CONSTRUCTION AND OPERATION OF SWITCHED RELUCTANCE MOTOR

2.1 Construction of SRM

Construction details of switched reluctance motor with six stator poles and four rotor poles can be explained by referring to figure 2.1.1. 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�do‘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.

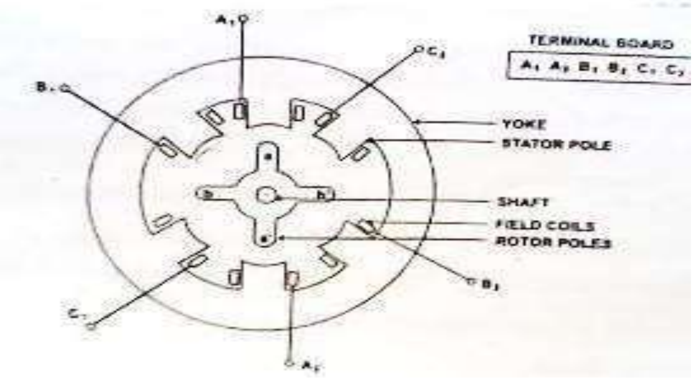


Figure 2.1.1 Cross sectional view of SRM
[Source: “special electric machines” by R.Srinivasan page:3.3]

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 poles.

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.

BLOCK DIAGRAM OF SRM

Fig. 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.

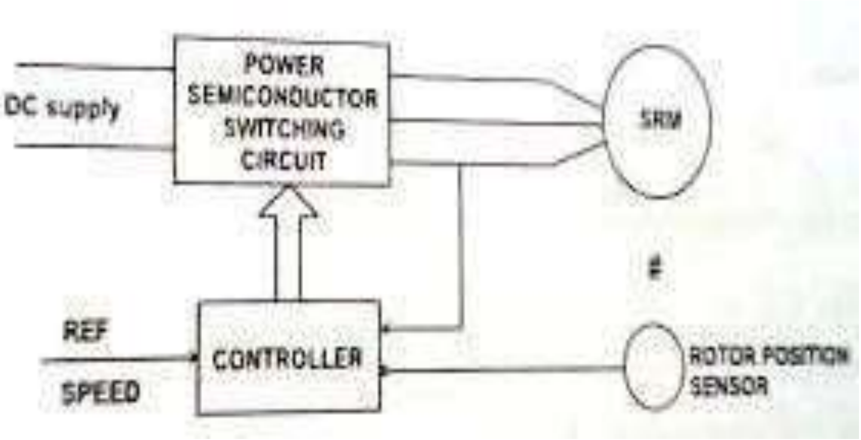


Figure 2.1.2 Block Diagram Of SRM

[Source: "special electric machines" by R.Srinivasan page:3.3]

PRINCIPLE OF OPERATION

Fig. 2.1.3 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. 2.1.3 (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 $dL_c/d\theta$.

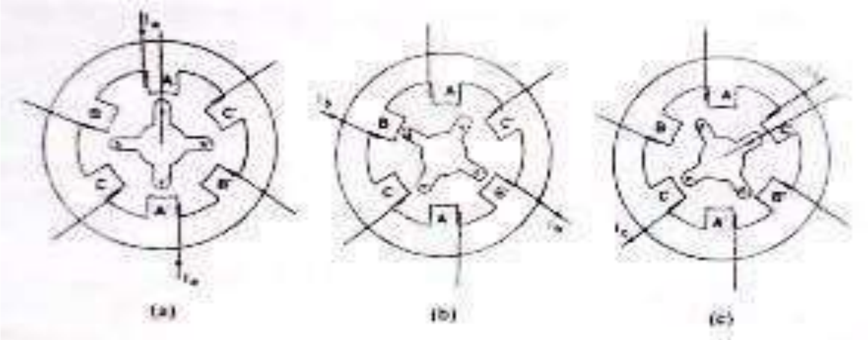


Figure 2.1.3 Physical location of the axis of stator and rotor poles of 6/4 SRM

[Source: “special electric machines” by R.Srinivasan page:3.12]

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$(1/2)i_B2(dL_B/d\theta)$. 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.,) $\theta=30°$, no torque is developed as in this position $dL_B/d\theta=0$. 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. 2.1.3(c)]Then the phase winding C is switched off and phase winding A is energized. Then rotorExperiences 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.

2.4 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 existing 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.

HYSTERISIS 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 Fig2.4.1 (a) shows the current waveform controlled by the hysteresis type current regulator. The schematic arrangement of the control circuit is shown in fig 2.4.1

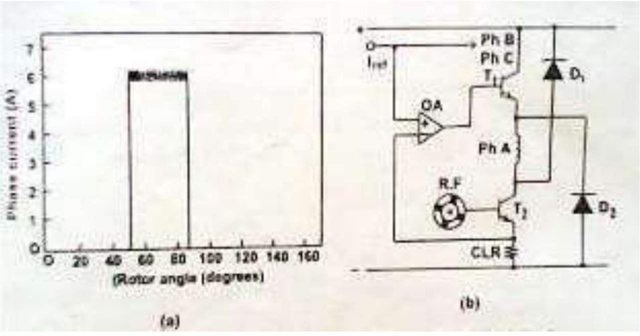


Figure 2.4.1 (a) Chopped current wave form, (b) Hysteresis type current regulation
[Source: "special electric machines" by R.Srinivasan page:3.53]

Principle of operation

As shown in fig. 2.4.1(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 T2. From the emitter of transistor T2, 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 oftransistor T1. This signal in combination with collector current will flow from the emitter oftransistor T1 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 sense fets with in build current sensing.

VOLTAGE PWM TYPE CURRENT REGULATION

The schematic arrangement of PWM type control circuit is shown in fig. 2.4.2

Principle of operation

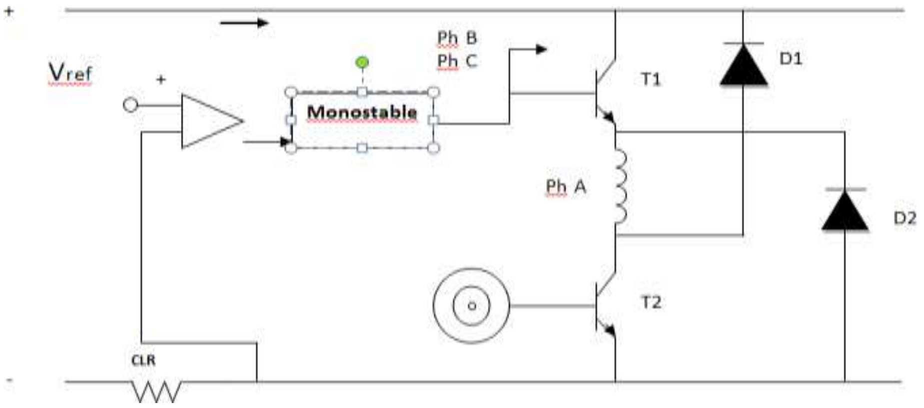


Figure 2.4.2 (a) voltage PWM type current regulator

[Source: "special electric machines" by R.Srinivasan page:3.53]

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 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.

CLR -Current limiting resistor

R.F-Rotor feed back

OA -Operational Amplifier

T1T2-Switching transistor

D1 D2-Diodes to return stored energy

A desirable future 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.

2.7 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.

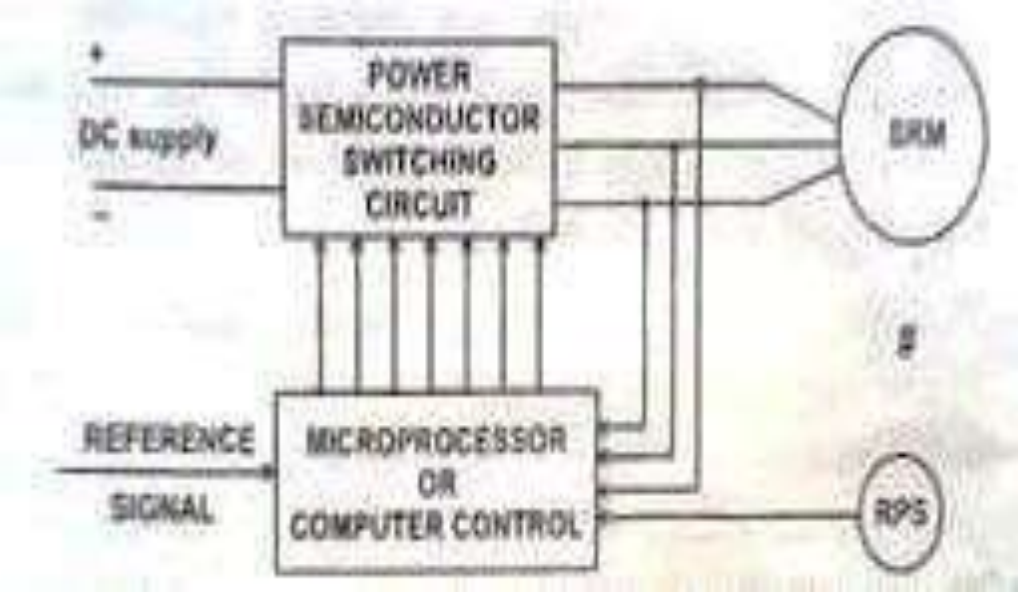


Figure 2.7.1 Block Diagram of the microprocessor control of srm
[Source: "special electric machines" by R.Srinivasan page:3.59]

Nowadays switched reluctance motors are increasingly used in industries. To meet the above requirements, uses of microprocessor have become important.

Microprocessor or computer based control of SRM Fig.2.7.1 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. 2.7.1, 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.

2.2 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.
3. Phase winding using bifilar wires.
4. Split-link circuit used with even-phase number.
5. C-dump circuit.

1. TWO POWER SEMICONDUCTOR SWITCHING DEVICES PER PHASE AND TWO DIODES

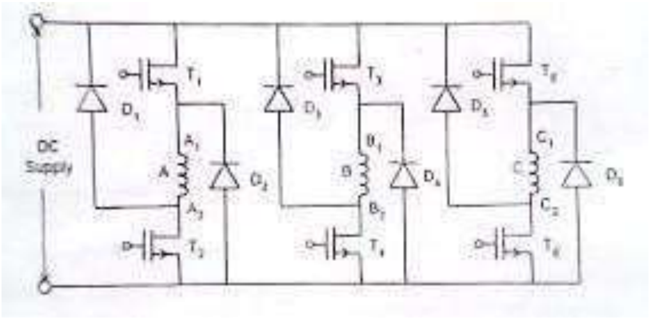


Figure 2.2.1 **Two Power Semiconductor switching devices and two diodes**
[Source: "special electric machines" by R.Srinivasan page:3.19]

As shown in fig 2.2.1 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 T1, T3 and T5 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 T2, T4, T6 are controlled from signals obtained by chopping frequency signal. The current in the phase winding is the result of logical AND 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

1. Control of each phase is completely independent of the other phase.
2. The converter is able to free wheel during the chopping period at low speeds which helps to reduce the reduce the switching frequency and thus the switching losses of the converter.

3. The energy from the off going phase is feedback to the source, which results in utilization of energy

DEMERITS

1. 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

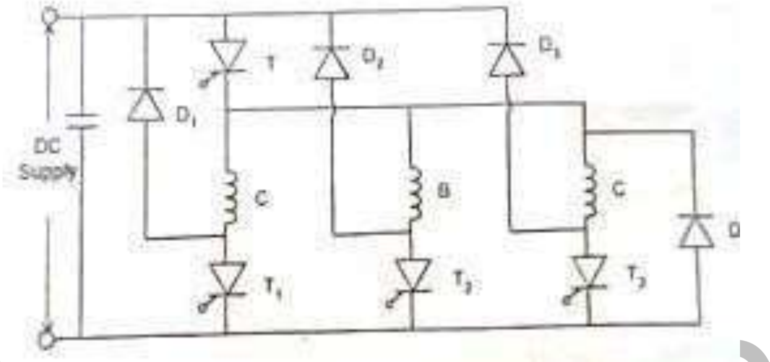


Figure 2.2.2 (n+1) power switching devices and (n+1) diodes
[Source: "special electric machines" by R.Srinivasan page:3.19]

This circuit makes use of less number of power switching devices and diodes as shown in fig 2. When the (SCRs) switching devices T and T1 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 D1. When devices T and T2 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

1. The converter uses low number of switching devices, which reduces the cost of the converter.
2. The converter is able to freewheel during the chopping, thus reducing the switching frequency and losses.
3. Voltage rating of all the switching devices and the diodes are V_{dc}, which is relatively low.
4. 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.

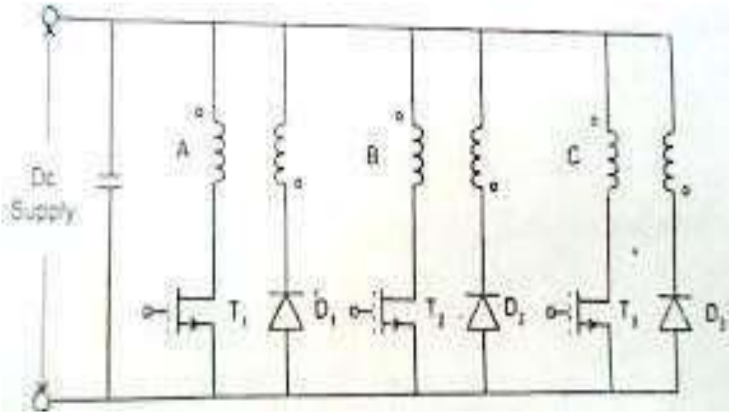
DEMERITS

1. Disability to magnetize a phase while the off going phase is still demagnetizing which results in higher torque ripple during commutation.
2. At higher speeds of the off going phase cannot be de-energized fast enough because the common switch —T keeps turnings on intermediately, disabling forced demagnetization.
3. 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 fig2.2.3.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.

Figure 2.2.3 Phase winding using bifilar wires

[Source: "special electric machines" by R.Srinivasan page:3.19]

When T1 is turned on the dc current passes through the phase winding A. when the devices T1 is turned off the stored energy in the magnetic field is fed back to the dc source through the winding A' and D1 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

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

DEMERITS

1. Bifilar winding suffers from double number of connections.
2. A poor utilization of copper.

3. Freewheeling is not possible during chopping as the phases have $-V_{dc}$. this causes of higher ripples in current and torque during chopping.

4. The imperfection in the coupling between the two winding causes voltage spikes during turn off.

5. The copper loss associated with the auxiliary winding is unacceptable high for many applications.

4. SPLIT – LINK CIRCUIT USED WITH EVEN PHASE NUMBER

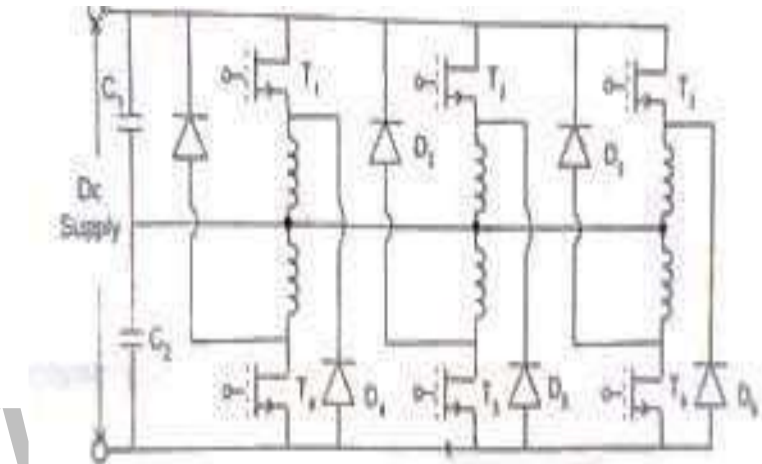


Figure 2.2.4 split link circuit used with even phase number

[Source: "special electric machines" by R.Srinivasan page:3.19]

The circuit shown in fig.2.2.4 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

1. It requires lower number of switching devices.

2. Faster demagnetization of phases during commutation.

Demerits

1. During chopping, freewheeling is not possible as the phaser have the voltage **V**dc/2. This causes higher switching frequency and more losses.

2. This is not feasible for low voltage application.

3. The converter is fewer faults tolerant as fault in any phase will unbalance the other phase that is connected to it.

C-DUMP CIRCUIT

In the C dump circuit shown in fig.2.2.5. the device count is reduced to n‘ plus one additional devices to bleed the stored energy from the dump capacitor C back to supply

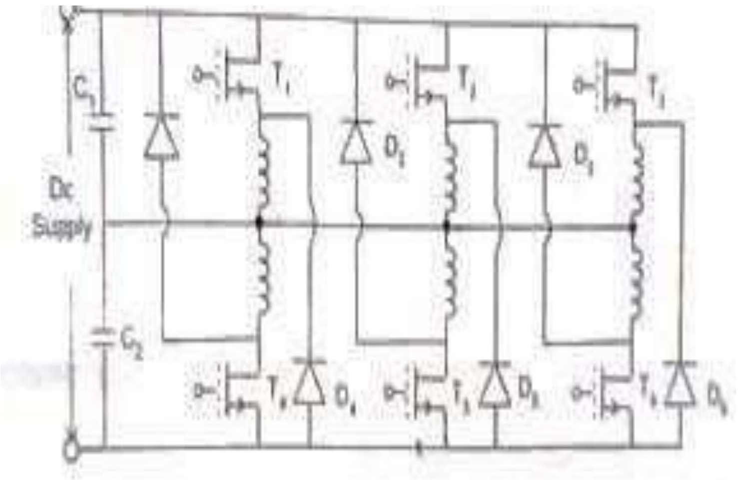


Figure 2.2.5 c dump circuit

[Source: "special electric machines" by R.Srinivasan page:3.24]

via the step down chopper circuit. The mean capacitor voltage is maintained well above the supply to permit rapid defluxing after commutation.

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

1. Dump capacitor voltage is maintained 2 Vdc 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

2. 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

2.6 ROTOR POSITION SENSOR

Rotor position information is important for the operation of SRM.Rotor angle information must be accurate for the high speed drives. Inaccurate position sensing results in decreased torque &efficiency. In high speed motors, error in 1° decreases the torqueby8%.Position sensing sensor is enough.

Disadvantages of electro mechanical sensors are:

Unreliable due to dust, high temperature, humidity, vibration.

Cost increases with resolution.

Additional manufacturing expenses.

Extra electrical connections.

Need more space at the shaft.

To over come the above problems, sensor less rotor position estimation methods are developed. Sensor less methods employs motor electrical parameters for position detection.

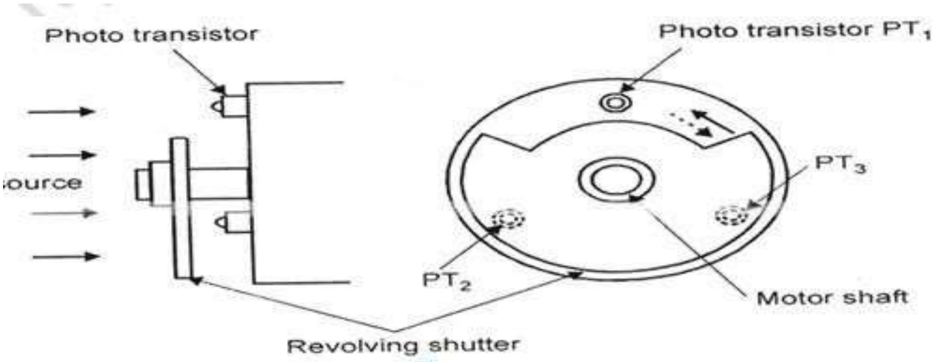


Fig.opticalposition sensor

Fig.opticalposition sensor

1. HALLPOSITION SENSOR:

- Based on Hall principle.
- On rotor shaft, 3hall components, rotating plate with permanent magnet.
- Output of hall components indicates the rotor position.
    - Observer based sensing methods
    - Incremental inductance based sensing
    - Direct inductance based sensing
    - Intelligent control based sensing methods

Observer based sensing methods:

Use a state observer or a sliding mode observer

Depends on the inductances lope for their convergence and functioning.

Computationally intensive and have the problem of convergence

2.5 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.

Figure 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

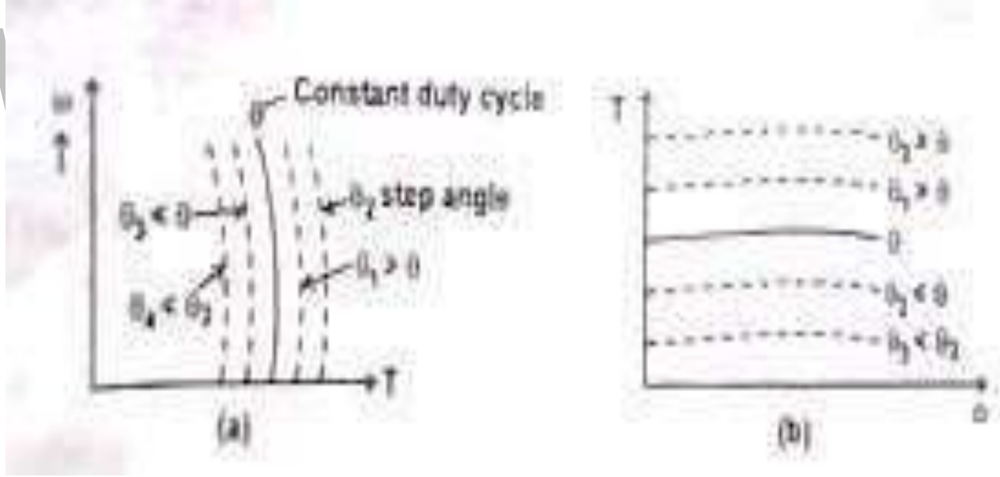


Figure 2.5.1 Torque speed characteristics of SRM
[Source: "special electric machines" by R.Srinivasan page:3.56]

Torque speed characteristics for fixed Ө and for various duty cycles are shown in fig.

2.5.1. Ө and duty cycle are varied by suitably operating the semiconductor devices.

Torque Speed Capability Curve

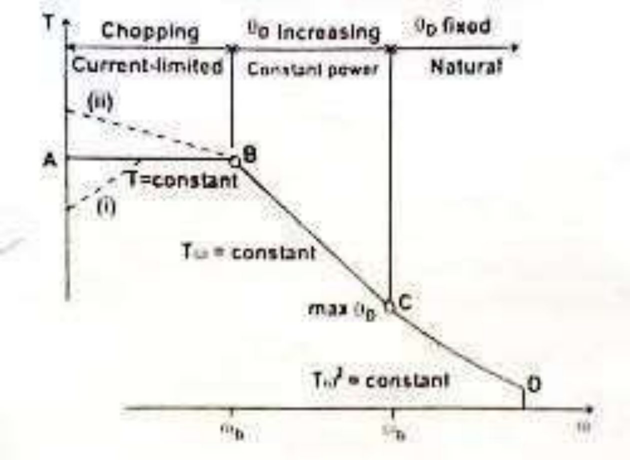


Figure 2.5.2 General Torque speed characteristics of SRM

[Source: "special electric machines" by R.Srinivasan page:3.56]

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.Fig2 Torque speed characteristic of switched reluctance motor AB in the fig.2 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 GƆ

The motor current limits the torque below base speed. The _corner point‘or base speed _GƆ 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.)Ɵ 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 Ɵ D to its maximum value Ɵ D max. Ɵ D is dwell angle of the main switching devices in each phase. Point C corresponds to maximum permissible power; maximum permissible conduction angle