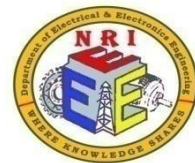




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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

SPECIAL ELECTRICAL MACHINES SEM

IV B. TECH II SEM EEE

BY

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SPECIAL ELECTRICAL MACHINES

SYLLABUS:

UNIT I:

PERMANENT MAGNET MATERIALS AND PMDC MOTORS

Introduction-classification of permanent magnet materials used in electrical machines-minor hysteresis loop and recoil line-Stator frames of conventional dc machines-Development of electronically commutated dc motor from conventional dc motor-Permanent-magnet materials and characteristics-B-H loop and demagnetization characteristics-Temperature effects: reversible and irreversible losses-high temperature effects-reversible losses-Irreversible losses recoverable by magnetization-Mechanical properties, handling and magnetization-Application of permanent magnets in motors-power density-operating temperature range-severity of operation duty.

UNIT II:

STEPPER MOTORS

Classification of stepper motors – Hybrid and Variable Reluctance Motor (VRM) - Construction and principle of hybrid type synchronous stepper motor – Different configuration for switching the phase windings control circuits for stepper motors – Open loop and closed loop control of 2-phase hybrid stepping motor. Construction and principle of operation of Variable Reluctance Motor (VRM) – Single stack and multiple stack – Open loop control of 3- phase VR Stepper Motor- Applications.

UNIT III:

SWITCHED RELUCTANCE MOTORS

Construction – Comparison of conventional and switched reluctance motors – Design of stator and rotor pole arcs – Torque producing principle and torque expression – Different converter configurations for SRM – Drive and power circuits for SRM – Position sensing of rotor – Applications of SRM.

SQUARE WAVE PERMANENT MAGNET BRUSHLESS DC MOTOR

Types of constructions – Surface mounted and interior type permanent magnet – Principle of operation of BLDC motor. Torque and EMF equations – Torque speed characteristics – Performance and efficiency- Square wave brushless motors with 1200 and 1800 magnetic areas commutation.

SINE WAVE PERMANENT MAGNET BRUSHLESS MOTOR

Torque and EMF equations – Phasor Diagram – Circle diagram – Torque/speed characteristics – Comparison between square wave and sine wave permanent magnet motors - Applications.

UNIT IV:

LINEAR INDUCTION MOTORS (LIM)

Construction– principle of operation–Double sided LIM from rotating type Induction Motor – Schematic of LIM drive for traction – Development of one sided LIM with back ironequivalent circuit of LIM.

PREREQUISITE:

Electrical machines

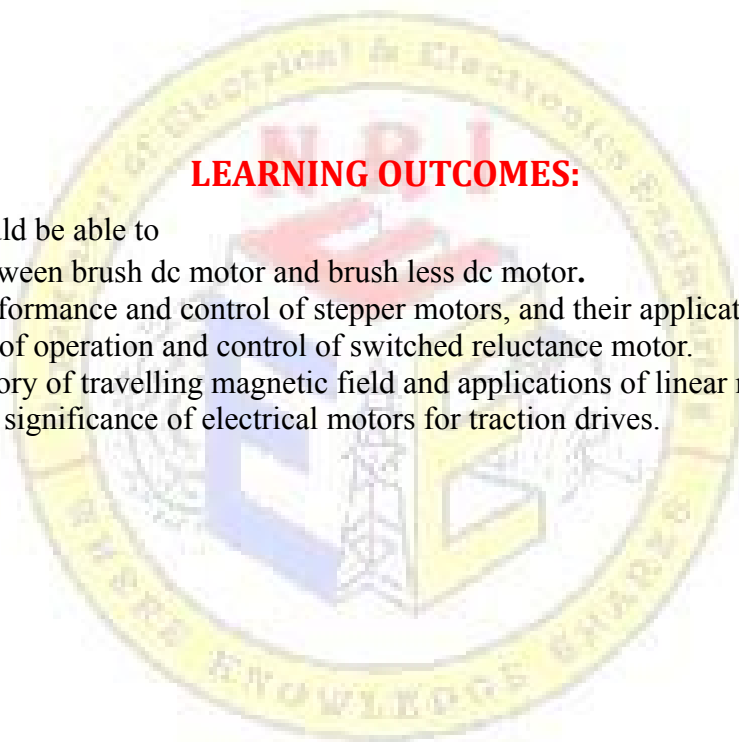
LEARNING OBJECTIVE:

- To explain theory of operation and control of switched reluctance motor.
- To explain the performance and control of stepper motors, and their applications.
- To describe the operation and characteristics of permanent magnet dc motor.
- To distinguish between brush dc motor and brush less dc motor.
- To explain the theory of travelling magnetic field and applications of linear motors.

LEARNING OUTCOMES:

The student should be able to

- Distinguish between brush dc motor and brush less dc motor.
- Explain the performance and control of stepper motors, and their applications.
- Explain theory of operation and control of switched reluctance motor.
- Explain the theory of travelling magnetic field and applications of linear motors.
- Understand the significance of electrical motors for traction drives.



UNIT I - SWITCHED RELUCTANCE MOTOR INTRODUCTION:

Switched reluctance motor (SRM) is electromagnetic and electrodynamics equipment which converts the electrical energy into mechanical energy. The electromagnetic torque is produced on variable reluctance principle. SRM makes use of

- Power semiconductor switching circuitry and
- Rotor position sensor.

SRM is singly excited and doubly salient electrical motor. This means that it has salient poles on both the rotor and the stator but the only one member carries winding. The rotor has no winding, magnets and cage winding but it is build from a stack of salient pole laminations.

- Its construction is simple and robust
- It requires less maintenance
- Its overall efficiency is better
- It is flexible control driving motor as motoring mode generating mode of operations of the machine can be easily achieved,

It is a competitive variable speed dc motor and variable speed 3 – phase cage induction motor.



CONSTRUCTION AND OPERATION OF SRM:

1. Construction of SRM:

Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure 1.1

The stator is made up of silicon steel stampings with inward projected poles. The number of poles. The number of poles of the stator can be either an even number or an odd number. Most of the motors available have even number of stator poles (6 or 8). All these poles carry field coils. The field coils of opposite poles are connected in series such that their mmf's are additive and they are called phase windings. Individual coil or a group of coils constitute phase windings. Each of the phase windings are connected to the terminal of the motor. These terminals are suitably connected to the output terminals of a power semiconductor switching circuitry, whose input is a d.c. supply.

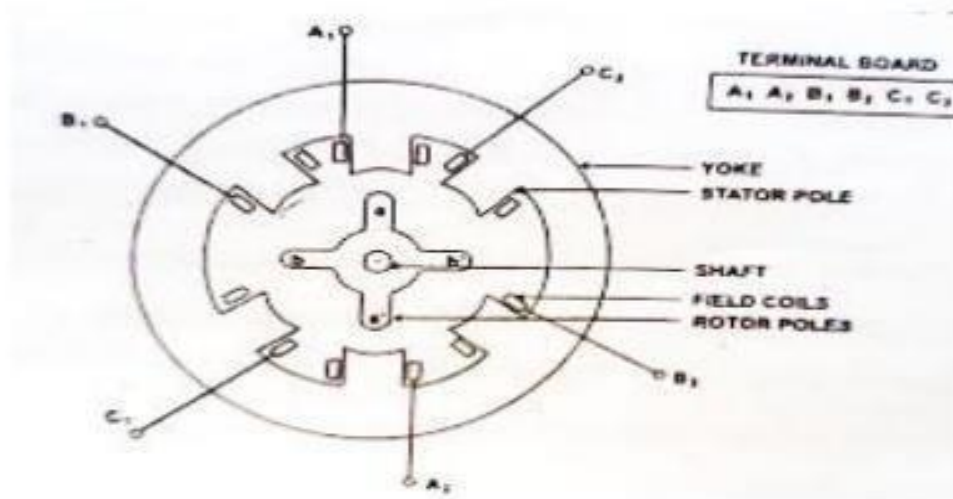


Fig 3.1 Cross sectional view of SRM

The rotor is also made up of silicon steel stampings with outward projected poles. Number of poles of rotor is different from the number of poles of the stator. In most of the available motors the number of poles of the rotor is 4 or 6 depending upon the number of stator poles 6 or 8.

The rotor shaft carries a position sensor. The turning ON and turning OFF operation of the various devices of the power semiconductor circuitry are influenced by the signals obtained from the rotor position sensor.

2. Block Diagram Of SRM:

Fig. 1.2 shows the block diagram of SRM. Dc supply is given to the power semiconductor switching circuitry which is connected to various phase windings of SRM. Rotor position sensor which is mounted on the shaft of SRM, provides signals to the controller about the position of the rotor with reference to reference axis. Controller collects this information and also the reference speed signal and suitably turns ON and OFF the concerned power semiconductor device to the dc supply. The current signal is also fed back to the controller to limit the current within permissible limits.

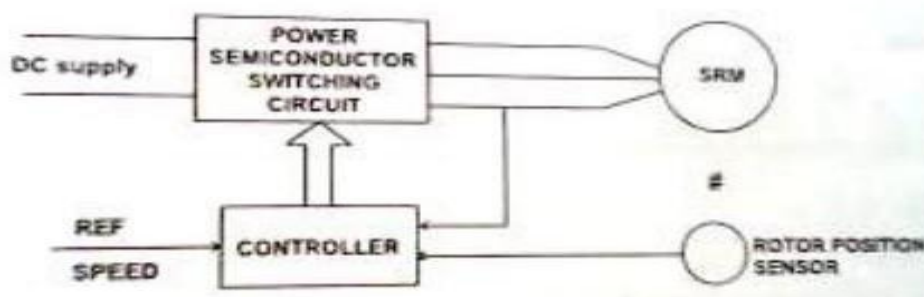
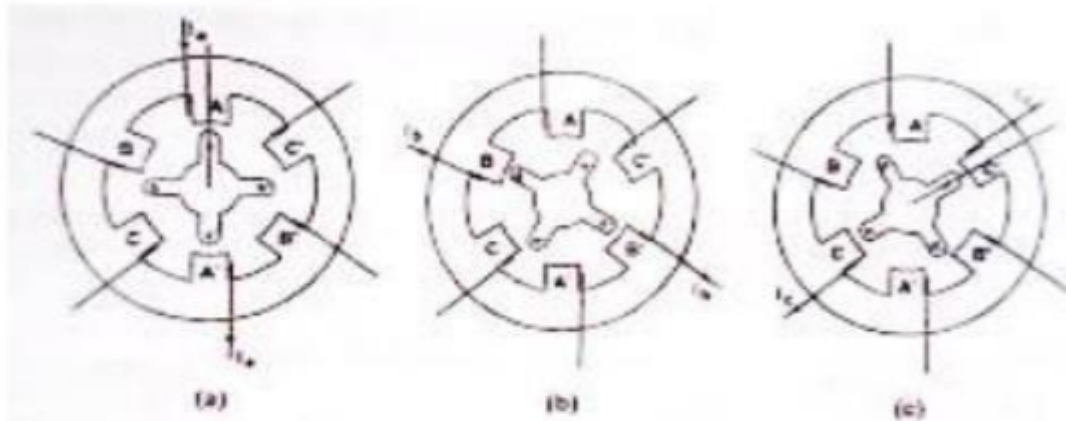


Fig. 3.2 Block Diagram Of SRM

3. Principle of operation:

Fig. 1.3 represents the physical location of the axis stator poles and rotor poles of a 6/4 SRM.

To start with stator pole axis AA' and rotor pole axis aa' are in alignment as shown in fig. 1.3(a). They are in the minimum reluctance position so far as phase windings is concerned. Then $dL_a/d\theta=0$. At this position inductance of B windings is neither maximum nor minimum. There exists $dL_b/d\theta$ and $dL_c/d\theta$.



Now if B phase is energized then the rotor develops a torque because of variable reluctance and existences of variation in inductance. The torque developed is equal to $(1/2)i_B^2(dL_B/d\theta)$. This direction is such that BB' and bb' try to get aligned. If this torque is more than the opposing load torque and frictional torque the rotor starts rotating. When the shaft occupies the position such that BB' and bb' are in alignment (i.e., $\theta=30^\circ$, no torque is developed as in this position $dL_B/d\theta=0$. [Vide fig. 1.3(b)]

Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as $(dL_C/d\theta)$ exists. The rotor continues to rotate. When the rotor rotates further 30° , the torque developed due to winding C is zero [vide fig. 1.3(c)] Then the phase winding C is switched off and phase winding A is energized. Then rotor experiences a torque and rotates further step 30° . This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor.

As the speed increases, the load torque requirement also changes. When the average developed torque is more than the load torque the rotor accelerates. When the torques balance the rotor attains dynamic equilibrium position. Thus the motor attains a steady speed. At this steady state condition power drawn from the mains is equal to the time rate of change of stored energy in magnetic circuit and the mechanical power developed.

When the load torque is increased, the speed of the motor tends to fall, so that the power balance is maintained. If the speed is to be develop at the same value, the develop torque is to be increased by increasing the current. Thus more power is drawn from the mains. Vice-versa

takes place when the load is reduced. Thus electrical to mechanical power conversion takes place.

POWER SEMICONDUCTOR SWITCHING CIRCUITS FOR SRM (POWER CONTROLLERS):

The selection of controller (converter) depends upon the application. One of the main aspects of the research in SRM drives has been the converter design. The main objectives of the design of the converter are performance of the drive and cost of the drive.

The power semiconductor switching circuits used are ---

1. Two power semiconductor switching devices per phase and two diodes.
 2. $(n+1)$ power semiconductor switching devices $(n+1)$ diodes.
- Phase winding using bifilar wires.
 - Split-link circuit used with even-phase number.
 - C-dump circuit.

1. Two Power Semiconductor Switching Devices per phase and two diodes

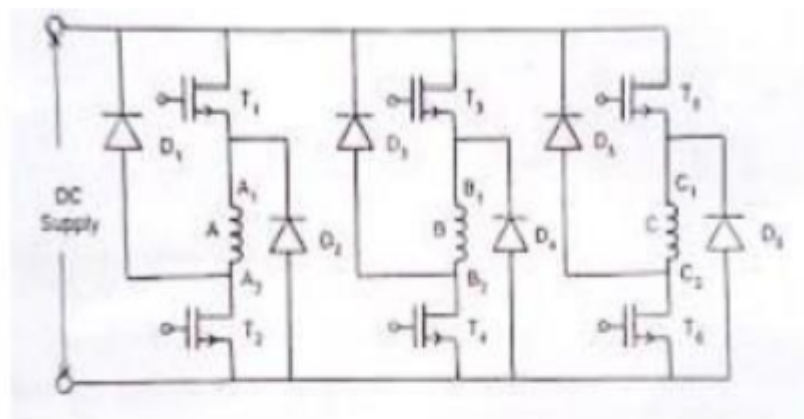


Fig. 3.4 Two Power Semiconductor switching devices and two diodes.

As shown in fig 1.4 phase winding A is connected to the dc supply through power semiconductor devices T₁ and T₂. Depending upon the rotor position, when the phase winding A is to be energized the devices T₁ and T₂ are turned ON. When the phase winding is to be disconnected from the supply (this instant is also dependent on the position of the shaft) the devices T₁ and T₂ are turned off. The stored energy in the phase winding A tends to maintain the current in the same direction. This current passes from the winding through D₁ and D₂ to the supply. Thus the stored energy is fed back to the mains.

Similarly phase winding B & C are also switched on to the supply and switched off from the supply in a cyclic manner. This circuit requires 2 power switching devices and 2 diodes for each phase winding. For high speed operation it is required to see that the stored energy can be fed back to the mains within the available period.

Usually the upper devices T_1 , T_3 and T_5 are turned on and off from the signals obtained from the rotor position sensor. The duration of conduction or angle of conduction θ can be controlled by using suitable control circuitry. The lower devices T_2 , T_4 , T_6 are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical AND ing of the rotor position sensor and chopping frequency. As a result it is possible to vary the effective phase current from a very low value to a high value. For varying the following methods are available.

1. By varying the duty cycle of the chopper.
2. By varying the conduction angle of the devices.

Merits

- Control of each phase is completely independent of the other phase.
- The converter is able to free wheel during the chopping period at low speeds which helps to reduce the switching frequency and thus the switching losses of the converter.
- The energy from the off going phase is feedback to the source, which results in utilization of energy

Demerits

- Higher number of switches required in each phase, which makes the converter expensive and also used for low voltage applications.

2. (n+1) power switching devices and (n+1) diodes

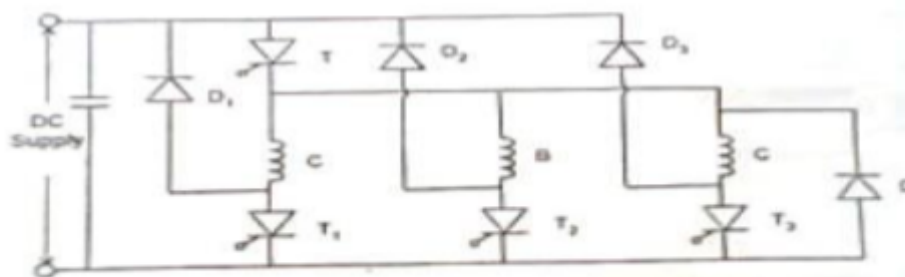


Fig. 3.5 (n+1) power switching devices and (n+1) diodes

This circuit makes use of less number of power switching devices and diodes as shown in fig 1.5. When the (SCRs) switching devices T and T_1 are turned on phase winding A is energized from the dc supply. When these devices are turned off the stored energy in the phase winding is fed back to the mains through diodes D and D_1 . When devices T and T_2 are turned on the phase winding B is energized. When they are turned off, the stored energy in B phase winding C is switched on and off from the mains. The cycle gets repeated.

This circuit makes use of $(n+1)$ power switching devices and $(n+1)$ diodes where n is equal to the number of phases.

Merits

- The converter uses low number of switching devices, which reduces the cost of the converter.
- The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses.
- Voltage rating of all the switching devices and the diodes are V_{dc} , which is relatively low.
- The energy for the off going phase is transferred back into the source, which results in useful utilization of the energy and also improves the efficiency.

Demerits

- Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.
- At higher speeds of the off going phase cannot be de-energized fast enough because the common switch —Tl keeps turnings on intermediately, disabling forced demagnetization.
- The common switch conducts for all the phases and thus has higher switching stress.

3. Phase winding using bifilar wires

Each phase winding has two exactly similar phase windings as shown in fig 1.6. For this bifilar wires are used. Each phase consists of two identical windings and are magnetically coupled when one of them are excited.

In stepper motor, the purpose of bifilar winding is for bipolar excitation with a reduced number of switching elements.

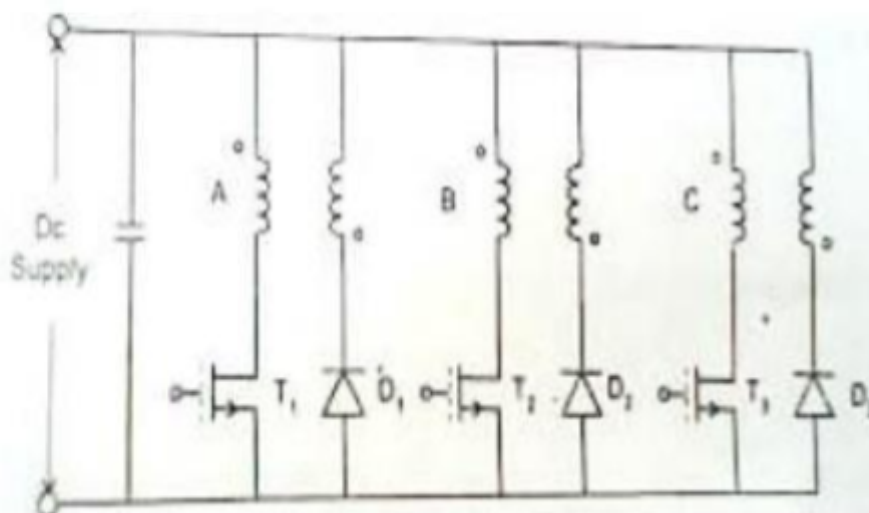


Fig 3.6 Phase winding using bifilar wires

When T_1 is turned on the dc current passes through the phase winding A. when the devices T_1 is turned off the stored energy in the magnetic field is fed back to the dc source through the winding A' and D_1 to the supply.

The three devices operate in a sequential way depending upon the signals obtained from the rotor position sensor and the chopping signals for PWM technique obtained from the controller.

Merits

- The converter uses lower number of switching devices thus reducing the cost on the converter.
- The converter allows fast demagnetization of phases during commutation.

Demerits

- Bifilar winding suffers from double number of connections.
- A poor utilization of copper.
- Freewheeling is not possible during chopping as the phases have $-V_{dc}$. this causes of higher ripples in current and torque during chopping.
- The imperfection in the coupling between the two winding causes voltage spikes during turn off.
- The copper loss associated with the auxiliary winding is unacceptable high for many applications.



4. Split – link circuit used with even phase number

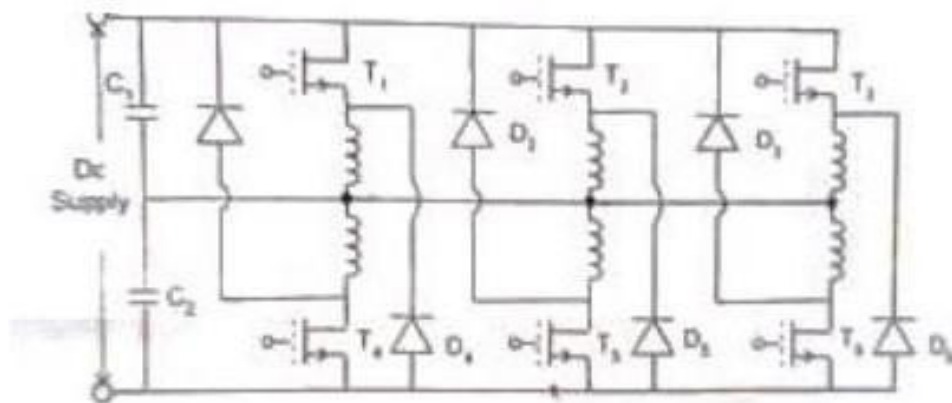


Fig. 3.7 split link circuit used with even phase number

The circuit shown in fig.1.7 is used in a range of highly efficient drives (from 4-80kw).

The main power supply is split into two halves using split capacitors. During conduction, energy is supplied to the phases by one half the power supply. During commutation period, the phases demagnetize into other half of the power supply.

When switch T1 is turned on, phase winding 1 is energized by capacitor c1. When switch T2 is turned off, the stored energy in the phase winding 1 is fed back to the capacitor c2 through diode D4.

When T4 is turned on by capacitor C2 and phase winding 4 is energized. When switch T4 is turned off, stored energy in the winding 4 is feedback to the capacitor C1 through diode D1. The similar operation takes place in the remaining winding also.

Merits

- It requires lower number of switching devices.
- Faster demagnetization of phases during commutation.

Demerits

- During chopping, freewheeling is not possible as the phasor have the voltage $V_{dc}/2$. This causes higher switching frequency and more losses.
- This is not feasible for low voltage application.
- The converter is fewer faults tolerant as fault in any phase will unbalance the other phase that is connected to it.

5. C-Dump circuit

In the C dump circuit shown in fig. 1.8. the device count is reduced to $n+1$ plus one additional devices to bleed the stored energy from the dump capacitor C back to supply via the step down chopper circuit. The mean capacitor voltage is maintained well above the supply to permit rapid defluxing after commutation.

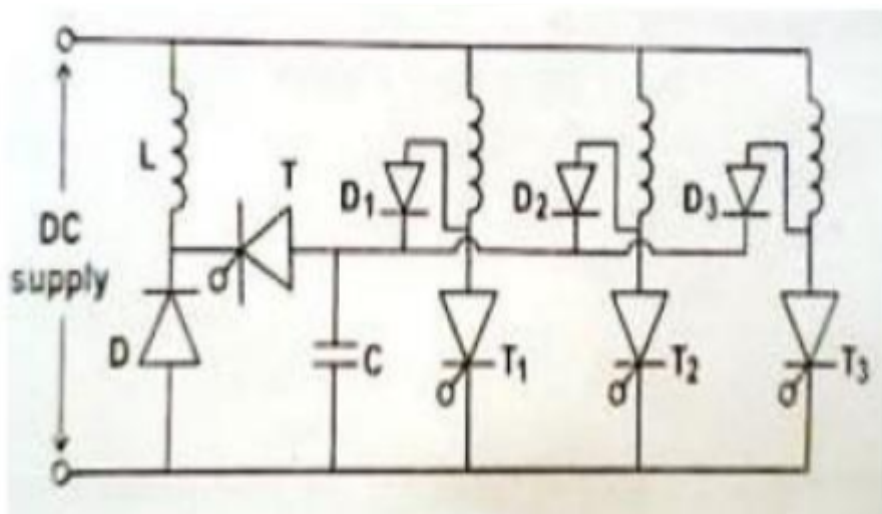


Fig. 3.8 C dump circuit

A control failure in the energy-recovery circuit would result in the rapid build-up of charge on the capacitor and if protective measures were not taken the entire converter could fail from over voltage.

Demerits

□ Dump capacitor voltage is maintained $\sim 2 V_{dc}$ to allow fast demagnetization. But use of a capacitor and an inductor in the dump circuit and also the voltage rating of other devices is twice the bus voltage

□ Monitoring of the dump capacitor voltage 'C' and control of dump switch T makes the converter very complicated and also the converter does not allow freewheeling.

VOLTAGE AND TORQUE EQUATIONS OF SRM:

Basic voltage equation of SRM:

From fig. 3.9

$$V = iR + \frac{d\lambda}{dt} \quad \dots\dots\dots (3.1)$$

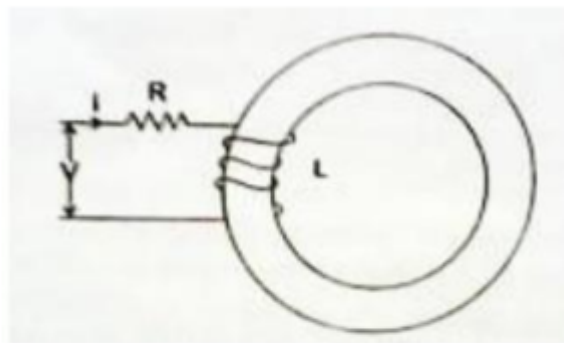


Fig. 3.9 Basic R-L circuit of SRM.

where λ is a function of θ and L

$$\frac{d\lambda}{dt} = \frac{d}{dt} i + \frac{di}{dt} \theta \quad \dots\dots\dots (3.2)$$

$$V = iR + \frac{d(Li)}{dt} \quad \dots\dots\dots (3.3)$$

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

$$= iR + L \frac{di}{dt} + i \frac{dL}{d} \times \frac{d}{dt}$$

$$V = iR + L \frac{di}{dt} + i\omega \frac{dL}{d} \quad \dots\dots\dots (3.4)$$

$$= iR + L \frac{di}{dt} + i \frac{dL}{dt} \times \frac{d}{dt}$$

$$V = iR + L \frac{di}{dt} + i \omega \frac{dL}{d} \quad \dots\dots\dots(3.4)$$

where iR $\square$ ohmic drop

$L \frac{di}{dt}$ $\square$ Emf due to incremental inductance

$i \omega \frac{dL}{d} \square$ self induced emf e or self emf

$$V = iR + L \frac{di}{dt} + e \quad \dots\dots\dots(3.5)$$

Self-induced emf e is proportional to current speed and rate of change of inductance with rotor angle.

If flat topped current is assumed $L \frac{di}{dt} = 0$ on the other hand if the inductance is constant, self emf is zero. So the first term $L \frac{di}{dt}$ absorbs all the applied voltage.

$$Vi = i^2 R + L \frac{di}{dt} + i^2 \omega \frac{dL}{d} \quad \dots\dots\dots(3.6)$$

Energy stored in the magnetic circuit $= \frac{1}{2} Li^2$

Rate of change of energy stored

$$\text{in the magnetic circuit} = \frac{d}{dt} \left[\frac{1}{2} Li^2 \right] \quad \dots\dots\dots(3.7)$$

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

$$= Li \frac{di}{dt} + \frac{1}{2} i^2 \frac{dL}{d} \times \frac{d}{dt}$$

$$\frac{dW_{mag}}{dt} = Li \frac{di}{dt} + \frac{1}{2} i^2 \omega \frac{dL}{d} \quad \dots\dots\dots(3.8)$$

Mechanical energy transferred = electrical energy input $\square i^2 R$ $\square$ rate of change of energy stored in the magnetic circuit.

$$\text{Mechanical energy transferred} = Vi \square i^2 R \square \frac{dW_{mag}}{dt}$$

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

$$P_m = \frac{1}{2} i^2 \omega \frac{dL}{d} \quad \dots\dots\dots(3.9)$$

$$P_m = \omega T \quad \dots\dots\dots(3.10)$$

$$\therefore \text{Torque } T = \frac{1}{2} i^2 \frac{dL}{d} \quad \dots\dots\dots(3.11)$$

POWER SEMICONDUCTOR SWITCHING CIRCUITS FOR SRM :

The selection of controller (converter) depends upon the application. One of the main aspects of the research in SRM drives has been the converter design. The main objectives of the design of the converter are performance of the drive and cost of the drive.

The power semiconductor switching circuits used are

1. Two power semiconductor switching devices per phase and two diodes.
2. $(n+1)$ power semiconductor switching devices $(n+1)$ diodes.
3. Phase winding using bifilar wires.
4. Split-link circuit used with even-phase number.
5. C-dump circuit.

CONTROL CIRCUITS FOR SRM:

For motoring operation the pulses of phase current must coincide with a period of accuracy inductance. The timing and dwell (i.e.) period of conductance of the current pulse determine the torque, the efficiency and other parameters. With fixed firing angles, there is a monotonic relationship exist between average torque and rms phase current but generally it is not linear. This may present some complications in feedback-controlled systems. Although it is possible to achieve 'near servo-quality' dynamic performance, particularly in respects of speed range torque/inertia and reversing capability.

More complex controls are required for higher power drives, particularly where a wide speed range is required at constant power, and microprocessor controls are used. As high-speed operation, the peak current is limited by the self-emf of the phase winding. A smooth current waveform is obtained with a peak/rms ratio similar to that of a half sinewave.

At low speed, the self-emf of the winding is small and the current must be limited by chopping or PWM of the applied voltage.

Two types of control circuits used are:

1. Hysteresis type to maintain constant current
2. Voltage pulse width modulation control (or) duty cycle control.

HYSTERESIS TYPE CURRENT REGULATION:

As by this control circuit current is maintained more or less constant like —hysteresis— throughout the conduction period in each phase it is known as hysteresis type control. Fig

1.10 (a) shows the current waveform controlled by the hysteresis type current regulator. The schematic arrangement of the control circuit is shown in fig 1.10 (b).

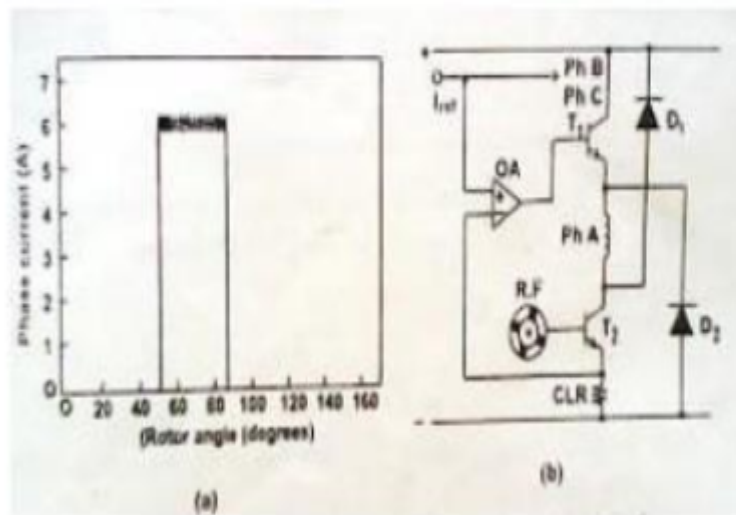


Fig 3.10 (a) Chopped current wave form, (b) Hysteresis type current regulator

Principle of operation

As shown in fig. 1.10(b) the transducer (a tachogenerator) is connected from the rotor and then the output signal from the transducer is given as a feedback signal at the base of transistor T_2 . From the emitter of transistor T_2 , the portion of the feedback signal (current) is fed at the input of the operational amplifier (O.A). There it is compared with the reference current and correspondingly after amplification the feedback signal is given at the base of transistor T_1 . This signal in combination with collector current will flow from the emitter of transistor T_1 through A phase winding of the machine. Thus the current through A phase winding can be controlled depending on the requirement. CLR is the resistance for limiting the current as per the design.

As the current reference increase the torque increases. At low currents the torque is roughly proportional to current squared but at higher current it becomes more nearly linear. At very high currents, saturation decreases the torque per ampere again. This type of control produces a constant-torque type of characteristics.

With loads whose torque increases monotonically with speed, such as fans and blowers, speed adjustment is possible without tachometer feedback but general feedback is needed to provide accurate speed control. In some cases the pulse train from the soft position sensor may be used for speed feedback, but only at relative high speeds.

As low speeds, a larger number of pulses per revolution are necessary and this can be generated by an optical encoder or resolver for alternatively by phase-locking a high frequency oscillator to the pulses of the commutation sensor. System with resolver-feedback or high-resolution optical encoders can work right down to zero speed.

The —hysteresis type current regulator may require current transducers of wide bandwidth, but the SR drive has the advantage that they can be grounded at one end with the other connected to the negative terminal of the lower phase leg switch. The sensors used are shunts or hall-effect sensors or sensefets with in build current sensing.

VOLTAGE PWM TYPE CURRENT REGULATION

The schematic arrangement of PWM type control circuit is shown in fig. 1.11

Principle of operation:

Through transducer (tachogenerator) the mechanical signal (speed) is converted into electrical signal (current), which is fed from at the base of transistor T2. Thos base current combining with collector current flows the emitter of transistor T2 through CLR to the

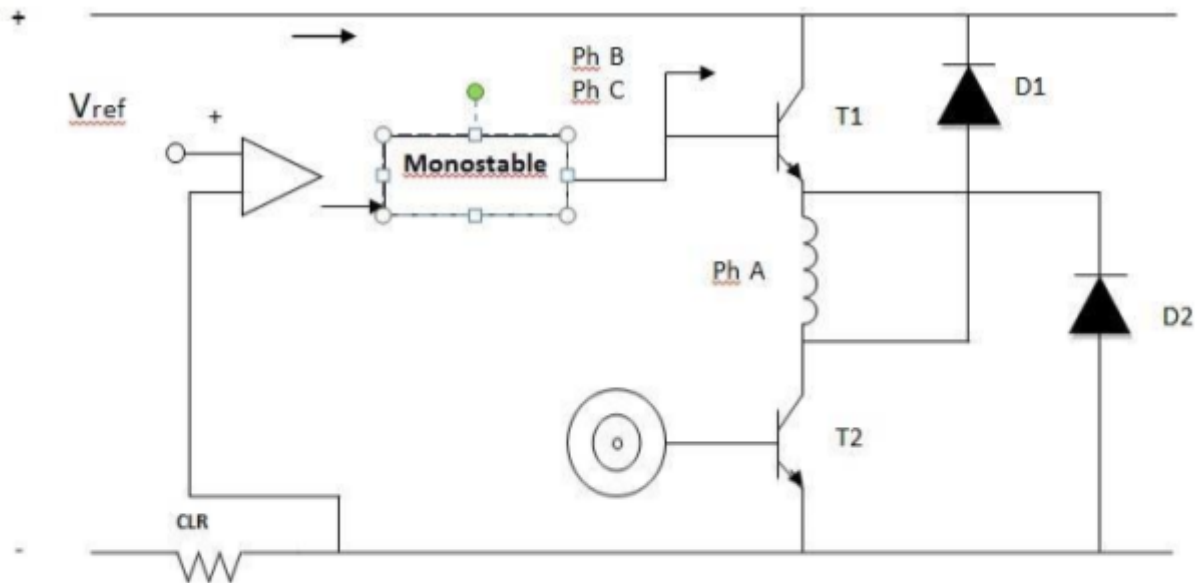


Fig.3.11 Voltage PWM type current regulator

CLR -Current limiting resistor

R.F-Rotor feed back

OA -Operational Amplifier

T1 T2-Switching transistor

D1 D2-Diodes to return stored energy

negative of the supply. Based on the feedback signal, the voltage at phase A changes. This feedback voltage is given as one input to the operational amplifier where it is compared with the reference voltage, correspondingly the difference is amplified and fed to the mono stable circuit. This circuit modulates the pulse width of the incoming signal based on the requirement and the modulated signal is given at the base of T1. This signal combines with collector current of T1 and flows through phase A as modulated current based on the requirement. Thus the current is regulated or controlled using pulse width modulation and rotor feedback.

A desirable feature of both control methods is that the current wave form tends to retain the same shape over a wide speed range.

When the PWM duty cycle reaches 100%, the motor speed can be increased by increasing the conduction period. These increases eventually reach maximum values after which the torque becomes inversely proportional to speed squared but they can typically double the speed range at constant torque. The speed range over which constant power can be maintained is also quite wide and very high maximum speeds can be achieved, as in the

synchronous reluctance motor and induction motor, because there is not the limitation imposed by fixed as in PM motors.

TORQUE-SPEED CHARACTERISTICS:

Torque developed (i.e.) average torque developed but SRM depends upon the current wave form of SRM phase winding. Current waveform depends upon the conduction period and chopping details. It also depends upon the speed.

Consider a case that conduction angle Θ is constant and the chopper duty cycle is 1.(i.e.) it conducts continuously. For low speed operating condition, the current is assumed to be almost flat shaped. Therefore the developed torque is constant. For high speed operating condition, the current wave form gets changed and the average torque developed gets reduced.

Fig. 1.12(a) represents the speed torque characteristics of SRM for constant Θ and duty cycle. It is constant at low speeds and slightly droops as speed increases. For various other constant value of Θ , the family of curves for the same duty cycle is shown in fig.1.12.

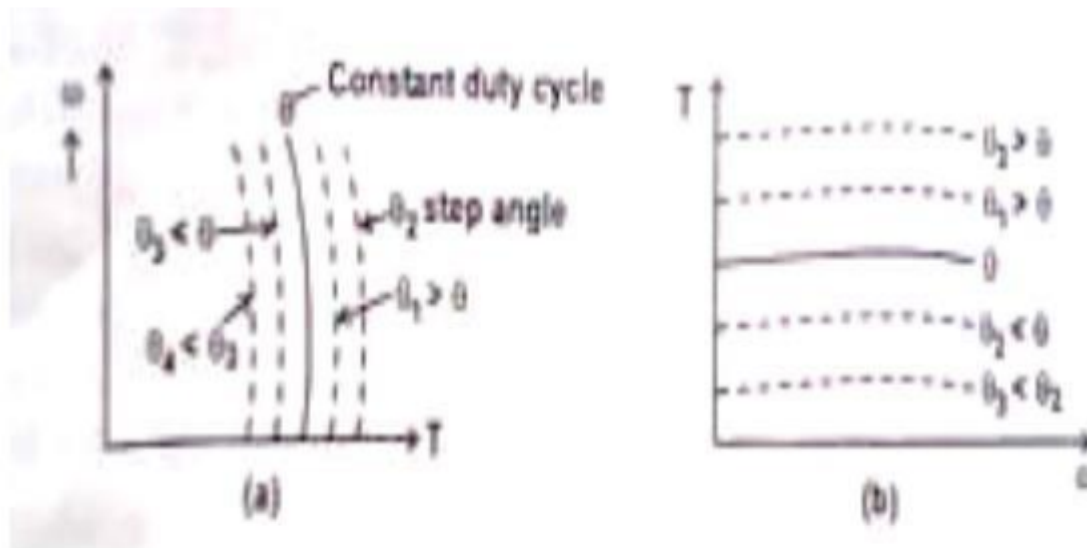


Fig. 3.12 Torque speed characteristics at constant conduction angle θ and duty cycle

Torque speed characteristics for fixed Θ and for various duty cycles are shown in fig. 1.12. Θ and duty cycle are varied by suitably operating the semiconductor devices.

1. Torque Speed Capability Curve

Maximum torque developed in a motor and the maximum power that can be transferred are usually restricted by the mechanical subsystem design parameters.

For given conduction angle the torque can be varied by varying the duty cycle of the chopper. However the maximum torque developed is restricted to definite value based on mechanical consideration.

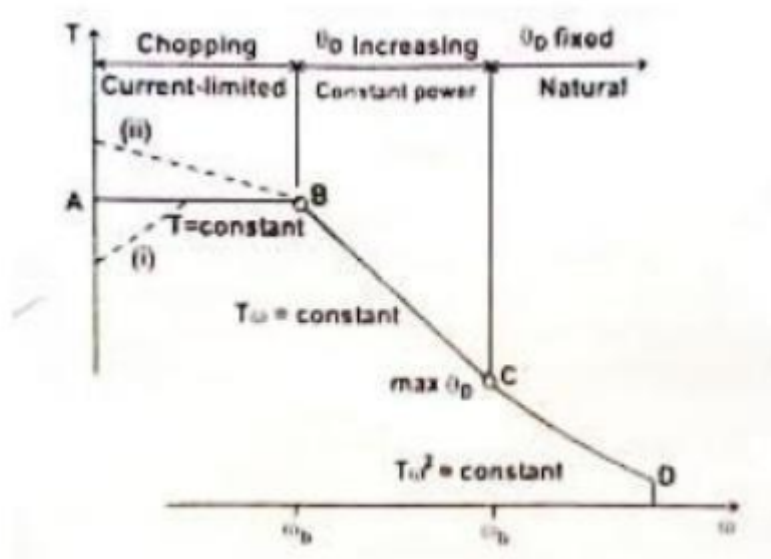


Fig. 3.13 Torque speed characteristic of switched reluctance motor

AB in the fig.1.13 represents constant maximum torque region of operation.

At very low speeds, the torque / speed capability curve may deviate from the clock torque characteristics. If the chopping frequency is limited or if the bandwidth of the current regulator is limited, it is difficult to limit the current without the help of self emf of the motor and the current reference may have to be reduced.

If very low windage and core loss permit the chopper losses to be increased, so that with higher current a higher torque is obtained. Under intermittent condition of course very much higher torque can be obtained in any part of the speed range up to ω_b .

The motor current limits the torque below base speed. The corner point ' or base speed ' ω_b ' is the highest speed at which maximum current can be supplied at rated voltage with fixed firing angles. If these angles are still kept fixed, the maximum torque at rated voltage decreases with speed squared. But if the conduction angle is increased, (i.e.) θ_{on} is decreased, there is a considerable speed range over which maximum current can be still be forced into the motor. This maintains the torque at a higher level to maintain constant power characteristic. But the core losses and windage losses increases with the speed. Thus the curve BC represents the maximum permissible torque at each speed without exceeding the maximum permissible power transferred. This region is obtained by varying θ_D to its maximum value $\theta_{D \max}$. θ_D is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power; maximum permissible conduction angle $\theta_{D \max}$ and duty cycle of the chopper is unity.

Curve CD represents $T\omega^2$ constant. The conduction angle is kept maximum and duty cycle is maximum by maintaining $T\omega^2$ constant. D corresponds to maximum ω permissible.

The region between the curve ABCD and X axis is the —permissible region of operation of SRMl

DISTINCTION BETWEEN SWITCHED RELUCTANCE MOTOR AND THE VARIABLE RELUCTANCE STEPPER MOTOR:

The conduction angle for phase currents is controlled and synchronized with the rotor position, usually by means of a shaft position sensor.

Thus, SR motor is exactly like a brushless dc motor. But the stepper motor is usually fed with a square-wave of phase current without rotor position feedback.

SR motor is designed for efficient power conversion at high speeds comparable with those of the PM brushless dc motor. The stepper motor is usually designed as a torque motor with a limited speed range. SR motor is more than a high-speed stepper motor. Its performance and low manufacturing cost make it a competitive motor to PM brushless dc system.

1. Merits of SRM:

1. Construction is simple and robust, as there is no brush.
2. Rotor carries no windings, no slip rings and brush-less maintenance.
3. No permanent magnet, neither in the stator nor in the rotor.
4. Ventilating system is simpler as losses take place mostly in stator.
5. Power semiconductor switching circuitry is simpler.
6. No shoot-through fault is likely to happen in power semiconductor circuits.
7. Torque developed does not depend upon the polarity of the current in the phase winding.
8. The operation of the machine can be easily changed from motoring mode to generating mode by varying the region of conduction.
9. It is impossible to have very high speeds.
10. Depending upon the requirement, the desired torque speed characteristics can be tailor made.
11. It is a self-starting machine.
12. Starting torque can be very high without excessive inrush currents.

2. Demerits of SRM

1. Stator phase winding should be capable of carrying the magnetizing current also, for setting up the flux in the air gap.
2. For high speed operations, the developed torque has undesirable ripples. As a result it develops undesirable acoustic losses (noise).

3. For high speeds, current waveform also has undesirable harmonics. To suppress this effect a large size capacitor is to be connected.
4. The air gap at the aligned axis should be very small while the air gap at the inter-polar axis should be very large. It is difficult to achieve. No standardized practice is available.
5. The size of the motor is comparable with the size of variable speed induction motor drive.
6. Number of power wires between power semiconductor circuitry and the motor and the number of control cables from one controller to the power semiconductor circuitry are more and all to be properly connected.
7. It requires a position sensor.

3. Application of SRM

- Washing machines
- Vacuum cleaners
- Fans
- Future automobile applications
- Robotic control applications

SHAFT POSITION SENSING:

Commutation requirement of the SR motor is very similar to that of a PM brushless motor.

- The shaft position sensor and decoding logic are very similar and in some cases it is theoretically possible to use the same shaft position sensor and the same integrated circuit to decode the position signals and control PWM as well.
- The shaft position sensors have the disadvantage of the associated cost, space requirement and possible extra source of failure. Reliable methods are well established. In position sensors or speed sensors, resolvers or optical encoders may be used to perform all the functions of providing commutation signals, speed feedback and position feedback.
- Operation without position sensor is possible. But to have good starting and running performance with a wide range of load torque and inertias, sensor is necessary.
- When the SR motor is operated in the 'open-loop' mode like a stepper motor in the slewing range, the speed is fixed by the reference frequency in the controller as long as the motor maintains 'step integrity'. (i.e) stay in synchronism. Therefore like an ac synchronous motor, the switched reluctance motor has truly constant speed characteristics.

This open-loop control suffers from two disadvantages.

- (a) To ensure that synchronism is maintained even though the load torque may vary.
 - (b) To ensure reliable starting.
- Because of the large step angle and a lower torque/inertia ratio, the SR motor usually does not have reliable 'starting rate' of the stepper motor.
 - Also some form of inductance sensing or controlled current modulation (i.e) such as sine wave modulation may be necessary in the control at low speeds.

MICROPROCESSOR OR COMPUTER BASED CONTROL OF SRM DRIVE:

Today in industrial places there is high demands on control accuracies, flexibility, ease of operation, repeatability of parameters for many drive applications. Nowadays switched reluctance motors are increasingly used in industries. To meet the above requirements, uses of microprocessor have become important.

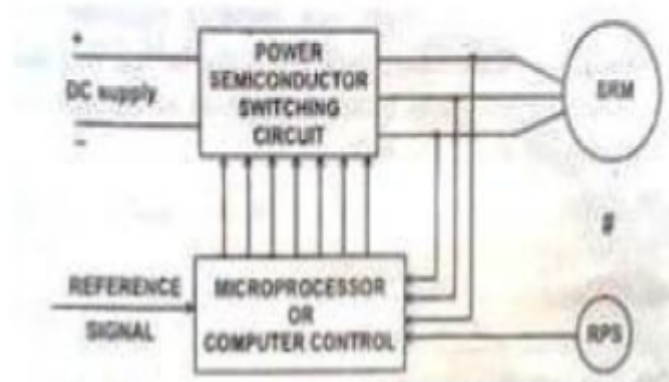


Fig. 3.14 Microprocessor or computer based control of SRM

Fig. shows the block diagram of microprocessor based control of SRM drive. This control system consists of power semiconductor switching circuit, SRM with rotor position sensor and microprocessor system. In this system microprocessor acts as a controller for the switched reluctance motor and generate control pulses to the power semiconductor switching circuits.

The input DC supply is fed to the power semiconductor switching circuits. Different types of power semiconductor switching circuits are used for different application. Normally the circuits are inverter circuit configuration.

The power semiconductor devices are turned on and off by controller circuit. Here the controller circuit is microprocessor or computer based control system.

In the SRM drive shown in fig. 3.14, the rotor position sensor gives the information about the rotor with respect to the reference axis to the microprocessor or computer control. The controller also receives the status of current, flow through the phase winding and reference signal.

The microprocessor or computer compares the signals obtained from the RPS and reference and generate square pulses to the power semiconductor devices. This signal is fed to the inverter circuit. The phase winding of the SRM is energized depending upon the turning on and off of the power semiconductor switching circuit.

The microprocessor or computer controller can perform the following functions.

- a) Control the feedback loops.
- b) PWM or square wave signal generation to inverters.
- c) Optimal and adaptive control.
- d) Signal monitoring and warning.
- e) General sequencing control.
- f) Protection and fault overriding control.
- g) Data acquisition.

The superiority of microprocessor or computer control over the conventional hardware based control can be easily recognized for complex drive control system. The simplification of hardware saves control electronics cost and improves the system reliability. The digital control has inherently improves the noise immunity which is particularly important because of large power switching transients in the converters.

SHORT QUESTIONS AND ANSWERS:

1. What is srm?

It is a doubly salient , single excited motor.this means that it has salient poles on both rotor and the stator.but only one member carries winding.the rotor has no windings,magnets or case windings.

2. What are the advantages od SRM?

- ☐ Construction is very simple
- ☐ Rotor carries no winding
- ☐ No brushes and requires less maintenance

3. What are the disadvantages of SRM?

- ☐ It requires a position sensor
- ☐ Stator phase winding shold be capable of carrying magnetizing currents

4. Why rotor position sensor is essential for the operation of switched reluctance motor?

It is necessary to use a rotor position sensor for commutation and speed feedback. The turning on and off operation of the various devices of power semiconductor

switching circuit are influenced by signals obtained from rotor position sensor.

5. What are the different power controllers used for the control of SRM?

- ☐ Using two power semi conductors and two diodes per phase
- ☐ Phase windings and bifilar wires
- ☐ Dump – C converter
- ☐ Split power supply converter

6. What are the applications of SRM?

- ☐ Washing machines
- ☐ Fans
- ☐ Robotic control applications
- ☐ Vacuum cleaner
- ☐ Future auto mobile applications

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

- ☐ Hysteresis type control
- ☐ PWM type control

8. What is meant by energy ratio?

$$\text{Energy ratio} = W_m / (W_m + R) = 0.45$$

W_m = mechanical energy transformed

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

9. Write the torque equation of SRM?

$$T = 1/2 (i^2 dL/d\theta)$$

10. What is phae winding?

Ststor poles carrying field coils.the field coils of opposite poles are connected in series such that mmf „s are additive and they are called „“phase winding”” of SRM.

11. Write the characteristics of SRM.

- ☐ Lowest construction complexity, many stamped metal elements
- ☐ Like a BLDC or stepper without the magnets
- ☐ High reliability (no brush wear), failsafe for Inverter but...acoustically noisy
- ☐ High efficiency

12. Write the voltage,power range of SRM.

Industrial

Voltage	Motor Power	Speed Range
100 - 240 Vac	50W - 10'sKW	0 - 60,000 RPM

Automotive

Voltage	Motor Power	Speed Range
12 - 42Vdc	50W -1kW	0 - 20,000 RPM

13. Define the control system of SRM.

The control system is responsible for giving the required sequential pulses to the power circuitry in order to activate the phases as required. There are two options for producing the sequence including a microcontroller to produce the signal or a timer circuit which could also produce the desired signal.

14. Define the timer circuit of SRM.

The use of a timer circuit would be very effective in producing the necessary signal in which to control the circuit. As the required signal is very simple it could easily be implemented by digital timer, such as the 555 timer. A digital timer is more precise than any other form of timer, such as a mechanical timer. With the widespread use of digital logic within integrated circuits the cost of these timers has reduced considerably. The latest controllers in use incorporate programmable logic controllers (PLC's) rather than electromechanical components in its implementation. Within PLC's, the timers are normally simulated by the software incorporated in the controller; the timer is therefore controlled by the software. There are obvious advantages to this system, although the control of a soft start could be hard to implement in this way.

15. Write the soft starters of SRM.

Mechanical – come in the form of torque limiters utilizing clutches and various couplings,

Electrical – these soft starters alter the power supply to the motor to reducing the torque and current demand. This is normally performed either by reducing the supply voltage, or controlling the frequency of excitation. Since switched reluctance motors are driven by a controlled pulsed supply, frequency control is an obvious choice in this case.

16. What are the goals to contro, soft starting?

Fixed start-up time - the start up will be controlled to achieve full speed within a fixed time

Current limit - the motor current can be monitored and the start up controlled to keep it below a specified limit

Torque limit - an intelligent starter can calculate the motor torque based on the current and voltage demand and control the start up to provide a constant starting torque

17. What are the major advantages of frequency control of SRM?

This has a major advantage of being easily controlled and changed at any point by simply altering the programming. By using this method the development time is reduced and the number of modules to implement is also reduced.

18. Define the isolation of SRM.

The electrical isolation of the control and power circuitry modules is very important and is used so that the control electronics are protected from any voltage fluctuations in the power circuitry. The major method of isolation used today are optoisolators, these isolators use short optical transmission paths to transfer a signal from one part of a circuit to another. The isolator incorporates a transmitter and a receiver, the signal therefore converts from electrical to optical before converting back to electrical thereby breaking any electrical connection between input and output.

19. Define the power circuitry of SRM.

- ☐ The most common approach to the powering of a switched reluctance motor is to use an asymmetric bridge converter.
- ☐ There are 3 phases in this in an asymmetric bridge converter corresponding to the phases of the switched reluctance motor. If both of the power switches either side of the phase are turned on, then that corresponding phase shall be actuated. Once the current has risen above the set value, the switch shall turn off. The energy now stored within the motor winding shall now maintain the current in the same direction until that energy is depleted.
- ☐ N+1 Switch And Diode
- ☐ This basic circuitry may be altered so that fewer components are required although the circuit shall perform the same action. This efficient circuit is known as the (n+1) switch and diode configuration.
- ☐ A capacitor can be added to either configuration, and is used to address noise issues by ensuring that the switching of the power switches shall not cause fluctuations in the supply voltage.

20. What are the current control schemes?

- ☐ Hysteresis type current regulator
- ☐ PWM type current regulator

PART – B

1. Explain the construction and working principle of switched reluctance motor. (16)
2. Describe the various power controller circuits applicable to switched reluctance motor and explain the operation of any one scheme with suitable circuit diagram. (16)
3. Draw a schematic diagram and explain the operation of a „C“ dump converter used for the control of SRM. (16)
4. Derive the torque equation of SRM. (16)
5. Draw and explain the general torque-speed characteristics of SRM and discuss the type of control strategy used for different regions of the curve. Sketch the typical phase current waveforms of low speed operation. (16)
6. Describe the hysteresis type and PWM type current regulator for one phase of a SRM. (16)



UNIT II - STEPPER MOTOR

INTRODUCTION

It is an electrodynamics and electromagnetic equipment.

These motors are also referred to as step motors or stepping motors.

On account of its unusual construction, operation and characteristics it is difficult to define a stepper motor. Definition given in British Standard specification (BSS) is -

A stepper motor is brushless dc motor whose rotor rotates in discrete angular displacements when its stator windings are energized in a programmed manner. Rotation occurs because of magnetic interaction between rotor poles and poles of the sequentially energized winding. The rotor has no electrical windings, but has salient and magnetic/or magnetized poles.

The stepper motor is a digital actuator whose input is in the form of digital signals and whose output is in the form of discrete angular rotation. The angular rotation is dependent on the number of input pulses the motor is suitable for controlling the position by controlling the number of input pulses. Thus they are identically suited for open position and speed control.

Applications:

Printers, Graph plotters , Tape driver , Disk Drives , Machine Tools, X-Y Recorders,
Robotics space Vehicle, IC Fabrication and Electric Watches.

CLASSIFICATION OF STEPPER MOTORS:

As construction is concerned stepper motors may be divided into two major groups.

1. Without Permanent Magnet (PM)

(a) Single Stack

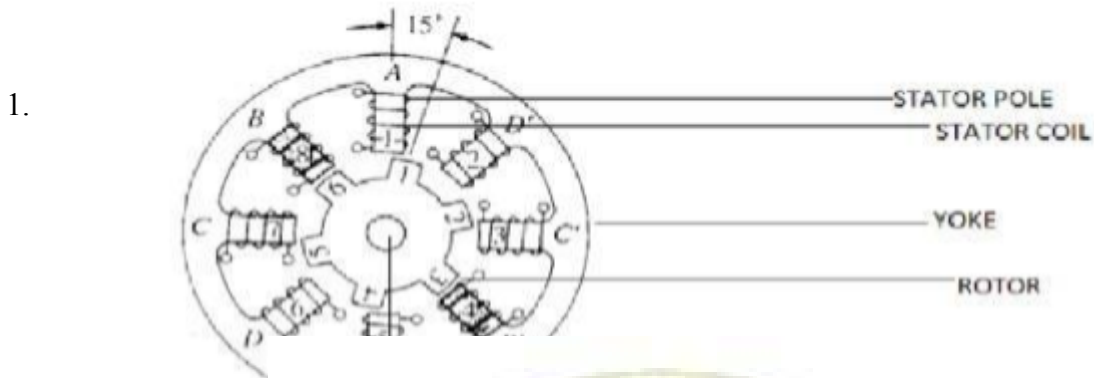
(b) Multi Stack

2. With Permanent Magnet

(a) Claw Pole Motor

(b) Hybrid Motors

SINGLE STACK VARIABLE RELUCTANCE STEPPER MOTOR



Fig

Construction:

The VR stepper motor is characterized by the fact there is no permanent magnet either on the rotor or the stator. The construction of a 3-phase VR stepper motor with 6 poles on the stator and 4-pole on the rotor as shown.

The stator is made up of silicon steel stampings with inward projected even or odd number of poles or teeth. Each and every stator pole carries a field coil or exciting coil. In case of even number of poles the exciting coils of opposite poles are connected in series. The two coils are connected such that their MMF gets added. The combination of two coils is known as phase winding.

The rotor is also made up of silicon steel stampings with outward projected poles and it does not have any electrical windings. The number of rotor poles should be different from that of stators in order to have self-starting capability and bi-directional operation. The width of rotor teeth should be same as stator teeth. Solid silicon steel rotors are extensively employed. Both the stator and rotor materials must have low reluctance to allow a high magnetic flux to pass through them even if a low magnetomotive force is applied.

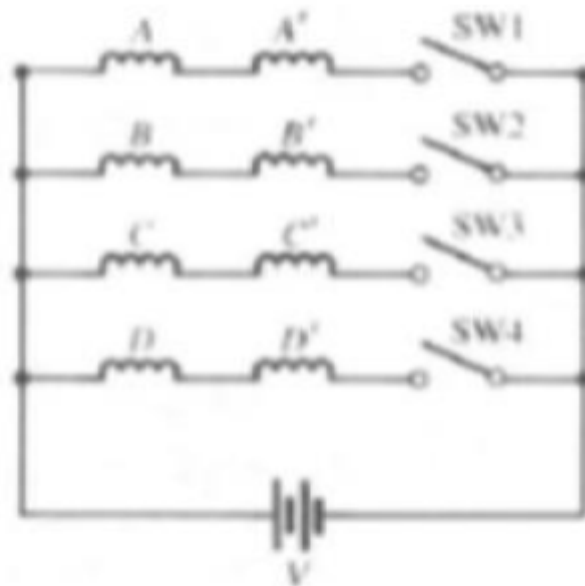
2. Electrical Connection

Electrical connection of VR stepper as shown in fig. Coil A and A' are connected in series to form a phase winding. This phase winding is connected to a DC source with the help of semiconductor switch S1. Similarly B and B' and C and C' are connected to the same source through semiconductor switches S2 and S3 respectively. The motor has 3 phases a, b and c.

'a' phase consists of A and A' Coils

'b' phase consist of B and B' Coils

'c' phase consist of C and C' Coils



3. Principle of Operation

It works on the principle of variable reluctance. The principle of operation of VR stepper motor explained by referring the fig.

(a). Mode 1 : One phase ON or full step operation

In this mode of operation of stepper motor only one phase is energized at any time. If current is applied to the coils of phase 'a' (or) phase 'a' is excited, the reluctance torque causes the rotor to run until aligns with the axis of phase a. The axis of rotor poles 1 and 3 are in alignment with the axis of stator poles 'A' and 'A''. Then angle $\theta = 0^\circ$ the magnetic reluctance is minimized and this state provides a rest or equilibrium position to the rotor and rotor cannot move until phase 'a' is energized.

Next phase b is energized by turning on the semiconductor switch S2 and phase 'a' is de-energized by turning off S1. Then the rotor poles 1 and 3 and 2 and 4 experience torques in opposite direction. When the rotor and stator teeth are out of alignment in the excited phase the magnetic reluctance is large. The torque experienced by 1 and 3 are in clockwise direction and that of 2 and 4 is in counter clockwise direction. The latter is more than the former. As a result the rotor makes an angular displacement of 30° in counterclockwise direction so that B and B' and 2 and 4 in alignment. The phases are excited in sequence a, b and c the rotor turns with a step of 30° in counter clockwise direction. The direction of

rotation can be reversed by reversing the switching sequence in which are energized and is independent of the direction of currents through the phase winding.

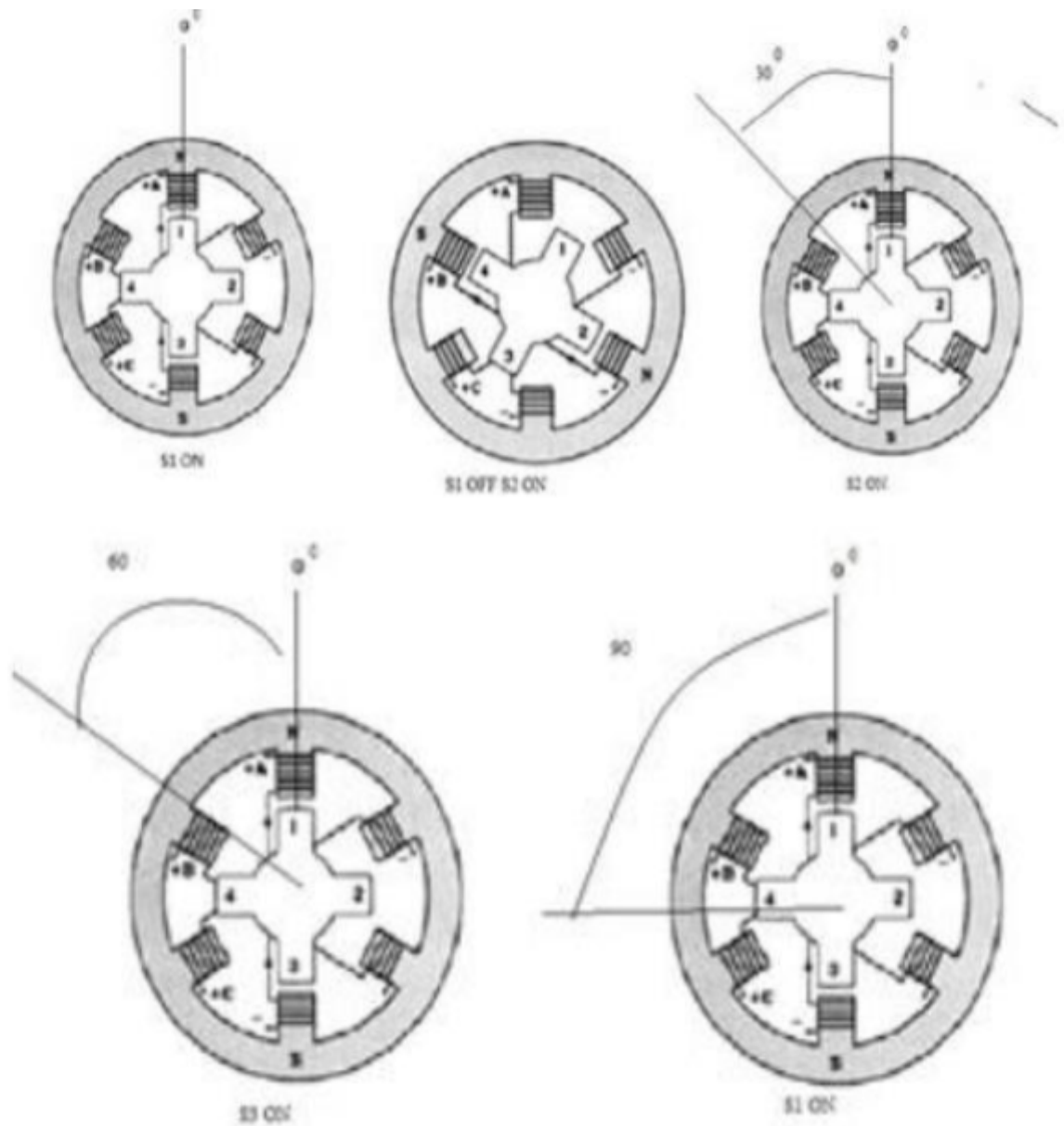


Fig 2.3 step motions as switching sequence process in a three phase VR motor

The truth table for mode I operation in counter and clockwise directions are given in the table

Table 2.1: Counter Clockwise Rotation (CCW)

S1	S2	S3	θ
*	-	-	0
-	*	-	30
-	-	*	60
*	-	-	90
-	*	-	120
-	-	*	150
*	-	-	180
-	*	-	210
-	-	*	240
*	-	-	270
-	*	-	300
-	-	*	330
*	-	-	360

Table 2 Clockwise Rotation (CW)

S1	S2	S3	θ
*	-	-	0
-	-	*	30
-	*	-	60
*	-	-	90
-	-	*	120
-	*	-	150
*	-	-	180
-	-	*	210
-	*	-	240
*	-	-	270
-	-	*	300
-	*	-	330
*	-	-	360

(b). Mode II: Two Phase on Mode

In this mode two stator phases are excited simultaneously. When phases a and b are energized together, the rotor experiences torque from both phases and comes to rest in a point mid-way between the two adjacent full step position. If the phases b and c are excited, the rotor occupies a position such that angle between AA' axis of stator and 1-3 axis of rotor is equal to 45° . To reverse the direction of rotation switching sequence is changed a and b, a and c etc. The main advantage of this type of operation is that torque developed by the stepper motor is more than that due to single phase ON mode of operation.

The truth table for mode II operation in counter clockwise and clockwise directions is given in table a

2.3: Counter Clockwise Rotation (CCW)

S1	S2	S3	θ°	
*	*	-	15°	AB
-	*	*	45°	BC
-	*	-	75°	CA
*	*	-	105°	AB
-	*	*	135°	BC
-	*	-	165°	CA
*	*	-	195°	AB
-	*	*	225°	BC
-	*	-	255°	CA
*	*	-	285°	AB

Table 2.4: Clockwise Rotation (CW) (C)

	S1	S2	S3	θ
AC	-	*	-	15°
CB	-	*	*	45°
BA	*	*	-	75°
AC	-	*	-	105°
CB	-	*	*	135°
BA	*	*	-	165°
AC	-	*	-	195°
CB	-	*	*	225°
BA	*	*	-	255°
AC				285°

Mode III: Half step Mode

In this type of mode of operation on phase is ON for some duration and two phases are ON during some other duration. The step angle can be reduced from 30° to 15° by exciting phase sequence a, a+b, b,b+c, c etc. The technique of shifting excitation from one phase to another from a to b with an intermediate step of a+b is known as half step and is used to realize smaller steps continuous half stepping produces smoother shaft rotation.

The truth table for mode III operation in counter and clockwise directions are given in the table

Table 2.5: Counter Clockwise Rotation (CCW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	*	-	15°	AB°
-	*	-	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
*	-	*	75°	CA°
*	-	-	90°	A°
*	*	-	105°	AB°
-	*	-	120°	B°
-	*	*	135°	BC°
-	*	-	150°	C°
*	-	*	165°	CA°

Table 2.6: Clockwise Rotation (CW)

S1	S2	S3	θ	
*	-	-	0°	A°
*	-	*	15°	AB°
-	-	*	30°	B°
-	*	*	45°	BC°
-	-	*	60°	C°
-	*	-	75°	CA°
*	*	-	90°	A°
*	-	-	105°	AB°
*	-	*	120°	B°
-	-	-	135°	BC°
-	*	*	150°	C°
-	*	-	165°	CA°

MICRO STEPPING CONTROL OF STEPPING MOTOR

Stepping motor is a digital actuator which moves in steps of θ_s in response to input pulses. such incremental motion results in the following limitations of the stepper motor

Limited resolution

As θ_s is the smallest angle through which the stepper motor can move, this has an effect on position accuracy of incremental servo system employing stepper motors because the stepper motor cannot position the load to an accuracy finer than θ_s .

Mid frequency Resonance

A phenomenon in which the motor torque suddenly drops to a low value at certain pulse frequencies as in fig

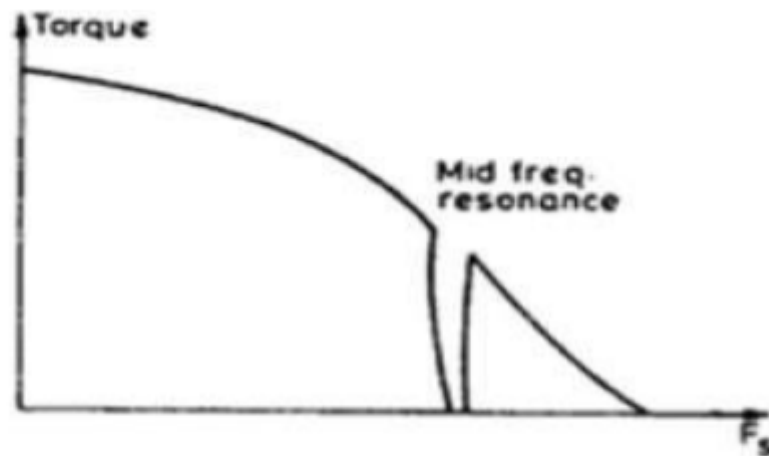


Fig 2.4 Mid frequency Resonance

A new principle known as micro stepping control has been developed with a view of overcoming the above limitation. It enables the stepping motor to move through a tiny micro step of size $\Delta \theta_s \ll \theta_s$ full step angle in response to input pulses.

1. Principle of micro stepping

Assume a two phase stepper motor operating in 'one phase ON' sequence. Assume also that only B2 winding is On and carrying current $I_{B2} = I_R$, the rated phase current. All the other windings are OFF. In this state the stator magnetic field is along the positive real axis as shown in fig (a). Naturally the rotor will also be in $\theta = 0^\circ$ position.

When the next input pulse comes, B2 is switched OFF while A1 is switched ON. In this condition $I_{A1} = I_R$ while all the phase currents are zero. As a result the stator magnetic field rotates through 90° in counter clockwise direction as shown in fig (a).

The rotor follows suit by rotating through 90° in the process of aligning itself with stator magnetic field. Thus with a conventional controller the stator magnetic field rotates through 90° when a new input pulse is received causing the rotor to rotate full step.

However in micro stepping we want the stator magnetic field to rotate through a small angle $\theta_s \ll 90^\circ$ in respect to input pulse. This is achieved by modulating the current through

B2 and A1 winding as show in fig (b) such that

$$I_{A1} = I_R \sin \theta$$

$$I_{B1} = I_R \cos \theta$$

$$\theta$$

Then the resulting stator magnetic field will be at an angle θ° with respect to the positive real axis. consequently the rotor will rotate through an angle $\theta_s \ll 90^\circ$.

This method of modulating current through stator winding so as to obtain rotation of stator magnetic field through a small angle θ°

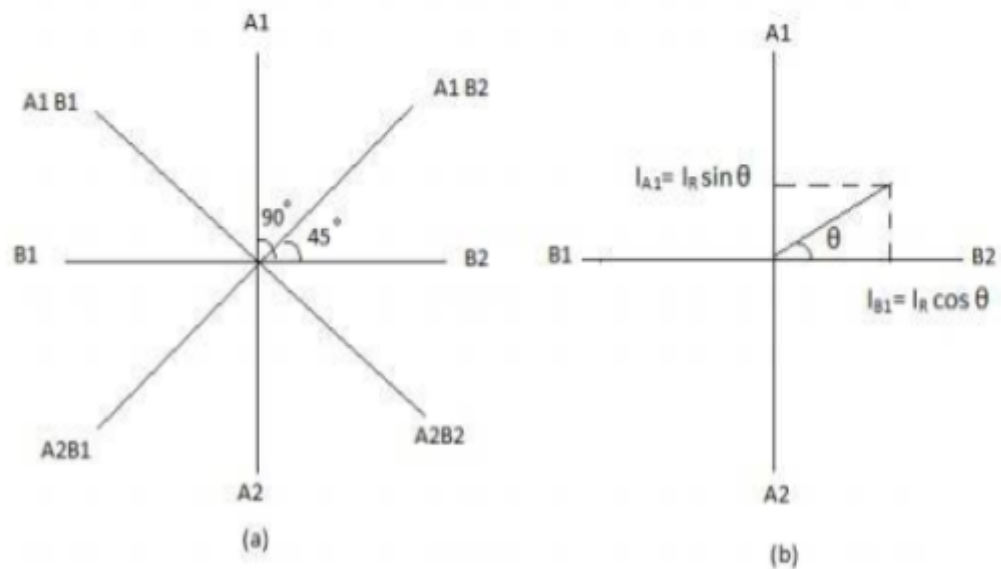


Fig 2.5 Principle of micro stepping

MULTISTACK VARIABLE RELUCTANCE STEPPER MOTOR

These are used to obtain smaller step sizes, typically in the range of 2° to 15° . Although three stacks are common a multistack motor may employ as many as seven stacks. This type is also known as the cascade type. A cutaway view of a three stack motor is shown

in fig. 2.6.

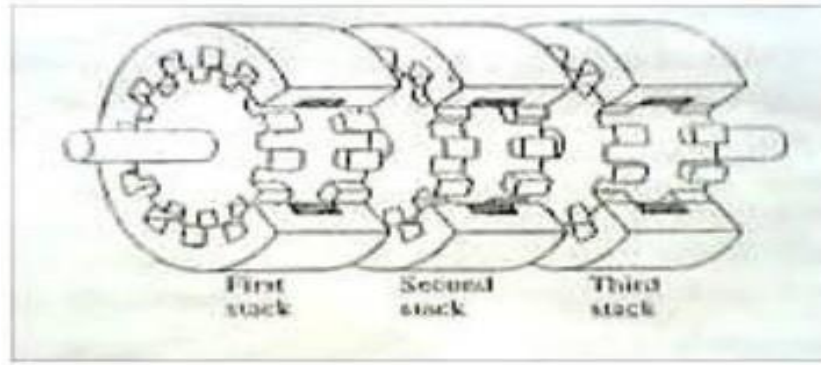


Fig. 2.6: Construction of multi-stack VR motor.

A multistack (or m-stack) variable reluctance stepper motor can be considered to be made up of 'm' identical single stack variable reluctance motors with their rotors mounted on a single shaft. The stators and rotors have the same number of poles (or teeth) and therefore same pole (tooth) pitch. For a m0stack motor, the stator poles (or teeth) in all m stacks are aligned, but the rotor poles (teeth) are displaced by $1/m$ of the pole pitch angle from one another. All the stator pole windings in a given stack are excited simultaneously and, therefore the stator winding of each stack forms one phase. Thus the motor has the same number of phases as number of stacks.

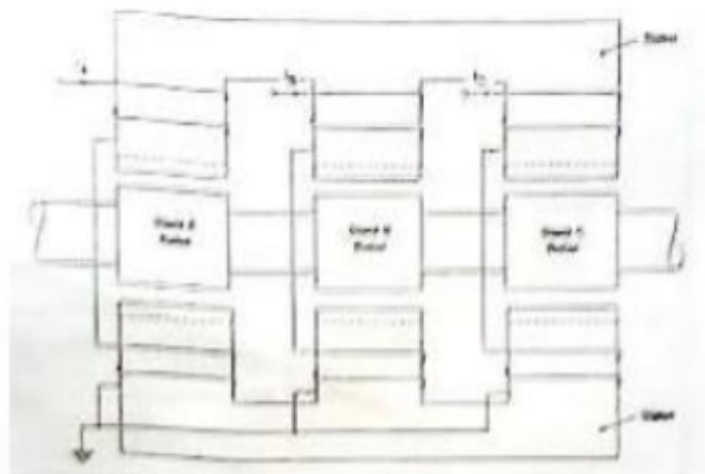


Fig. 2.7: Cross-section of a 3-stack, VR stepper motor parallel to the shaft.

Figure 2.7 shows the cross section of a three stack (3-phase) motor parallel to the shaft. In each stack, stator and rotors have 12 poles (teeth). For a 12 pole rotor, pole pitch is 30° and therefore, the rotor poles (teeth) are displaced from each other by $1/3$ rd of the pole pitch or 10° . The stator teeth in each stack are aligned. When the phase winding A is excited rotor teeth of stack A are aligned with the stator teeth as shown in fig. 2.8.

When phase A is de-energized and phase B is excited the rotor teeth of stack B are aligned with stator teeth. The new alignment is made by the rotor movement of 10° in the

anticlockwise direction. Thus the motor moves one step (equal to $\frac{1}{2}$ pole pitch) due to change of excitation from stack A to stack B

Next phase B is de-energized and phase C is excited. The rotor moves by another step $\frac{1}{3}$ rd of pole pitch in the anticlockwise direction. Another change of excitation from stack C to stack A will once more align the stator and rotor teeth in stack A. however during this process (A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ A) the rotor has moved one rotor tooth pitch.

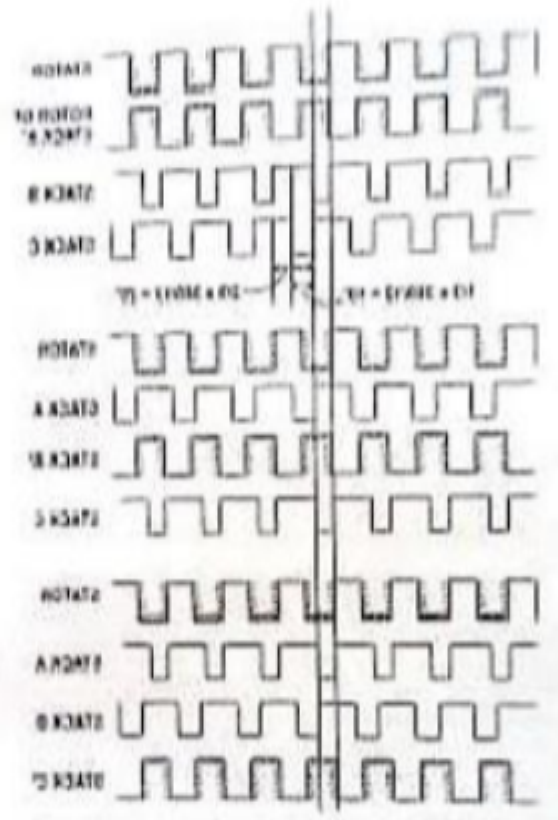


Fig. 2.8: Position of stator & rotor teeth of 3 stack VR motor

Let N_r be the number of rotor teeth and m the number of stacks or phases, then

$$\text{Tooth pitch } T_p = 360/N_r \quad (2.1)$$

$$\text{Step Angle } \alpha = 360^\circ/mN_r \quad (2.2)$$

HYBRID STEPPER MOTOR

Principle of operation

Most widely used hybrid motor is the two phase type as shown in fig2.11. This model has four poles and operates on one phase on excitation.

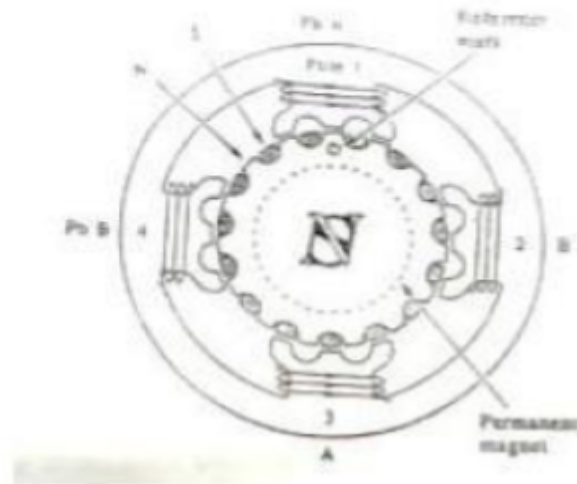


Fig2.9 cross-section of a two phase hybrid motor

The coil in pole 1 and that in pole 3 are connected in series consisting of phase A, and pole 2 and 4 are for phase B. Fig 2.12 shows the process of rotor journey as the winding currents are switched in one phase ON excitation.

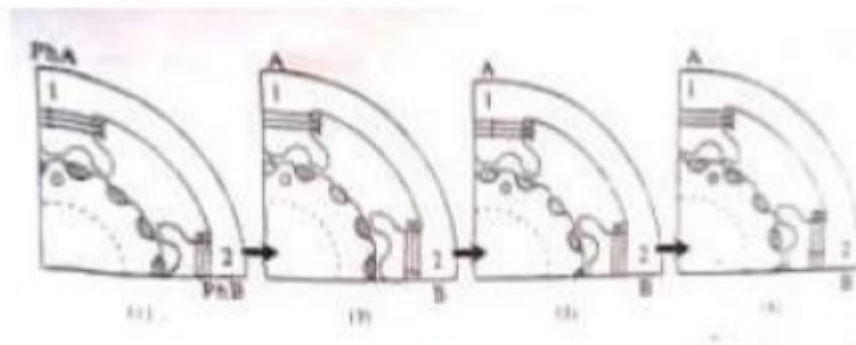


Fig2.10 one-phase on operation of a two-phase hybrid motor.

The poles of phase A are excited the teeth of pole 1 attract some of the rotors north poles, while the teeth of pole 3 align with rotor's south poles. Current is then switched to phase B, The rotor will travel a quarter tooth pitch so that tooth alignment takes place in 2 and 4.

Next current is switched back to phase A but in opposite polarity to before, the rotor will make another quarter tooth journey. The tooth alignment occurs in opposite magnetic polarity to state 1. When current is switched to phase B in opposite polarity (4) Occurs as a result of quarter tooth pitch journey.

The structures of two phase motor considered in fig.2.11 will not produce force in a symmetrical manner with respect to the axis. The motor having 8 poles in the stator shown in fig2.13 considered as the structure in which torque is generated at a symmetrical position on the surface.



Fig2.11 Two-phase hybrid motor with 8 stator poles.



SINGLE PHASE STEPPING MOTOR

These are motors which are designed to be operated from single phase supply. They are widely use in watches and clocks, timers and counters. Present single phase stepping motors use one or more (two) permanent magnets, because permanent magnets are quite necessary to raise the ratio of torque to input power in a miniature motor.

The two requirements of single phase stepping motor are -

To detent the motor at a particular position when the coil is not excited.

To rotate the motor at desired direction by switching the magnetic polarity of only one coil.

1. CONSTRUCTION

It is a permanent magnet type stepper motor with two poles. Rotor is a circular type of permanent magnet as shown in figure 2.27. stator is made of silicon steel stampings with two salient poles. Stator carries a coil which is connected to a pulsed supply. The air gap is specially designed so that specific reluctance at different radial axes are different. Minimum values occur at one tip of the poles. Under normal conditions the rotor occupies any one of the decent position shown in fig 2.28(a) or as in (b) to minimum reluctance position. two positions shown in figures 2.28(a) & (b) are the detent positions of the rotor of the stepper motor.



Fig. 2.14 A single-phase stepping motor

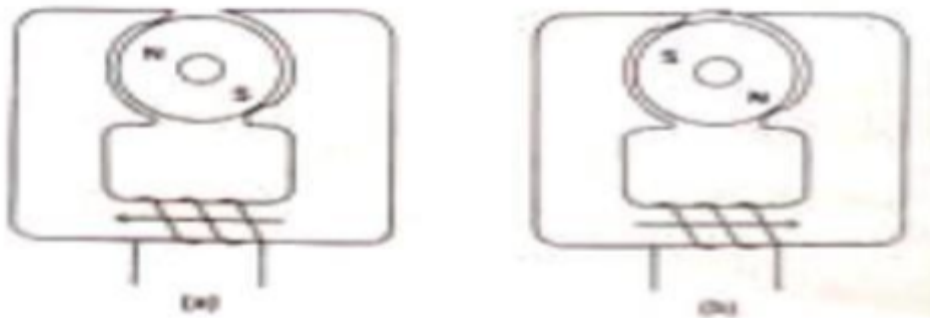


Fig. 2.15 Detent positions and coil polarity to rotate motor.

2. PRINCIPLE OF OPERATION

When the coil is given an electric positive pulse, pole A in position 1 as shown in figure. 2.28(a) it experiences a torque in clockwise direction and finally attains a steady state as in fig 2.28(b). then pulse given to the coil is zero. After a lapse of a second, from the start of the pulse, a negative pulse is given to the coil which makes the pole A as south and pole B as north. Rotor experiences another torque in figure 2.28(a). by repeating the cycle the rotor rotates continuously in step. it is not possible to develop torque in counter clockwise direction by altering pulses.

THEORY OF TORQUE PREDICTION

According to Faradays laws of electromagnetic induction

$$\text{Flux linkages } \lambda = N\phi \quad \dots\dots\dots (2.3)$$

$$\lambda = Li \quad \dots\dots\dots (2.4)$$

Flux linkages can be varied by

Varying flux ϕ

Varying the current 'i' of an electromagnet (i.e) equivalent of varying the mmf

$$\text{Varying the reluctance } L = \frac{N^2}{S}$$

By varying reluctance

$$\text{mmf} = N\phi \quad \dots\dots\dots (2.5)$$

$$\text{Reluctance} = \frac{1}{\mu N^2} \quad \dots\dots\dots (2.6)$$

$$\text{Flux} = \frac{Ni}{S} \quad \dots\dots\dots (2.7)$$

$$\text{Flux linkages } \lambda = \frac{N.Ni}{S} = \frac{N^2 i}{S} \quad \dots\dots\dots (2.8)$$

$$\text{Inductance } L = \frac{\text{flux linkages}}{\text{Ampere}} \quad \dots\dots\dots (2.9)$$

$$L = \frac{N^2 i}{Si} \quad \dots\dots\dots (2.10)$$

$$L = \frac{N^2}{S} \quad \dots\dots\dots (2.11)$$

If the reluctance of magnetic circuit can be varied, inductance L and the flux linkages λ can also be varied.

Consider a magnetic circuit as shown in fig. 2.29.

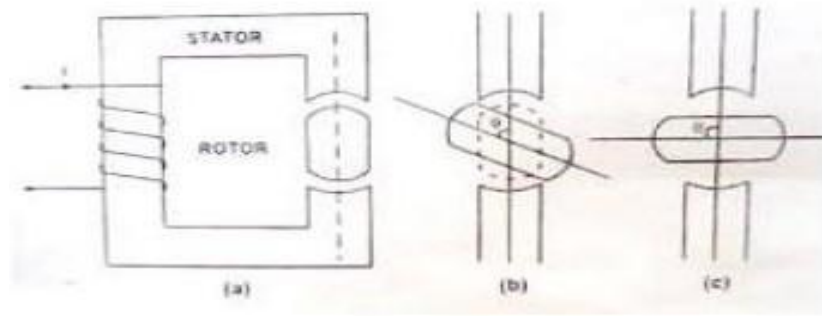


Fig. 2.16 Magnetic circuit

The stator consists magnetic core with two pole arrangement. Stator core carries a coil. Rotor is also made up of ferrous material. The motor core is similar to a salient pole machine. Let the angle between the axis of stator pole and rotor pole be θ . let the angular displacement be illustrated using fig. 2.29 (a, b and c).

Case 1: $\theta = 0$

As shown in fig. 2.29 (a) the air gap between the stator and rotor is very very small. Thereby the reluctance of the magnetic path is least. Due to minimum reluctance, the inductance of the circuit is minimum. Let it be $L_{\max}$

Case 2 : $\theta = 45^\circ$

As shown in fig. 2.29(b) in this only a portion of rotor poles cover the stator poles. Therefore reluctance of the magnetic path is more than that of case 1.due to which the inductance becomes less than $L_{\max}$.

Case 3: $\theta = 90^\circ$

As shown in fig. 2.29(c) the air gap between the stator poles has maximum value. Thereby reluctance has a value yielding minimum inductance. Let it be $L_{\min}$.

Variation in inductance with respect to the angle between the stator and rotor poles is shown in fig. 2.30.

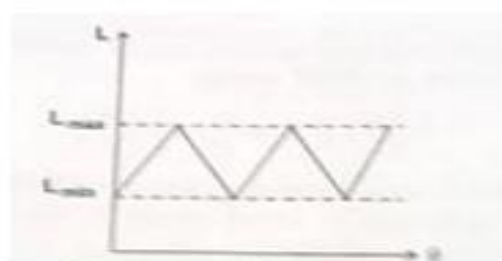


Fig. 2.17 Variation in induction w.r to θ .

Derivation for reluctance torque

As per faradays law of electromagnetic induction an emf induced in an electric circuit when there exists a change in flux linkages.

$$\text{emf induced } e = - \frac{\partial y}{\partial t}$$

$$\text{Where } \lambda = N\Phi \text{ or } \lambda = Li \quad \dots\dots\dots (2.12)$$

$$\text{Therefore } e = - \frac{d}{dt} [Li] \quad \dots\dots\dots (2.13)$$

$$= - L \frac{\partial i}{\partial t} - i \frac{\partial L}{\partial t} \quad \dots\dots\dots (2.14(a))$$

$$= - L \frac{\partial i}{\partial t} - i \frac{\partial L}{\partial \theta} \times \frac{\partial \theta}{\partial t} \quad \dots\dots\dots (2.14(b))$$

$$= - L \frac{\partial i}{\partial t} - i \omega \frac{\partial L}{\partial \theta} \quad \dots\dots\dots (2.14(c))$$

$$\text{Magnitude of } e = L \frac{di}{dt} + \omega i \frac{\partial L}{\partial \theta} \quad \dots\dots\dots (2.15)$$

If the direction of current I is opposite to that of e, then the electric power is transferred from the source to the inductor. On the other hand, if the direction of current I is same as that of e, then the source gets the electrical power from the inductor.

On the basis of magnetic circuit/field theory it is known that the stored energy in a magnetic field.

$$W_e = \frac{1}{2} Li^2 \quad \dots\dots\dots (2.16)$$

The rate of change of energy transfer due to variation in stored energy or power due to variation in stored energy.

$$\frac{dW_e}{dt} = \frac{1}{2} L \cdot 2i \frac{\partial i}{\partial t} + \frac{1}{2} i^2 \frac{\partial L}{\partial t} \quad \dots\dots\dots (2.17)$$

Mechanical power developed/consumed = power received from the electrical source – power due to change in stored energy in the inductor

Power received from the electrical source = $e i$

$$\therefore e i = i L \frac{di}{dt} + \omega i^2 \frac{\partial L}{\partial \theta} \quad \dots\dots (2.18)$$

Power due to change in stored energy

$$= L i \frac{di}{dt} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \dots\dots (2.19)$$

Mechanical power developed

$$= i L \frac{di}{dt} + \omega i^2 \frac{\partial L}{\partial \theta} + L i \frac{di}{dt} + \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \dots\dots (2.20)$$

Mechanical power developed

$$P_m = \frac{1}{2} \omega i^2 \frac{\partial L}{\partial \theta} \quad \dots\dots (2.21)$$

$$P_m = \frac{2\pi N T}{60} \quad \dots\dots (2.22)$$

$$P_m = \omega T \quad \dots\dots (2.23)$$

$$\text{Where } \omega = \frac{2\pi N}{60}$$

$$\text{Therefore reluctance torque } T = \frac{P_m}{\omega} \quad \dots\dots (2.24)$$

$$\text{Reluctance torque } T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \quad \dots\dots (2.25)$$

Note:

* Torque corresponds to motoring when $\frac{\partial L}{\partial \theta}$ is +ve.

* Torque corresponds to generating when $\frac{\partial L}{\partial \theta}$ is -ve.

* Torque is proportional to i^2 : Therefore, it does not depend upon the direction of the current.

TERMINOLOGIES USED IN STEPPER MOTOR

- | | | |
|-------------------|--------------------|-------------------|
| 1. Step angle | 2. Resolution | 3. Stepping rate |
| 4. Hold position | 5. Detent position | 6. Stepping error |
| 7. Position Error | | |

1. Step angle (θ_s or β)

It is the angular displacement of rotor of a stepper motor for every pulse of excitation given to the stator winding of the motor. It is determined by the number of teeth on the rotor and stator, as well as the number of steps in the energisation sequence. It is given by

$$\theta_s = \beta = \frac{360}{m N_r}$$

Where, m = Number of phases (m and q)

N_r - number of teeth on rotor.

Also, $\theta_s = ((N_s \sim N_r) / (N_s \cdot N_r)) \cdot 360$

2. Resolution

It is the number of steps per revolution. It is denoted as S or Z . It is given by

$$Z = 360 / (\theta_s)$$

For variable reluctance motor $Z = (q N_r)$ or $(m N_r)$

For PM motor and hybrid motor $Z = 2q N_r$

Also, $Z = (N_s \cdot N_r) / (N_s \sim N_r)$

Where N_s -number of teeth/poles on stator.

3. Stepping Rate

The number of steps per second is known as stepping rate or stepping frequency.

4. Hold Position

It corresponds to the rest position when the stepper motor is excited or energized (this corresponds to align position of VR motor)

5. Detent Position

It corresponds to rest position of the motor when it is not excited.

6. Stepping Error

Actual step angle is slightly different from the theoretical step angle. This is mainly due to tolerances in the manufacture of stepper motor and the properties of the magnetic and other materials used.

The error in the step angle is expressed as a percentage of the theoretical step angle.

$$\% \text{error} = ((\text{step angle} - \text{theoretical step angle}) / \text{theoretical step angle}) * 100$$

Percentage error is restricted to $\pm 5\%$. In some cases it is restricted to $\pm 2\%$. The cumulative error between the actual angular displacement and theoretical angular displacement is expressed as a percentage of theoretical angular displacement. It is usually considered for one complete cycle.

7. Positional Error

The maximum range of cumulative percentage of error taken over a complete rotation of stepper motor is referred to as positional accuracy as shown in fig below.

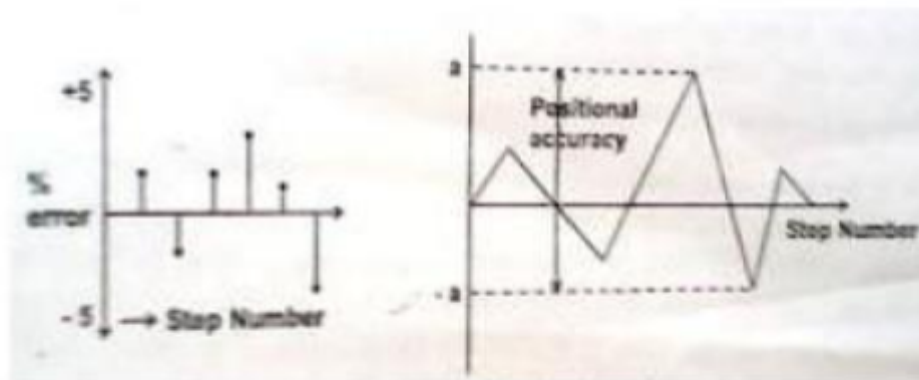


Fig. 2.18 Positional Accuracy

CHARACTERISTICS OF STEPPER MOTOR

Stepper motor characteristics are divided into two groups

Static characteristics

Dynamic characteristics

1. Static characteristics

It is divided into two characteristics.

- (i) Torque Angle curve
- (ii) Torque current curve

(i) Torque-Angle curve

Torque angle curve of a step motor is shown in fig.2.32. it is seen that the Torque increases almost sinusoid ally, with angle Θ from equilibrium.

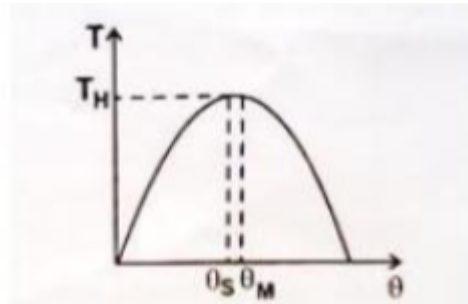


Fig. 2.19 Torque Angle

Holding Torque (TH)

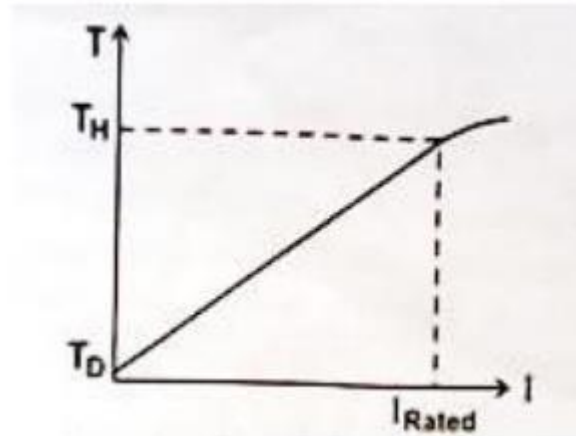
It is the maximum load torque which the energized stepper motor can withstand without slipping from equilibrium position. If the holding torque is exceeded, the motor suddenly slips from the present equilibrium position and goes to the static equilibrium position.

Detent torque (TD):

It is the maximum load torque which the un-energized stepper motor can withstand slipping. Detent torque is due to magnetism, and is therefore available only in permanent magnet and hybrid stepper motor. It is about 5-10 % of holding torque.

(ii) Torque current curve

A typical torque curve for a stepper motor is shown in fig.2.34. It is seen the curve is initially linear but later on its slope progressively decreases as the magnetic circuit of the motor saturates.



Torque constant (K_t)

Torque constant of the stepper is defined as the initial slope of the torque-current (T-I) curve of the stepper motor. It is also known as torque sensitivity. Its units N-mA, kg-cm/A or OZ-in/A

2. Dynamic characteristics:

A stepper motor is said to be operated in synchronism when there exist strictly one to one correspondence between number of pulses applied and the number of steps through which the motor has actually moved. There are two modes of operation.

Start-Stop mode

Also called as pull in curve or single stepping mode.

Slewing mode

In start –stop mode the stepper motor always operate in synchronism and the motor can be started and stopped without using synchronism. In slewing mode the motor will be in synchronism, but it cannot be started or stopped without losing synchronism. To operate the motor in slewing mode first the motor is to be started in start stop mode and then to slewing mode. Similarly to stop the motor operating in slewing mode, first the motor is to be brought to the start stop mode and then stop.

Start Stop mode

Start stop mode of operation of stepper motor is shown in fig.2.35 (a). In this second pulse is given to the stepper motor only after the rotor attained a steady or rest position due to first pulse. The region of start-stop mode of operation depends on the operation depends on the torque developed and the stepping rate or stepping frequency of stepper motor.

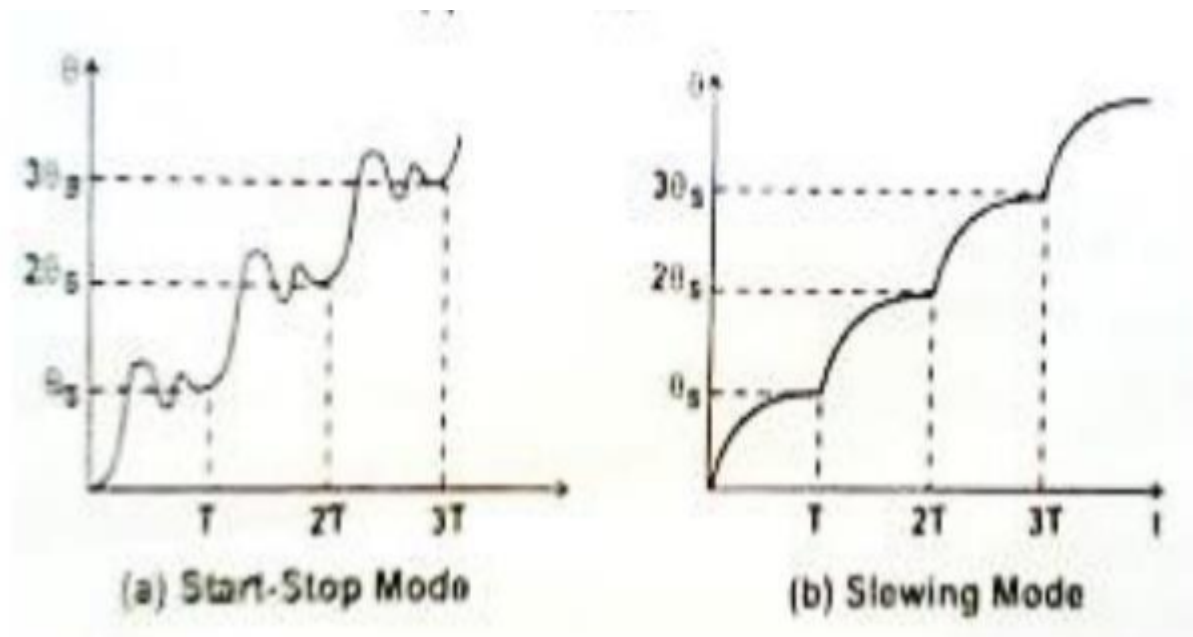


Fig. 2.21 Modes of operation

pulse is given to the stepper motor only after the rotor attained a steady or rest position due to first pulse. The region of start-stop mode of operation depends on the operation depends on the torque developed and the stepping rate or stepping frequency of stepper motor.

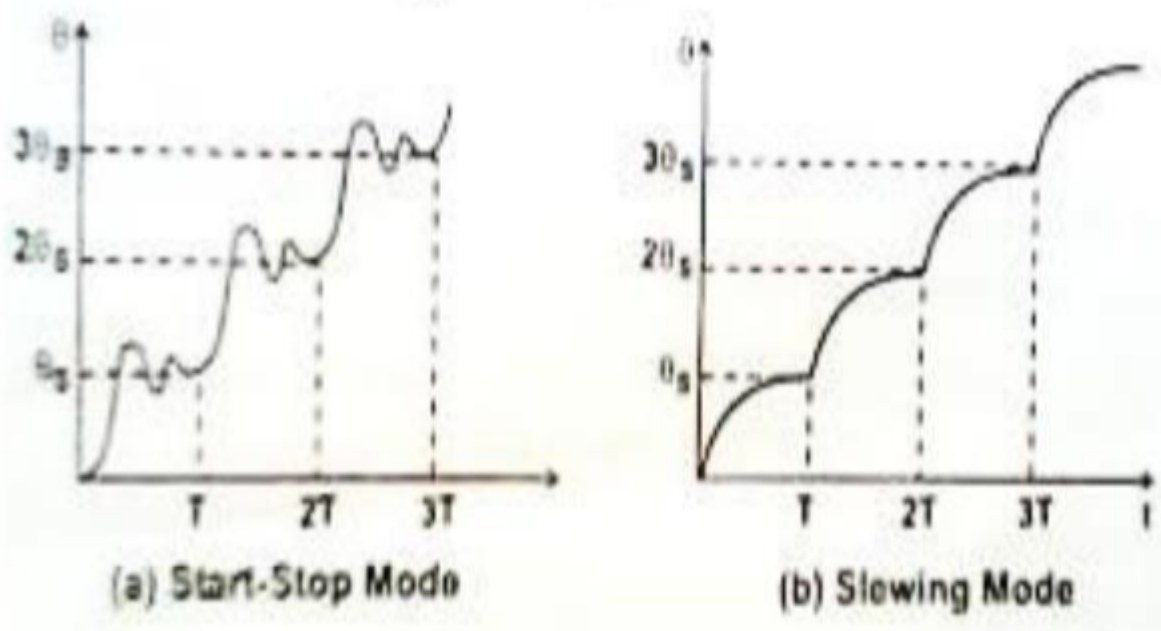


Fig. 2.21 Modes of operation

TORQUE-SPEED CHARACTERISTICS

Torque developed by the stepper motor and stepping rate characteristics for both modes of operation are shown in fig.2.36. the curve ABC represents the "pull in" characteristics and the curve ADE represents the "pull-out" characteristics.

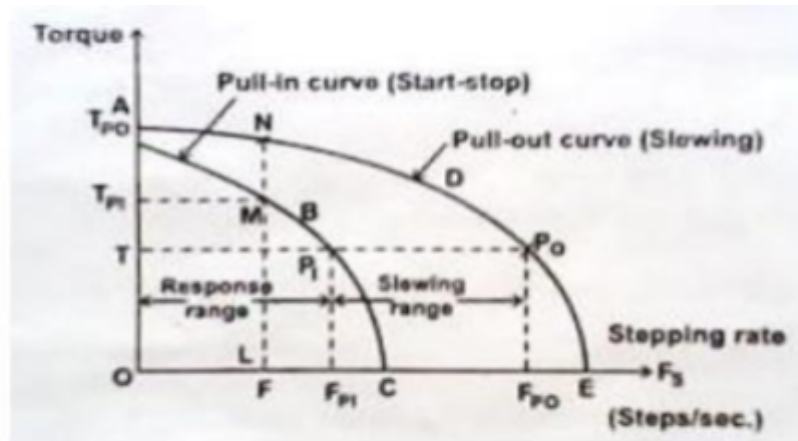


Fig. 2.22 Torque-Speed Characteristics

The area OABCO represents the region for start stop mode of operation. At any operating point in the region the motor can start and stop without losing synchronism. The area ABCEDA refers to the region for slewing mode of operation. At any operating point without losing synchronism to attain an operating point in the slewing mode at first the motor is to operate at a point in the start-stop mode and then stepping rate is increased to operate in slewing mode, similarly while switching off it is essential to operate the motor from slewing mode to start-stop mode before it is stopped.

Pull in torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the start-stop mode of operation without losing synchronism. In the fig.2.36 LM represents the pull in torque (i.e.)TPI corresponding to the stepping rate F (i.e.) OL.

Pull out torque

It is the maximum torque developed by the stepper motor for a given stepping rate in the slewing mode without losing synchronism. In fig.2.36 LN represents the pull in torque (i.e.) TPO corresponding to F (i.e.) OL.

Pull in range

It is the maximum stepping rate at which the stepper motor can operate in start-stop mode developing a specific torque (without losing synchronism).In fig. 2.36 PIT represents pull in range for a torque of T (i.e.) OP. This range is also known as response range of stepping rate for the given torque T.

Pull out range

It is the maximum stepping rate at which the stepper motor can operate in slewing mode developing a specified torque without losing synchronism. In fig.2.36 PIPO represents the pull out range for a torque of T. The range PIPO is known slewing range.

Pull in rate (FPI)

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

Pull out rate (FPO)

It is the maximum stepping rate at which the stepper motor will slew, without missing steps, against load torque T.

Synchronism

This term means one to one correspondence between the number of pulses applied to the stepper motor and the number of steps through which the motor has actually moved.

Mid frequency resonance

The phenomenon at which the motor torque drops to a low value at certain input pulse frequencies.



FIGURES OF MERIT (FM'S)

Figures of merit (FM'S) are performance indices which give quantitative information on certain aspects of performance and design of actuators such as stepper motors. DC or AC servomotors etc.

1. Electrical Time constant (Te)

$$T_e = L_m / R_m \quad (2.26)$$

Where, L_m - Inductance of motor winding

R_m - resistance of motor.

T_e - governs the rate at which current rises when the motor winding is turned on. It also determines how quickly the current decays when the winding is turned off.

In motion control, the speed of response is of importance. Hence electrical time constant T_e must be minimized.

T_e dependent upon inductance and resistance of the motor winding. Inductance is determined by magnetic circuit. (i.e.) magnet iron volume as well as volume of copper used in the motor design. Once these have been designed, neither reducing conductor size nor increasing the number of turns will reduce T_e . Otherwise magnetic circuit itself has to be redesigned.

2. Motor time constant (T_m)

$$T_m = J / (K_e K_t R_m) = J R_m / K_e \quad (2.27)$$

Where, J -moment of inertia of motor (kg-m²)

R_m -resistance of the motor winding

(Ω) K_e -back emf constant(volt s/ rad)

K_t - torque constant (Nm/A)

Motor back emf and torque constants are determined by magnetic circuit and phase winding design. Winding resistance also from winding design. Moment of inertia is determined by mechanical design.

In this way motor time constant T_m combines all the three aspects of motor design viz, magnetic circuit, electrical circuit and mechanical design. Achieving a low T_m requires excellence in motor design. As a thumb rule the ratio of T_e/T_m 0.1

Initial Acceleration (A_0):

$$A_0 = T / J (\text{rad/S}^2)$$

Where , T -rated torque (N-M)

J -moment of inertia(kg-m²)

A_0 gives a quantitative idea of how fast the motor accelerates to its final velocity or position. Maximization of A_0 calls for good magnetic circuit design to produce high torque in conjunction with good mechanical design to minimize rotor inertia. The moment of inertia of the load coupled to motor also determines A_0 .

Motor Constant (k_m)

$$k_m = T / \sqrt{\omega}$$

where , T - rated motor torque

ω -rated power(w) of the motor

$$k_m = \sqrt{K_t K_e / R_m}$$

This shows that maximizing k_m causes minimizing R , maximizing K_e and K_t . Maximizing K_e and K_t call for optimization of magnetic circuit design, decreasing electrical time constant T_e which is undesirable. A trade off between electrical and magnetic circuit design is necessary to achieve a good k_m .

Power rate (dP/dt):

$$\text{Power rate is } (dP/dt) = (d/dt)(T \cdot (d\theta/dt)) = T \cdot (d^2\theta/dt^2) = T \cdot (T/J) = (T^2/J) \quad \dots\dots(2.28)$$

Now $T = K_t I$ so

DRIVE SYSTEM AND CONTROL CIRCUITRY FOR STEPPER MOTOR

1. DRIVE SYSTEM

The stepper motor is a digital device that needs binary (digital) signals for its operation. Depending on the stator construction two or more phases have to be sequentially switched using a master clock pulse input. The clock frequency determines the stepping rate, and hence the speed of the motor. The control circuit generating the sequence is called a translator or logic sequencer.

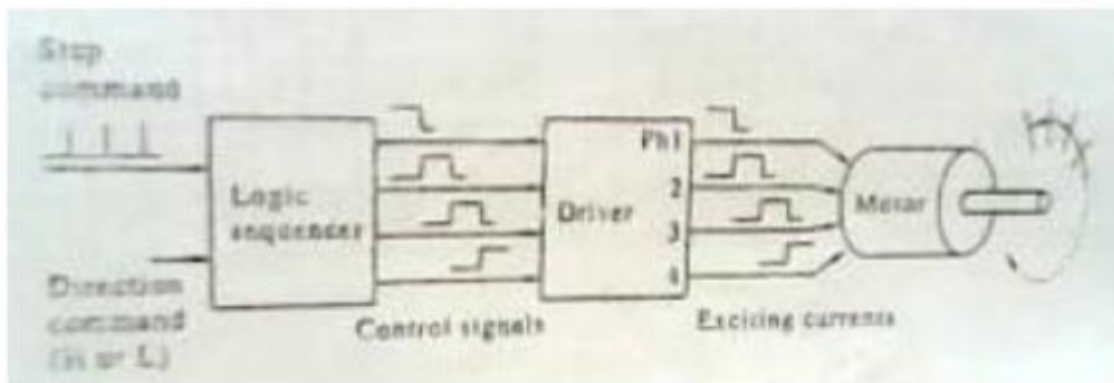


Fig. 2.23 Block Diagram of the drive system of a stepping motor.

The fig 2.38 shows the block diagram of a typical control circuit for a stepper motor. It consists of a logic sequencer, power driver and essential protective circuits for current and voltage limiting. This control circuit enables the stepper motor to be run at a desired speed in either direction. The power driver is essentially a current amplifier, since the sequence generator can supply only logic but not any power. The controller structure for VR or hybrid types of stepper motor

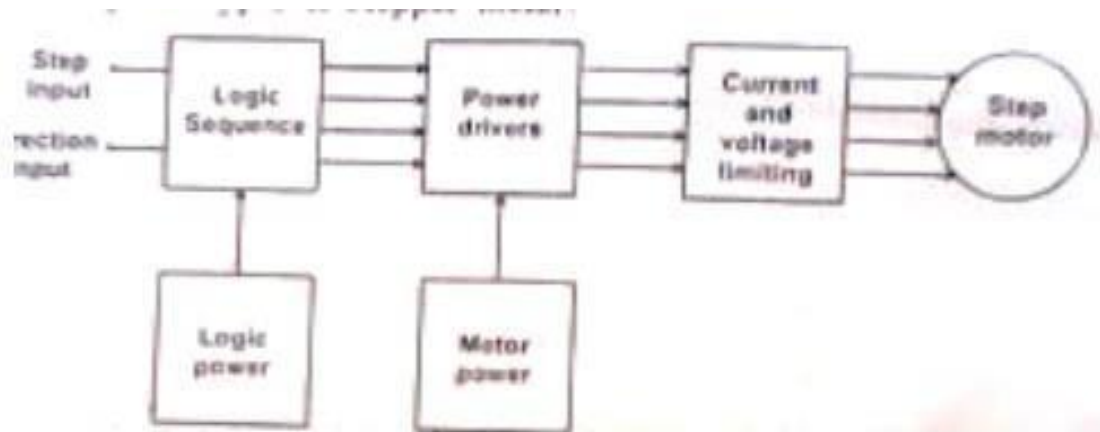


Fig. 2.24 Block diagram of a typical step motor control

2. LOGIC SEQUENCER :

The logic sequencer is a logic circuit which control the excitation of the winding sequentially, responding to step command pulses. A logic sequencer is usually composed of a shifter register and logic gates such as NANDs, NORs etc. But one can assemble a logic sequencer for a particular purpose by a proper combination of JK flip flop, IC chips and logic gate chips.

Two simple types of sequencer build with only two JK-FFs are shown in fig 2.39 for unidirectional case. Truth tables for logic sequencer also given for both the directions.



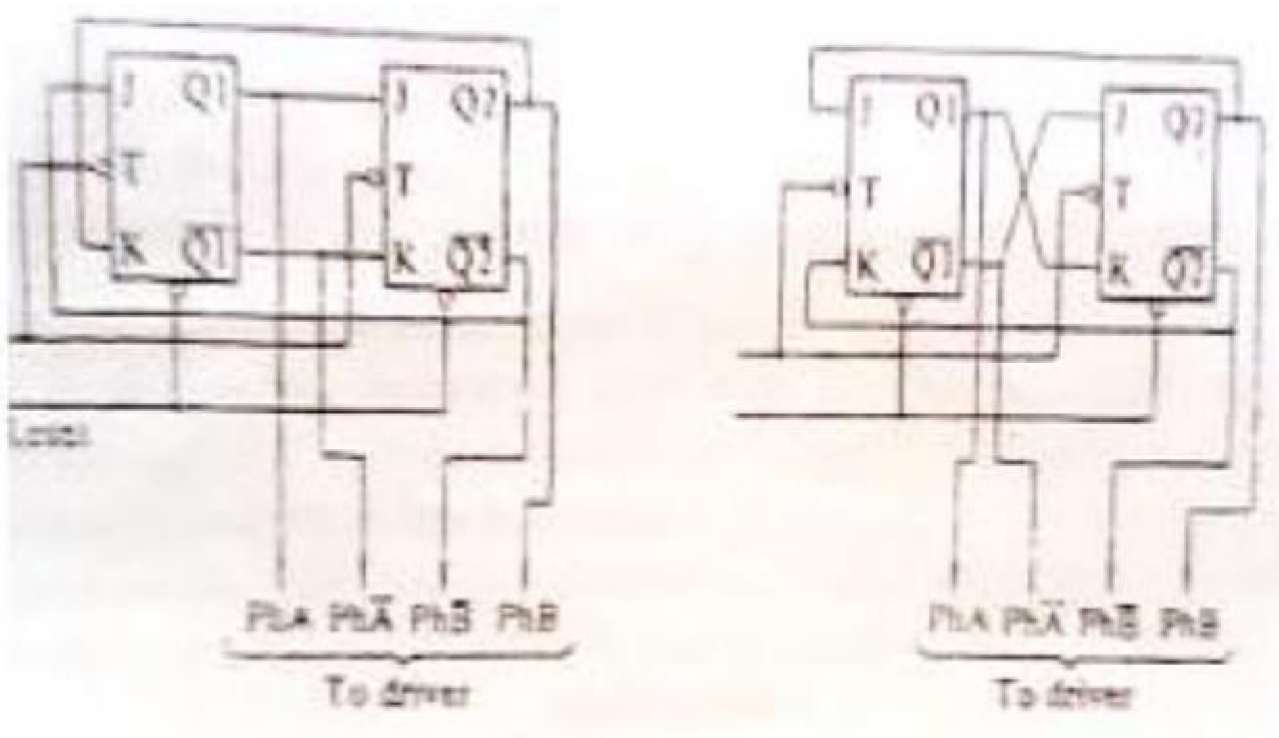


Fig.2.25 A unidirectional logic sequencer for two phase on operation of a two phase hybrid motor

TABLE 2.7 Logic Sequencer

	R	1	2	3	4	5	6	
Ph A,Q1	0	1	1	0	0	1	1	
Ph B,Q2	0	0	1	1	0	0	1	
Ph $\bar{A}$,Q1	1	0	0	1	1	0	0	
Ph $\bar{B}$,Q2	1	1	0	0	1	1	0	...

	R	1	2	3	4	5	6	
Ph A,Q1	0	0	1	1	0	0	1	
Ph B,Q2	0	1	1	0	0	1	1	
Ph $\bar{A}$,Q1	1	1	0	0	1	1	0	
Ph $\bar{B}$,Q2	1	0	0	1	1	0	0	

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

Q1-----Ph A

$\overline{Q1}$ -----Ph $\overline{A}$

Q2-----Ph B

$\overline{Q2}$ -----Ph $\overline{B}$

If Q1 is on the H level the winding Ph A is excited and if Q1 is on L level, Ph A is not excited.

To reserve the rotational direction, the connection of the sequencer must be interchanged. The direction switching circuits shown in fig 2.40 may be used for this purpose. The essential functions being in the combination of three NAND gates or two AND gates and a NOR gate.

3. Power Driver Circuit

The number of logic signals discussed above is equal to the number of phases and the power circuitry is identical for all phases. Fig. 2.44(a) shows the simplest possible circuit of one phase consisting of a Darlington pair current amplifier and associated protection circuits. The switching waveform shown in fig. 2.44(c) is the typical R-L response with an exponential rise followed by decay at the end of the pulses.

In view of the inductive switching operation, certain protective elements are introduced in the driver circuit. These are the inverter gate 7408, the forward biased diode D1 and the freewheeling diode D. The inverter IC provides some sort of isolation between the logic circuit and the power driver.

There are some problems with this simple power circuit. They can be understood by considering each phase winding as a R-L circuit shown in fig. 2.44(b) subject to repetitive switching. On application of a positive step voltage, the current rises exponentially as

$$i(t) = I(1 - e^{-t/\tau}) \quad \dots \dots (2.29)$$

Where $I = V/R$ – rated current and

$\tau = L/R$ winding time constant.

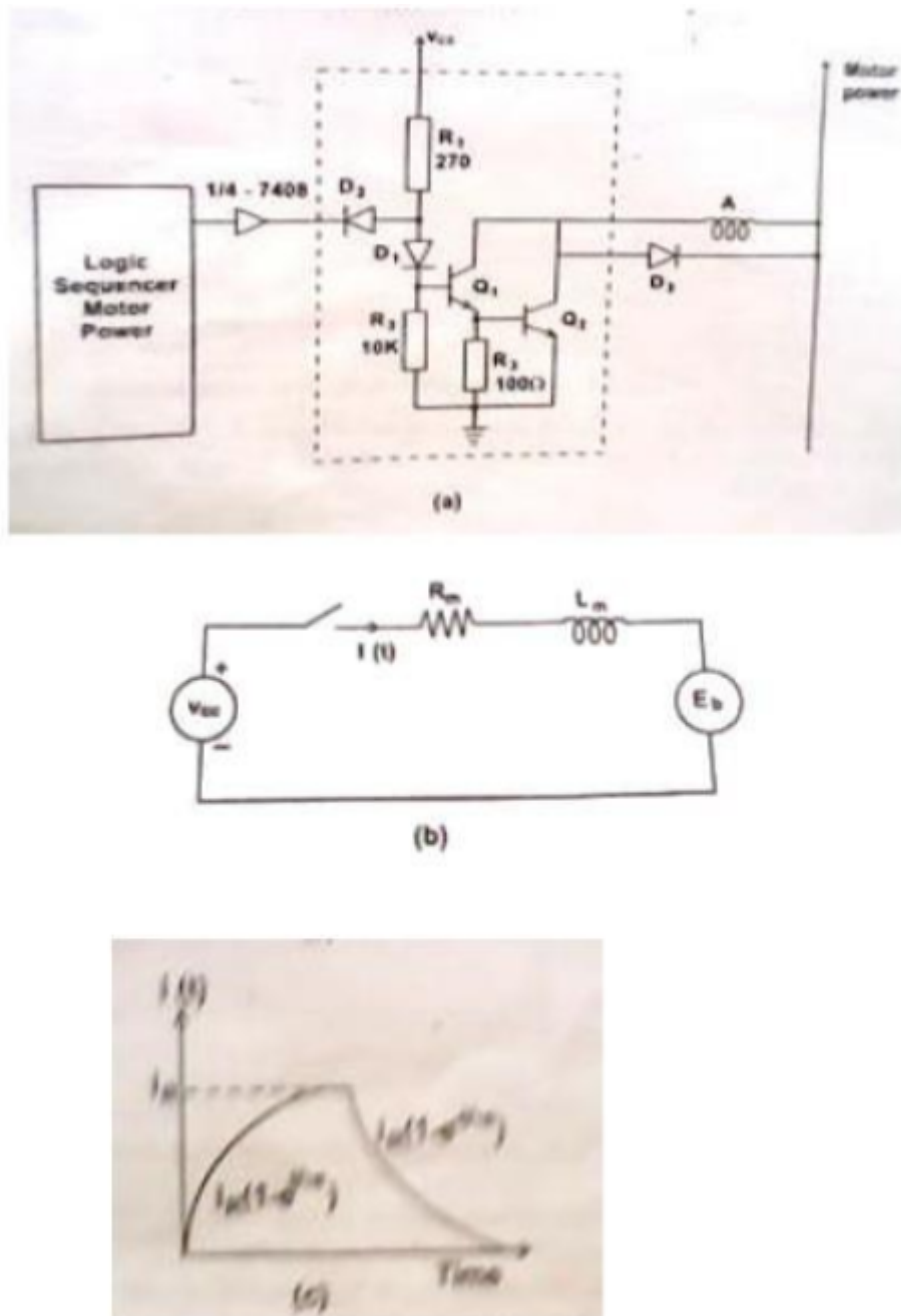


Fig. 2.26 Power Driver Stage of Stepper Motor Controller

In practice, the time constant τ limits the rise and fall of current in the winding. At low stepping rate the current rises to the rated value in each ON interval and falls to zero value in each OFF interval. However as the switching rate increases, the current is not able to rise to the steady state, nor fall down to zero value within the on/off time intervals set by the pulse waveform. This in effect, smoothens the winding current reducing the swing as shown in fig. 2.45. As a result the torque developed by the motor gets reduced considerably and for higher frequencies, the motor just 'vibrates' or oscillates within one step of the current mechanical position.

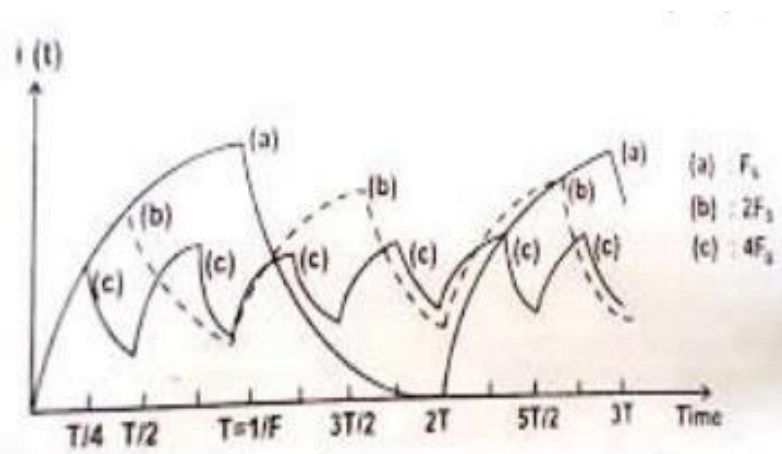


Fig. 2.27 Effect of increasing Stepping Rate on Current Swing

In order to overcome these problems and to make improvement of current build up several methods of drive circuits have been developed.

For example when a transistor is turned on to excite a phase, the power supply must overcome effect of winding inductances has tendency to oppose the current built up. As switching frequency increases the position that the buildup time takes up within the switching cycle becomes large and it results in decreased torque and slow response.

4. Improvement of current buildup/special driver circuit

(a) Resistance drive (L/R drive)

Here the initial slope of the current waveform is made higher by adding external resistance in each winding and applying a higher voltage proportionally. While this increases the rate of rise of the current, the maximum value remains unchanged as shown in fig. 2.46.

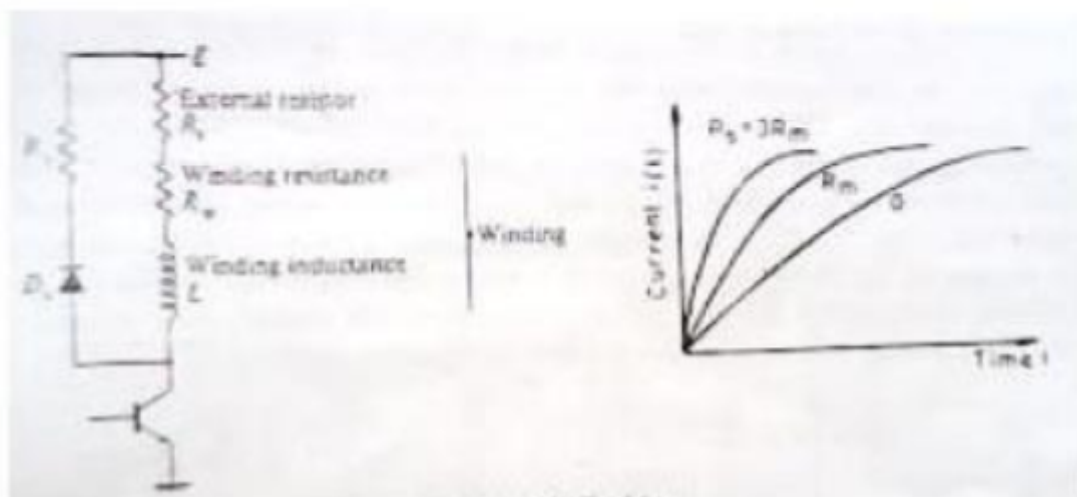


Fig. 2.28 L/R drive

The circuit time constant is now reduced and the motor is able to develop normal torque even at high frequencies. The disadvantage of this method is Flow of current through external resistance causes I^2R losses and heating. This denotes wastage of power as far as the motor is concerned.

In order to reach the same steady state current I_R as before, the voltage required

To be applied is much higher than before. Hence this approach is suitable for small instrument stepper motor with current ratings around 100 mA, and heating is not a major problem.

(b) Dual voltage driver (or) Bi-level driver

To reduce the power dissipation in the driver and increase the performance of a stepping motor, a dual-voltage driver is used. The scheme for one phase is shown in fig. 2.47.

When a step command pulse is given to the sequencer, a high level signal will be put out from one of the output terminal to excite a phase winding. On this signal both T1 and T2 are turned on, and the higher voltage E_H will be applied to the winding. The diode D1 is now reverse biased to isolate the lower voltage supply. The current build up quickly due to the higher voltage E_H . The time constant of the monostable multivibrator is selected so that transistor T1 is turned off when the winding current exceeds the rated current by a little. After the higher

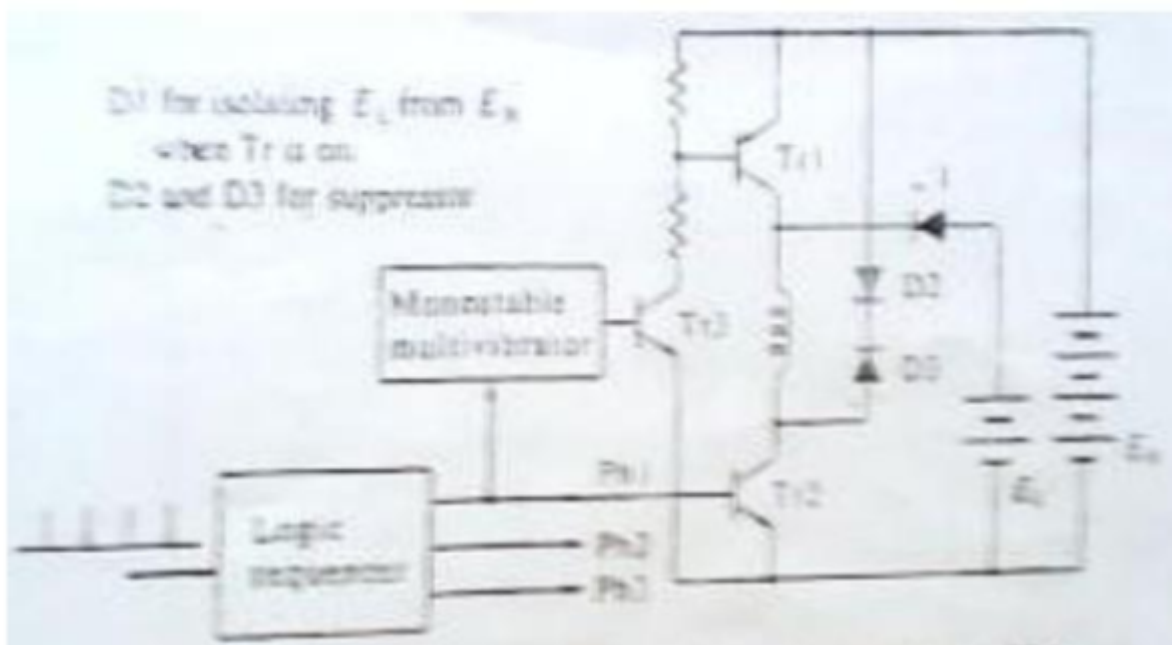


Fig. 2.29 Improvement of current buildup by dual voltage drive

Voltage source is cut off the diode is forward biased and the winding current is supplied from the lower voltage supply. A typical current wave form is shown in fig. 2.48.

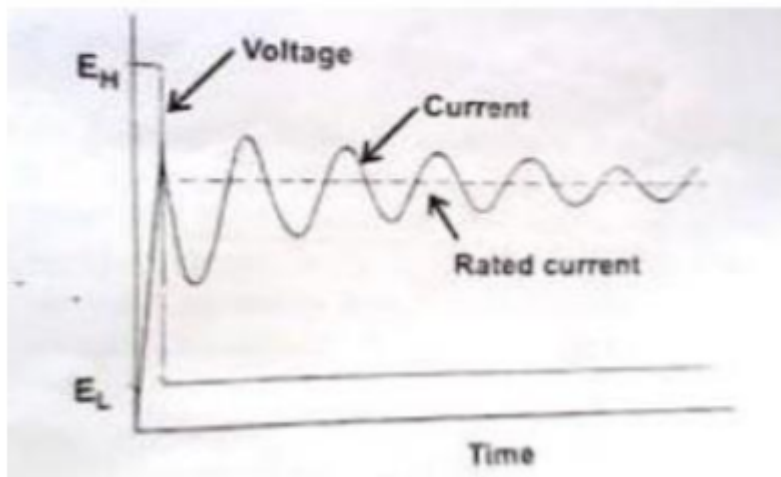


Fig. 2.30 Voltage and current wave form in dual voltage driver

When the dual voltage method is employed for the two phase on drive of a two phase hybrid motor, the circuit scheme will be such as that shown in fig.2.49. Two transistors T_1 & T_2 and two diodes D_1 and D_2 are used for switching the higher voltage. In dual voltage scheme as the stepping rate is increased, the high voltage is turned on for a greater percentage of time.

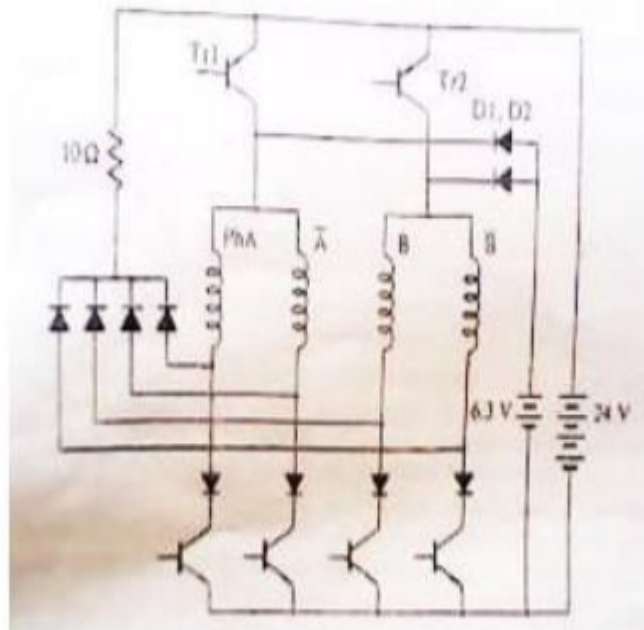


Fig. 2.31 A dual-voltage driver for the two-phase-on drive of a two phase hybrid motor

This drive is good and energy efficient. However it is more complex as it requires two regulated power supplies E_H & E_L and two power transistor switches T_1 & T_2 and complex switching logic. Hence it is not very popular.

(c) Chopper drive

Here a higher voltage 5 to 10 times the related value is applied to the phase winding as shown in fig.2.50(a) and the current is allowed to raise very fast. As soon as the current reaches about 2 to 5% above the rated current, the voltage is cut off, allowing the current to decrease exponentially. Again as the current reaches some 2 to 5% below the rated value, the voltage is applied again. The process is repeated some 5-6 times within the ON period before the phase is switched off. During this period the current oscillates about the rated value as shown in fig. A minor modification is to chop the applied dc voltage at a high frequency of around 1kHz, with the desired duty cycle so as to obtain the average on-state current equal to the rated value.

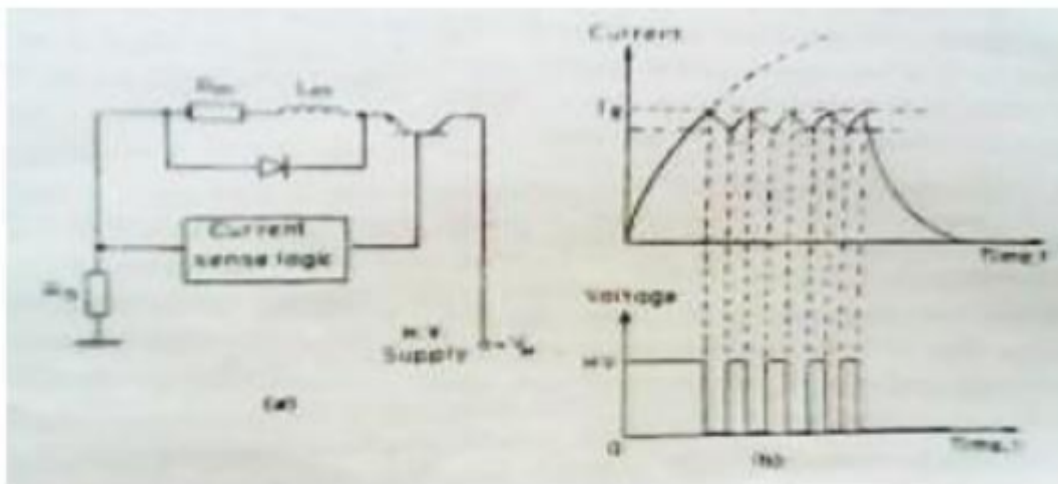


Fig. 2.32 Chopper drive

The chopper drive is particularly suitable for high torque stepper motors. It is energy efficient like the bi-level drive but the control circuit is simpler.

(d) Problems with driver circuits

A winding on a stepping motor is inductive and appears as a combination of inductance and resistance in series. In addition, as a motor revolves a counter emf is produced in the winding. The equivalent circuit to a winding is hence, such as that shown for designing a power driver one must take into account necessary factors and behavior of this kind of circuit. Firstly the worst case conditions of the stepping motor, power transistors, and supply voltage must be considered. The motor parameters vary due to manufacturing tolerance and operating conditions. Since stepping motors are designed to deliver the highest power from the smallest size, the case temperature can be as high as about 100°C and the winding resistance therefore increases by 20 to 25 per cent.

Suppressor circuits

These circuits are needed to ensure fast decay of current through the winding when it is turned off. When the transistor in the above fig is turned off a high voltage builds up to $L di/dt$ and this voltage may damage the transistor. There are several methods of suppressing this spike voltage and protecting the transistor as shown in the following.

(a) Diode suppressor

If a diode is put in parallel with the winding in the polarity as shown in fig. a circulating current will flow after the transistor is turned off, and the current will decay with time. In this scheme, no big change in current appears at turn off, and the collector potential is the supply potential E plus the forward potential of the diode. This method is very simple but a drawback is that the circulating current lasts for a considerable length of time and it produces a braking torque.

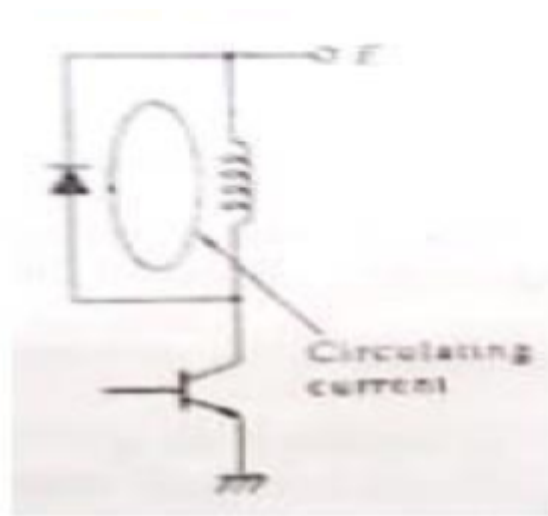


Fig. 2.33 Diode suppressor

(b) Diode-Resistor suppressor

A resistor is connected in series with the diode as shown in fig to damp quickly the circulating current. The voltage V_{CE} applied to the collector at turn-off in this scheme is

$$V_{CE} = E + I R_s + V_D$$

Where E = supply potential

I = Current before turning off

R_s - resistance of suppressor resistor and V_D - forward potential of diode

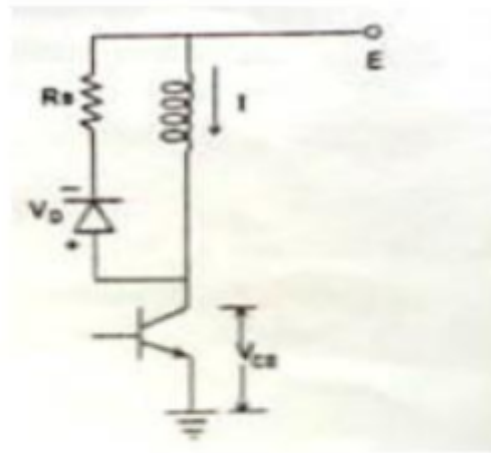


Fig. 2.34 Diode-resistor suppressor

A high resistance R_s is required to achieve a quick current decay, but this also results in a higher collector potential V_{ce} , thus a transistor with a high maximum voltage rating is necessary.

(a) Zener diode suppressor

In this zener diode are often used to connect in series with the ordinary diode as shown in fig. Compared with preceding two cases zener diode which provides negative bias causes the current to decay more quickly after turn off. In addition to this, it is a merit of this method that the potential applied to the collector is the supply potential plus the zener potential, independent of the current. This makes the determination of the rating of the maximum collector potential easy. However zeners are signal diodes, rather than power diodes. Their power dissipation is limited to 5w. Consequently, this suppressor can be used for very small instrument stepper motors of typical size 8 to 11.

Comparison of effects of various suppressor schemes of various suppressor schemes

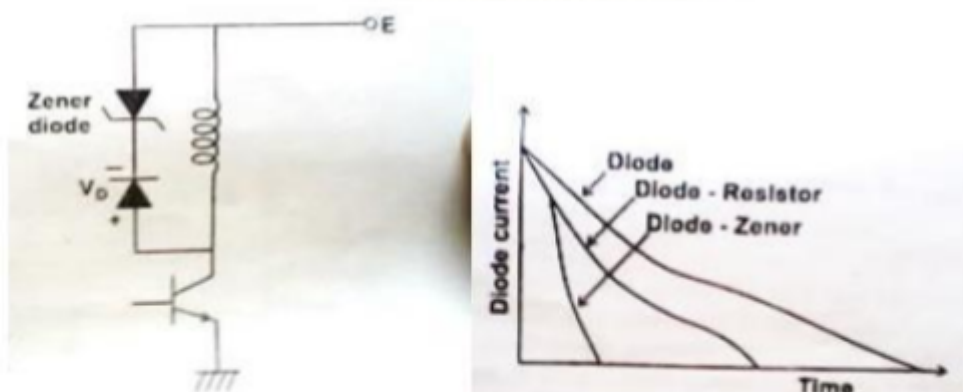


Fig. 2.35 Zener diode

(d) Condenser suppressor

This scheme is often employed for bifilar-wound hybrid motor. An explanation is given for the given for the circuit shown in fig:

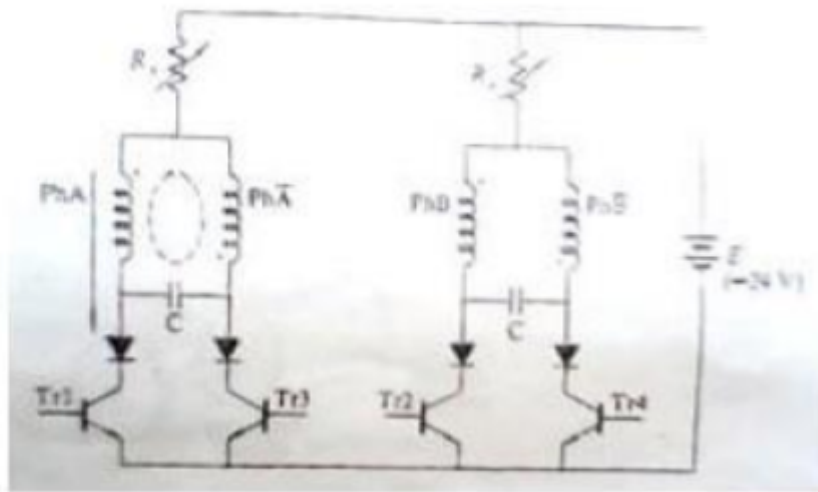


Fig. 2.37 Condenser suppressor

A condenser is put between ph A and ph A1. These condensers serve two fold purposes.

1. When a transistor is turned off, the condenser connected to it via a diode absorbs the decaying current from the winding to protect the transistor.

Let us see the situation just after the Tr 1 is turned off in the one phase on mode. Either Tr2 or Tr4 will turn on, but Tr3 will still be in the turned off state . Since the winding of ph A and ph A1 are wound in the bifilar fashion, a transient current will circulate in loop. If Tr 3 is turned on when the transient current becomes zero and the charge stored in the condenser becomes maximum, a positive current can easily flow through phase A winding. By this resonance mechanism, currents are used efficiently in this scheme. This feature remains in the two phase on mode too. The condenser suppressor is suited to drives in which stepping rate is limited in a narrow range.

- 2 .Another utility of condensers is as an electrical damper, a method of damping rotor oscillations is to provide a mechanism to convert kinetic energy to joule heating. If a rotor having a permanent magnet oscillates, an alternating emf is generated in the winding. However if a current path is not provided or a high resistance is connected, no current will be caused by this emf. When the condenser is connected between phases an oscillatory current will flow in the closed loop and joule heat is generated in the windings, which means that the condenser works as an electrical damper.

LINEAR AND NON LINEAR ANALYSIS

The linear and nonlinear analysis of the motor performance with respect to the torque produced by the rotor of the motor is explained.

Let,

T_m be the motor torque produced by the rotor in Nm

J be the inertia of the rotor and load combination in kgm²

ω be the angular velocity of the rotor

D be the damping coefficient or viscous frictional coefficient

T_f be the frictional load torque independent of the speed

θ_s be the step angle in radians

F be the stepping rate in steps/sec or pps

Frictional load torque $T_f = K \theta$

According to rotor dynamics

$$T_m = J \frac{d\omega}{dt} + D\omega + T_f \quad (2.30)$$

Also $\theta_s = \theta = \omega t = \text{step angle}$

$$\omega = \theta_s / t = f \theta_s \quad (2.31)$$

$$\text{where } f = 1/t \quad (2.32)$$

By putting $\omega = f \theta_s$

$$T_m = J \frac{d}{dt}(f \theta_s) + D(f \theta_s) + T_f \quad (2.33)$$

$\theta_s = 360 / mNr$ is fixed for a particular type of motor

So θ_s can be considered as constant

$$\text{Therefore } T_m = J \theta_s \frac{d}{dt}(f) + D \theta_s(f) + T_f \quad (2.34)$$

In equation 2.47 if viscous friction constant is neglected the equation will be a linear equation, the corresponding acceleration will be nonlinear and the equation will be nonlinear which given rise to nonlinear analysis.

Linear acceleration on linear analysis-----

If the damping coefficient is neglected $D=0$

The expression for motor torque becomes

$$T_m = J \frac{d\omega}{dt} + T_f \quad (2.35)$$

$$T_m - T_f = J \frac{d\omega}{dt}$$

$$(T_m - T_f) / J = d\omega / dt$$

$$d\omega = ((T_m - T_f) / J) dt \quad (2.36)$$

Integrating

$$\omega = ((T_m - T_f)/J)dt + \omega_1 \quad (2.37)$$

Where,

ω_1 = Integration constant

Mathematically ω_1 is the constant of integration but it indicates the initial angular velocity of the motor before the occurrence of acceleration.

Therefore,

$$\omega = \theta s f \text{ and } \omega_1 = \theta s f_1$$

Substituting ω and ω_1 in equation 2.50

$$((T_m - T_f)/J)t + \theta s f_1 = \theta s f \quad (2.38)$$

Dividing throughout by θs we get

$$((T_m - T_f)/J \theta s)t + f_1 = f$$

$$\text{Therefore stepping rate } f = ((T_m - T_f)/J \theta s)t + f_1 \quad (2.39)$$

And $T_f = K \theta$

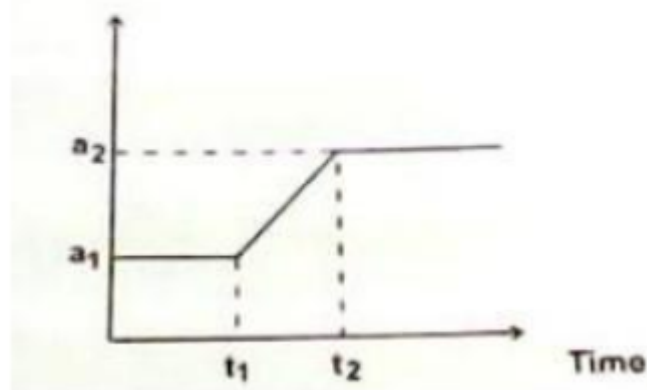


Figure 2.38 shows the linear acceleration from ω_1 to ω_2

Nonlinear (exponential) acceleration on Nonlinear analysis-----

Considering the torque produced by the motor

$$T_m = j\theta s \, df/dt + D\theta s f + T_f \dots\dots\dots(2.40)$$

$$(T_m - T_f) = j\theta s \, df/dt + D\theta s f$$

Dividing throughout by $j\theta s$, we get

$$(df/dt) + (D/J)f - (T_m - T_f / j \theta_s) = 0$$

$$(or) (df/dt) + (D/J)f = (T_m - T_f / j \theta_s) \dots (2.41)$$

The above eqn. 2.54 is of the form

$(dy/dx) + py = Q$ Which have the solution of

$$y e^{\int p dx} = \int Q e^{\int p dx} + C \quad (2.42)$$

Here $y=f$; $x=t$; $p=(D/j)$ and $Q=(T_m - T_f)/j\theta_s = \text{constant}$

$$f e^{\int D/J dt} = \int (T_m - T_f)/j\theta_s e^{\int D/J dt} + C \quad (2.43)$$

$$f e^{\int D/J t} = \int (T_m - T_f)/j\theta_s e^{\int D/J t} + C \quad (2.44)$$

$$f e^{\int D/J t} = (T_m - T_f)/j\theta_s (e^{\int D/J t} / (D/J)) + C \quad (2.45)$$

where C is the integration constant

To find C substituting initial condition at $t=0$; $f=f(0)=f_1$ $f_1 e^0 = (T_m -$

$$T_f)/j\theta_s (1/(D/J)) + C \quad (2.46)$$

$$f_1 = (T_m - T_f)/J\theta_s (J/D) + C \quad (2.47)$$

$$f_1 = (T_m - T_f)/D\theta_s + C \quad (2.48)$$

$$C = f_1 - (T_m - T_f)/D\theta_s \quad (2.49)$$

Substituting eqn. (2.62) in eqn. (2.58)

$$f e^{(D/J)t} = (T_m - T_f)/J\theta_s (J/D) e^{(D/J)t} + (f_1 - (T_m - T_f)/D\theta_s) \quad (2.50)$$

$$f e^{(D/J)t} = (T_m - T_f)/D\theta_s e^{(D/J)t} + (f_1 - (T_m - T_f)/D\theta_s) \quad (2.51)$$

Dividing throughout by $e^{(D/J)t}$ we get

$$F = T_m - T_f/D\theta_s + (f_1 - T_m - T_f/D\theta_s) e^{-D/j t} \quad (2.52)$$

Stepping frequency, $f = T_m - T_f/D\theta_s + (f_1 - T_m - T_f/D\theta_s) e^{-D/j t}$

The above equation is a nonlinear exponential equation which gives rise to nonlinear acceleration of the rotor of the motor.

APPLICATION OF STEPPER MOTOR:

The main application of stepper motor may be divided into the following groups.

1. Instrumentation applications.
2. Computer peripherals & Office equipment's.
3. Numerical control of machine tools and robotics.

4. Applications in semiconductor technology.
5. Space vehicles and satellites.
6. Electro medical and
7. Miscellaneous applications.

1. Instrumentation application:

This involve low torque applications such as -----

Quartz watches.

Synchronized clocks.

Camera shutter operations.

2. Stepper motor application in computer peripherals:

This involve medium torque, high performance and high volume application such as

Dot matrix and line printers.

Graph plotters.

Floppy disk drives

Digital X-Y plotters.

Magnetic tape drives.

Paper tape drives.

3. Application is office equipment:

Electronic typewriters.

Copiers

Facsimile machines.

4. Machine tool applications:

This involve high torque application such as -----

Numerical control system for milling machine

X-Y tables and index table.

Home use and industrial sewing machines.

5. Application in semiconductor technology:

Stepper motors used in high vacuum.

Goniometer-An instrument used to determine crystalline structure.

Electron beam micro fabricator.

6. Stepper motor used in space vehicles and satellites.

7. Robotics.

8. Electro medical applications:

This involve high torque applications such as

X-ray machines.

Radiation therapy units.

Ultra sound scanner.

9. Miscellaneous applications:

Nuclear reactors.

Heavy industry applications.

Automatic focusing mechanism in camera

SHORT QUESTIONS AND ANSWERS:

1. What is stepper motor?

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

2. Define step angle.

Step angle is definrd as the angle through which the motor rotates for each command pulse.it is denoted as β .

$$\beta = (N_s - N_r / N_s \cdot N_r) 360 \text{ (or) } 360 / (m N_r)$$

3. Define slewing

The stepper motor operates at very high speed is called slew angle.i.e (25000 steps per sec).

4. Define resolution

It is defined as the no.of steps needed to complete one revolution of the shaft.
 $\text{Resolution} = \text{no. of steps / revolution}$

5. Mention some applications of stepper motor

- i. floppy disc drives
- ii. quartz watch
- iii. camera shutter operation
- iv. dot matrix and line printers
- v. small tool application
- vi. robotics

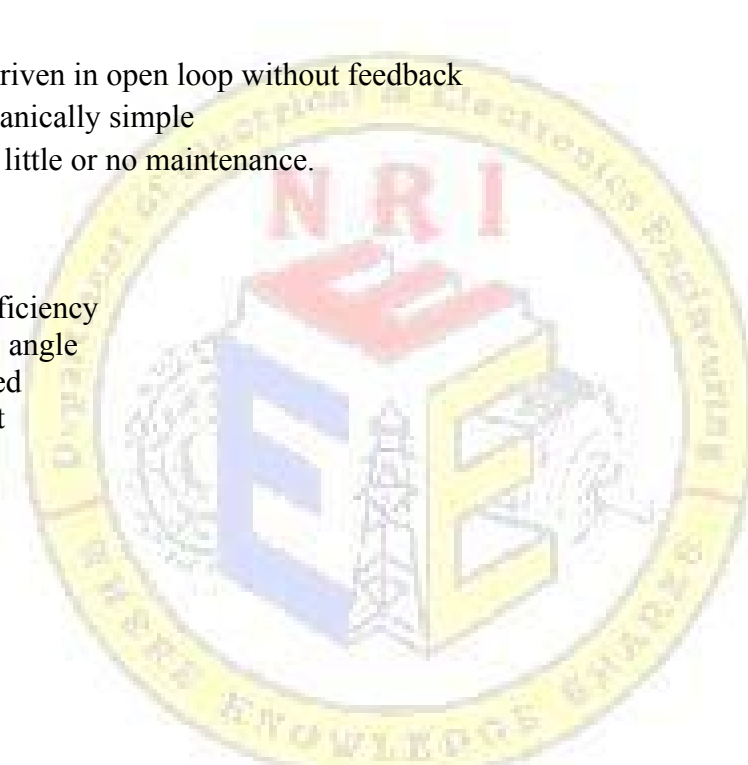
6. What are the advantages and disadvantages of stepper motor?

Adv:

- 1. it can be driven in open loop without feedback
- 2. it is mechanically simple
- 3. it requires little or no maintenance.

Disadv:

- 1. low efficiency
- 2. fixed step angle
- 3. limited power output



7. Define holding torque.

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

8. Define detent torque

Detent torque is the maximum torque which the unenergised stepper motor can withstand without slipping. it is also known as cogging torque.

9. What is meant by full step operation?

Full step operation or single phase on mode is the one in which at a time only one phase winding is energized, due to which one stator winding is energized and causes the rotor to rotate some angle.

10. What is meant by two phase mode of operation?

Two phase on mode is the one in which two phase windings are energized at a time, due to which two stator windings are energized and causes the rotor to rotate through some angle.

11. Define pull in torque.

It is the maximum torque the stepper motor can develop in start – stop mode at a given stepping rate F_s (step/sec) without losing synchronism.

12. Define pull out torque.

It is the maximum torque the stepper motor can develop in slewing mode at a given stepping rate F_s (step/sec) without losing synchronism.

13. What is synchronism in stepper motor?

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

14. Define mid frequency resonance in stepper motor.

The phenomenon at which the motor torque drops to a low value at certain input pulse frequencies.

15. Define static stiffness.

It is a measure of ability of the actuator to resist disturbing torques and forces and thereby to maintain position. it is defined as

$$S = \text{torque} / \text{rad}$$

16. Give the types of driver circuits.

- ☐ Resistance or L/R drive
- ☐ Dual voltage or bilevel drive
- ☐ Chopper drive

17. What is multi stack VR motor

Multi stack VR motor is the one in which the stepper motor has three separate magnetically nisolated sections or stacks. here the rotor and stator teeths are equal.

18. What is meant by micro stepping in stepper motor.

The methods of modulating currents through stator windings so as to obtain rotation of stator magnetic field through a small angle to obtain micro stepping action is known as micro stepping.

19. What are the advantages of micro stepping?

- ☐ Improvement in resolution.
- ☐ Dc motor like performance
- ☐ Elimination of mid frequency resonance
- ☐ Rapid motion at micro stepping rate.

20. Define bandwidth in stepper motor.

It is a measure of the frequencies upto which the actuator or servo motor system can respond.

PART-B

1. Explain the construction and various modes of excitation of VR stepper motor. (16)
2. Explain the construction and various modes of excitation of PM stepper motor. (16)
3. Explain the construction and working principle of Hybrid Stepper motor. (16)
4. State and explain the static and dynamic characteristics of a stepper motor. (16)
5. Explain in detail about different types of power drive circuits for stepper motor. (16)
6. Explain the mechanism of torque production in VR stepper motor. (16)
7. Draw any two drive circuits for stepper motor. (16)

UNIT III

SWITCHED RELUCTANCE MOTORS

1.1 INTRODUCTION

The switched reluctance motor (SRM) drives for industrial applications are of recent origin. This chapter contains a brief introduction to SRM and its principle of operation. Key to an understanding of any machine is its torque expression, which is derived from first principles. The implications of machine operation and its salient features are inferred from the torque expression. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position; for the sake of brevity and to illustrate the basic theory, only unsaturated operation is considered here. The machine operation in all of its four quadrants of torque vs. speed is derived from the inductance vs. rotor position characteristic of the machine, and, in line with other machines, the dynamic equivalent circuit for SRM is formulated. Its use may be limited in design but it has a larger impact on the high-performance controller derivations and understanding. Various configurations of the rotary SRM, including single-phase machines, are described. The single-phase

machines have applications in low-performance but high-volume applications. An SRM capable of linear motion is introduced and its principles of operation and many of its configurations are presented in this chapter.

1.2 BACKGROUND

Since 1969, a variable reluctance motor¹ has been proposed for variable speed applications. The origin of this motor can be traced back to 1842, but the “reinvention” has been possible due to the advent of inexpensive, high-power switching devices. Even though this machine is a type of synchronous machine, it has certain novel features. It has wound field coils of a dc motor for its stator windings and has no coils or magnets on its rotor. Both the stator and rotor have salient poles, hence the machine is referred to as a doubly salient machine. Such a typical machine^{2,3} is shown in Figure 1.1a, and a modified version with two teeth per pole is shown in Figure 1.1b.^{4,5}

The rotor is aligned whenever diametrically opposite stator poles are excited. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different

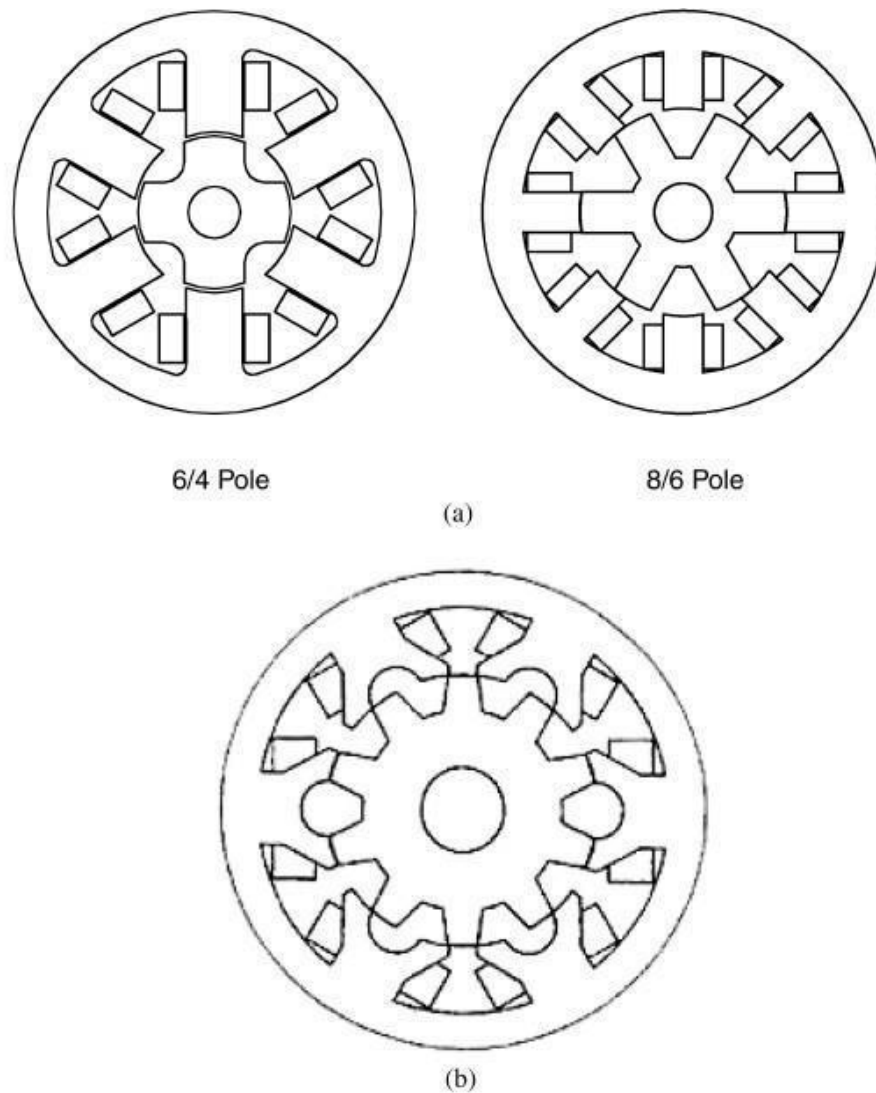


FIGURE 1.1 Switched reluctance motor configurations. (a) One tooth per pole. (b) Two teeth per pole (12/10 poles).

set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment. Likewise, by sequentially switching the currents into the stator windings, the rotor is rotated. The movement of the rotor, hence the production of torque and power, involves switching of currents into stator windings when there is a variation of reluctance; therefore, this variable speed motor drive is referred to as a switched reluctance motor drive.

where e is the induced emf and F is the mmf. This input electrical energy, W_e , is equal to the sum of energy stored in the coil, W_f , and energy converted into mechanical

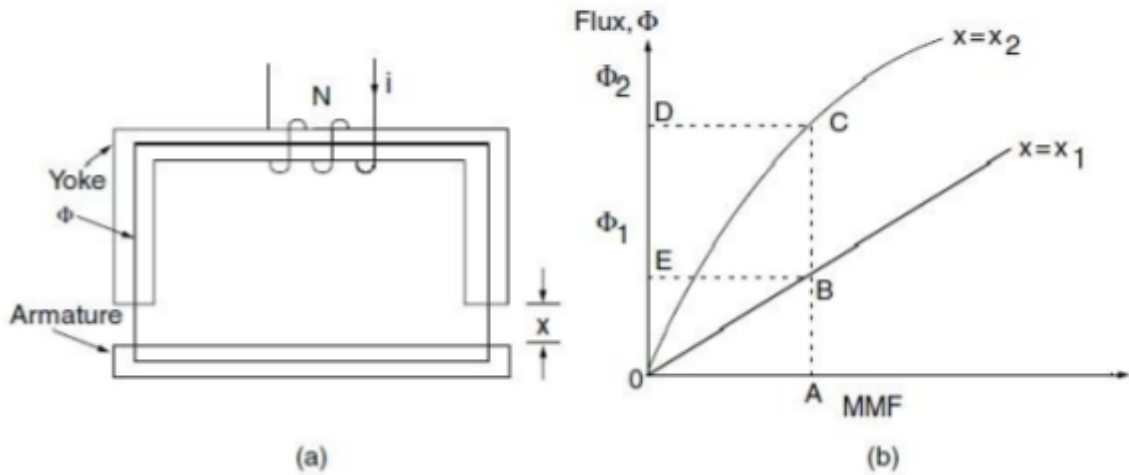


FIGURE 1.3 Solenoid and its characteristics. (a) A solenoid. (b) Flux v. mmf characteristics.

1.4 PRINCIPLE OF OPERATION OF THE SWITCHED RELUCTANCE MOTOR

The torque production in the switched reluctance motor is explained using the elementary principle of electromechanical energy conversion in a solenoid, as shown in Figure 1.3a. The solenoid has N turns, and when it is excited with a current i , the coil sets up a flux Φ . Increasing the excitation current will make the armature move towards the yoke, which is fixed. The flux vs. magnetomotive force (mmf) is plotted for two values of air gap, x_1 and x_2 , where $x_1 > x_2$, and is shown in Figure 1.3b. The flux vs. mmf characteristics for x_1 are linear because the reluctance of the air gap is dominant, making the flux smaller in the magnetic circuit. The electrical input energy is written as:

$$W_e = \int e i dt = \int i dt \frac{dN\Phi}{dt} = \int N i d\Phi = \int F d\Phi \quad (1.1)$$

work, W_m . It is written as:

$$W_e = W_f + W_m \quad (1.2)$$

When no mechanical work is done, as in the case of the armature starting from position x_1 , the stored field energy is equal to the input electrical energy given by Eq. (1.1). This corresponds to area OBEO in Figure 1.3b. The complement of the field energy, termed *coenergy*, is given by area OBAO in Figure 1.3b and mathematically expressed as $\int \Phi dF$. Similarly, for the position x_2 of the armature, the field energy corresponds to area OCDO and the coenergy is given by area OCAO. For incremental changes, Eq. (1.2) is written as:

$$\delta W_e = \delta W_f + \delta W_m \quad (1.3)$$

where e is the induced emf and F is the mmf. This input electrical energy, W_e , is equal to the sum of energy stored in the coil, W_f , and energy converted into mechanical

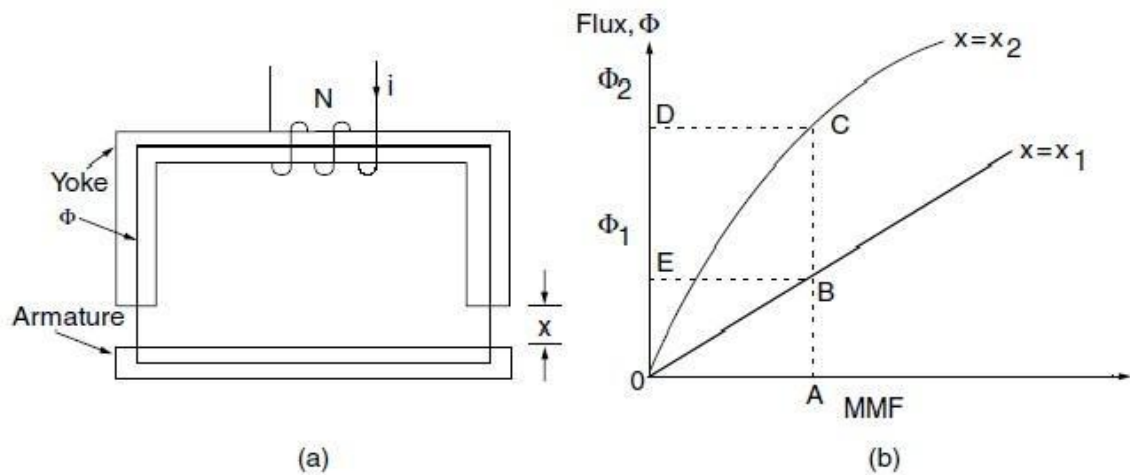


FIGURE 1.3 Solenoid and its characteristics. (a) A solenoid. (b) Flux v. mmf characteristics.

For a constant excitation of F_1 given by the operating point A in Figure 1.3b, the various energies are derived as:

$$\delta W_e = \int_{\phi_1}^{\phi_2} F_1 d\phi = F_1(\phi_2 - \phi_1) = \text{area(BCDEB)} \quad (1.4)$$

$$\delta W_f = \delta W_{f|_{x=x_2}} - \delta W_{f|_{x=x_1}} = \text{area(OCDO)} - \text{area(OBEO)} \quad (1.5)$$

Using Eqs. (1.3) to (1.5), the incremental mechanical energy is derived as:

$$\delta W_m = \delta W_e - \delta W_f = \text{area(OBCO)} \quad (1.6)$$

and that is the area between the two curves for a given magnetomotive force. In the case of a rotating machine, the incremental mechanical energy in terms of the electromagnetic torque and change in rotor position is written as:

$$\delta W_m = T_e \delta \theta \quad (1.7)$$

where T_e is the electromagnetic torque and $\delta \theta$ is the incremental rotor angle. Hence, the electromagnetic torque is given by:

$$T_e = \frac{\delta W_m}{\delta \theta} \quad (1.8)$$

For the case of constant excitation (i.e., when the mmf is constant), the incremental mechanical work done is equal to the rate of change of coenergy, W'_f , which is nothing but the complement of the field energy. Hence, the incremental mechanical work done is written as:

$$\delta W_m = \delta W'_f \quad (1.9)$$

where

$$W'_f = \int \Phi dF = \int \Phi d(Ni) = \int (N\Phi) di = \int \lambda(\theta, i) di = \int L(\theta, i) i di \quad (1.10)$$

where the inductance, L , and flux linkages, λ , are functions of the rotor position and current. This change in coenergy occurs between two rotor positions, θ_2 and θ_1 . Hence, the air gap torque in terms of the coenergy represented as a function of rotor position and current is

$$T_e = \frac{\delta W_m}{\delta \theta} = \frac{\delta W'_f}{\delta \theta} = \left. \frac{\delta W'_f(i, \theta)}{\delta \theta} \right|_{i=\text{constant}} \quad (1.11)$$

If the inductance is linearly varying with rotor position for a given current, which in general is not the case in practice, then the torque can be derived as:

$$T_e = \frac{dL(\theta, i)}{d\theta} \cdot \frac{i^2}{2} \quad (1.12)$$

where

$$\frac{dL(\theta, i)}{d\theta} = \left. \frac{L(\theta_2, i) - L(\theta_1, i)}{\theta_2 - \theta_1} \right|_{i=\text{constant}} \quad (1.13)$$

and this differential inductance can be considered to be the torque constant expressed in $\text{N} \cdot \text{m}/\text{A}^2$. It is important to emphasize at this juncture that this is not a constant and that it varies continuously. This has the implication that the switched reluctance motor will not have a steady-state equivalent circuit in the sense that the dc and ac motors have.

Equation (1.12) has the following implications:

1. The torque is proportional to the square of the current, hence the current can be unipolar to produce unidirectional torque. Note that this is quite contrary to the case for ac machines. This unipolar current requirement has a distinct advantage in that only one power switch is required for control of current in a phase winding. Such a feature greatly reduces the number of power switches in the converter and thereby makes the drive economical.
2. The torque constant is given by the slope of the inductance vs. rotor position characteristic. It is understood that the inductance of a stator winding is a function of both the rotor position and current, thus making it nonlinear. Because of its nonlinear nature, a simple equivalent circuit development for this motor is not possible.
3. Since the torque is proportional to the square of the current, this machine resembles a dc series motor; hence, it has a good starting torque.
4. A generating action is made possible with unipolar current due to its operation on the negative slope of the inductance profile.
5. The direction of rotation can be reversed by changing the sequence of stator excitation, which is a simple operation.
6. Due to features 1, 4, and 5, this machine is suitable for four-quadrant operation with a converter.
7. Torque and speed control is achieved with converter control.
8. This machine requires a controllable converter for its operation and cannot be operated directly from a three-phase line supply. Hence, for constant speed applications, this motor drive is expensive in comparison to induction and synchronous motors.
9. Because of its dependence on a power converter for its functioning, this motor drive is an inherently variable-speed motor drive system.

10. There is very little mutual inductance between machine phase windings in SRM, and for all practical purposes it is considered to be negligible. Since mutual coupling is absent, each phase is electrically independent of other phases. This is a feature unique to this machine only. Due to this feature, note that a short-circuit fault in one phase winding has no effect on other phases. For one thing, it makes possible operation of other healthy phases of the machine and their operation will not be derated, as the voltage requirement is the same before and after the fault. Such independence of machine phases has tremendous consequence in aircraft actuators and generators, actuators used in defense applications, motors used in coolant pumps in nuclear power plants, and traction and electric vehicles, to mention a few applications. In extreme contrast to the operation of SRM under short-circuit fault, consider a permanent magnet synchronous motor with a single-phase, short-circuit fault condition.
11. Because the current only needs to be unidirectional for all quadrants of operation, unlike in other machines, all power converter configurations for this machine have a switch in series with a machine phase winding facing the dc source voltage. In case of a machine partial-winding fault or switch misfiring, or short circuit, there is a significant delay time in the rise of the current which allows the protection circuit to be activated to isolate the faults. Also, there is no shoot-through failure mode even when the power switch fails. In contrast, all other ac machine drives require the placement



of two power switches in series facing the dc source, with the center point connection of the switches connected to one end of the machine phase winding. Such an arrangement for one phase is called a *phase leg* or the *inverter*. Only one switch in a phase leg can be on at any time. Failure in another switch leading to a short circuit or misfiring will lead to a short circuit of the dc source. Such a fault is known as a shoot-through fault.

From the above description, it is deduced that the switched reluctance motor is similar to the step motor except that it has

1. Fewer poles
2. Larger stepping angle
3. Usually one tooth per pole
4. Higher power output capability

The comparison should not be carried too much further due to the nonlinearity of the magnetic circuit.

1.7 SRM CONFIGURATIONS

Switched reluctance motors are classified as shown in Figure 1.6. Initial classification is made on the basis of the nature of the motion (i.e., rotating or linear). The linear SRMs have found application in the marketplace by catering to machine tool servos.

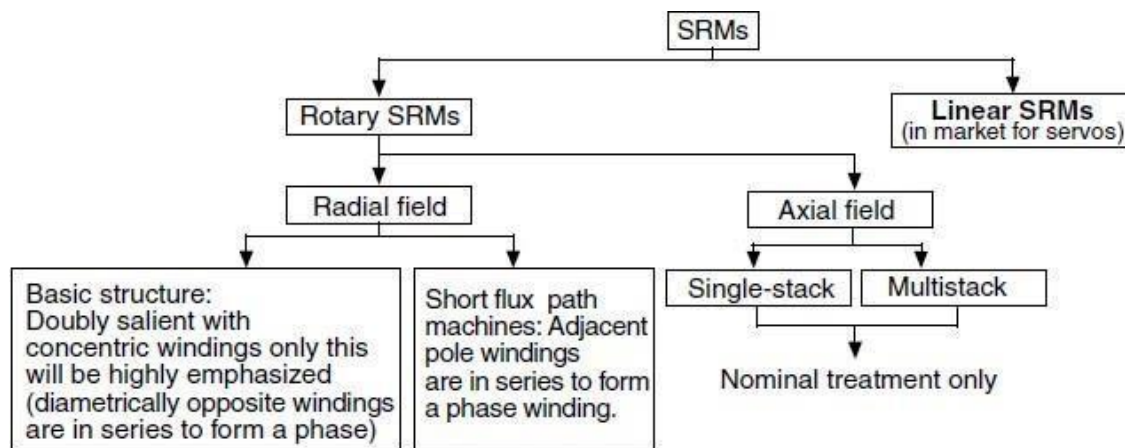


FIGURE 1.6 Classification of SRMs.

1.7.1 ROTARY SRM

The rotary machine-based SRMs are further differentiated by the nature of the magnetic field path as to its direction with respect to the axial length of the machine. If the magnetic field path is perpendicular to the shaft, which may also be seen as along the radius of the cylindrical stator and rotor, the SRM is classified as radial field. Such radial field SRMs are shown in Figure 1.1. When the flux path is along the axial direction, the machine is called an *axial field SRM*.

The axial configuration of an SRM¹¹ is shown in Figure 1.7a, and the stator and rotor discs are shown in Figures 1.7b and c, respectively. The flux pattern is shown in Figure 1.7d. The flux path is through the upper stator pole tip, air gap 1, upper rotor pole tip, air gap 2, upper opposite stator pole tip, back iron, stator lower pole tip, air gap 2, rotor lower pole tip, air gap 1, stator lower pole tip, and its back iron. Note that the flux path is parallel to the shaft, a configuration known as axial field SRM. Note that there are six stator poles but only two rotor poles in this axial field SRM. The number of stator discs can be reduced to one, but in that case the rotor laminations have to carry a back iron to provide a closed iron path for the flux. A pair of one rotor and one stator stacks or one rotor and two stator stacks or two rotor and one stator stacks constitutes a single-stack axial field SRM. Multiples of such single stacks can be arranged on the same shaft to augment the power rating. Such a machine is known as a multiple-stack axial field SRM and was the first of the viable axial prototypes in the early 1970s for electric vehicle propulsion.¹² Another example of an axial field SRM with two types of claw pole design for single-phase operation is shown in Figure 1.8.^{13,14} Both these designs are intended for ceiling-fan applications. Ingenious designs are possible in the axial type SRMs, as seen by the limited designs in the discussion. Emerging applications are the driving forces behind the quest for design variations and novel designs. The axial field SRMs are ideal for applications where the total length may be constrained, such as in a ceiling fan or in a propulsion application. The disadvantage of this configuration is that the stator laminations have to be folded one on top of the other unlike the simple stacking of laminations in the radial field configuration. The converter configurations and controller algorithms for both configurations of the SRMs are the same.

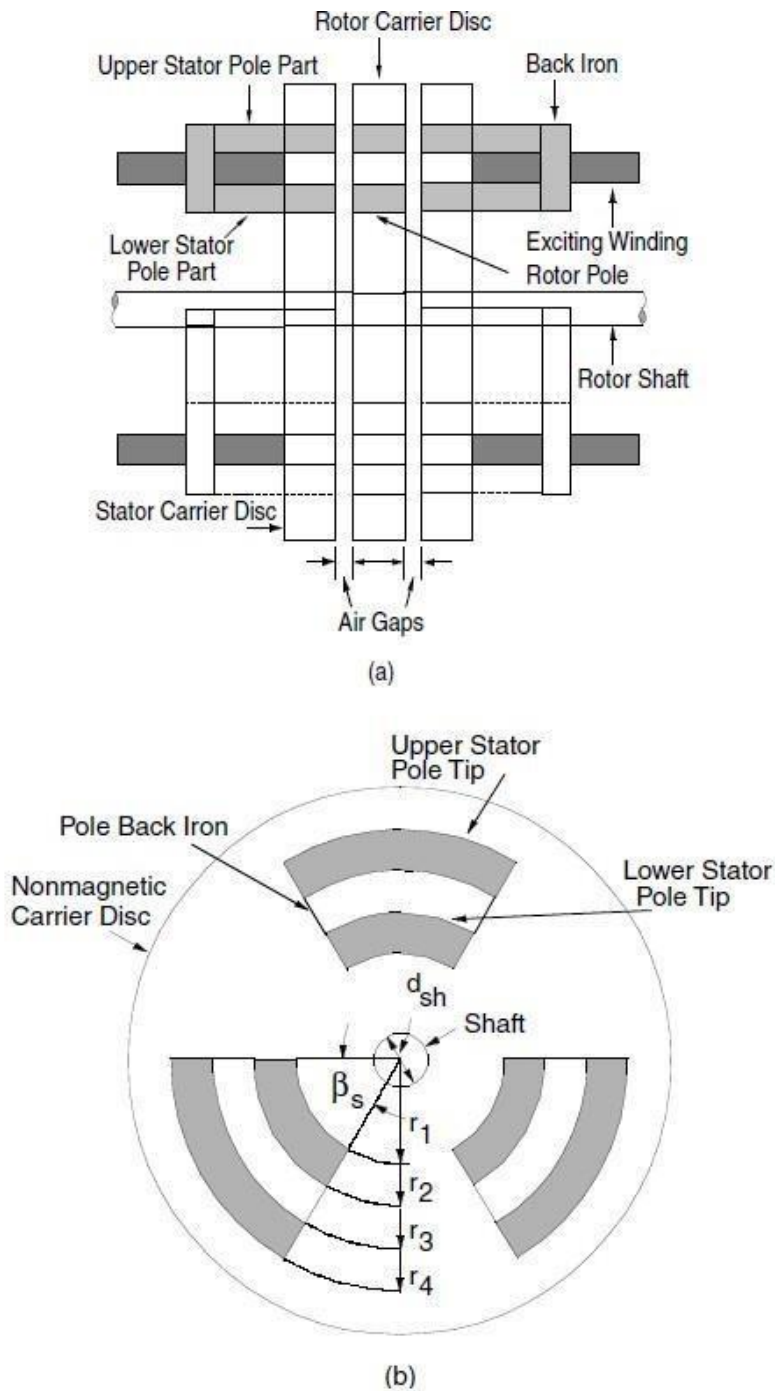


FIGURE 1.7 (a) Axial field SRM. (b) Endview of the stator. (c) Endview of the rotor. (d) Flux path in the axial field SRM.

The developments in theory, principle, and operation are equally applicable to both the SRM configurations.

Radial field SRMs have emerged with both shorter and longer flux paths. This development is based on whether a phase coil is placed in the slots adjacent to each other to obtain a pair of poles as shown in Figure 1.9 or the coil is placed in the diametrically opposite slots, as shown in Figure 1.1. Short flux path SRMs¹⁵ have

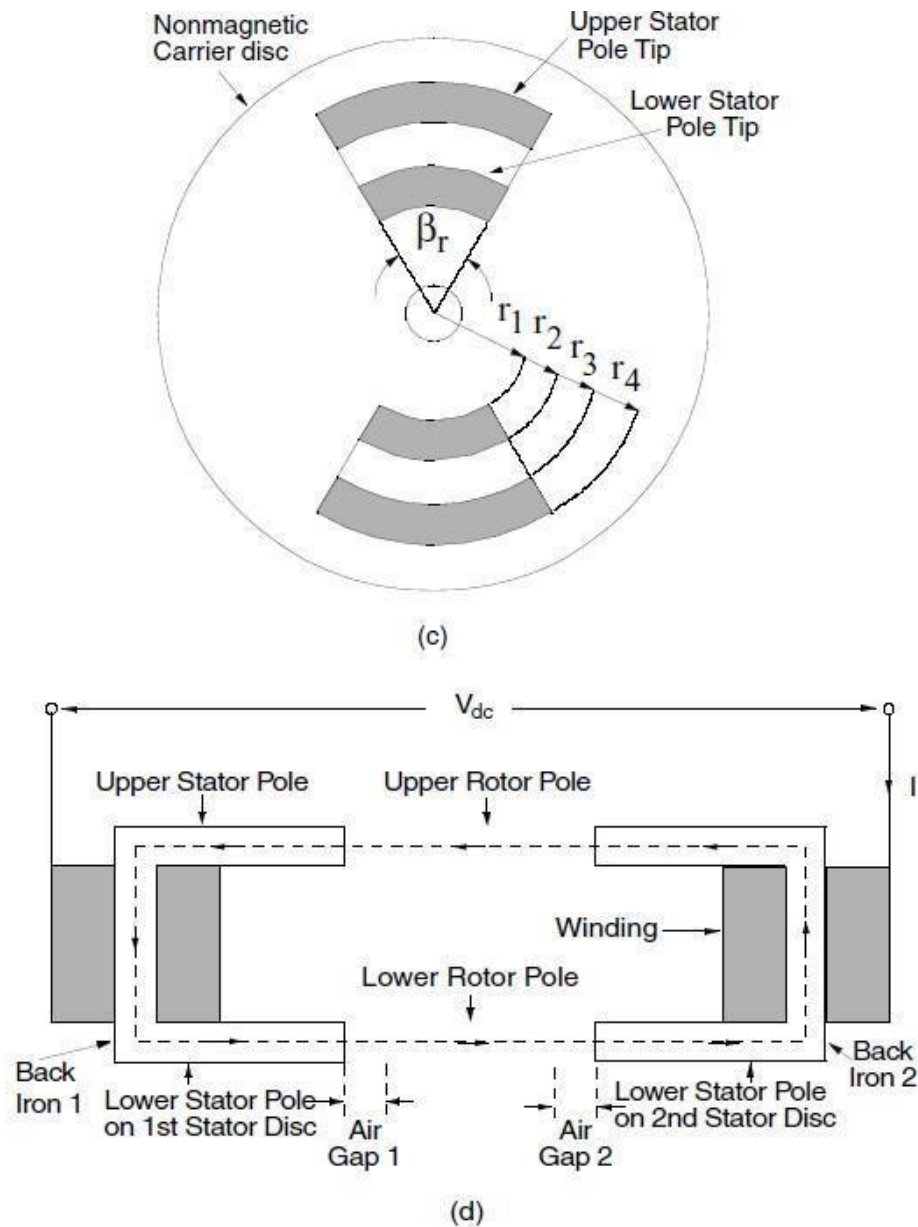


FIGURE 1.7 (Continued)

the advantage of lower core losses due to the fact that flux reversals do not occur in stator back iron in addition to having short flux paths. They have the disadvantages of having a slightly higher mutual inductance compared to conventional radial field SRMs and a possible higher uneven magnetic pull on the rotor.

Conventional radial field SRMs with longer flux paths have been established for many applications due to overwhelming research and development data available on these machines. A recent variation of this type has full pitch coils. A hybridized version of radial field SRMs with permanent magnets placed either in the back iron or on the stator poles, similar to pole shoes in configuration, has been studied and is known as a flux reversal machine. By bringing the permanent magnets onto the stator, these machines can have the high-speed and high-response operational advantages unique to the SRMs.^{16–18} They also carry the disadvantages of having magnets

Sensorless Operation of SRM Drives

8.1 INTRODUCTION

The control of SRM drives depends on the phase current, absolute rotor position, and rotor speed signals to obtain closed-loop control of current (torque) and speed. Depending on the quality of performance required for a particular application, such as for a low performance, the phase current and speed signals may be dispensed within the control system. The feedback signals are usually measured with transducers, which increase the cost of the electronic controller and its packaging size. In the case of a rotor position/speed transducer, the size of the motor housing and the cost are increased significantly. Emerging high-volume applications in heating, ventilation, and air conditioning (HVAC); fans; pumps; home appliances; automobile accessory drives; and many others are cost sensitive. The performance requirements for such applications are not high as is required for machine tool servo drives. The requirement of low cost with high performance for motor drives has placed the agenda of low-cost, sensor-based or sensorless technology at the forefront of present-day research and development of motor drives. SRM drives are no exception to this trend, as seen from the high degree of interest shown by industrial and academic researchers worldwide on this topic.

This chapter considers the study of a low-cost, sensor- or sensorless-based, current- and speed-controlled SRM drive system. The current and position sensorless algorithms and schemes are reviewed with some new unpublished schemes for low-cost, current-sensor-based controls. While no attempt has been made to cover all the schemes proposed in the literature, an attempt is made to present the most useful, fairly accurate, cost-effective, and industrially relevant algorithms and schemes in the following sections.

8.2 CURRENT SENSING

8.2.1 CURRENT-SENSING METHODS

Current control could be inexpensively achieved both with sensors and without sensors. A number of options emerge as indicated in the flow diagram shown in [Figure 8.1](#). Direct measurement with galvanically isolated current transducer is still an expensive solution. Noninductive, low-ohmic resistors can be used to monitor the current by measuring the voltage drop across them. They are not galvanically isolated, as in many applications galvanic isolation is not a strict requirement. This method provides the most accurate current measurement with the least amount of investment in materials and processing circuitry, but it does introduce an external

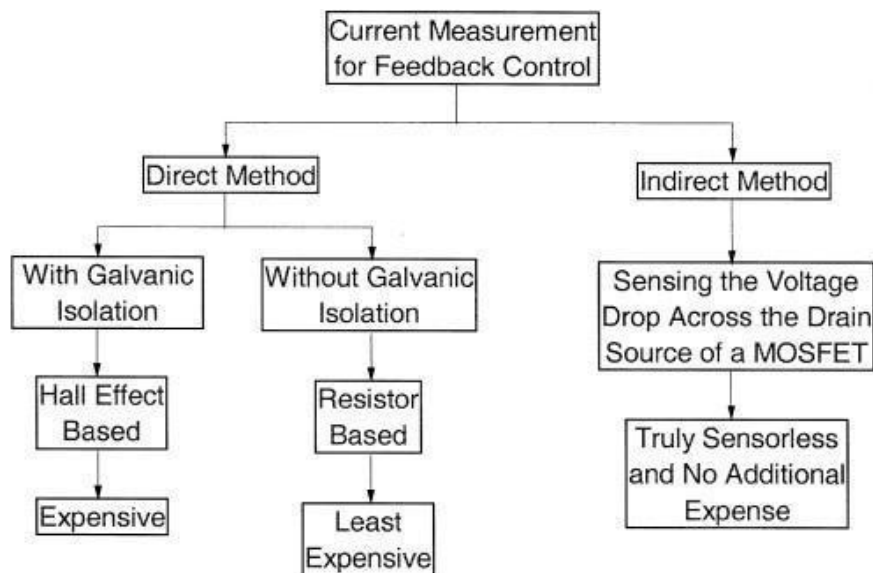


FIGURE 8.1 Classification of current measurement for feedback control.

resistor component in the circuit that consumes power on the order of a watt or less. The indirect method, such as the one utilizing the resistive nature of the drain-to-source conduction path of a MOSFET for monitoring the current, is an attractive alternative. It also does not require any additional components to serve as a transducer, as the phase power switches could be used for monitoring indirectly²⁸ the currents. Special MOSFETs, called senseFETs, are available with processed current signals that minimize additional control electronic circuitry to transform the drain–source conduction voltage drop to the control level and keep it isolated during its off state from the control circuit. Otherwise, the drain voltage at turn-off will be at least equal to the dc source voltage, which is multiple times greater than the control supply voltage and will damage the control circuitry.

8.2.2 CURRENT SENSING WITH RESISTORS

Two different implementations of resistor-based current measurement are possible. Only one resistor could be used in the path from all the bottom switches to the negative dc bus rail (say, for an asymmetric converter), as shown in Figure 8.2. The phase-current measurement is not available with this implementation during freewheeling of a phase. More or less an average current can be obtained with this setup. If two phases are simultaneously conducting, then it is not possible to separate each phase current in this method. Therefore, it is useful when no overlapping conduction occurs in the machine phases and average current control is acceptable.

In the second arrangement, each phase current is sensed independently with one resistor, as shown in Figure 8.3. Including the resistor in the freewheeling path allows the monitoring of phase currents continuously except when the current is being turned off (commutated) once and for all at the end of the phase cycle. In most of the control arrangement, the decaying current need not be monitored. If torque smoothing control

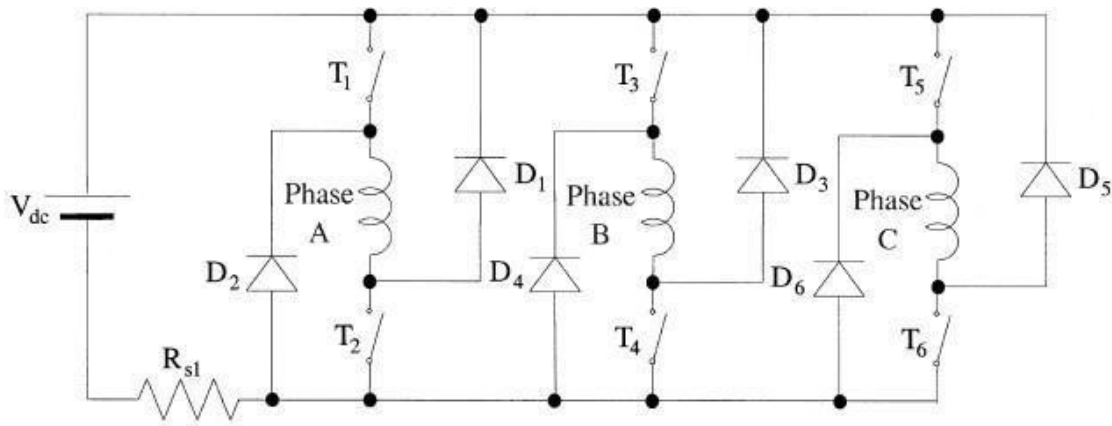


FIGURE 8.2 Single-resistor-based, current-sensing arrangement in the SRM drive.

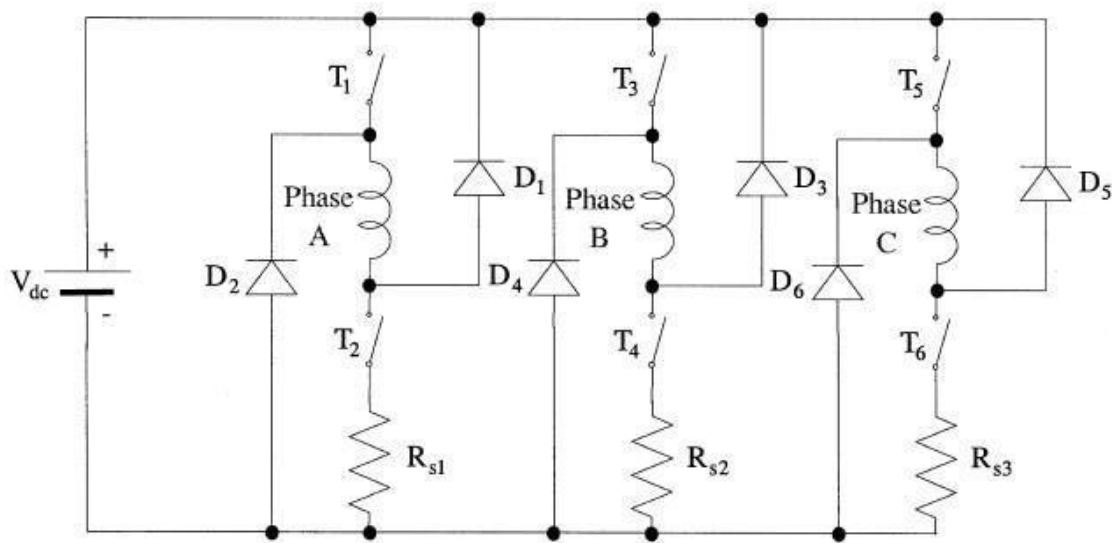


FIGURE 8.3 Current sensing of individual phases with one resistor per phase.

is implemented, then coordination of phase currents at all times is essential, but this arrangement is unsatisfactory only for this reason. If the machine is intended for generation but not for motoring, then this scheme is also not useful because most of the time, in generation mode, both the phase switches have to be turned off to enable both the diodes to reverse the current flow in the dc link to transfer energy from the machine to the dc bus. The current then bypasses the sensing resistor. Alternatively, the resistor can be connected in that path or one common resistor in the dc rail may be more satisfactory, as shown in Figure 8.4.

Sensing resistor R_{s1} (say, for phase A) provides the excitation current drawn from the dc source to provide magnetization of the machine to set up the generation. When switches T_1 and T_2 are opened, the phase current is diverted through diode D_1 , the phase-A winding, D_2 , the dc source, and the sensing resistor R_{s1} . With the measurement common at the anode of D_2 , the voltage signal measured across R_{s1} has to be reversed to indicate that the dc source is receiving the current from the machine.

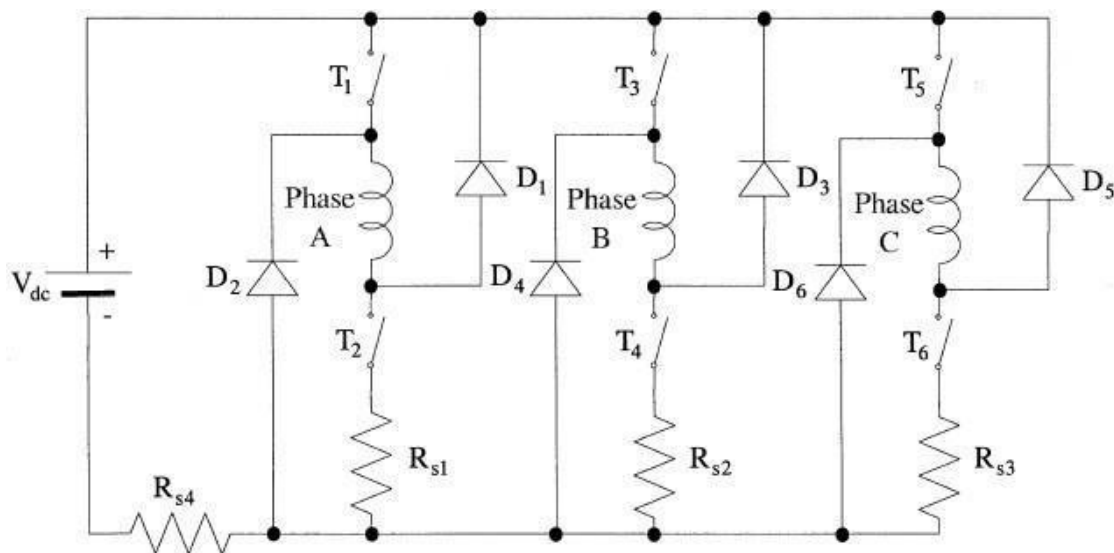


FIGURE 8.4 Current-sensing resistor arrangement for both motoring and generating action.

Overlapping phase currents in generation mode are still difficult to measure in this arrangement. Note that in both the arrangements considered the current signal is obtained with respect to the negative dc bus rail, and this could be the common for control circuitry. The gate-drive amplifiers for the upper power switches can be isolated from the power bus by any one of the conventional techniques.

8.2.3 DRIVE SCHEME WITH CURRENT LIMITER

If feedback current control is not required for an application but only current limiting is needed to protect the power devices and ensure that the machine current is within the prescribed limit, then the devices themselves could be exploited to provide the current limit signal. Their collector-to-emitter or anode-to-cathode conduction voltages, whatever the case may be, could be monitored for desired maximum currents through their gate drivers. Many commercial gate drivers are equipped to do this task. In one or two microseconds, the device will turn off, thereby limiting the current in the machine phase. Note that this will not provide instantaneous current control, in that tracking of a reference is not possible, but serves as an over-current signal. Motor drives catering to applications such as pumps and fans with no great dynamic performance requirements can utilize this technique. A control schematic using current limiting is shown in Figure 8.5 for a speed controlled drive system.

The speed error obtained from the difference between the rotor speed and its reference is amplified and limited in the speed controller, which usually is a proportional-plus-integral (PI) controller. Its output, the torque command signal is compared with a triangular carrier frequency to generate the pulse width modulated (PWM) logic signals to drive the power converter's devices. Depending on the rotor position, phase energization instants are generated which are known as phase position pulses. The PWM signals are steered into the appropriate phases of the converter with the help of the phase position pulses. The converter power devices are equipped with current-limiting circuits through their gate-drive amplifiers. If the phase current

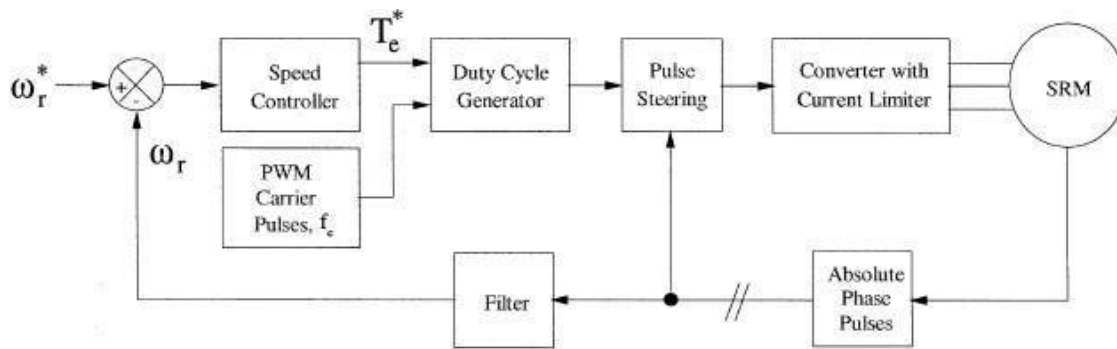


FIGURE 8.5 Speed-controlled drive schematic with current limiter.

exceeds the set current limit, the device is turned off only for that carrier cycle. Again, in the next carrier cycle, the phase will be energized for its turn-on duration and so on.

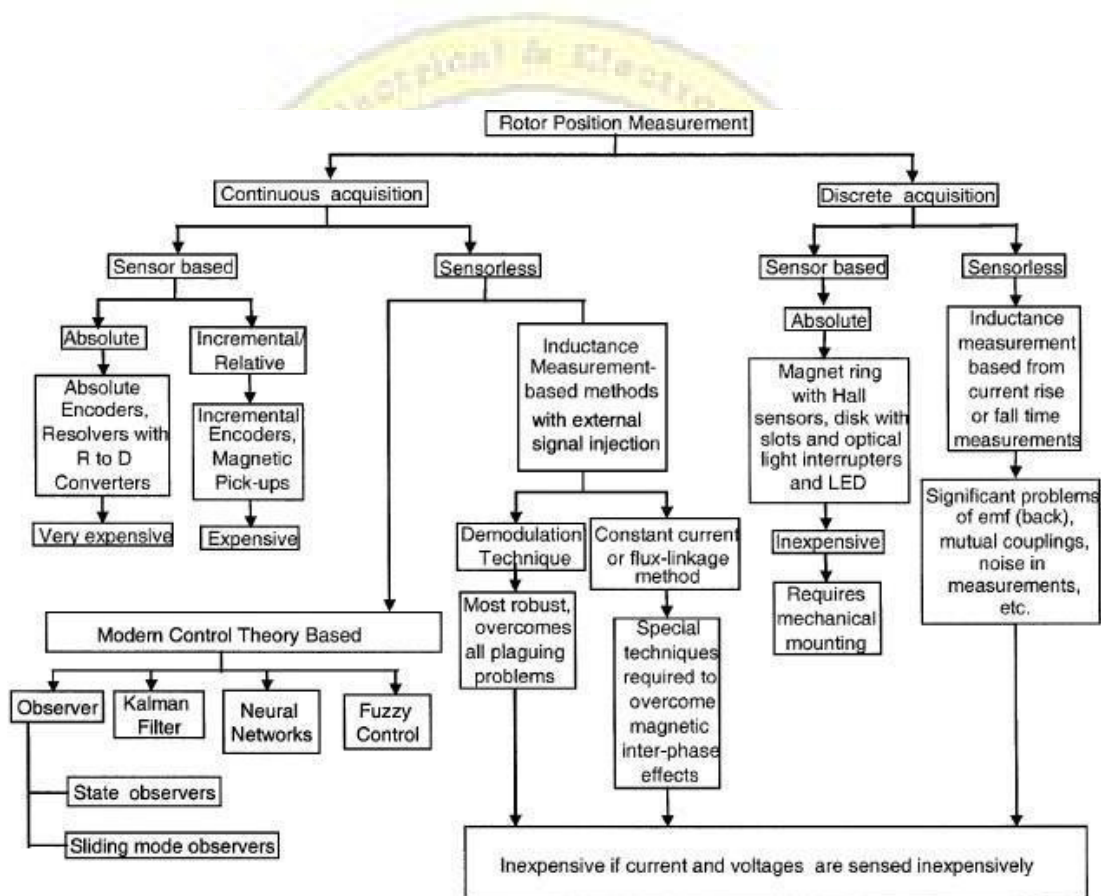


FIGURE 8.6 Rotor position measurement and estimation methods.

UNIT IV

PERMANENT MAGNET BRUSHLESS D.C. MOTORS

Introduction:

Conventional DC motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawbacks that they need a commutator and brushes which are subject to wear and require maintenance.

When the functions of commutator and brushes were implemented by solid state switches, maintenance free motors were realized. These motors are known as brushless DC motors. The function of magnets is the same in both brushless motor and the dc commutator motor. The motor obvious advantage of brushless configuration is the removal of brushes. Brush maintenance is no longer required, and many problems associated with brushes are removed.

An advantage of the brushless configuration in which the rotor inside the stator is that more cross sectional area is available for the power or armature winding. At the same time conduction of heat through the frame is providing greater specific torque. The efficiency is likely to be higher that of a commutator motor of equal size and the absence of brush friction help further in this regard.

Constructional Features Of Blpm Motors:

1. Construction:

The stator of the BLPM dc motor is made up of silicon steel stampings with slots in its interior surface. These slots accommodate either a closed or opened distributed armature winding usually it is closed. This winding is to be wound for a specified number of poles. This winding is suitably connected to a dc supply through a power electronic switching circuitry (named as electronic commutator).



Fig 4.1 Arrangement of permanent magnet in the rotor

Rotor is made of forged steel. Rotor accommodates permanent magnet. Number of poles of the rotor is the same as that of the stator. The rotor shaft carries a rotor position sensor. This position sensor provides information about the position of the shaft at any instant to the controller which sends suitable signals to the electronic commutator.

2. Merits and

Demerits Merits

- There is no field winding. Therefore there is no field cu loss.
- The length of the motor is less as there is no mechanical commutator.
- Size of the motor becomes less.
- It is possible to have very high speeds.
- It is self-starting motor. Speed can be controlled.
- Motor can be operated in hazardous atmospheric condition.
- Efficiency is better.
-

Demerits

- Field cannot be controlled.
- Power rating is restricted because of the maximum available size of permanent magnets.
- A rotor position sensor is required.
- A power electronic switch circuitry is required.

3. Comparison of brushless dc motor relative to induction motor drives

- In the same frame, for same cooling, the brushless PM motor will have better efficiency and p.f and therefore greater output. The difference may be in the order of 20 – 50% which is higher.
- Power electronic converter required is similar in topology to the PWM inverters used in induction motor drives.
- In case of induction motor, operation in the weakening mode is easily achieved providing a constant power capability at high speed which is difficult in BLPM dc motor.
- PM excitation is viable only in smaller motors usually well below 20 kw also subject to speed constraints, In large motors PM excitation does not make sense due to weight and cost.

4. Commutator and brushes arrangement

Because of the heteropolar magnetic field in the air gap of dc machine the emf induced in the armature conductors is alternating in nature. This emf is available across brushes as unidirectional emf because of commutator and brushes arrangement.

The dc current passing through the brushes is so distributed in the armature winding that unidirectional torque is developed in armature conductor.

A dc current passing through the brushes because of commutator and brushes action, always sets up a mmf whose axis is in quadrature with the main field axis, irrespective of the speed of the armature.

5. Construction of Mechanical

Commutator Commutator Segment:

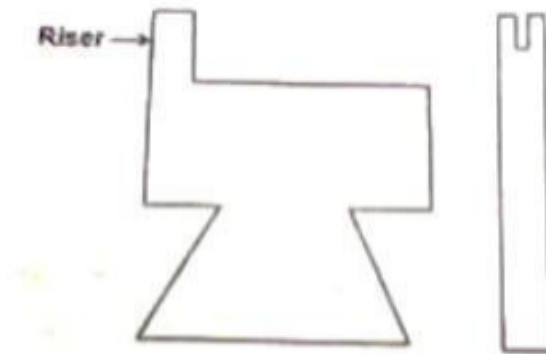


Fig 4.2 Commutator Segment

Commutator is made up of specially shaped commutator segments made up of copper. These segments are separated by thin mica sheets (ie) Insulation of similar shape. The commutator segments are tapered such that when assembled they form a cylinder.

These segments are mechanically fixed to the shaft using V – shaped circular steel clamps, but are isolated electrically from the shaft using suitable insulation between the clamps and the segment.

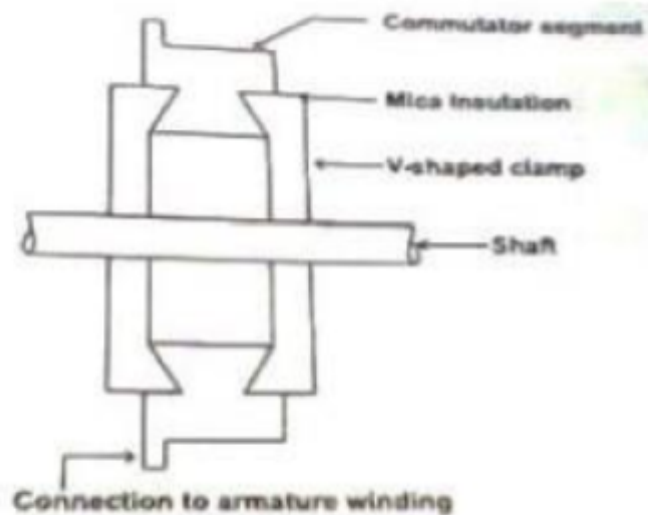


Fig 4.3 connection of commutator segments to shaft

6. Mechanical Commutator and Brushes Arrangement

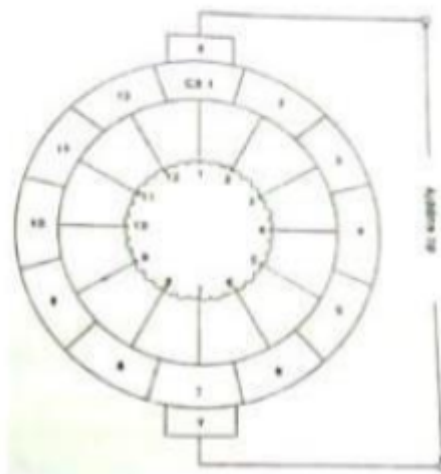


Fig 4.4 Mechanical Commutator and Brushes Arrangement

The figure represents a case with 2poles and 12 commutator segments.

To start with the brush X contacts with CSI and brush Y with 7. A dc supply is connected across the brushes X and Y. The dc current I passes through brush X, CSI, tapping 1, tapping 7 and brush Y. There are two armature parallel paths between tapping's 1 and 7. The current passing through the armature winding sets up a magnetomotive force whose axis is along the axes of tapping 7 and 1 of the brush axes Y and X.

Allow the armature to rotate by an angle in a counter clockwise direction. Then the brush X contacts CS2 and the tapping's a and the brush Y. Contact CS8 and tapping 8. The dc current passes through the tapping's 2 and 8 there are two parallel paths.

- (i) 2 – 3 – 4 – 5 – 6 – 7 – 8
- (ii) 2 – 1 – 12 – 11 – 10 – 9 – 8

Now the mmf set up by the armature winding is from tapping 8 to 2 along the brush axis YX. Thus the armature mmf direction is always along the brush axis YX, even though the current distribution in the armature winding gets altered.

In a normal dc machine brushes are kept in the interpolar axis. Therefore, the axis of the armature mmf makes an angle 90° elec with the main field axis.

The function of commutator and brushes arrangement in a conventional dc machine is to set up an armature mmf always in quadrature with the main field mmf respectively of the speed of rotation of the rotor.

7. Electronic commutator

The armature winding which is in the stator has 12 tapping's. each tapping is connected to the positive of the dc supply node and through 12 switches designated as S1, S2, ..., S12 and negative of the supply at node Y through switches S'1, S'2, ..., S'12.

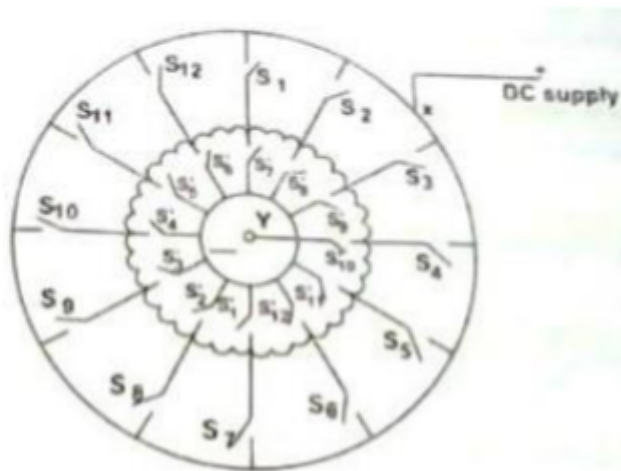


Fig 4.5 Electronic Commutator

When S1 and S'1 are closed the others are in open position, the dc supply is given to the trappings 1 and 7. there are two armature parallel path.

- (i) 1 – 2 – 3 – 4 – 5 – 6 – 7
- (ii) 1 – 12 – 11 – 10 – 9 – 8 – 7

They set up armature mmf along the axis 7 to 1.

After a small interval S1 and S'1 are kept open and S2 and S'2 are closed. Then dc current passes from tapping 2 to 8 sets up mmf in the direction 8 – 2.

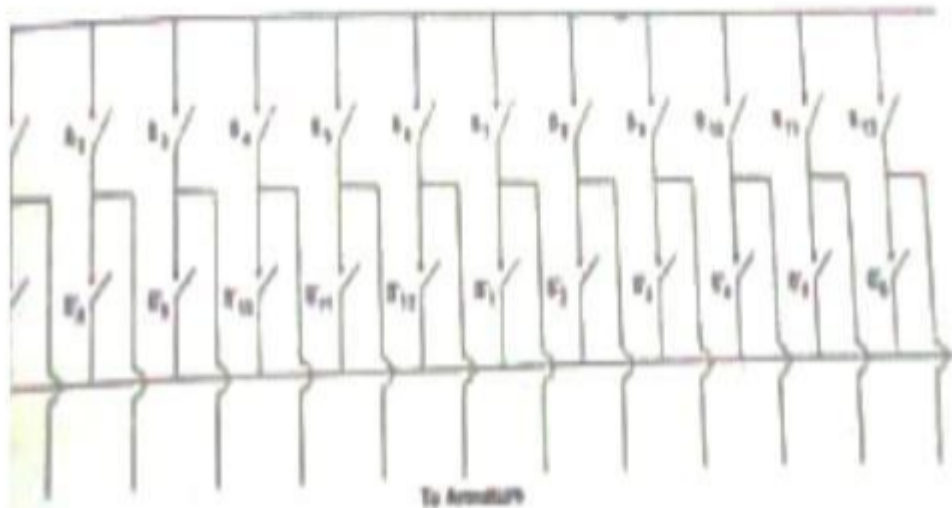


Fig 4.6 switching circuit of electronics commutator

Thus by operating the switch in a sequential manner it is possible to get a revolving mmf in the air gap. The switches S1 to S12 and S'1 to S'12 can be replaced by power electronic switching devices such as SCR's MOSFET's IGBT's, power transistor etc.

When SCR's are used suitable commutating circuit should be included. Depending upon the type of forced commutated employed, each switch requires on or two SCRs and other commutating devices. As number of devices is increased, the circuit becomes cumbersome.

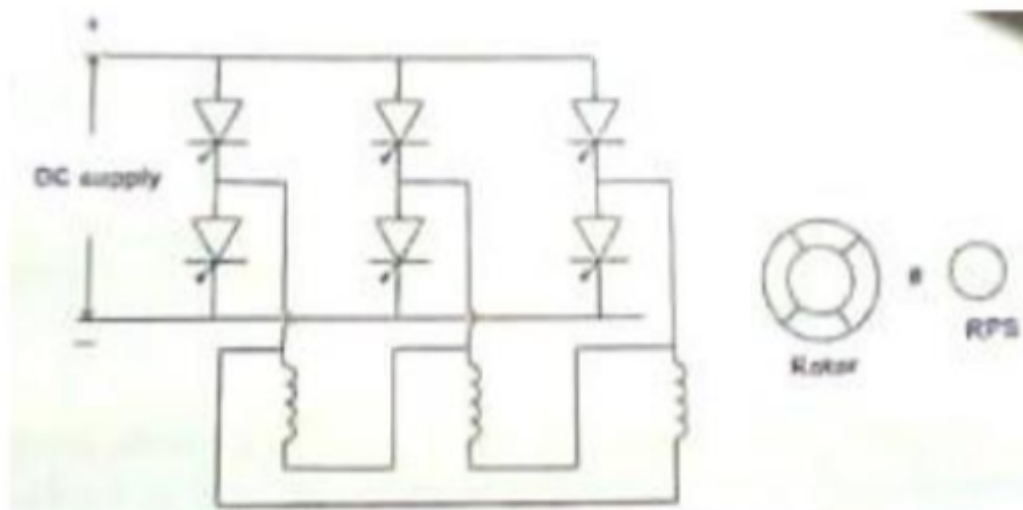


Fig 4.7 Delta Connected Stator Armature Winding

For normal electronic commutator, usually six switching devices are employed. Then the winding should have three tapping's. Therefore the winding can be connected either in star or in delta.

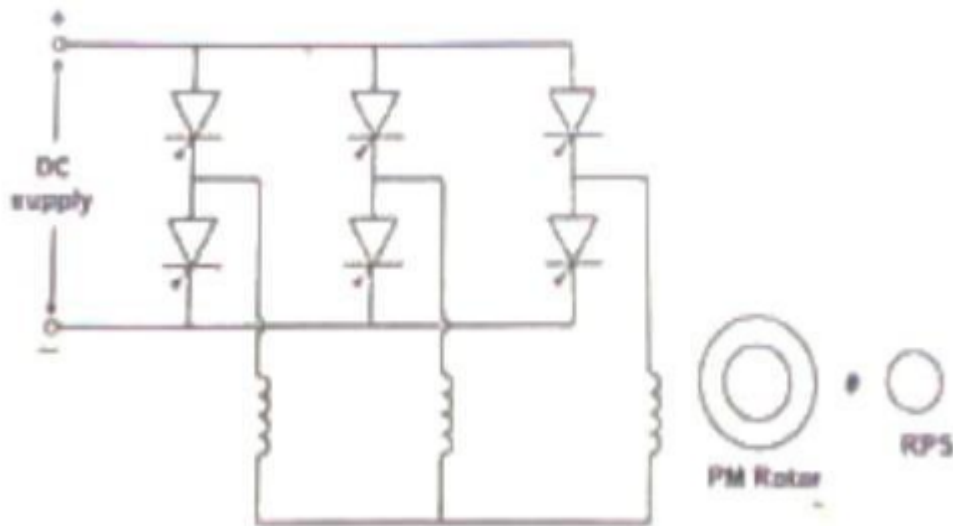


Fig 4.8 Star Connected Armature Winding

8. Comparison between mechanical Commutator and brushes and Electronic Commutator

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

B-H LOOP AND DEMAGNETIZATION CHARACTERISTICS:

1. Permanent Magnets Material

NdFeB – Neodymium – iron – boron has the highest energy product of all commercially available magnets at room temperature. It has high remanence and coercivity in the motor frame size for the same output compared with motors using ferrite magnets. But it is costlier. But both of the above stated magnets are sensitive to temperature and care should be taken for working temperature above 100° . For very high temperature applications, alnico or rare earth cobalt magnets must be used.

2. B – H Loop

It is used for understanding characteristics hysteresis loop as shown.

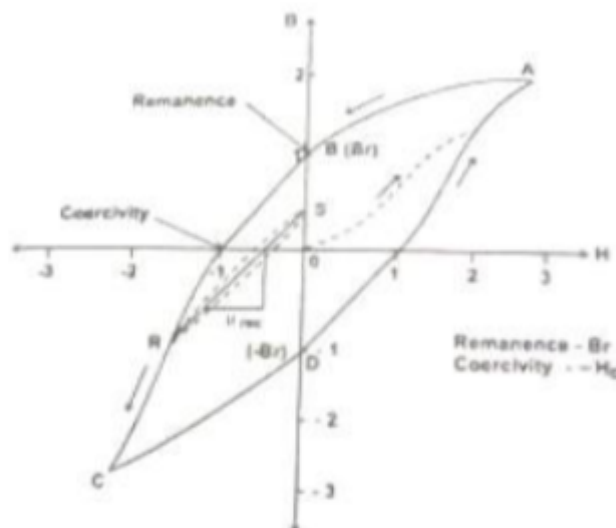


Fig 4.9 BH Hysteresis loop of hard permanent magnet material

X – axis – Magnetizing force or field intensity H.

Y – axis – Magnetic flux density B in the material.

- An un-magnetized sample has $B = 0$ and $H = 0$ and therefore starts out at the origin.

Curve OA

□ If it is subjected to a magnetic field, magnetic fixture (an electromagnetic with shaped pole pieces to focus flux into the magnet), then B and H in the magnet follow the curve OA as the external ampere – turns are increased.

Curve AB

□ If the external ampere – turns are switched off, the magnet relaxes along AB . The operating point (H , B) depends on the shape of the magnet and permanence of the surrounding magnetic circuit. If the magnet is surrounded by a highly permeable magnetic circuit, that is if it is kepted then its poles are effectively shorted together so that $H = 0$ and then the flux density is the value at point remanence B_r .

Permanence: Maximum flux density that can be retained by the magnet at a specified temperature after being magnetized to saturation.

Curve BC

□ External ampere turns applied in the opposite direction cause the magnets operating point to follow the curve from B through the second quadrant to C .

Curve CD

□ If the ampere – turns are switched off at c the magnet relaxes along CD . It is now magnetized in the opposite direction and the maximum flux density it can retain when kepted is $-B_r$.

□ To bring B to zero from negative remanence point D , the field $+H_c$ must be applied.

□ The entire loop is usually symmetrical and be measured using instruments such as hysteresis graph.

3. Soft PM

- Soft PM materials have Knee in the second quadrant such as Alnico.
- Alnico magnets have very high remanence and excellent mechanical and thermal properties. But they are limited in the demagnetizing field they can withstand.
- These soft PM are hard when compared with lamination steels the hysteresis loop of typical non oriented electrical steel is very narrow when compared with Alnico.

4. Demagnetization curve

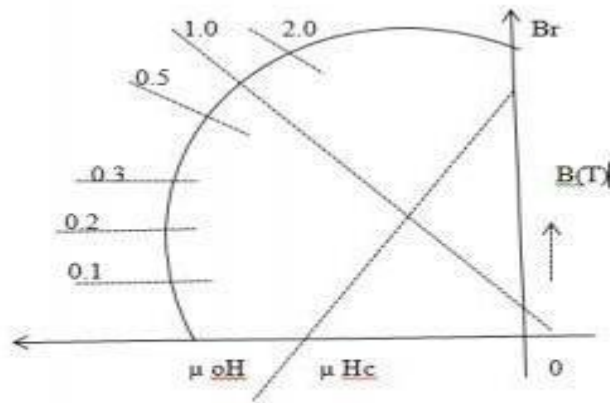


Fig 4.10 Demagnetization curve

In the absence of externally applied ampere – turn, the magnets operating point is at the intersection of the demagnetization curve and the load line.

□ The slope of the load line is the product of μ_0 and the permeance coefficient of the external circuit.

In a permanent magnet, the relationship between B and H is

$$B = \mu_0 H + J$$

$\mu_0 H$ – flux density that would exist if the magnet were removed and the magnetizing force remain at the value H.

J – contribution of the magnet to the flux - density within its own volume.

□ If the demagnetization curve is a straight line, and therefore its relative slope and there by the μ_{rec} is unity, Then J is constant.

J – Magnetization of the magnet, unit T tesla

- Hard magnets have $\mu_{rec} > 1$, J decreases as the $-H_c$ increases.
- The magnet can recover or recoil back to its original flux density as long as the magnetization is constant.
- The coercive force required to permanently demagnetize the magnet is called the intrinsic coercivity and it is H_{ci} .

PRINCIPLE OF OPERATION OF BRUSHLESS PM DC MOTOR

Starting

When dc supply is switched on to the motor the armature winding draws a current. The current distribution within the stator armature winding depends upon rotor position and the devices turned on. An emf perpendicular to the permanent magnet field is set up. Then the armature conductors experience a force. The reactive force develops a torque in the rotor. If this torque is more than the opposing frictional and load torque the motor starts. It is a self-starting motor.

Demagnetization curve

As the motor picks up speed, there exists a relative angular velocity between the permanent magnet field and the armature conductors. As per Faraday's law of electromagnetic induction, an emf is dynamically induced in the armature conductors. This back emf as per Lenz's law opposes the cause armature current and is reduced. As a result the developed torque reduces. Finally the rotor will attain a steady speed when the developed torque is exactly equal to the opposing frictional load torque. Thus the motor attains a steady state condition.

Electromechanical transfer

When the load – torque is increased, the rotor speed tends to fall. As a result the back emf generated in the armature winding tends to get reduced. Then the current drawn from the mains is increased as the supply voltage remains constant. More torque is developed by the motor. The motor will attain a new dynamic equilibrium position when the developed torque is equal to the new torque. Then the power drawn from the mains $V \cdot I$ is equal to the mechanical power delivered $2\pi nT/60 = P_m = \omega T$ and the various losses in the motor and in the electronic switching circuitry.

CLASSIFICATION OF BLPM DC MOTOR

BLPM dc motors can be classified on the basis of the flux density distribution in the air gap of the motor. They are

- (a). BLPM Square wave dc motor [BLPM SQW DC Motor]
- (b). BLPM sinusoidal wave dc motor [BLPM SINE WAVE DC Motor]

(a) BLPM Square wave motor

These are two types: 180° pole arc. 120° pole arc.

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

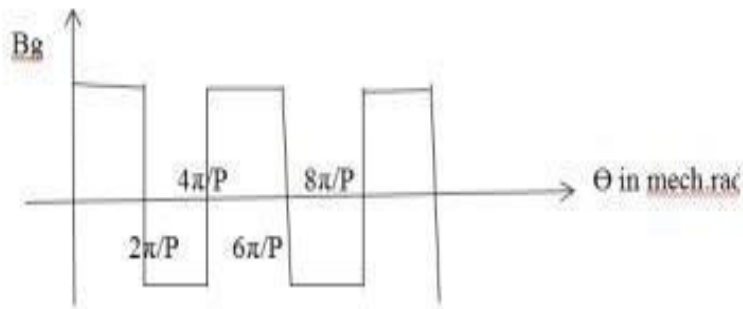


Fig 4.11 Air gap flux density distribution in 180° BLPM SQW motor.

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

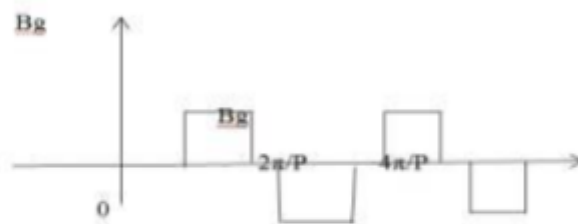


Fig 4.12 Air gap flux density distribution in 120° BLPM SQW motor

(b)BLPM Sine wave DC Motor

Air gap density distribution of BLPM dc sine wave motor as shown in fig.

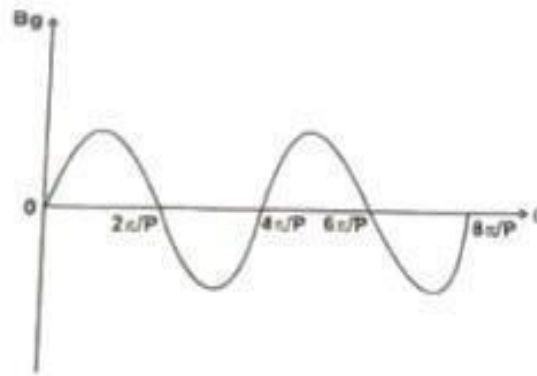


Fig 4.13 Flux density distribution of BLPM DC sine wave motor

Emf Equation Of Blpm Sqw Dc Motors

The basic torque emf equations of the brushless dc motor are quite simple and resemble those of the dc commutator motor.

The co-ordinate axis have been chosen so that the center of a north pole of the magnetic is aligned with the x-axis at $\Theta = 0$. the stator has 12 slots and a three phasing winding. Thus there are two slots per pole per phase.

□ Consider a BLPM SQW DC MOTOR

Let, 'p' be the number of poles (PM)

' B_g ' be the flux density in the air gap in wb/m².

B_k is assumed to be constant over the entire pole pitch in the air gap (180° pole arc)

'r' be the radius of the airgap in m.

'l' be the length of the armature in m.

' T_c ' be the number of turns per coil.

' ω_m ' be the uniform angular velocity of the rotor in mechanical rad/sec.

$\omega_m = 2\pi N/60$ where N is the speed in rpm.

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

Let, at $\omega_m t=0$, the centre of N-pole magnet is aligned with x-axis.

At $\omega_m t=0$, x-axis is along PM axis.

Therefore flux enclosed by the coil is

$$\Phi_{\max} = B \times 2\pi r / p \times l$$

=flux/pole

(1)

$$\Phi_{\max} = r l \int_0^\pi B(\theta) d\theta$$

$$= B_g r l [\theta]_0^\pi$$

$$= B_g r l [\pi]$$

At $\omega_{mt}=0$, the flux linkage of the coil is

$$\Lambda_{\max} = (B_g \times 2\pi r / p \times l) T_c \omega_b - T \quad (2)$$

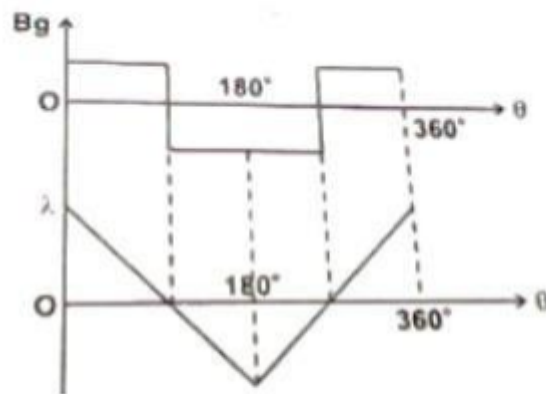


Fig 4.14 Magnetic Flux Density around the Air gap.

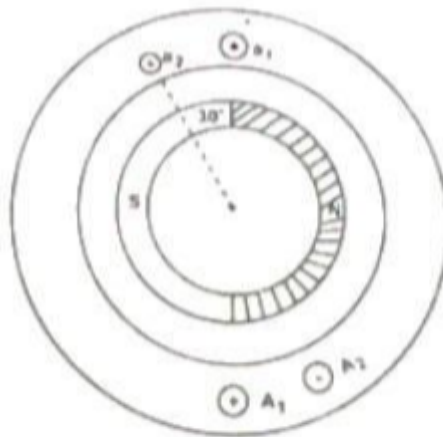


Fig 4.15 Motor Showing two Coils of One Phase.

Let the rotor rotating in ccw direction and when $\omega_{mt} = \pi/2$, the flux enclosed by the coil Φ , Therefore $\lambda=0$.

The flux linkages of the coil vary with θ variation of the flux linkage is as shown above.

The flux linkages of the coil changes from $B_g r l T_c \pi / p$ at $\omega_{mt}=0$ (i.e) $t=0$ to θ at $t=\pi/p\omega_m$.

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

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

$$= 0 - (2B_{gr}lTc\pi/p) / (\pi/p\omega_m)$$

$$= -(2B_{gr}lTc\omega_m) \quad (3)$$

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

$$e_c = 2B_{gr}lTc\omega_m \quad (4)$$

Distribution of e_c with respect to t is shown in fig

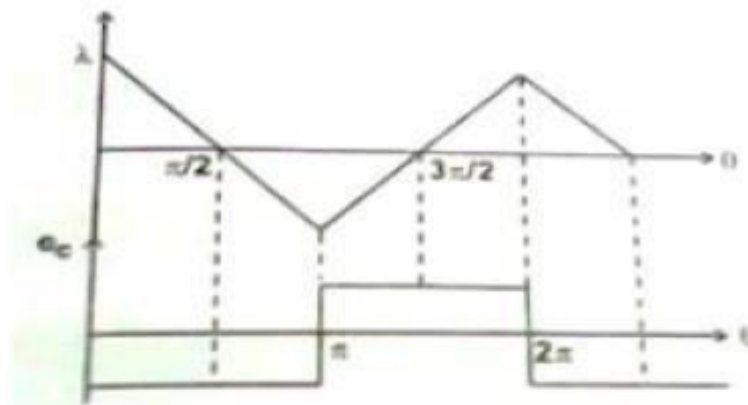


Fig 4.16 Emf waveform of coil 1

It is seen that the emf waveform is rectangular and it toggles between $+e_c$ to $-e_c$. The period of the wave is $2\pi/p\omega_m$ sec and magnitude of e_c is

$$e_c = 2B_{gr}lTc\omega_m \text{ volts} \quad (5)$$

Consider two coils a_1A_1 and a_2A_2 as shown in fig. Coil a_2A_2 is adjacent to a_1A_1 is displaced from a_1A_1 by an angle 30° (i.e.) slot angle γ .

The magnitude of emf induced in the coil a_1A_1

$$e_{c2} = B_{gr}lTc\omega_m \text{ volts} \quad (6)$$

The magnitude of emf induced in the coil a_2A_2

$$e_{c2} = B_{gr}lTc\omega_m \text{ volts} \quad (7)$$

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

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

$$e_{c1} + e_{c2} = 2B_g l T_c \omega_m \quad (8)$$

Let n_c be the number of coils that are connected in series per phase $n_c T_c = T_{ph}$ be the number of turns/phase.

$$e_{ph} = n_c [2B_g l T_c \omega_m] \quad \dots\dots\dots(9)$$

$$e_{ph} = 2B_g l T_{ph} \omega_m \text{ volts} \quad (10)$$

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

The waveforms are as shown in fig

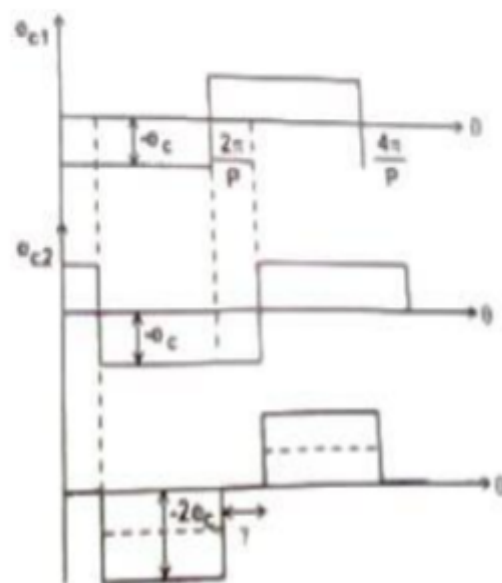


Fig 4.17 Emf waveform of phase a

The waveform of e_{ph} is stepped and its amplitude is $2B_g l T_{ph} \omega_m$ volts.

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

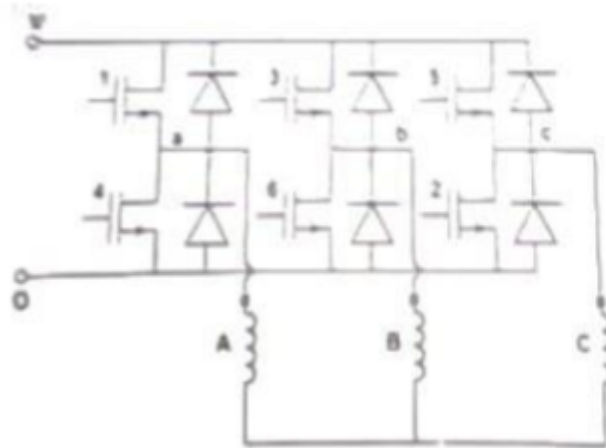


Fig.4.18 converter of brushless dc motor with star connected phase winding.

Assumption

Armature winding is Y connected.

Electronic switches are so operated using rotor position sensor that the resultant emfs across the winding terminals is always = 2 e_{ph}.

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

Basic Voltage Equation Of Blpm dc Motor

Let, V be the dc supply voltage

I be the armature current

R_{ph} be the resistance per phase of the λ connected armature winding.

V_{dd} be the voltage drop in the device (it is usually neglected)

e_{ph} be the back emf generated per phase of Y connected armature winding

$$V = 2 e_{ph} + 2 I R_{ph} + 2 V_{dd} \dots\dots\dots(4.11)$$

If V_{dd} is neglected

$$V = 2 e_{ph} + 2 I R_{ph}$$

$$I = \frac{V - 2 e_{ph}}{2 R_{ph}}$$

$$I = \frac{V - E}{R} \dots\dots\dots(4.12)$$

(a) Starting condition

Speed is zero $\omega_m = 0$

Supply voltage is V

Since $\omega_m = 0$; $e_{ph} = 0$

$$\text{Starting current } I_{stg} = \frac{V - 0}{2 R_{ph}} = \frac{V}{2 R_{ph}} = \frac{V}{R} \dots\dots\dots(4.13)$$

$R = 2 R_{ph}$ is Y connected

This current is also known as starting current.

(b) NO load condition

Current is very very small

$$\text{Then } V = 2 e_{ph} + 2 I R_{ph}$$

$2I R_{ph}$ – negligible

$$V = 2 e_{pho} \dots\dots\dots(4.14)$$

$$= 2 [2 B_g r l \omega_{mo} T_{ph}]$$

$$= 4 [B_g r l \omega_{mo} T_{ph}]$$

$$V = k_e \omega_{mo} \dots\dots\dots(4.15)$$

$$\text{No load speed, } \omega_{mo} \cong \frac{V}{4 B_g r l T_{ph}} \dots\dots\dots(4.16)$$

$$= \frac{V}{k_e} \dots\dots\dots(4.17)$$

No load current $I_o=0$

(c) ON load condition:

$$V = 2 e_{ph} + 2 I R_{ph}$$

$$= 4 B_g r l \omega_m t_{ph} + 2 I R_{ph} \dots\dots\dots(4.18)$$

On load current

$$I = \frac{V - 2 e \phi}{2 R_{ph}} = \frac{V - 4 B g r l \omega_m t_{ph}}{2 R_{ph}} \quad (4.19)$$

$$= \frac{V - k_e \omega_m}{2 R_{ph}} \quad (4.20)$$

$$I = \frac{V - k_e \omega_m}{2 R_{ph}} \quad (4.21)$$

I vs ω_m curve is shown in fig 4.19

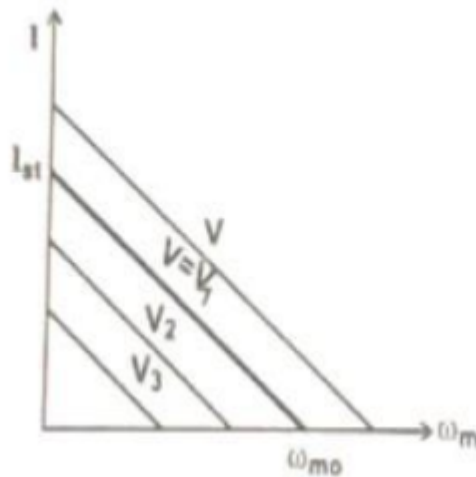


Fig.4.19 I Vs. ω_m Curve

Torque Equation Of Blpm Square Wave Motor

$$\text{Power input} = VI$$

$$= [2 e \phi + 2 I R_{ph} + 2 V_{dd}] I$$

$$(4.22)$$

Where,

$$VI = [2 e \phi + 2 I R_{ph} + 2 V_{dd}] I$$

$$(4.23)$$

VI= electrical power input

$2 e \phi I$ = power converted as mechanical

$2 I^2 R_{ph}$ = power loss in the armature winding

$2 V_{dd} I$ = power loss in the device

$$\text{Mechanical power developed} = 2 \text{ eph I} \quad (4.24)$$

$$e_{ph} = 2(2B_{grl}T_{ph}\omega_m)I$$

$$e_{ph} = 4B_{grl}T_{ph}\omega_m \quad (4.25)$$

$$\text{Mechanical power} = (2\pi N/60)T \quad (4.26)$$

$$= \omega_m T \quad (4.27)$$

Where, N =Speed in rpm

T =Torque in N-m

ω_m =Speed in rad/sec

$$\text{Therefore, } T = 4B_{grl}T_{ph}I \quad (4.28)$$

$$= K_t T \quad (4.29)$$

$$\text{Where } K_t = 4B_{grl}T_{ph} = K_e \quad (4.30)$$

(a) Case1: Starting Torque

$$\omega_m = 0$$

$$I_{stg} = (V/2R_{ph}) \quad (4.31)$$

$$T_{stg} = 4B_{grl}T_{ph}(V/2R_{ph}) \quad (4.32)$$

$$T_{stg} = K_t(V/2R_{ph}) \quad (4.33)$$

Starting torque or stalling torque depends upon V .

To vary the starting torque the supply voltage is to be varied.

(b) Case 2: On load condition

$$T = K_t I \quad \dots\dots\dots (4.34)$$

$$= 4 B_g r l T_{ph} I$$

$$I = (V - 2e_{ph}) / (2R_{ph}) \quad \dots\dots\dots (4.35)$$

$$2e_{ph} = V - 2I R_{ph}$$

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

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

$$\omega_m = (V - 2I R_{ph}) / K_e \quad \dots\dots\dots (4.37)$$

$$\omega_{m0} = V / K_e \quad \dots\dots\dots (4.38)$$

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

$$= (V - 2I R_{ph}) / V$$

$$\omega_m / \omega_{m0} = 1 - ((V - 2I R_{ph}) / V) \quad \dots\dots\dots (4.39)$$

$$I / (T_{stg}) = (K_t I) / (K_t I_{stg})$$

$$= I . (2R_{ph} / V)$$

$$T / T_{stg} = 2I R_{ph} / V \quad \dots\dots\dots (4.40)$$

Substituting eqn. 5.40 in eqn. 5.39

$$\omega_m / \omega_{m0} = 1 - (T / T_{stg}) \quad \dots\dots\dots (4.41)$$

$$\omega_m / \omega_{m0} = 1 - (I - I_{stg}) \quad \dots\dots\dots (4.42)$$

TORQUE- SPEED CHARACTERISTICS OF BLPM SQM DC MOTOR

Let the supply voltage V be constant. A family of torque speed characteristics for various constant supply voltages is as shown in figure

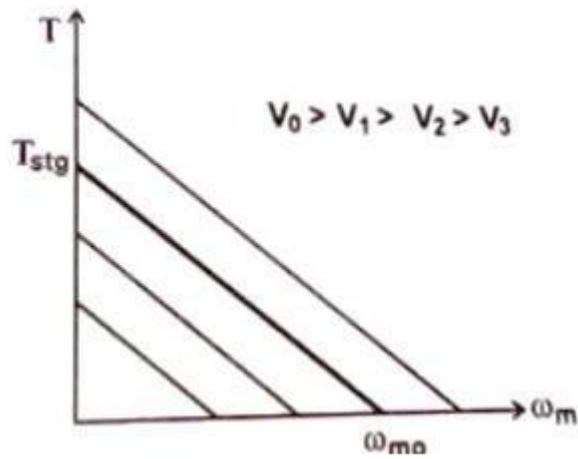


Fig 4.20 T- ω_m curve for various supply voltages

Permissible region of operation in T- ω_m plane

Torque speed characteristics of BLPM square wave motor is shown in fig.4.21. The constraints are

1. The continues current should not exceed the permissible current limit I_n (i.e) Torques should not exceed $K_t I_n$.
2. The maximum permissible supply voltage = V_n .
3. The speed should not exceed ω_{mn} .

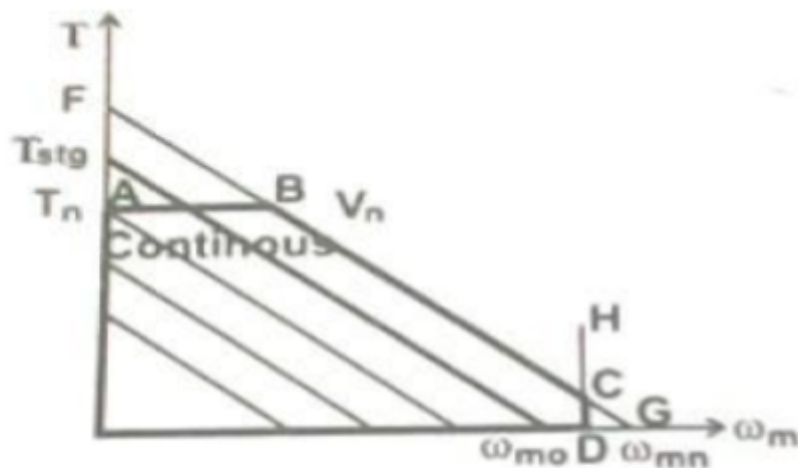


Fig. 4.21 Torque-speed characteristics

Line AB

Parallel to X-axis represents maximum permissible torque line which corresponds to maximum permissible current I_n .

Line FG

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

Line DH

It represents constant maximum permissible speed line (i.e) ω_{mn} is constant. DH intersects FG and x axis at D.

The area OABCD is the permissible region of operation. To obtain a particular point P corresponding to given load-torque and speed condition the only way to operate the motor at P is by suitably adjusting the supply voltage fed to the motor.

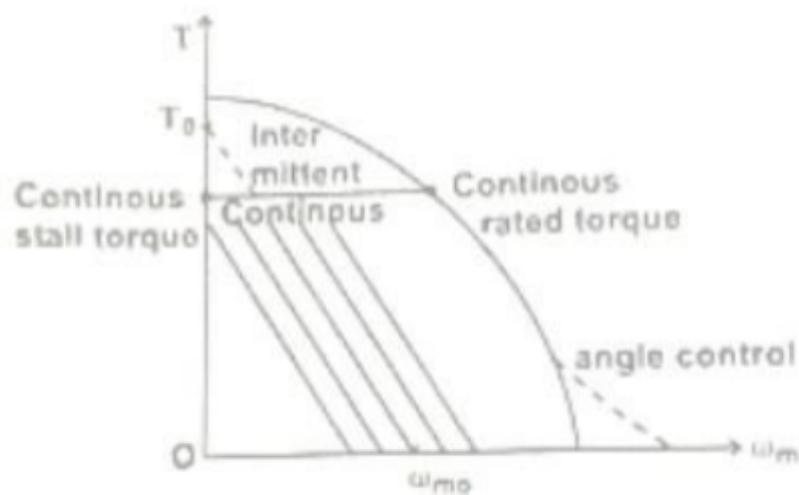


Fig.4.22 Torque speed characteristics of ideal brushless DC motor

- If the phase resistance is small as it should be in an efficient design, then the characteristics to that of a shunt dc motor. The speed is essentially controlled by the voltage V and may be changed by changing the supply voltage. Then the current drawn just to drive the torque at its speed.
- As the load torque is increased, the speed drops and the drop is directly proportional to the phase resistance and the torque.

- The voltage is usually controlled by chopping or PWM. This gives rise to a family of torque speed characteristics as shown in fig. . The boundaries of continuous and intermittent limits are shown.

Continuous limit - determined by the heat transfer and temperature rise.

Intermittent limit – determined by the maximum ratings of semiconductor devices in circuit.

In practice the torque speed characteristics deviates from the ideal form because of the effects of inductance and other parasitic influences. Also the speed range can be extended by increasing the dwell of conduction period relative to the rotor position.

Commutation In Motors With 120° And 180° Magnet Arc

BLPM dc motor with 180° magnet arcs and 120° square wave phase currents arc shown in figs.

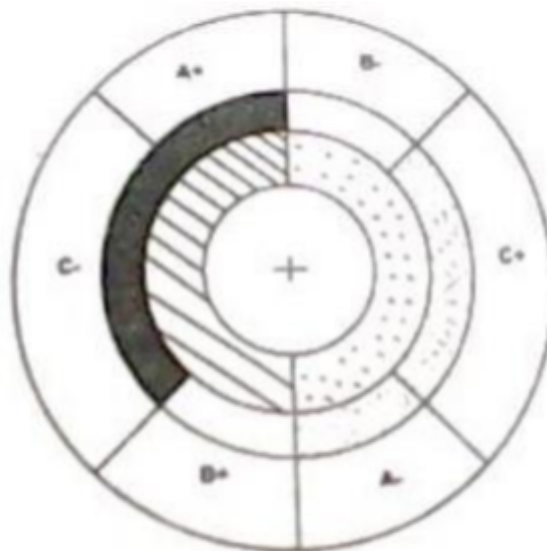


Fig.4.23 BLDC motor with 180° magnet arc and 120° square wave phase currents



Fig.4.24 BLDC motor with 120° magnet arcs and 180° square wave phase currents

In Fig. the rotor magnet poles are shaded to distinguish north and south. The phase belts are shaded as complete 60° sector of the stator bore. There are two slots in each of these phase belts. The current in these two slots are identical and conductors in them are in series

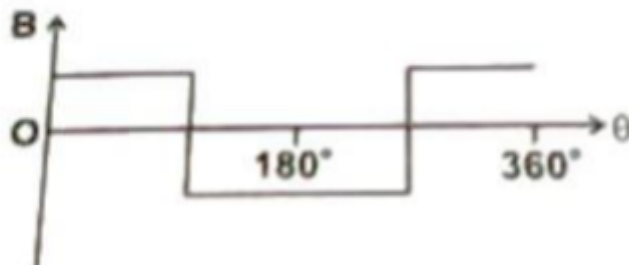


Fig.4.25 Flux density around air gap

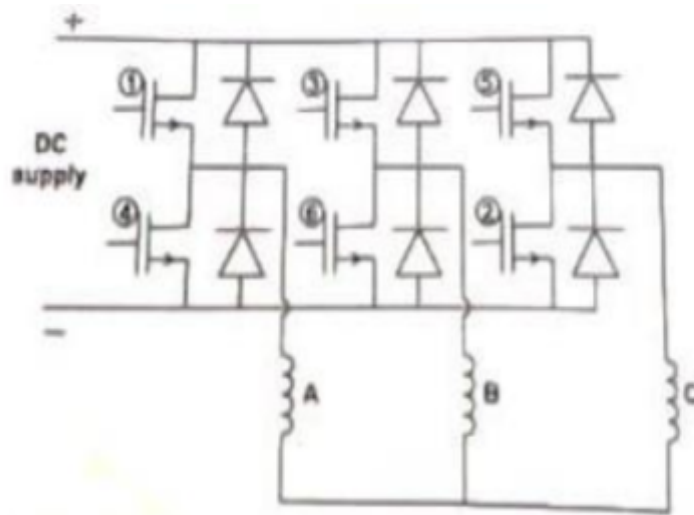


Fig.4.26 Converter of brushless DC motor for star connected phase winding

Between the rotor ring and the stationary belt ring in fig. there is a third ring called the 'mmf ring'. This represents the mmf distribution of the stator currents at a particular instant.

- At the instant shown $\omega t=0$, phase A is conducting positive current and phase C is conducting negative current. The resulting mmf distribution has the same shading as the N and S rotor poles to indicate the generation of torque,
- Where the mmf distribution has like shading, positive torque is produced. Where mmf and flux shading are unlike, negative torque is produced. Where one is zero, no torque is zero, no torque is produced. The total torque is the integral of the contributions from around the entire air gap periphery.

The rotor is rotating in the clockwise direction. After 60° of rotation, the rotor poles start to 'uncover' the C phase belts and the torque contribution of phase C starts to decrease linearly.

During this period, the magnet poles, have been 'covering' the B phase belts. Now if the negative current is commutated from C to B exactly at then point 60° , then the torque will be unaffected and will continue constant for a further 60° . After 120° , positive current must be commutated from A to C.

Commutation Tables For Three-Phase Brushless Dc Motors.

TABLE : 180° Magnet-Star Winding. 120° Square wave phase Currents

Rotor Position	A	B	C	au(1)	aL(4)	bu(3)	bL(6)	cu(5)	cL(2)
0 – 60	+1	0	-1	1	0	0	0	0	1
60 – 120	+1	-1	0	1	0	0	1	0	0
120 – 180	0	-1	+1	0	0	0	1	1	0
180 – 240	-1	0	+1	0	1	0	0	1	0
240 – 300	-1	+1	0	0	1	1	0	0	0
300 – 360	0	+1	1	0	0	1	0	0	1

- The production of smooth, ripple free torque depends on the fact the magnet pole arc exceeds the mmf arc by 60°.
- Here only 2/3 of the magnet and 2/3 of the stator conductors are active at any instant

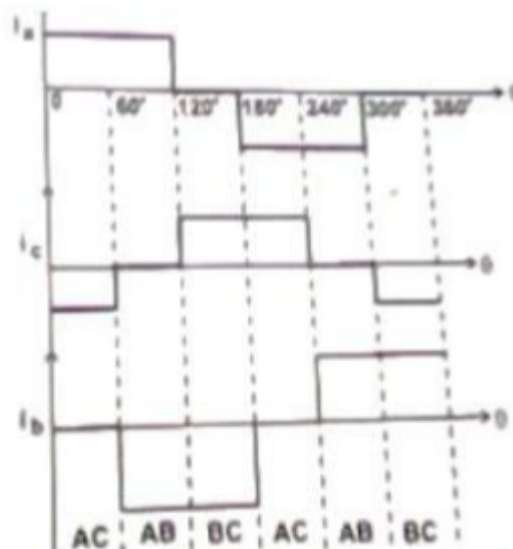


Fig. 4.27 phase current waveforms of BLDC motor with 180° pole arc.

In a practical motor the magnet flux-density distribution cannot be perfectly rectangular as shown in fig.. for a highly coercive magnets and full 180° magnet arcs there is a transition section of the order of 10-20° in width. This is due to fringing effect. Likewise on the stator

side, the mmf distribution is not rectangular but have a stepped wave form as shown in fig.4.28 that reflects the slotting.

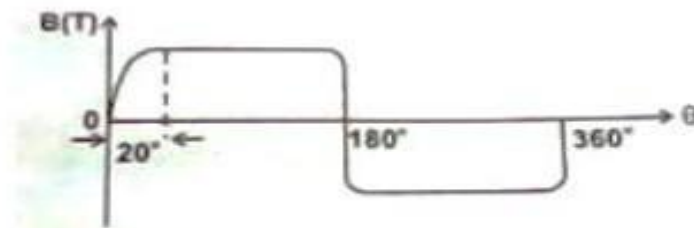
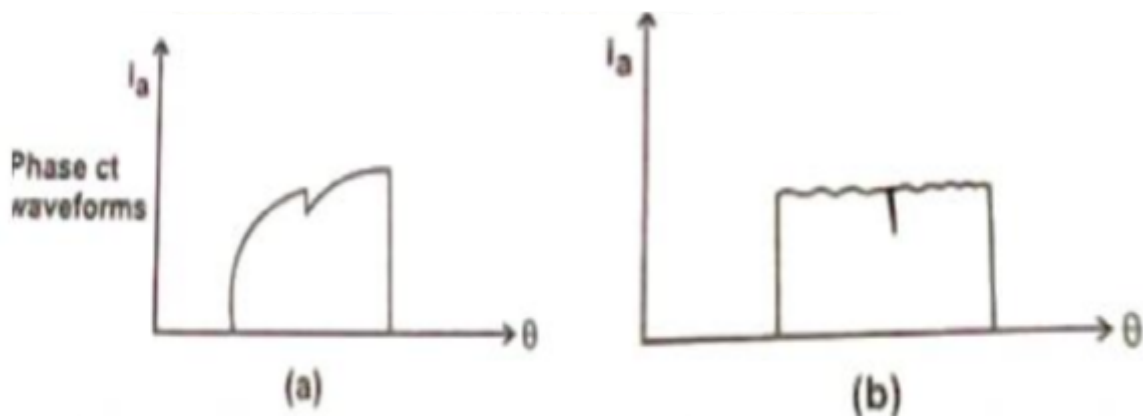


Fig 4.28 Air Gap Flux Density on Open Circuit

To some extent these effects cancel each other so that satisfactory results are obtained with a magnet arc as short as 150° , and two slots per pole per phase.

But there is always dip in the torque in the neighborhood of the commutation angles. This torque dip occurs every 60° elec degrees, giving rise to a torque ripple component with a fundamental frequency equal to $6P$ times the rotation frequency where P is the number of pole pairs. The magnitude and width of the torque dip depends on the time taken to commutate the phase current.

Phase current waveforms corresponding to high speed and low speed operations are as shown in fig. (a & b)



- (a) High speed, full voltage. Note the dip caused by commutation of other 2 phases,
 (b) Low speed with current controlled by chopping.

Fig.4.29 Phase current wave forms.

The back emf is of equal value in the incoming phase and is in such a direction as to

- oppose the current build up.

- While the flux distribution of the magnet rotates in a continuous fashion, the mmf distribution of the stator remains stationary for 60° and then jumps to a position 60° ahead.

Similar analysis is made with a motor having 120° pole arc magnets with delta connected armature winding.

Table 120° Magnet Delta Winding, 180° Square Wave Phase Currents.

Rotor Position	A	B	C	ab u (1)	ab L (4)	bc u (3)	bc L (6)	ca u (5)	ca L (2)
0 – 60	+1	+1	-1	0	0	1	0	0	1
60 – 120	+1	-1	-1	1	0	0	0	0	1
120 – 180	+1	-1	+1	1	0	0	1	0	0
180 – 240	-1	-1	+1	0	0	0	1	1	0
240 – 300	-1	+1	+1	0	1	0	0	1	0
300 - 360	-1	+1	1	0	1	1	0	0	0



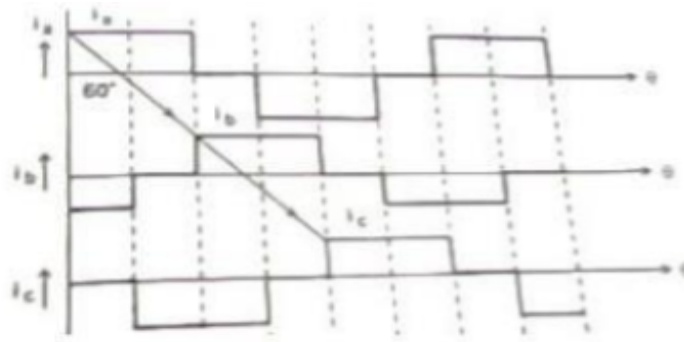


Fig.4.30 phase currents wave forms of BLDC motor with 120° pole arc

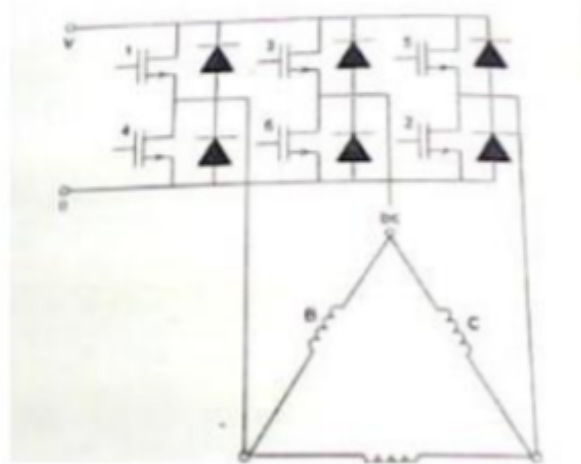


Fig 4.31 converter of brushless dc motor for delta connected phase winding

- C phase belt remains covered by the magnet poles. While the coverage of A phase belt increases thereby decreasing that of B phase belt.
- Since all the conductors are varying same current the increasing torque contribution of phase A is balancing by the decreasing contribution of phase B. Therefore, the total torque remains constant.
- Similarly there is a linear increase in the back emf of A and equal and opposite decrease in the back emf in phase B, Therefore the back emf at the terminals remains constant.
- Line current divides equally between two paths One-phase C Second-phase A & B series.

This balance is not perfect in practice because of the resistance and inductance of the windings. But the current balance should be maintained, otherwise circulating current may produce excessive torque ripple and additional losses.

When compared with 180° pole arc machine.

- For the same ampere-conductors per slot and for the same peak flux density, the 120° pole arc machine has 1.5 times copper losses, but produces the same torque.
- Also the ampere-conductors per slot would have to be reduced because the duty cycle is 1.0 instead of $2/3$.

Merits

- For the same magnet flux density the total flux is only $2/3$ of that of 180° pole arc motor, so that only $2/3$ of the stator yoke thickness is required. If the stator outside diameter is kept the same, the slots can be made deeper so that the loss of ampere conductors can be at least partially covered. consequently the efficiency of the motor may not be very much less than that of 180° pole arc machine.
- In this machine also, the effects of fringing flux, slotting and commutation overlap combine to produce torque ripple.
- Only emf and torque are discussed. The concept of hanging flux-linkage and energy balance can also be used to analyze the operation.

Magnetic Circuit Analysis On Open Circuit

Cross section of a 2 pole brushless dc motor having high energy rare earth magnets on the rotor and the demagnetization curve are as shown in fig

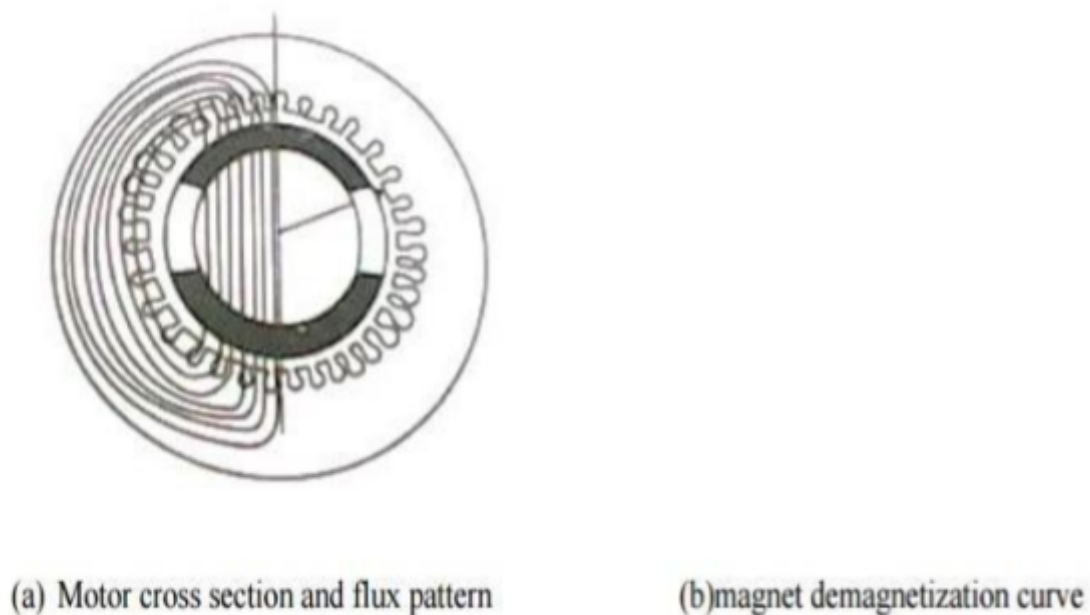


Fig 4.32 magnetic circuit analysis of BLDC motor

First step to analyze a magnetic circuit is to identify the main flux paths and the reluctance or permeances assigned to them.

The equivalent magnetic circuit is shown in fig. only half of the equivalent circuit is shown & the lower half is the mirror image of the upper half about the horizontal axis, which

is at equipotential. This assumption is true only if the two halves are balanced. If not the horizontal axis might still be an equipotential but the fluxes and the magnetic potentials in the two halves would be different and there could be residual flux in the axial direction along the shaft. The axial flux is undesirable because it can induce current to flow in the bearing.

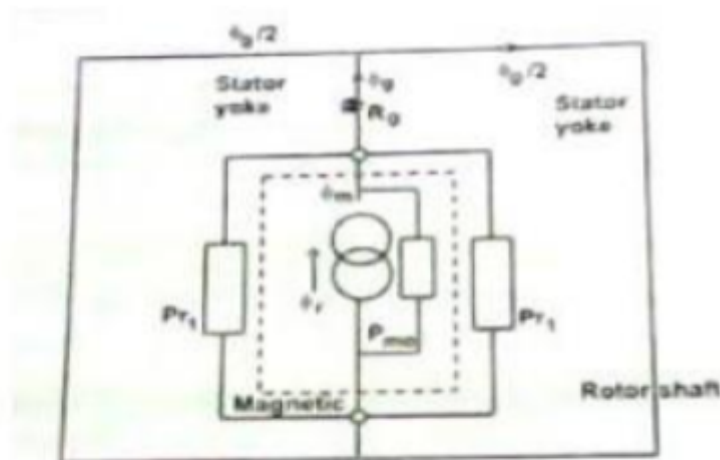


Fig .4.33 magnetic equivalent circuit.

The steel cores of the stator and rotor shaft are assumed to be infinitely permeable.

Each magnet is represented by a 'Norton' equivalent circuit consisting of a flux generator in parallel with an internal leakage permeance p_{mo} .

$$\psi_r = B_r A_m \quad \dots\dots(4.43)$$

$$p_{mo} = \mu_0 \mu_{rec} A_m / l_m \quad \dots\dots(4.44)$$

where A_m – pole area the magnet

l_m – length of the magnet in the direction of magnetization (in this case its radial thickness) B_r - remanent flux density

μ_{rec} - relative recoil permeability (the slope of the demagnetization curve)

In this case the outer pole area is larger than the inner pole area but to keep the analysis simple average pole area is considered.

with a magnet arc of 120°

$$A_m = \frac{2}{3} \pi [r_1 - g - l_m/2] l \quad (4.45)$$

r_1 - radius of the rotor

g - air gap length

Most of the magnet flux crosses the air gap via the air gap reluctance, R_g

$$R_g = g' / \mu_0 A_g \quad (4.46)$$

g' - equivalent air gap length allowing for slotting.

The slotting can be taken into account by means of Carter's coefficient, which case,

$$g' = K_c g \quad (4.47)$$

A_g - air gap area through which the flux passes as it crosses the gap. The precise boundary of this area is uncertain because of fringing both at the edges of the magnet and at the ends of the rotor. An approximate allowance for fringing can be made by adding $\frac{1}{2}g'$ at each of the four boundaries, giving

$$A_g = \left[\frac{2}{3} (r_1 - g/2) + 2g \right] (l + 2g) \quad (4.48)$$

the remaining permeance in the magnetic circuit is the rotor leakage permeance p_{rl} , which represents the paths of the magnet flux components that fail to cross the air gap. This can be conveniently included in a modified magnet internal permeance by writing

$$p_m = p_{mo} + p_{rl} \quad (4.49(a))$$

$$p_m = p_{mo}(1 + p_{rl}) \quad (4.49(b))$$

p_{rl} - normalized rotor leakage permeance

A controller for BLPM SQW DC Motor

1. Power Circuit

Power Circuit of BLPM DC motor is as shown fig consists of six power semiconductor switching device connected in bridge configuration across a DC supply. A suitable shunt resistance is connected in series to get the current feedback. Feedback diodes are connected across the device. The armature winding is assumed to be star connected. Rotor has a rotor position sensor and a tachogenerator is coupled to the shaft to get feedback signal.

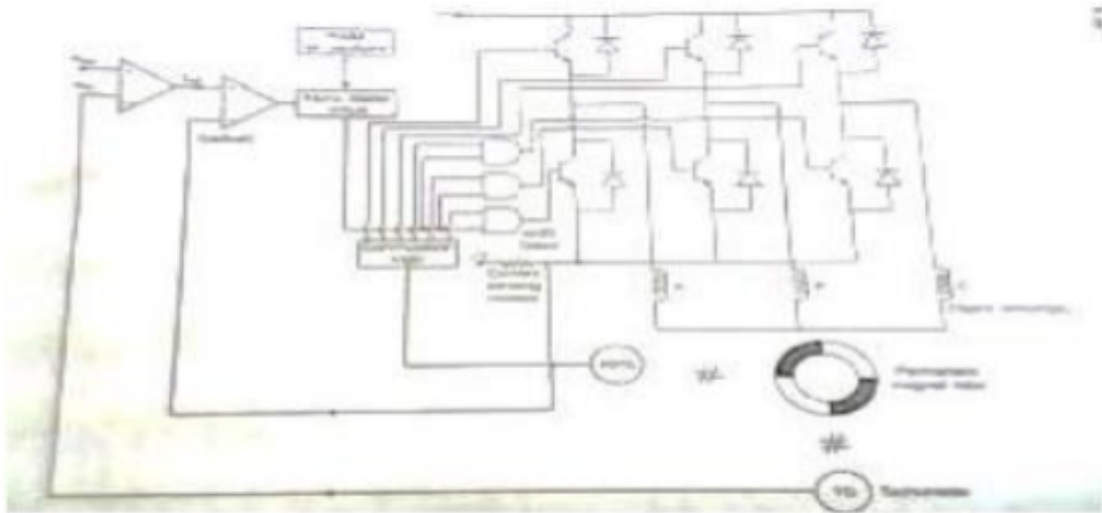


Fig 4.34 structure of controller for brushless PM DC Motor

2. Control circuit

The control circuits consist of a commutation logic unit. Which get the information about the rotor shaft position and decides which switching devices are to be turned on and which devices are to be turned off. This provides six output signals out of which three are used as the base drive for the upper leg devices. The other three output signal are logically AND with the high frequency pulses and the resultant signals are used to drive the lower leg devices.

A comparator compares the tachogenerator output with reference speed and the output signal is considered as the reference current signal for the current comparator which compare the reference current with the actual current and the error signal output is fed to the monostable multivibrator which is excited by high frequency pulses. The duty cycle of the output of monostable is controlled by error signal. This output signal influences the conduction period and duty cycle of lower leg devices.

Rotor Position sensors for BLPM motor

It converts the information of rotor shaft position into suitable electrical signal. This signal is utilized to switch ON and OFF the various semiconductor devices of electric switching and commutation circuitry of BLPM motor.

Two popular rotor sensors are --- (a) Optical Position Sensor.

(b) Hall Effect Position Sensor.

(a) Optical position sensor

This makes use of six photo transistors. This device is turned into ON state when light rays fall on the devices. Otherwise the device is in OFF state the schematic representation is shown in fig.

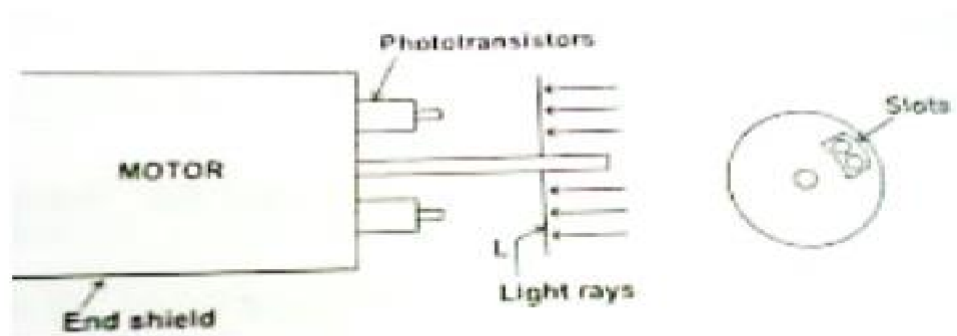


Fig 4.35 Optical position sensor

The phototransistors are fixed at the end shield cover such that they are mutually displaced by 60 degree electrical by a suitable light source. The shaft carries a circular disc which rotates along the shaft. The disc prevents the light ray falling on the devices. Suitable slot are punched in the disc such turned into on state suitably turns the main switching devices of electronic commutation circuitry into on state.

As the shaft rotates, the devices of electronic commutation which are turned into ON are successively changed.

(b) Hall effect position sensor

Consider a small pellet of n-type semiconducting material as shown in fig .

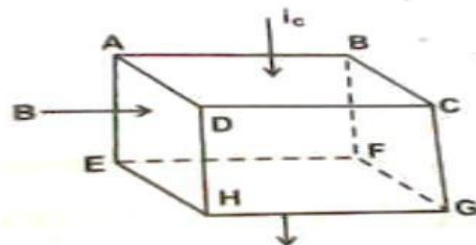


Fig 4.36 Hall Effect

A current I_c is allowed to pass from the surface ABCD to the surface EFGH. Let the surface ABEF be subjected to a North pole magnetic field of flux density B tesla. As per Fleming left hand rule, the positive charge in the pellet get concentrated near surface ADHE and negative

charges near the surface BCFG. Since n-type material has free negative charges, there electrons gets concentrated near the surface BCGF. This charge in distribution makes the surface ADHE more positive than the surface BCGF. This potential known as Hall emf or emf due to Hall Effect.

It has been experimentally shown that emf due to hall effect is V_H is given by

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

Where, i_c - current through the pellet in amps B- Flux density in tesla

d- Thickness of the pellet in m.

R_H – Constant which depends upon the physical dimensions or physical properties of the pellet. If the polarity of B is changed from North Pole to South Pole the polarity of the emf due to Hall Effect also get changed.

3. Hall Effect Position Sensor

Hall effect position sensor can be advantageously used in a BLPM motor. Consider a 2 pole BLPM motor with two winding w_1 and w_2 as shown in fig.

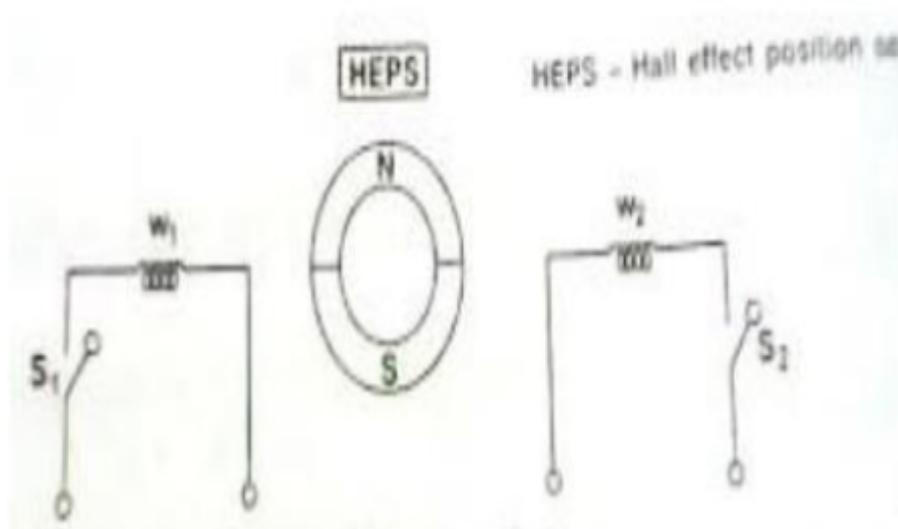


Fig 4.37 2 pole BLPM motor

When w_1 carries a current on closing S_1 it set up a North Pole flux in the air gap. Similarly when S_2 is closed w_2 is energized and sets up a North Pole flux. w_1 and w_2 are located in the stator such that their axes are 180 degree apart. A Hall Effect position sensor is kept in an axis of the winding.

When Hall Effect position sensor is influenced by North Pole flux the hall emf is made to operate the switch S1. Then w1 sets up North Pole flux. The rotor experiences a torque and South Pole of the rotor tends to align with the axis of w1. because of inertia it overshoots the rotor hence rotates in clockwise direction. Now HEPS is under the influence of S pole flux of the rotor. Then the polarity of hall emf gets changed. This makes the switch S1 in off state and S2 is closed. Now w2 sets up N pole flux in the air gap, the rotor rotates in clockwise direction. So that the S pole gets aligned with w2 axis. Then this process continues. The rotor rotates continuously.

Types of BLPM motor:

BLPM motor is classified on the basis of number of phase windings and the number of pulses given to the devices during each cycle.

1. One phase winding one pulse BLPM motor

The stator has one phase winding as shown in fig.

It is connected to the supply through a power semiconductor switch. When the rotor position sensor is influenced by say n pole flux, the stator operates and the rotor develops a torque. When the RPS is under the influence of S pole, the transistor is in off state. The rotor gets torque whenever the rotor position is under the influence of n pole.

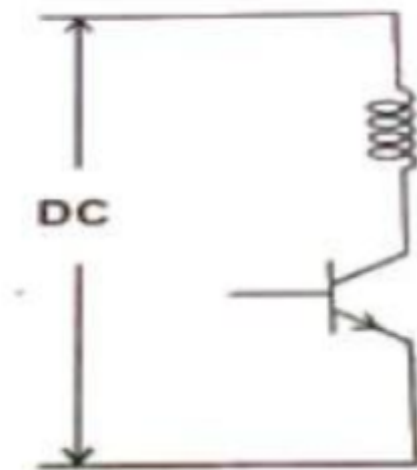


Fig. 4.38 one phase one pulse BLPM motor.

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

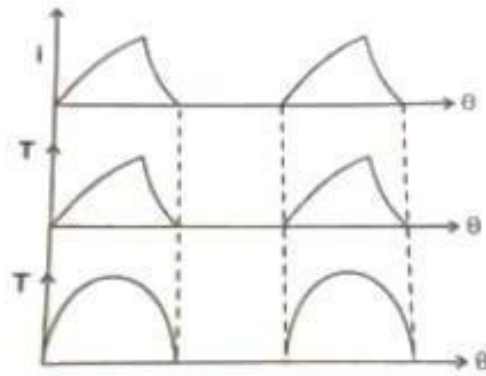


Fig.4.39 Current and torque waveform

Advantages:

- ☐ One transistor and one position sensor is sufficient.
- ☐ Inertia should be such that the rotor rotates continuously.
- ☐ Utilization of transistor and winding are less than 50%.
- ☐

2. One phase two pulse BLPM motor

Stator has only one winding. It is connected to DC three wire supply through two semiconductor devices as shown in fig. .

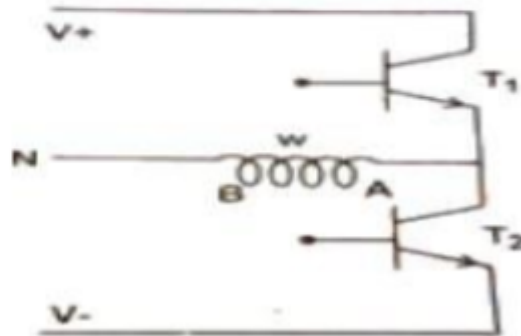


Fig. 4.40 One phase two pulse BLPM motor

There is only one position sensor. When the position sensor is under the N-pole influence, T1 is in on-state and T2 is in off-state. When it is under the influence of S-pole, T2 is on and T1 is off.

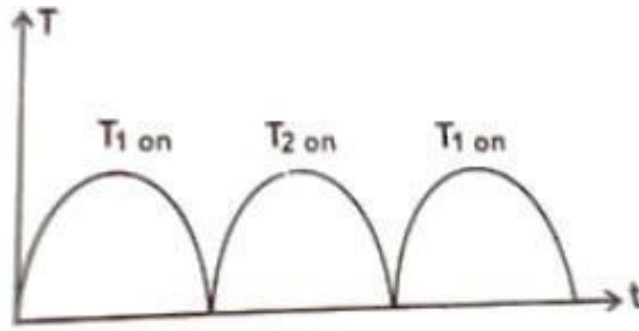


Fig. 4.41 Torque waveform

In the first case, the winding carries current from A to B and when T2 is on, the winding carries current from B to A. The polarity of the flux setup by the winding gets alerted depending upon the position of the rotor. This provides the unidirectional torque as shown in fig. .

Advantages:

- ☐ Winding utilization is better.
- ☐ Torque developed is more uniform.

Disadvantages:

- ☐ Transistor utilization is less
- ☐ The current needs a 3-wire dc supply.

3. Two phase winding and two pulse BLPM motor

Stator has two phase windings which are displaced by 180° electrical. Electrical connections are as shown in fig.. It makes use of two semiconductor switches.

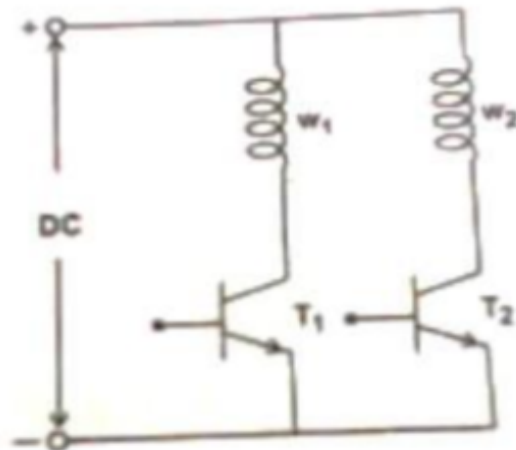


Fig. 4.42 two phase winding and two pulse motor

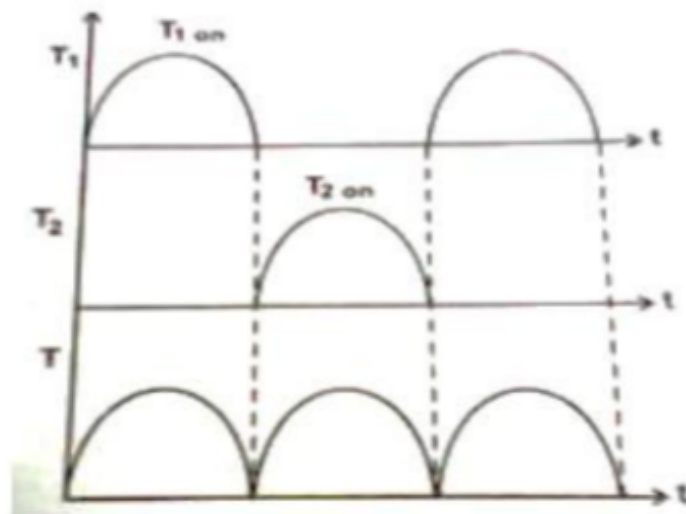


Fig. 4.43 torque waveform

Performance of this type is similar to one phase 2 pulse BLPM motor. Torque waveform are as shown in fig. . However it requires two independent phase windings.

Merit

- Better torque waveform.

Demerit

Their utilization is only 50% which is less.

Cabling with rotor position sensor should be made proper.

4. Three phase winding and three pulse BLPM motor

The stator has 3 Φ windings as shown in fig.. Whose areas are displaced by 120°elec. apart. Each phase windings is controlled by a semiconductor switch which is operated depending upon the position of the rotor. Three position sensors are required for this purpose.

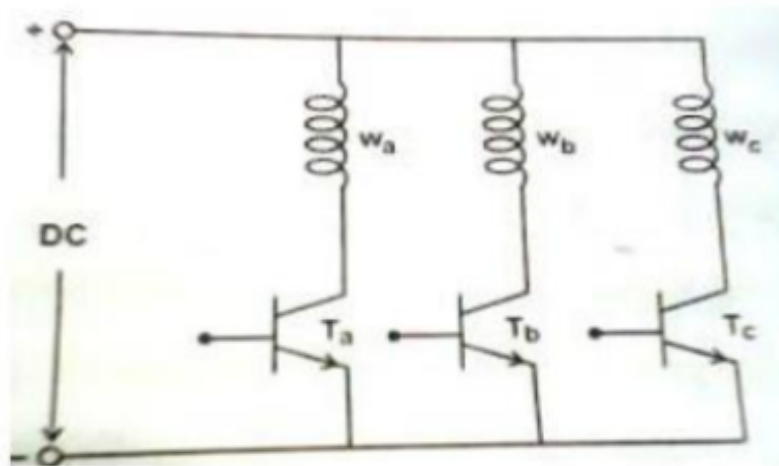
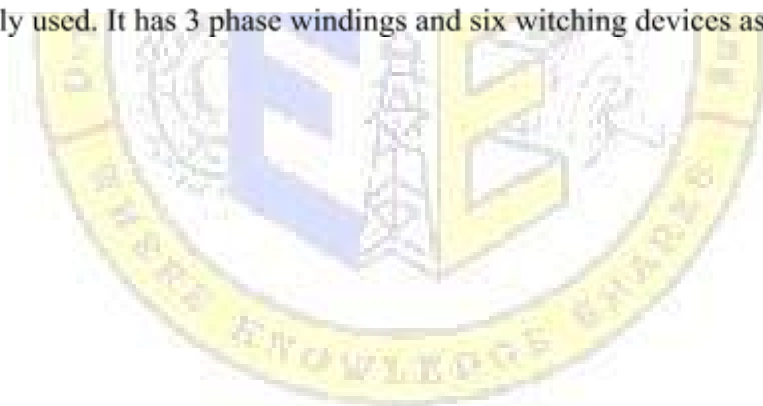


Fig. 4.44 3 phase, 3 pulse BLPM motor.

5. Three phase six pulse BLPM motor

Most commonly used. It has 3 phase windings and six switching devices as shown in fig. .



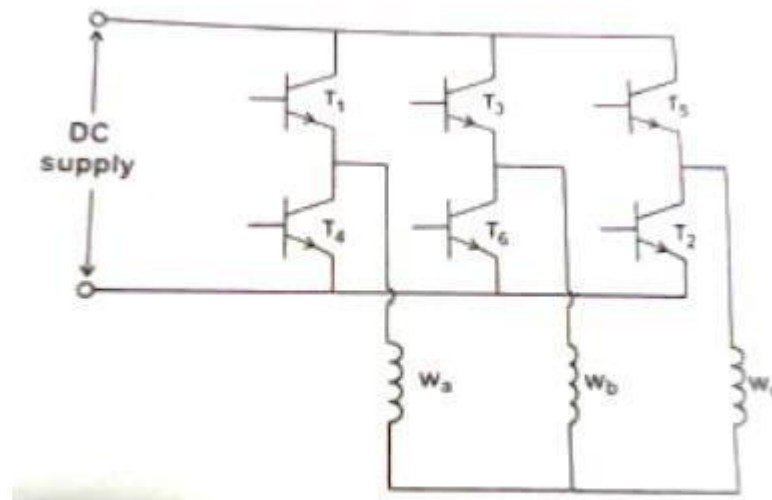


Fig. 4.45 3-phase six pulse BLPM motor.

Short Questions and Answers:

1. what are the advantages of brushless dc motors drives?

- ✓ Regenerative braking is possible
- ✓ Speed can be easily controllable

2. what are the disadvantages of brushless dc motors drives?

- ✓ It requires a rotor position sensor
- ✓ It requires a power semiconductor switching circuits.

3. Define mechanical commutators?

Its arrangement is located in the rotor
No of commutators segments are very high .

4. Define electronic commutators?

- ✓ Its arrangement is located in the stator
- ✓ No of switching devices limited to six

5. Mention some applications of PMBL DC motor?

- ✓ Power alternators
- ✓ Automotive applications
- ✓ Computer and Robotics applications
- ✓ Textile and Glass industries

6. What are conventional Dc motor?

- ✓ Field magnets on the stator

- ✓ Maintenance is high

7.What are PMBL DC motor?

- ✓ Field magnets on the rotor
- ✓ Low maintenance

8.Why is the PMBLDC motor called electronically commutated motor?

The PMBL DC motor is also called electronically commutated motor because the phase windings of PLMBL DC motor is energized by using power semiconductor switching circuits.here the power semiconductor switching circuits act as a commutator.

9.What are the classification of BLPM DC motor?

- ✓ BLPM square wave motor
- ✓ BLPM sine wave motor

10.What are the two types of BLPM SQW DC motor?

- ✓ 180° pole arc BLPM SQW motor
- ✓ 120° pole arc BLPM SQW motor

11. What are the two types of rotor position sensors?

- ✓ Optical position sensor
- ✓ Hall effect position sensor

12.What are the materials used for making Hall IC pallet?

- ✓ Indium-antimony
- ✓ Gallium-arsenide

13.What are applications of stator?

- ✓ Automotive applications
- ✓ Venticular electric drive motors

14.What are the classification of BLPM dc motor?

- ✓ One phase winding and one pulse BLPM dc motor
- ✓ One phase winding and two pulse BLPM dc motor
- ✓ Two phase winding and two pulse BLPM dc motor
- ✓ Three phase winding and three pulse BLPM dc motor
- ✓ Three phase windings and six pulse circuits

15.What are the features of one phase winding and one pulse BLPM dc motor?

- ✓ Its inertia should be high,such that rotor rotates continuously
- ✓ Utilization of transistor and windings are less

16. What are the features of one phase winding and two pulse BLPM dc motor?

- ✓ In this case winding utilization is better, however transistor utilization is less.
- ✓ Torque developed is more uniform

17. What are the features of two phase winding and two pulse BLPM dc motor?

- ✓ Winding utilization is only 50% which is less
- ✓ It provides better torque waveforms

18. What are the features of three phase windings and 6 pulse circuits?

- ✓ Utilization factor of winding will be better
- ✓ Torque pulse and ripple frequency components are less

21. What is meant by self control?

Self control ensures that for all operating points the armature and rotor fields move exactly at the same speed.

22. What is meant by vector control?

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

PART – B

1. Sketch the structure of controller for PMBLDC motor and explain the functions of various blocks. (16)
2. Explain the closed loop control scheme of a permanent magnet brushless dc motor drive with a suitable schematic diagram. (16)
3. Derive the expressions for the emf and torque of a PMBLDC motor. (16)
4. Draw the diagram of electronic Commutator. Explain the operation of electronic Commutator. (16)
5. Discuss the use of Hall sensors for position sensing in PMBLDC motor. (16)
6. Sketch the torque-speed characteristics of a PMBLDC motor. (16)



SINE WAVE PERMANENT MAGNET BRUSHLESS MOTOR

The characteristic features of the brushless d.c. motors considered in Chapter 4 were:

- (1) rectangular distribution of magnet flux in the airgap;
- (2) rectangular current waveforms;
- (3) concentrated stator windings.

The sinewave motor differs in all three respects. It has:

- (1) sinusoidal or quasi-sinusoidal distribution of magnet flux in the airgap;
- (2) sinusoidal or quasi-sinusoidal current waveforms;
- (3) quasi-sinusoidal distribution of stator conductors; i.e. short-pitched and distributed or concentric stator windings.

The quasi-sinusoidal distribution of magnet flux around the airgap is achieved by tapering the magnet thickness at the pole edges and by using a shorter magnet pole arc, typically 120° . The quasi-sinusoidal current waveforms are achieved through the use of p.w.m. inverters which may be 'current regulated' to produce the best possible approximation to a pure sinewave. The use of short-pitched, distributed or concentric windings is exactly the same as in a.c. motors.

Indeed the sinewave motor is a simple synchronous motor. It has a rotating stator m.m.f. wave and can therefore be analysed with a phasor diagram; this is especially useful in designing the control system and calculating the performance.

Section 5.1 describes the ideal sinewave motor, that is, one with flux and winding distributions that are perfectly sinusoidal. We determine expressions for the torque, the open-circuit phase e.m.f. due to the magnet, the actual winding inductance, and the synchronous reactance. These expressions are derived in terms of the number of sine-distributed turns per pole.

In Section 5.2 these results are modified for practical windings by means of the standard winding factors of a.c. machines. These results provide the basis for the phasor diagram, which is developed in Section 5.3. In Section 5.4 the phasor diagram is used to develop the circle diagram and study its variation with speed; from this the torque/speed characteristic is derived. It is shown that the surface-magnet sinewave motor has limited capability to operate along a constant-power locus at high speed.

Section 5.5 presents a theoretical comparison of the torque per ampere and kVA requirements of squarewave and sinewave motors. Section 5.6 provides a comparison of wound-field and PM motors in such a way as to justify the

preference for PM motors in smaller sizes. In Section 5.7 there is a treatment of the slotless motor, in which interest has revived as a result of the development of extremely high-energy magnet materials. Finally in Section 5.8 the subject of torque ripple is reviewed.

5.1 Ideal sinewave motor: torque, e.m.f., and reactance

5.1.1 Torque

The torque production can be analysed in terms of the interaction of the magnet flux and the stator ampere-conductor distribution, as in the squarewave motor. Figure 5.1 shows the basic concept for a machine with two poles. The stator conductors are distributed as a sine-distributed conductor-density around the stator bore, such that in any angle $d\theta$ the number of conductors is

$$\frac{N_s}{2} \sin p\theta d\theta.$$

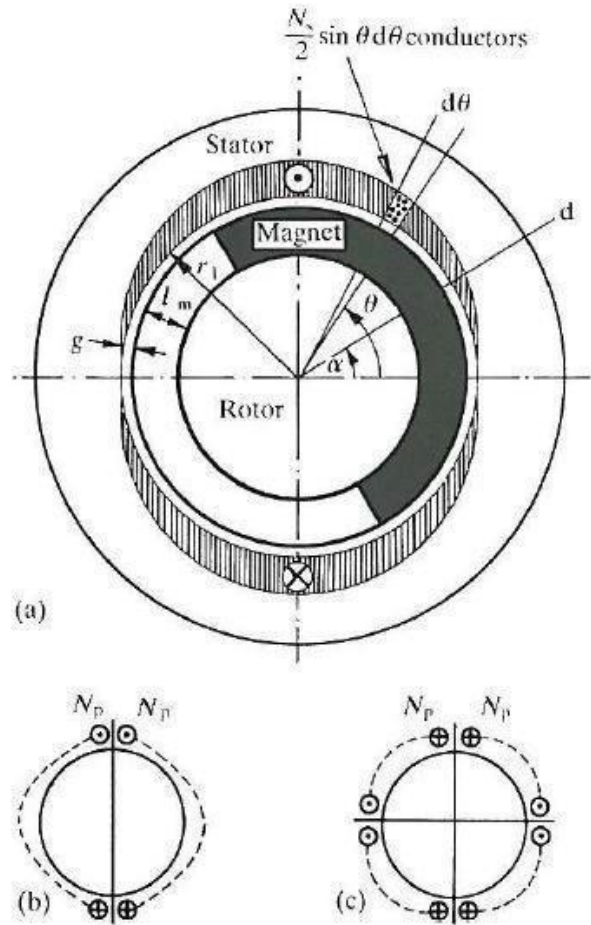


FIG. 5.1. (a) Ideal sinewave brushless motor with pure sine-distributed phase winding and permanent-magnet rotor with sine-distributed flux. (b) Turns/pole for two-pole winding. (c) Turns/pole for four-pole winding.

north d-axis 'lagging' 90 electrical degrees behind the axis of the stator ampere-conductor distribution.

This analysis has been carried out for a stationary stator winding. To produce a constant torque with the rotor rotating at a steady speed, the stator ampere-conductor distribution must be made to rotate in synchronism with the rotor. This is done exactly as in induction motors, by means of a polyphase winding supplied with polyphase balanced currents. The most common number of phases is three, but two-phase motors are sometimes built, and occasionally four, six, and nine-phase motors. With p pole-pairs, if $N_p = N_s/2p$ is the number of sine-distributed turns per pole, the total number of turns per phase is N_s . If the phase current flows through all these in series, then with balanced sinewave currents and three phase windings whose axes are 120 electrical degrees apart, the rotating ampere-conductor distribution can be derived as

$$\begin{aligned} i \cos \omega t \frac{N_s}{2} \sin p\theta + i \cos\left(\omega t - \frac{2\pi}{3}\right) \frac{N_s}{2} \sin\left(p\theta - \frac{2\pi}{3}\right) \\ + i \cos\left(\omega t + \frac{2\pi}{3}\right) \frac{N_s}{2} \sin\left(p\theta + \frac{2\pi}{3}\right) = \frac{3}{2} I \sqrt{2} \frac{N_s}{2} \sin(p\theta - \omega t), \end{aligned}$$

and the rotating magnet flux distribution is

$$B(\theta) = \hat{B} \cos(p\theta - \omega t - \alpha).$$

The torque is obtained using the same expression as for the stationary winding, with $p\theta - \omega t$ substituted for $p\theta$, thus;

$$T = \frac{3}{2} I \sqrt{2} \frac{\pi r_1 l \hat{B} N_s}{2} \sin \beta$$

where $\beta = -\alpha$. The angle β is called the torque angle, and is positive for motoring; it is measured in electrical radians or degrees. If the phase winding is divided into ' a ' parallel paths, then the equation remains valid provided that I is the total phase current and there is no change in the total number of turns per phase, i.e. N_s . (The number of turns in series per phase is then N_s/a .)

It is worth emphasizing that the flux-density $\hat{B}$ in the torque equation is the peak airgap flux-density produced by the magnet acting alone; in other words, it is the open-circuit value and does not include any contribution due to the m.m.f. of the stator currents. Although the armature-reaction m.m.f. modifies the airgap flux-density, it does not figure in the torque expression unless it significantly affects the saturation level of the magnetic circuit. Physically the stator may be regarded as being incapable of producing torque on itself. The armature reaction flux is aligned with the stator ampere-conductor distribution and therefore has an effective 'torque angle' of zero. The armature-reaction flux does, however, rotate and induce a voltage drop in the phase windings, which must be overcome by the supply voltage. (See Section 5.2).

In normal operation the stator frequency (in rad/sec) is made equal to the rotation frequency (in electrical rad/sec), i.e.,

$$\omega = 2\pi f \text{ electrical rad/sec}$$

and the mechanical angular velocity is

$$\omega_m = \frac{\omega}{p}.$$

The stator ampere-conductor distribution rotates in synchronism with the rotor and the torque angle is kept constant, usually by means of a simple form of 'vector' control or 'field-oriented control' which requires a shaft position sensor (i.e. encoder or resolver feedback). If the supply frequency and the rotation frequency were unequal, the motor would be running asynchronously. No average torque would be produced, but there would be a large alternating torque at the 'beat' frequency or pole-slipping frequency.

5.1.2 *E.m.f.*

The e.m.f. equation of the sinewave motor can be derived by considering the e.m.f. induced in the elementary group of conductors in Fig. 5.1. Noting that Fig. 5.1 is drawn for a two-pole machine ($p=1$), for a machine with p pole-pairs in series this e.m.f. is

$$de = B(\theta) l \omega_m r_1 \frac{N_s}{2} \sin p\theta \, d\theta.$$

But

$$B(\theta) = \hat{B} \cos(p\theta - \omega t - \alpha)$$

and by integrating the contributions of all the elementary groups of conductors we get the instantaneous phase e.m.f.:

$$e = 2p \int_0^{\pi/p} de = \frac{\hat{B} l \omega r_1 N_s \pi}{2p} \sin(\omega t + \alpha).$$

The r.m.s. phase e.m.f. is therefore

$$E_{ph} = \frac{\pi}{2\sqrt{2}} \frac{\hat{B} l \omega r_1 N_s}{p} V_{r.m.s.}$$

and the line-line e.m.f. is $E\sqrt{3}$. In Section 5.2 this equation is used to derive the fundamental e.m.f. for a practical winding in slots, and practical expressions for N_s are derived.

It is worth emphasizing again that the flux-density $\hat{B}$ is the peak airgap flux-density produced by the magnet acting alone; in other words, it is the open-circuit value and does not include any contribution due to the m.m.f. of the

stator currents. The voltage drop induced by flux attributable to armature reaction is dealt with below.

The e.m.f. equation can also be derived from Faraday's law. This alternative method is included here because it is the basis of the phasor diagram and provides the means for calculating the inductive volt drop due to armature reaction. Faraday's law is more rigorous than the BLV formulation, but it is useful to show that for E both methods give the same result.

By Faraday's law, the instantaneous e.m.f. induced in the stationary phase winding of Fig. 5.1 is given by

$$e = -\frac{d\psi}{dt} \text{ V}$$

where ψ is the instantaneous flux-linkage. To calculate the flux-linkage consider the coil formed by the elementary group of conductors within the angle $d\theta$ at angle θ , and assume that the return conductors of this coil are located within the angle $d\theta$ at angle $-\theta$. Although Fig. 5.1 is drawn for a two-pole machine ($p=1$), the results are derived for p pole-pairs.

On open-circuit there is no current in the coil, and all the flux is due to the magnet. The flux through the elementary coil is

$$\phi = \int_{-\theta}^{\theta} B(\theta)r_1 l \, d\theta \text{ Wb.}$$

But

$$B(\theta) = \hat{B} \cos(p\theta - \omega t - \alpha)$$

so the integral gives

$$\phi = \frac{\hat{B}Dl}{p} \sin p\theta \cos(\omega t + \alpha) \text{ Wb}$$

where $D=2r_1$ is the stator bore. The flux per pole can be extracted from this expression by setting $\theta = \pi/p$ and $t=0$. Thus

$$\Phi_M = \frac{\hat{B}Dl}{p} \text{ Wb.}$$

This is a fixed flux that rotates with the rotor. The flux-linkage of the elementary coil is

$$d\psi = \phi \left[\frac{N_s}{2} \sin p\theta \, d\theta \right] \text{ V s.}$$

The total flux-linkage of the winding is obtained by integrating the contributions of all the elementary coils: with p pole-pairs the result is

$$\psi_M = p \int_0^{\pi/p} d\psi = \hat{\psi}_M \cos(\omega t + \alpha) \text{ V s}$$

where

$$\hat{\psi}_M = \frac{\hat{B} l r_1 N_s \pi}{2p} = \frac{\pi}{4} N_s \Phi_M \text{ V s.}$$

The subscript 'M' has been added as a reminder that the flux is produced only by the magnet. By Faraday's law the instantaneous phase e.m.f. is

$$e = -\frac{d\psi_M}{dt} = \omega \hat{\psi}_M \sin(\omega t + \alpha) \text{ V.}$$

The r.m.s. phase e.m.f. is

$$E_{ph} = \frac{\omega \hat{\psi}_M}{\sqrt{2}} = \frac{\pi}{2\sqrt{2}} \frac{\hat{B} l \omega r_1 N_s}{p} \text{ V}_{\text{r.m.s.}}$$

as before.

5.1.3 Inductance of phase winding

Figure 5.2 shows the same single-phase, two-pole sine-distributed winding as in Fig. 5.1. But the flux is now produced by the current in the stator winding, and we assume that the magnet is unmagnetized while we calculate the inductance by determining the flux-linkage of the winding due to its own current, i . If the steel in the rotor and stator is assumed to be infinitely permeable, then the m.m.f. is concentrated entirely across the two airgaps. Across each airgap the m.m.f. drop is equal to one-half the ampere-conductors enclosed within an 'Ampere's law contour' or flux-line:

$$\begin{aligned} F_g = H_g g'' &= \frac{1}{2} \int_{\theta}^{\pi/p - \theta} i \frac{N_s}{2} \sin p\theta \, d\theta \\ &= \frac{N_s i}{2p} \cos p\theta. \end{aligned}$$

The flux-density across the gap and the magnet is assumed to be radial, and the magnet is assumed to be equivalent to an airgap of length l_m/μ_{rec} , as before: this gives an 'effective airgap'

$$g'' = g' + \frac{l_m}{\mu_{\text{rec}}}.$$

Hence

$$B(\theta) = \mu_0 H_g = \frac{\mu_0 N_s i}{2p g''} \cos p\theta = \hat{B}_a \cos p\theta.$$

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

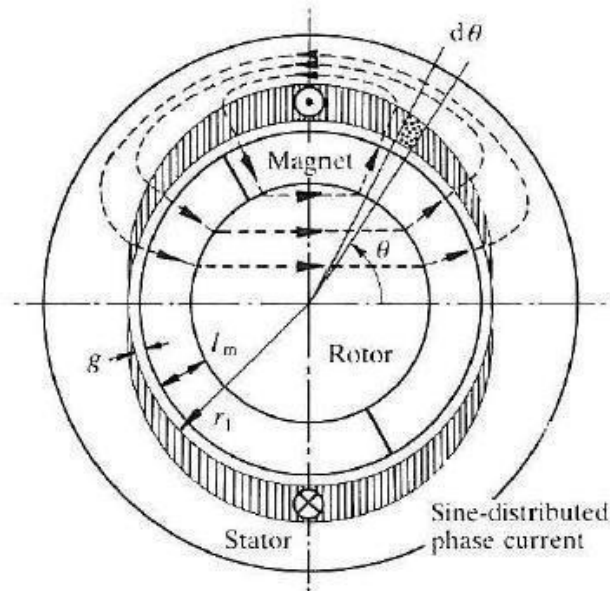


FIG. 5.2. Calculation of armature reaction m.m.f. of sinewave winding.

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

$$\Phi_a = \frac{\hat{B}_a D l}{p} \text{ Wb}$$

where, again, $D = 2r_1$ is the stator bore. This expression has exactly the same form as the flux per pole of the magnet and therefore it produces a flux-linkage

$$\psi_a = \frac{\pi}{4} N_s \Phi_a.$$

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

$$L_g = \frac{\pi \mu_0 N_s^2 l r_1}{4 p^2 g''} \text{ H.}$$

The inductance is only half the value which would be obtained with the same number of turns concentrated into one pair of slots spanning 180 electrical degrees (Section 4.7).

The inductance calculated above is the actual 'airgap' inductance, i.e. the value which would be measured with the rotor stationary and unmagnetized; with the other phases open-circuited; and with negligible leakage inductance from the slots or the end-turns. The actual inductances of three simple full-pitch windings with one, two, and three slots per pole per phase were calculated in Section 4.7 on the same basis. The sine-distributed winding is a hypothetical case with an infinite number of slots per pole per phase, the

number of conductors per slot being modulated sinusoidally to produce a sine-distributed airgap m.m.f.

5.1.4 Synchronous reactance

Earlier we showed that three sine-distributed phase windings carrying balanced three-phase sinusoidal currents produce a sine-distributed ampere-conductor distribution represented by the expression

$$\frac{3}{2} I \sqrt{2} \frac{N_s}{2} \sin(p\theta - \omega t).$$

This sets up a rotating flux wave

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

where

$$\hat{B}_a = \frac{\mu_0}{g''} \frac{3}{2} I \sqrt{2} \frac{N_s}{2p}.$$

This rotating flux wave, established by armature reaction, generates voltages in all three phases. In each phase the voltage is proportional to I and is therefore regarded as the voltage drop $X_s I$ across a fictitious reactance, the 'synchronous reactance', X_s . By substituting the peak flux-density into the expression derived earlier for e.m.f., and dividing by I , we get

$$X_s = \frac{3\pi\mu_0 N_s^2 l r_1 \omega}{8p^2 g''} \text{ Ohms.}$$

This expression applies to an ideal two-pole sine-distributed three-phase winding with N_s turns in series per phase, and it neglects the leakage inductance of the slots and end-turns. To obtain a practical formula for a real winding, we must first find an effective value for the sine-distributed turns. This is done by means of Fourier analysis and winding factors in the next section.

5.2 Sinewave motor with practical windings

The expressions developed for torque, e.m.f., inductance, and reactance in Section 5.1 can be modified for practical windings by means of Fourier analysis and harmonic winding factors. It is normally assumed for a.c. machines that the operation is dominated by the fundamental space-harmonic components of the conductor and flux distributions. Machines are designed to operate in this way to minimize the torque ripple and parasitic losses that would be caused by nonsynchronous rotating field components. When the

harmonic effects are neglected in favour of the fundamentals, the effective number of sine-distributed turns is easy to derive, and can be substituted in the equations of Section 5.1.

Consider first the concentrated two-pole full-pitched coil in Fig. 5.3, with one slot per pole per phase and N conductors in each slot. This winding is regarded as having $N/2$ turns per pole, which may seem a little artificial; however, this makes the treatment of the two-pole machine consistent with that of windings with more than two poles, where the coils can usually be identified clearly with the poles (see Fig. 5.1(b)). The rectangular m.m.f. wave has a fundamental harmonic component equal to $4/\pi$ times the peak flat-topped value. The effective number of sine-distributed turns per pole is therefore

$$N_s = \frac{4}{\pi} N.$$

If there are p pole-pairs in series, the actual number of series turns per phase is

$$N_{ph} = 2pN.$$

The effective number of sine-distributed turns in series per phase is $2p$ times the number of sine-distributed turns per pole, i.e. N_s . Therefore

$$N_s = \frac{\pi}{4} N_{ph}.$$

The corresponding result for any winding distributed in slots can be built up by considering the winding as an aggregate of coils, each of which occupies one

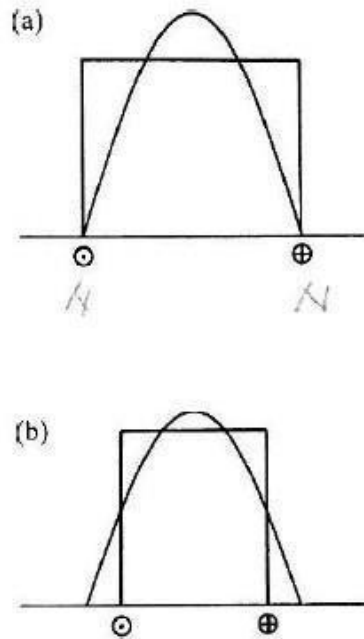


FIG. 5.3. Distribution and fundamental harmonic component of single full-pitched coil.

slot pair. For a distributed full-pitch winding with q slots per pole per phase, such as those in Section 4.7, the effective sine-distributed turns are given by

$$N_s = \frac{4}{\pi} k_{d1} N_{ph}$$

where k_{d1} is the 'distribution' or 'spread' factor for the fundamental, and is given by

$$k_{d1} = \frac{\sin \frac{q\gamma}{2}}{q \sin \frac{\gamma}{2}}.$$

Here γ is the slot-pitch in electrical degrees and q is the number of slots per pole per phase. With three phases,

$$\gamma = \frac{\pi}{3q}.$$

For example, in a four-pole three-phase machine with 2 slots per pole per phase there are 24 slots and the fundamental distribution factor is 0.966. With 3 slots per pole per phase, there are 36 slots and the fundamental distribution factor is 0.960. The distribution factor reduces the actual number of turns per phase to the number of turns per phase required in a concentrated coil that will produce the same fundamental component of airgap m.m.f. with the same current flowing.

Many windings are not only distributed into more than one slot per pole per phase, but are also 'chorded' or short-pitched. For a single chorded coil the fundamental component of airgap m.m.f. is equal to that produced by a full-pitched coil with k_{p1} times the number of turns, where k_{p1} is the fundamental 'pitch factor' or 'chording factor':

$$k_{p1} = \cos \frac{\varepsilon}{2}.$$

For example, in a winding with six slots per pole, a winding with coils spanning five slots would have 5/6 pitch and

$$\varepsilon = \frac{\pi}{6}$$

giving

$$k_{p1} = 0.966.$$

In the case of skewed windings there is a skew factor that is treated in the same way as the distribution and pitch factors; this is given by

$$k_{s1} = \frac{\sin \sigma}{\sigma}$$

where σ is the half the skew angle in mechanical radians or degrees, (Levi 1984).

When a winding has coils that are distributed, chorded, and skewed, the overall result is a 'fundamental winding factor'

$$k_{w1} = k_{d1} k_{p1} k_{s1}$$

and the number of effective sine-distributed turns per phase is given by

$$N_s = \frac{4}{\pi} k_{w1} N_{ph}$$

where N_{ph} is the actual number of turns in series per phase.

Substitution of this result in the equations of Section 5.1 produces the following formulas for the torque, e.m.f., and synchronous reactance.

The open-circuit phase e.m.f. is

$$E_{ph} = \frac{2\pi}{\sqrt{2}} (k_{w1} N_{ph}) \Phi_{M1} f V_{r.m.s.} \quad \frac{\omega_e}{\frac{60}{\pi}}$$

The subscript '1' has been added to the magnet flux per pole to denote its fundamental space-harmonic component. If, as is usually the case, the magnet flux distribution is not perfectly sinusoidal, the fundamental component should be used. The winding has the effect of filtering out the harmonics in the flux distribution. The degree of suppression of individual harmonics is determined by the harmonic winding factors.

The e.m.f. can be written in an alternative useful form by recognizing that the peak phase flux-linkage due to the magnet is

$$\hat{\psi}_{M1} = k_{w1} N_{ph} \Phi_{M1}$$

With this, the e.m.f. can be written

$$E_{ph} = \frac{1}{\sqrt{2}} \omega \hat{\psi}_{M1} = E_q$$

The subscript 'q' means that the e.m.f. phasor is aligned with the q-axis in the phasor diagram (see Section 5.3), since it leads the flux-linkage by 90 electrical degrees.

From Section 5.1 the torque is given by

$$\begin{aligned} T &= \frac{3}{2} I \sqrt{2} \frac{\pi r_1 \hat{B}_{M1} l N_s}{2} \sin \beta \\ &= \frac{3\pi p}{8} I \sqrt{2} \Phi_{M1} N_s \sin \beta. \end{aligned}$$



Replacing N_s by $(4/\pi)k_{w1}N_{ph}$ and using the above expressions for flux-linkage and E_{ph} , the result is

$$T = \frac{3p}{\omega} E_q I \sin \beta \text{ N m.}$$

Turning now to the actual phase inductance, it is meaningless to substitute the effective sine-distributed turns. The actual inductance must include all the self flux-linkage, not just the fundamental component. The inductance formula for a practical winding therefore remains the same as in Section 4.7, including the leakage inductance.

The synchronous inductance or reactance is quite different from the actual inductance, being associated with the voltage drop in one phase caused by the fundamental component of rotating armature-reaction flux, under balanced conditions with all three phases in operation. Substituting for the effective sine-distributed turns per phase, we get

$$X_{sg} = \frac{6\mu_0 D l f}{p^2 g''} (k_{w1} N_{ph})^2 \text{ Ohms.}$$

To this value must be added the per-phase leakage reactance, giving the total synchronous reactance

$$X_s = X_{sg} + X_\sigma.$$

5.3 Phasor diagram

If the magnets are on the rotor surface, and if the shaft cross-section is circular, the sinewave motor is a 'non-salient pole' synchronous machine: that is, its d-axis and q-axis synchronous reactances are equal. The calculation of the synchronous reactance was discussed in Section 5.2. In the steady state with balanced, sinusoidal phase currents the operation can be represented by the phasor diagram shown in Fig. 5.4.

The construction of the phasor diagram can be understood by considering in turn how each phasor in it is derived. This analysis provides the basis for understanding the performance characteristics, and what happens at different speeds and torques. It is also the basis for the design of effective controls.

The squarewave motor (Chapter 4) is not amenable to phasor analysis because the stator ampere-conductor distribution does not rotate: it is not a rotating-field machine in the a.c. sense.

In Section 5.2 it is shown that the open-circuit phase e.m.f. E , is a sinewave which lags behind the magnet flux by 90 electrical degrees. Its r.m.s. value is

$$E_{ph} = \frac{2\pi}{\sqrt{2}} k_{w1} N_{ph} \Phi_{M1} f \text{ V}_{r.m.s.}$$

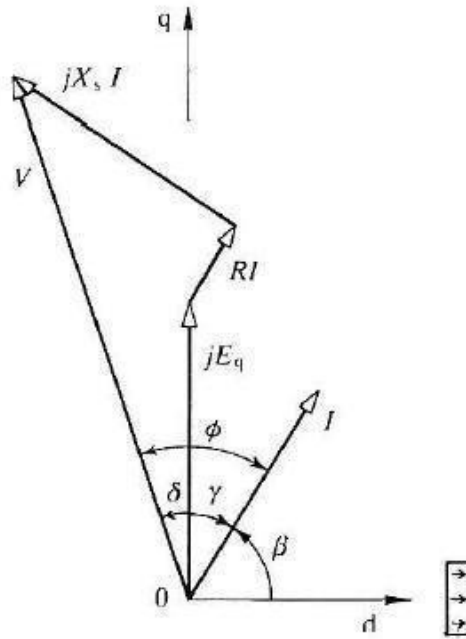


FIG. 5.4. Phasor diagram of surface-magnet sinewave motor.

The phasor relationship between E_{ph} and the fundamental flux-linkage due to the magnet can be written as follows:

$$\tilde{E}_{ph} = jE_q = j\omega\tilde{\psi}_{Md1} \text{ V.}$$

The subscript 'd' in the magnet flux-linkage denotes that this phasor is synchronized with the direct axis of the rotor. The subscript '1' indicates the fundamental space-harmonic component, whose phasor rotates on paper in synchronism with the rotor in physical space. The subscript 'q' in E_q denotes that it is synchronized with the q-axis. In all phasor diagrams the d-axis is taken to define the real axis of the complex plane of the phasor diagram, as in Fig 5.4. In physical space the rotor flux axis is the direct axis, i.e., the centre of the magnet pole arc. The rotation is 'cancelled out' by choosing this as a reference axis, so that an 'observer' rotates with this frame of reference at synchronous speed, and perceives a magnetic field that is stationary with respect to the rotor. It can be shown by mathematical transformation (Park's transformation) that this choice of reference frame is equivalent to cancelling out the $e^{j\omega t}$ from the voltages and currents, leaving a phasor diagram that is stationary on paper. Note that as the rotor flux rotates in space, the flux-linkage of a stationary phase winding pulsates in time.

The angle α defines the position of the physical rotor d-axis at $t=0$, measured from the positive axis of the phase 'a' winding.

Next we determine the current phasor. To preserve the relationship between phasors and rotating fields, we need the rotating ampere-conductor distribution of all three phases taken together. Assuming balanced currents,

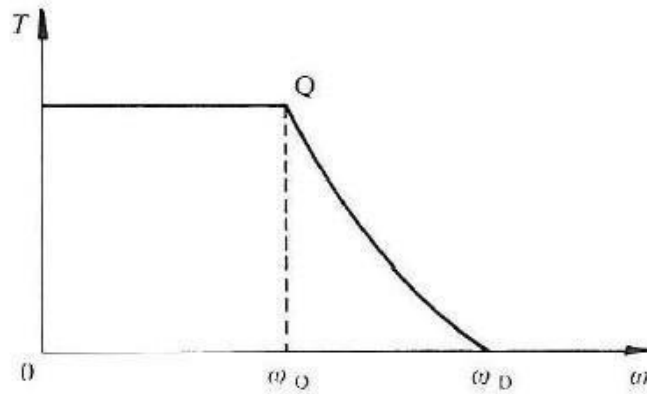


FIG. 5.8. Torque/speed characteristic of sinewave motor.

The ratio between the speeds at points D and Q is

$$k = \frac{\omega_D}{\omega_Q} = \frac{f_D}{f_Q}.$$

If we continue to neglect resistance, at Q we have

$$I_d = 0; I_q = I_c; V_q = E_0; \text{ and } V_d = -X_{s0}I_c.$$

The subscript 0 in the synchronous reactance denotes the value at the corner-point frequency. From the phasor diagram

$$\tilde{I} = jI_q = jI_c \text{ and } V_c^2 = E_0^2 + X_{s0}^2 I_c^2$$

so that

$$I_c = \sqrt{\frac{V_c^2 - E_0^2}{X_{s0}^2}}.$$

At point D,

$$\tilde{I} = I_d = -I_c = \frac{V_c - kE_0}{kX_{s0}}.$$

Equating the expressions for I_c at the two speeds, we get the following expression for k :

$$k = \frac{V_c}{E_0 - \sqrt{V_c^2 - E_0^2}}.$$

Now define e_0 as the per-unit open-circuit voltage at the corner-point, with the maximum r.m.s. a.c. voltage of the converter as the base voltage:

$$e_0 = \frac{E_0}{V_c}.$$

Then

$$k = \frac{1}{e_0 - \sqrt{1 - e_0^2}}.$$

For example, suppose the motor is required to operate at maximum torque up to 3000 r.p.m., and be capable of just reaching 6000 r.p.m. with no load. Then $k=2$, and to achieve this e_0 must be 0.911.

At the corner point the d-axis current is zero and, from the phasor diagram at this point, the power factor is given by

$$\cos \phi_0 = \frac{E_0}{V_c} = e_0.$$

Also,

$$\sin \phi_0 = \frac{X_q I_q}{V} = \frac{X_s I_c}{V_c} = x_{s0}.$$

Here x_{s0} is the per-unit synchronous reactance at the corner-point frequency, that is, the synchronous reactance normalized to a base of V_c/I_c . In the example quoted above with $k=2$, the corner-point power factor is 0.911 and the per-unit synchronous reactance is $x_{s0}=0.411$. This is a large value for a surface-magnet motor: typically x_{s0} is in the range 0.1–0.2, giving a higher corner-point power factor but a value of k closer to 1.0. (Methods for calculating the reactance are discussed in section 5.1.4) The surface-magnet motor has very limited capability to operate above its corner-point speed, and certainly cannot maintain a constant-power characteristic as the speed is increased. The fundamental physical reason for this is that the airgap flux is fixed predominantly by the magnet and direct field-weakening is not possible to any useful degree. In this discussion the resistance has been neglected, but in practice it introduces further phase shifts which make the speed-torque envelope even more restricted than that presented. An analysis that includes resistance is given by Leonhard (1985).

If the speed is increased beyond point D, there is a risk of overcurrent

because the back-e.m.f. E_q continues to increase while the terminal voltage remains constant. The current is then almost a pure reactive current (with nearly zero power factor) flowing from the motor back to the supply. There is a small q-axis current and a small torque because of losses in the motor and the converter. The power flow is reversed and this mode of operation is possible only if the motor 'over-runs' the converter or is driven by an external load or prime-mover. The reactive current is limited only by the synchronous reactance, and as the speed increases it approaches the short-circuit current E_q/X_s , which may be many times the normal continuous rating of the motor windings or the converter, and may be sufficient to partially demagnetize the magnets, particularly if their temperature is high. The current is rectified by the flyback diodes in the converter and there is a risk not only of overcurrent in the diodes but also of overvoltage on the d.c. side of the converter, especially if a filter capacitor and a.c. line rectifier are used to supply the d.c. Fortunately this operating condition is unusual, but in any system design the possibility should be assessed. An effective solution is to use an overspeed relay to short-circuit the phase windings into a three-phase resistor or a short-circuit, to produce a braking torque without stressing the converter.



A **linear induction motor (LIM)** is an alternating current (AC), asynchronous linear motor that works by the same general principles as other induction motors but is typically designed to directly produce motion in a straight line. Characteristically, linear induction motors have a finite primary or secondary length, which generates end-effects, whereas a conventional induction motor is arranged in an endless loop.

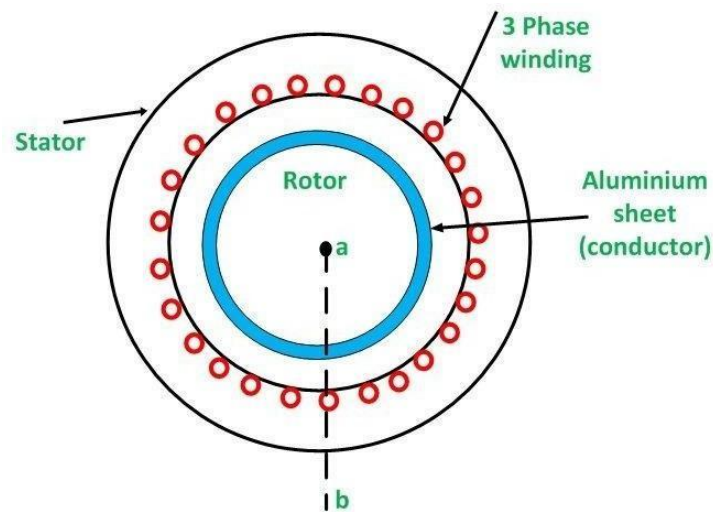
Despite their name, not all linear induction motors produce linear motion; some linear induction motors are employed for generating rotations of large diameters where the use of a continuous primary would be very expensive.

As with rotary motors, linear motors frequently run on a three-phase power supply and can support very high speeds. However, there are end-effects that reduce the motor's force, and it is often not possible to fit a gearbox to trade off force and speed. Linear induction motors are thus frequently less energy efficient than normal rotary motors for any given required force output.

LIMs, unlike their rotary counterparts, can give a levitation effect. They are therefore often used where contactless force is required, where low maintenance is desirable, or where the duty cycle is low. Their practical uses include magnetic levitation, linear propulsion, and linear actuators. They have also been used for pumping liquid metals

Construction

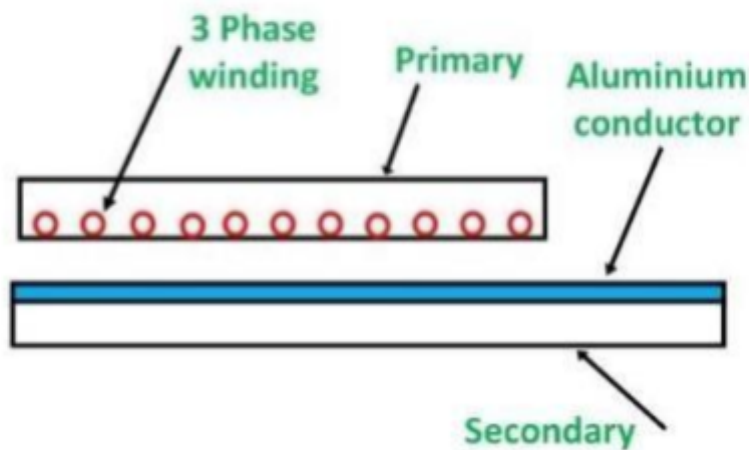
The stator is cut axially and spread out flat in Linear Induction Motor (LIM). In this type of motor, the stator and rotor are called **primary** and **secondary** respectively. The secondary of the linear induction motor consists of a flat Aluminium conductor with a ferromagnetic core. For understanding the construction of Linear Induction Motor, we will first take a look at the construction of Induction Motor as shown in figure below.



If we cut the Stator along the line ab and make it flat then the Stator will look like as shown below.



This is what which makes the Primary of a LIM. So Primary of Linear Induction Motor is flat and three phase winding is wound on it. Now if we make the Rotor of Induction Motor flat then it will be nothing but a sheet of flat Aluminium which is called the Secondary of Linear Induction Motor (LIM) as shown in figure below

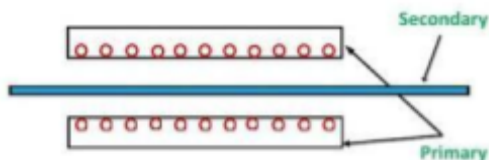


Hope construction part of LIM is clear.

principle of operation of LIM(Double sided LIM from rotatingtype Induction Motor)

If a three phase supply is connected to the stator of an Induction Motor, a rotating flux is produced. This flux rotates at a synchronous speed in the air gap. Similarly, if the primary of the Linear Induction Motor is connected to the three phase supply, a flux is produced which will travel across the length of the primary. Because of the travelling magnetic flux, a current will be generated in the conductor which is made of the aluminium material in the secondary of Linear Induction Motor.

This current, which is induced in the LIM secondary interacts with the travelling flux and produces a linear force from $i(d\mathbf{L} \times \mathbf{B})$. If secondary is fixed and the primary is free to move, the force will move the primary in the direction of the travelling wave. The working principle is depicted in figure below using Double Linear Induction Motor.



Performance of the Linear Induction Motor:

As we know that for a P pole Induction Motor, synchronous speed is given as

$N_s = 2f/P$ rps where f = Frequency of Supply

Therefore, for LIM the speed of travelling flux will be

$V = 2f$ (Pole Pitch) m/s where V = Velocity

The Linear Force is given as,

Power = Force $\times$ Velocity

Here Power will be Air Gap Power and velocity will be the velocity of travelling flux.

Force = (Air gap Power) / $2f$ (Pole Pitch) Newton

Interesting point which shall be noted that,

- If a rotary induction motor is compared with the linear induction motor, the LIM requires a larger air gap and hence, the magnetising current is greater and the power factor and efficiency of the motor are lower.
- In the rotary induction motor the stator and the rotor area are same whereas in the LIM the one of the two is shorter than the other. At the steady speed, the shorter part will be passing continuously over a new part of the other member.

Double sided LIM from rotating type Induction Motor

There is another variant of LIM also being used for increasing efficiency known as the **Double Sided Linear Induction Motor** or **DLIM**, as shown in the figure below. It has primary on either side of the secondary, for more effective utilization of the flux from both sides.

When the primary of a LIM gets excited by a balanced three-phase power supply, a flux starts traveling along the entire length of the primary. This linearly traveling magnetic field is equivalent to the rotating magnetic field in the stator of a three phase induction motor or a synchronous motor. Electric current gets induced in the conductors of the secondary due to the relative motion between the traveling flux and the conductors. Then the induced current interacts with the traveling flux wave to produce linear force or thrust.

$$V_s = 2tf_s \text{ m/sec}$$

If the primary is fixed and the secondary is free to move, the force will pull the secondary in the direction of the force and will result in the required rectilinear motion. When we give supply to the system the developed field will result in a linear traveling field, the velocity of which is given by the equation,

Where f_s is the supply frequency in Hz, V_s is the velocity of the linear traveling field meter per second, and t is the linear pole pitch i.e. pole to pole linear distance in meter.

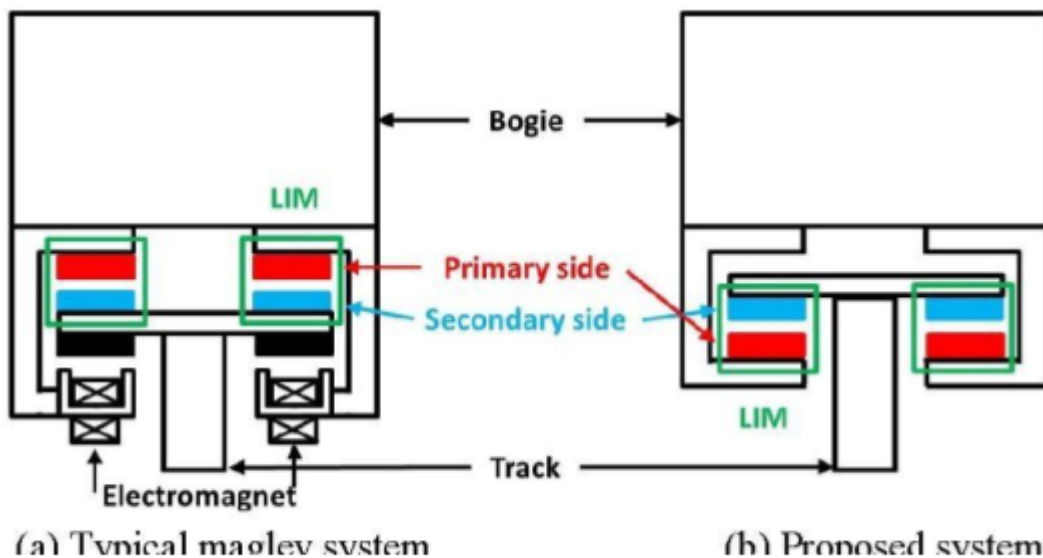
$$V = (1 - s)V_s$$

For the same reason as in the case of an induction motor, the secondary or runner cannot catch the speed of the magnetic field.

Schematic of LIM drive for traction

- The main application of the LIM is in transportation and in electric traction system. The primary is mounted on the vehicle and the secondary is laid on the track.

magnets are unnecessary.



The electric traction system is the most efficient of all other traction system such as steam and internal combustion (IC) engine type systems. It offers several benefits over other systems, including quick start and stop, very efficient, pollution-free, easy to handle and easy speed control.

With the advancement of electrical drives for traction systems, this electrification of traction becomes much popular in several traction services including metro or suburban railways. A system which causes the propulsion of vehicle in which tractive or driving force is obtained from various devices such as diesel engine drives, steam engine drives, electric motors, etc. is called as traction system.

It can also be defined as the railway vehicle that provides the necessary traction power to move the train is referred as the traction or locomotive. This traction power can be diesel, steam or electric power.

The principal, compared with a standard motor, is shown here. This simple diagram shows the principal of the linear motor. The conventional DC motor consists of a fixed part (the stator) and a moving part (the rotor). Both parts are contained in a case on the train and the rotor is connected to the axle by a pinion/gear arrangement. When the armature turns, the wheel turns.

For the linear motor, the two parts are separated with one placed on the train and the other on the track. Both parts are unwrapped and they are swapped so that the fixed part of the DC motor becomes the moving part of the linear motor mounted on the train while the former moving part of the DC motor is fixed to the track. The electro-magnetic interaction between the current in the fixed part and that in the moving part causes the train to be drawn along the line. There is a very small air gap (about 10 mm) between the two parts as shown in this photo.

The efficiency of the linear motor is about 60% of the conventional motor but it has the advantage of less moving parts and it does not have the reliance on adhesion of the conventional motor.

Development of one sided LIM with back iron

Single sided linear induction motor Single sided linear induction motor consist of a primary (coil assembly) and a secondary (reaction plate). The coil assembly comprises of steel laminations and phase winding. The reaction plate maybe of aluminum/steel, copper/steel or steel sheet. The reaction plate faces the coil assembly. The width of the reaction plate must at least be equal to the coil assembly. A bearing system maintains the air-gap between the coil and reaction plate along the length.

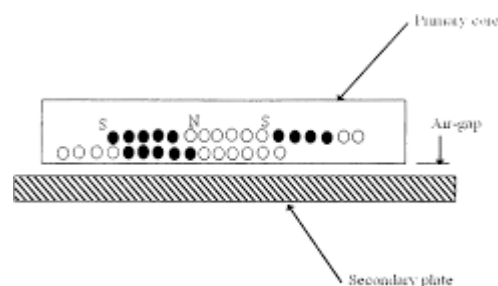
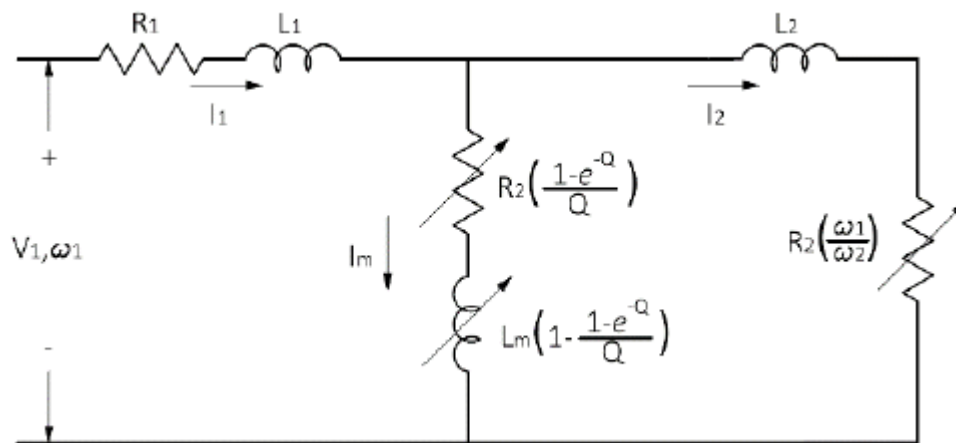


Fig. 2.2 Transverse view of single sided LIM

Equivalent circuit of LIM.

It is helpful to use an equivalent circuit for a simple modeling of a LIM. Circuit constants are assumed to be functions of speed because the end-effect depends mainly on its operational speed, in order to apply the frame of classical equivalent circuits of rotary induction motors to the LIM, in the region of actual operation point. These circuit constants are treated as “circuit parameters” and they are written as $L_0(v)$, $R_2(v)$, $L_2(v)$ as shown in Fig



If this conventional circuit frame is applicable to a LIM using only small modifications described above, then If this conventional circuit frame is applicable to a LIM using only small modifications described above, similar control theories to conventional rotary motors such as vector control can be applied to the LIM, which will contribute improving performance of a LIM-driven transport system.