suitable tension control.
vi. The motor must be capable of inching in order that the wire be cleaned up.
vii. Every section must be able to run at crawling speeds.
viii. The starting and acceleration of the sections must be smooth as well as. The starting system should be such that peaks of starting current may be avoided, besides obtaining sufficiently high accelerating torques for fast acceleration.