3. SWITCHED RELUCTANCE MOTORS

3.1 INTRODUCTION

The switched reluctance motor (SRM) drives for industrial applications are of recent origin. Since 1969, a variable reluctance motor 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.

3.2 CONSTRUCTION OF SWITCHED RELUCTANCE MOTOR

SRM are made up of laminated stator and rotor cores with N_s=2mq poles on the stator and N_r poles on the rotor. The number of phases is m and each phase is made up of concentrated coils place on 2q stator poles. Most favored configuration amongst many more options are 6/4 three phase and 8/6 four phase SRM's as shown in the figure 3.1(a).

These two configurations correspond to q=1(one pair of stator poles (and coils) per phase) but q may be equal to 2, 3 when, for the three phase machine, we obtain 12/8 or 18/12 topologies applied either for low speed high torque direct drives or for high speed stator generator systems for aircraft. The stator and rotor pole angles β_s and β_r are, in general, almost equal to each other to avoid zero torque zones.

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 is shown in Figure 3.1a, and a modified version with two teeth per pole is shown in Figure 3.1b.

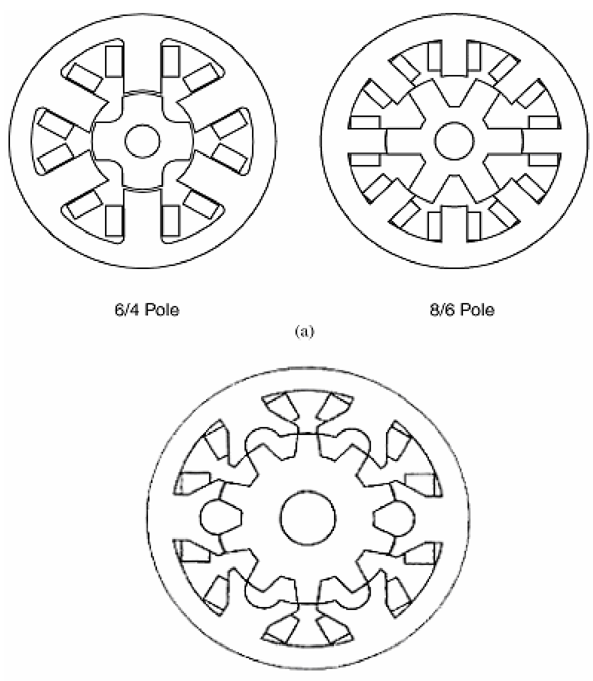


FIGURE 3.1 Switched reluctance motor configurations. (a) One tooth per pole. (b) Two teeth per pole (12/10 poles).

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 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.

3.3 ADVANTAGES AND DISADVANATGES OF SRM

3.3.1 ADVANTAGES

The SRM possess a few unique features that makes it a vigorous competitor to existing AC and DC motors in various adjustable-speed drive and servo applications. The advantages of an SRM can be summarized as follows:

- Machine construction ***is simple and low-cost because*** of the ***absence of rotor winding*** and permanent magnets.
- There are ***no shoot-through faults between the DC buses*** in the SRM drive converter because ***each rotor winding is connected in series with converter*** switching elements.
- ***Bidirectional currents are not necessary***, which facilitates ***the reduction of the number of power switches*** in certain applications.
- The bulk of the losses appear in the stator, which is relatively ***easier to cool***.
- The torque–speed characteristics of the motor ***can be modified to the application requirement more easily*** during the design stage than in the case of induction and PM machines.
- The starting torque can be ***very high without the problem of excessive in-rush current*** due to its higher self-inductance.
- The open-circuit voltage and short-circuit current at faults ***are zero or very small***.
- The maximum permissible ***rotor temperature is higher***, since there are no permanent magnets.
- There is ***low rotor inertia and a high torque/inertia ratio***.
- Extremely ***high speeds with a wide constant power region*** are possible.
- There are independent stator phases, ***which do not prevent drive operation*** in the case of loss of one or more phases.

3.3.2 DISADVANTAGES

The SRM also comes with a few disadvantages among ***which torque ripple and acoustic noise are the most critical***. The higher torque ripple also ***causes the ripple current in the DC supply*** to be quite large, ***necessitating a large filter capacitor***. The doubly salient structure of the SRM also causes ***higher acoustic noise compared with other machines***.

The absence of permanent magnets ***imposes the burden of excitation on the stator windings and converter***, which increases the ***converter KVA requirement***. Compared with PM brushless machines, the ***per unit stator copper losses will be higher, reducing the efficiency and torque per ampere***. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRMs.

3.4 APPLICATIONS OF SRM

The simple motor structure and inexpensive power electronic requirement have made the SRM an attractive alternative to both AC and DC machines in adjustable-speed drives. Few of such applications are listed below.

a) General purpose industrial drives;
b) Application-specific drives: compressors, fans, pumps, centrifuges;
c) Domestic drives: food processors, washing machines, vacuum cleaners;
d) Electric vehicle application;
e) Aircraft applications;
f) Servo-drive.

3.5 ELEMENTARY OPERATION OF THE SWITCHED RELUCTANCE MOTOR

Consider that the rotor poles r_1 and $r_1^{'}$ and stator poles c and $c^{'}$ are aligned. Apply a current to phase a with the current direction as shown in Figure 3.2a. A flux is established through stator poles a and $a^{'}$ and rotor poles r_2 and $r_2^{'}$ which tends to pull the rotor poles r_2 and $r_2^{'}$ toward the stator poles a and $a^{'}$, respectively. When they are aligned, the stator current of phase a is turned off and the corresponding situation is shown in Figure 3.2b. Now the stator winding b is excited, pulling r_1 and $r_1^{'}$ toward b and $b^{'}$ in a clockwise direction. Likewise, energization of the c phase winding results in the alignment of r_2 and $r_2^{'}$ with c and $c^{'}$, respectively. Hence, it takes three phase energizations in sequence to move the rotor by 90^0 and one revolution of rotor movement is effected by switching currents in each phase as many times as there are number of rotor poles. The switching of currents in the sequence *acb* results in the reversal of rotor rotation is seen with the aid of Figures 3.2a and b.

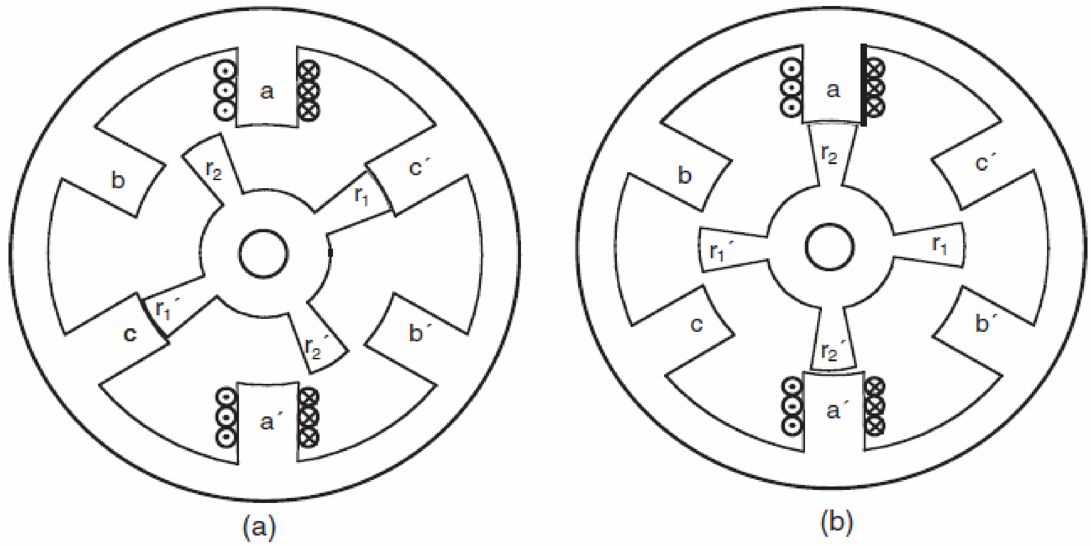


FIGURE 3.2 Operation of an SRM. (a) Phase *c* aligned. (b) Phase *a* aligned.

3.6 PRINCIPLE OF OPERATION OF THE SWTICHED 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 3.3a. 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. magneto motive 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 3.3b.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:

$$W_e = \int ei\,dt = \int i\,\mathrm{dt}\,\frac{\mathrm{dN}\phi}{\mathrm{dt}} = \int Ni\,d\phi = \int Fd\phi ....(3.1)$$

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 work, W_m. It is written as:

$$W_e = W_f + W_m ....(3.2)$$

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 equation (3.1). This corresponds to area OBEO in Figure 3.3b. The complement of the field energy, termed *co energy*, is given by area OBAO in Figure 3.3b 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 co energy is given by area OCAO. For incremental changes, equation (3.2) is written as:

$$\delta W_e = \delta W_f + \delta W_m \quad (3.3)$$

For a constant excitation of F_1 given by the operating point A in Figure 3.3b, the various energies are derived as:

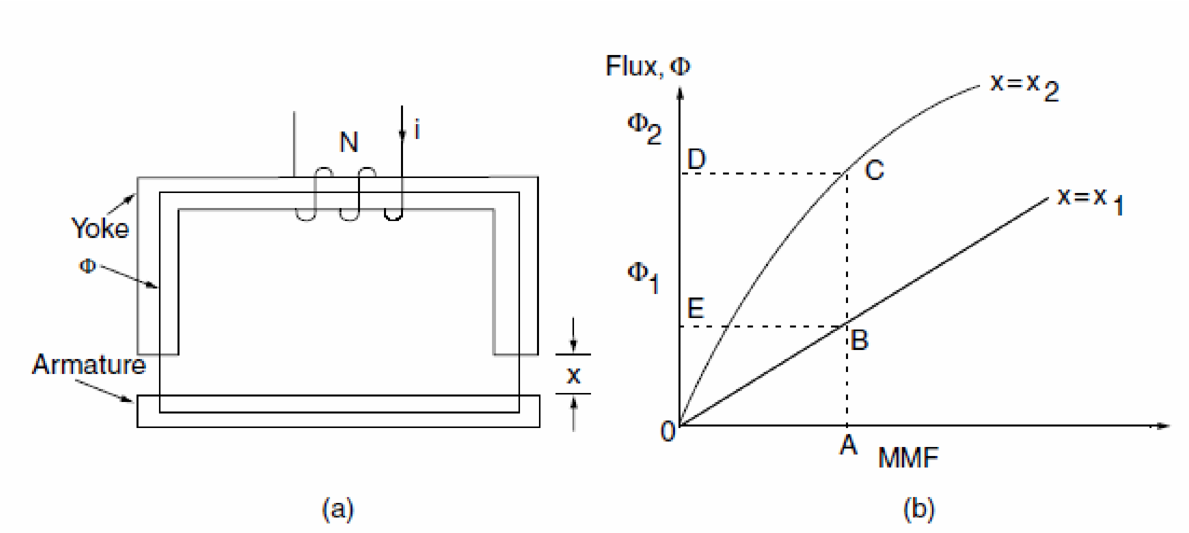


FIGURE 3.3 Solenoid and its characteristics. (a) A solenoid. (b) Flux v. mmf characteristics.

For a constant excitation of F_1 given by the operating point A in Figure 3.3b, the various energies are derived as:

$$\delta W_e = \int_{\phi_1}^{\phi_2} F_1 d\phi = F_1(\phi_2 - \phi_1) = area(BCDEB) \quad (3.4)$$

$$\delta W_f = \delta W_{f|_{X=X_2}} - \delta W_{f|_{X=X_1}} = area(OCDO) - area(OBEO) \quad (3.5)$$

Using Eqs. (3.3) to (3.5), the incremental mechanical energy is derived as:

$$\delta W_m = \delta W_e - \delta W_f = area(OBCO) \quad (3.6)$$

and that is the area between the two curves for a given magneto motive 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:

$$\delta W_m = T_e \delta\theta \quad (3.7)$$

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

$$T_e = \frac{\delta W_m}{\delta\theta} \quad (3.8)$$

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 co energy, W_f' which is nothing but the complement of the field energy. Hence, the incremental mechanical work done is written as:

$$\delta W_m = \delta W_f' \quad (3.9)$$

Where

$$W_f' = \int \phi dF = \int \phi d(Ni) = \int (N\phi) di = \int \lambda(\theta, i) di = \int L(\theta, i) i di \text{..........(3.10)}$$

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

$$T_e = \frac{\delta W_m}{\delta \theta} = \frac{\delta W_f'}{\delta \theta} = \left. \frac{\delta W_f'(i, \theta)}{\delta \theta} \right|_{i=\text{constant}} \text{...................(3.11)}$$

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:

$$T_e = \frac{dL(\theta, i)}{d\theta} \cdot \frac{i^2}{2} \text{...(3.12)}$$

Where

$$\frac{dL(\theta, i)}{d\theta} = \left. \frac{L(\theta_2, i) - L(\theta_1, i)}{\theta_2 - \theta_1} \right|_{i=\text{constant}} \text{................................(3.13)}$$

and this differential inductance can be considered to be the torque constant expressed in N. m/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.

The following are the implications of equation (3.12)

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.

3.7 COMPARISION BETWEEN SRM AND STEPPER MOTORS

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
5. The SRM motor is normally operated with shaft position feed back to synchronize the commutation of the phase currents with precise rotor positions, where as stepper motor is normally run in open loop, i.e with out shaft position feed back.
6. SRM is normally designed for efficient conversion of significant amounts of power, stepper motors are more usually designed to maintain step integrity in position controls.

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

3.8 DERIVATION OF THE RELATIONSHIP BETWEEN INDUCTANCE AND ROTOR POSITION-*NON LINEAR ANALYSIS*

Since the torque characteristics are dependent on the relationship between flux linkages and rotor position as a function of current, it is worthwhile to conceptualize the control possibilities and limitations of this motor drive. For example, a typical phase inductance vs. rotor position is shown in Figure 3.4 for a fixed phase current. The inductance corresponds to that of a stator-phase coil of the switched reluctance motor neglecting the fringe effect and saturation. The significant inductance profile changes are determined in terms of the stator and rotor pole arcs and number of rotor poles. The rotor pole arc is assumed to be greater than the stator pole arc for this illustration, which is usually the case. From Figures 3.4a and b, the various angles are derived as:

$$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{P_r} - \left(\beta_s + \beta_r\right)\right] \quad \ldots\ldots (3.14a)$$

$$\theta_2 = \theta_1 + \beta_s \quad \ldots\ldots (3.14b)$$

$$\theta_3 = \theta_2 + \left(\beta_r - \beta_s\right) \quad \ldots\ldots (3.14c)$$

$$\theta_4 = \theta_3 + \beta_s \quad \ldots\ldots (3.14d)$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r} \quad \ldots\ldots (3.14e)$$

Where β_s and β_r are stator and rotor pole arcs, respectively, and P_r is the number of rotor poles.

Four distinct inductance regions emerge:

1. $0 - \theta_1$ and $\theta_4 - \theta_5$: The stator and rotor poles are not overlapping in this region and the flux is predominantly determined by the air path, thus making the inductance minimum and almost a constant. Hence, these regions do not contribute to torque production. The inductance in this region is known as unaligned inductance, L_u.

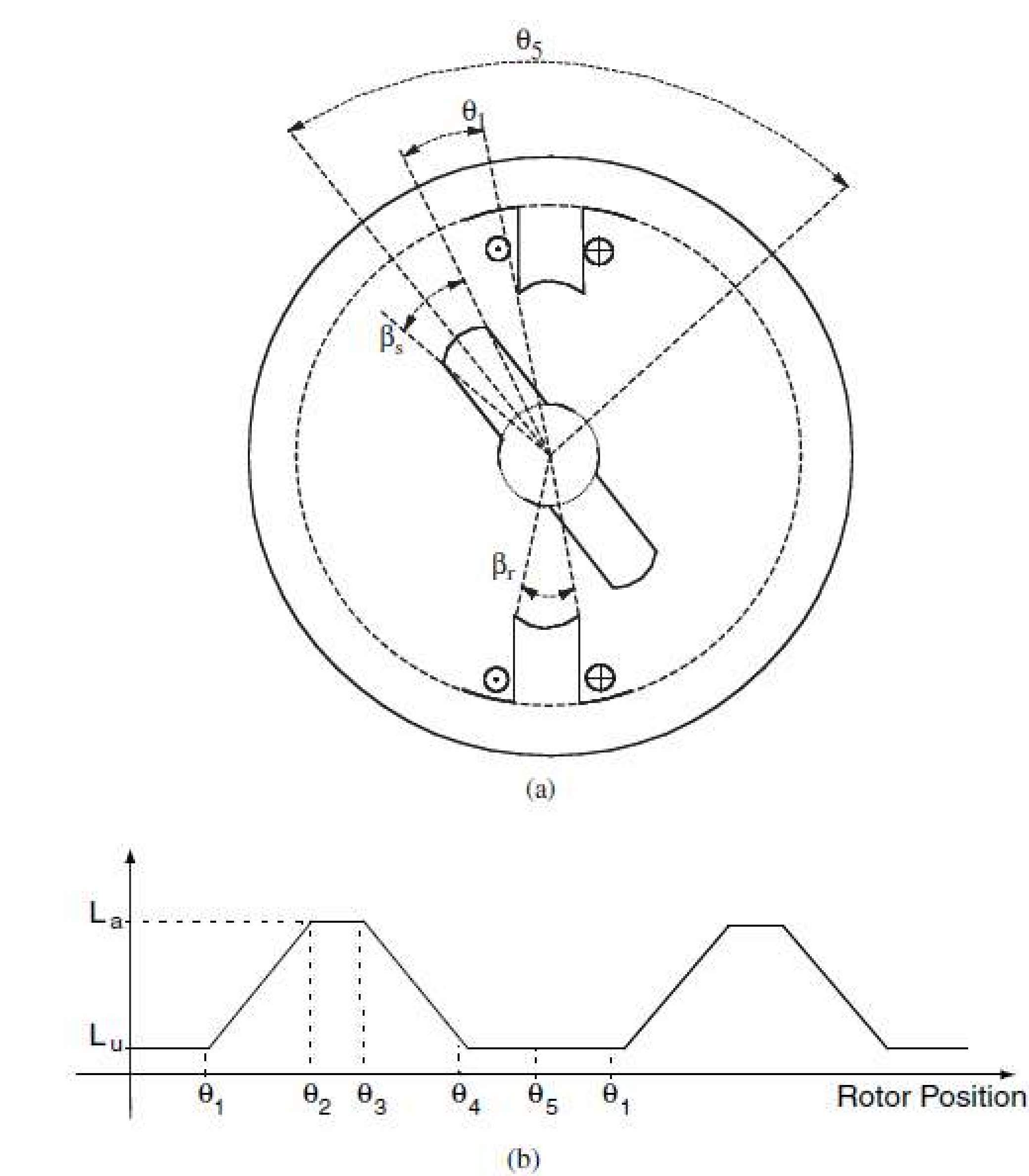


FIGURE 3.4 Derivation of inductance vs. rotor position from rotor and stator pole arcs for an unsaturated switched reluctance machine. (a) Basic rotor position definition in a two pole SRM. (b) Inductance profile.

2. $\theta_1 - \theta_2$: Poles overlap, so the flux path is mainly through stator and rotor laminations. This increases the inductance with the rotor position, giving it a positive slope. A current impressed in the winding during this region produces a positive (i.e., motoring) torque. This region comes to an end when the overlap of poles is complete.
3. $\theta_2 - \theta_3$: During this period, movement of rotor pole does not alter the complete overlap of the stator pole and does not change the dominant flux path. This has the

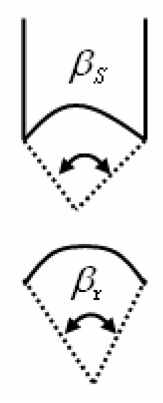
effect of keeping the inductance maximum and constant, and this inductance is known as aligned inductance, L_a. As there is no change in the inductance in this region, torque generation is zero even when a current is present in this interval. In spite of this fact, it serves a useful function by providing time for the stator current to come to zero or lower levels when it is commutated, thus preventing negative torque generation for part of the time if the current has been decaying in the negative slope region of the inductance.

4. $\theta_3 - \theta_4$: The rotor pole is moving away from overlapping the stator pole in this region. This is very much similar to the $\theta 1 - \theta 2$ region, but it has decreasing inductance and increasing rotor position contributing to a negative slope of the inductance region. The operation of the machine in this region results in negative torque (i.e., generation of electrical energy from mechanical input to the switched reluctance machine).

It is not possible to achieve the ideal inductance profiles shown in Figure 3.4 in an actual motor due to saturation. Saturation causes the inductance profile to curve near the top and thus reduces the torque constant. Hence, saturating the machine beyond a point produces a diminishing return on torque and power output.

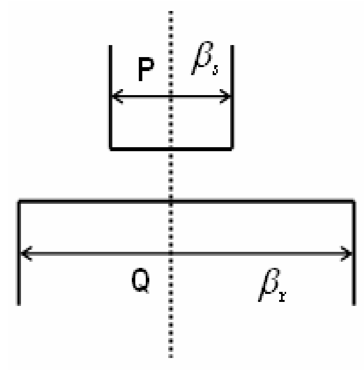
DETAILED DERIVATION

Let L_A be the aligned inductance of a coil/Phase and L_U be the unaligned inductance of the coil / phase. β_s and β_r are stator and rotor pole arcs, respectively. Let us assume that $\beta_r > \beta_s$ and $L_A > L_U$.



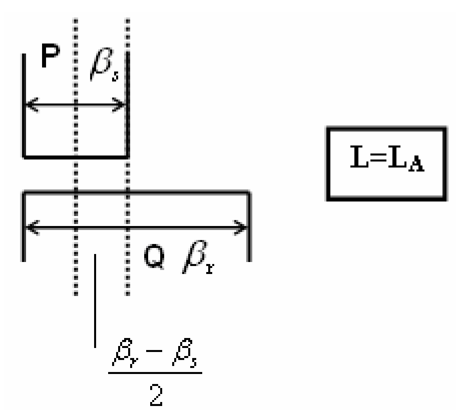
Case 1: When $\theta=0^0$

Axis of the stator pole is in alignment with the stator pole as shown in the figure below. Therefore the inductance of the coil is L_A, because the stator reference axis and rotor reference axis are in alignment. At this position flux linkage of phase winding of stator has maximum value and hence inductance of phase winding has maximum value for given current.



CASE II: When $\theta = \frac{\beta_r - \beta_s}{2}$

The rotor reference axis makes angular displacement of $\frac{\beta_r - \beta_s}{2}$ stator reference axis one edge of rotor pole is along the edge of stator pole. At this position reluctance is minimum. Then the inductance of the coil continues to be L_A. When θ varies from 0 to $\frac{\beta_r - \beta_s}{2}$**.** At this position also **$L=L_A$**.



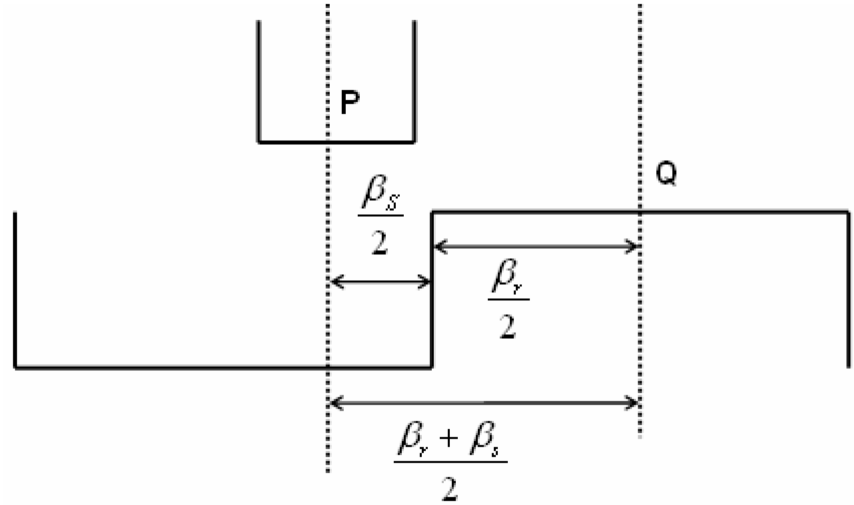
CASE III: WHEN $\theta = \frac{\beta_r + \beta_s}{2}$

Pole pitch of the rotor = $\frac{2\pi}{N_r}$

Half the pole pitch of the rotor = $\frac{\pi}{N_r}$ Assume $\theta = \frac{\beta_r + \beta_s}{2} < \frac{\pi}{N_r}$

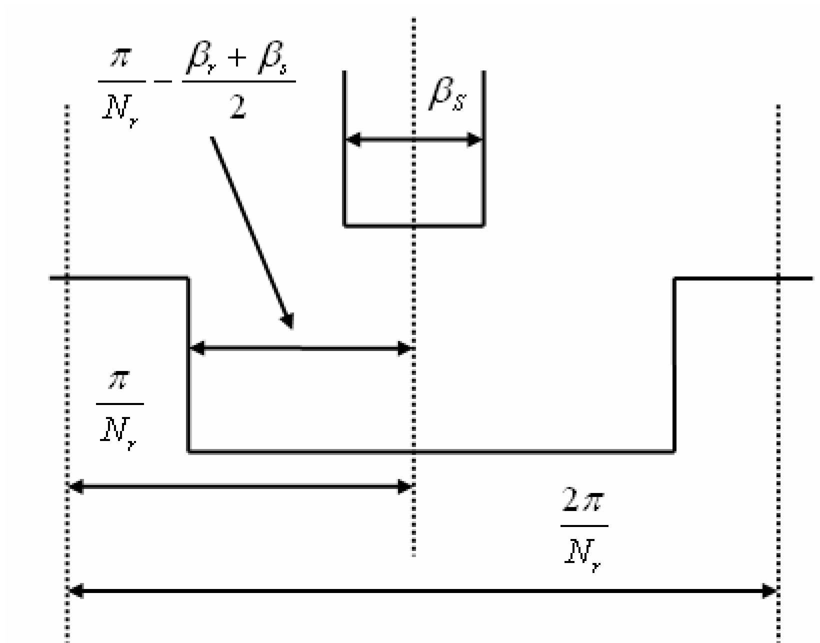
In this position, the flux pattern is such that the flux linkages / unit current of the stator is less than the previous case but not minimum. Therefore $L < L_A$ and $L > L_U$.

$$\boxed{L_U < L < L_A} \quad \text{At} \quad \boxed{\frac{\beta_r - \beta_s}{2} < \theta < \frac{\beta_r + \beta_s}{2}}$$

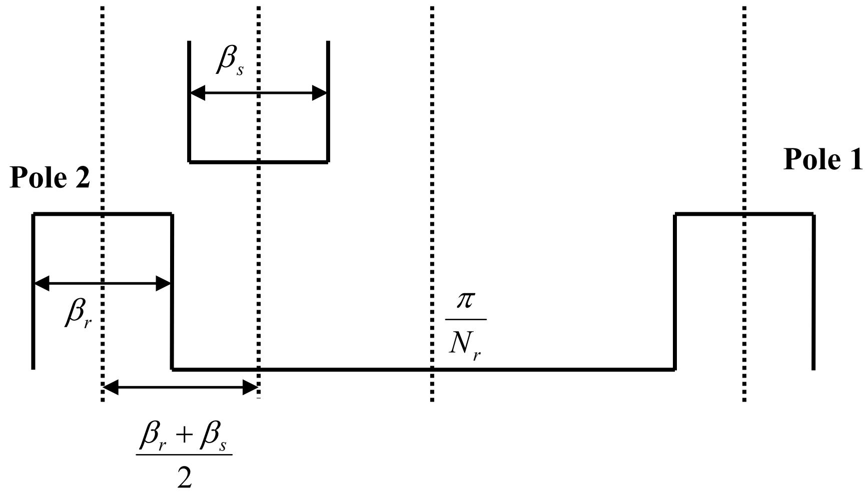


CASE IV: WHEN $\theta = \frac{\pi}{N_r}$

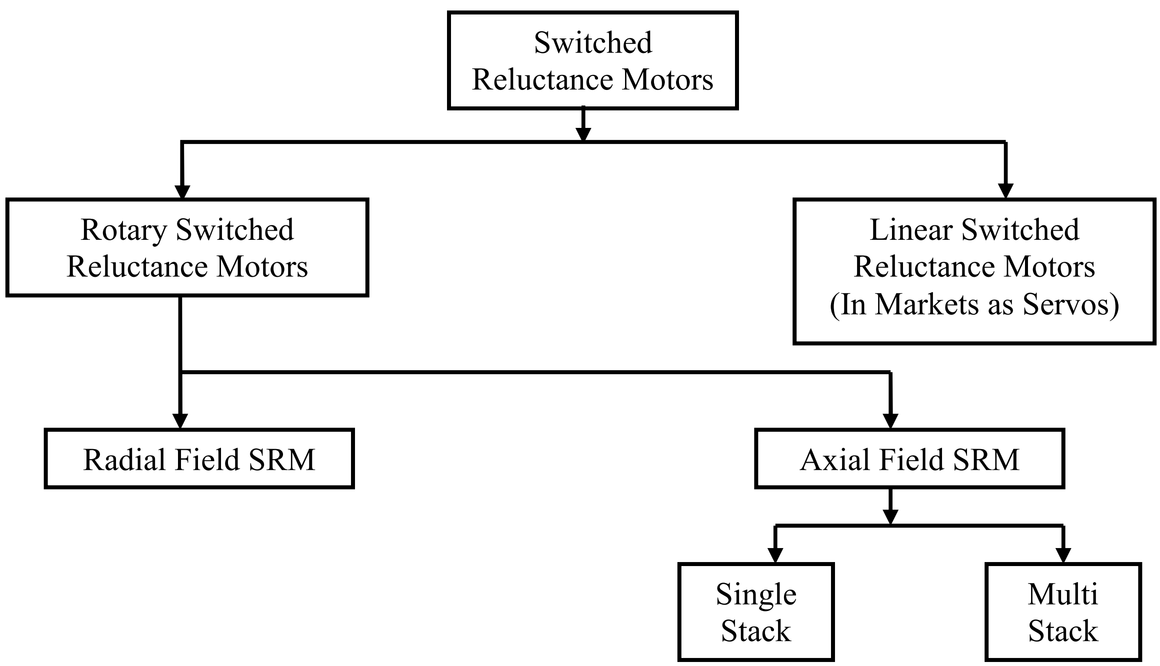
For $\frac{\beta_r+\beta_s}{2} \le \theta \le \frac{\pi}{N_r}$ **L=L$_U$**



CASE V: WHEN $\theta = \frac{\beta_r+\beta_s}{2}$ after $\frac{\pi}{N_r}$ **(or)** $\theta = \frac{2\pi}{N_r} - \frac{\beta_r+\beta_s}{2}$ as far as the rotor pole is considered. After which stator pole comes under the influence of the rotor pole 2. Now the inductance variation is from L_U to L_A as the rotor pole moves towards so as to cover the stator pole.



3.9 TYPES OF SRM



3.10 CONVERTERS FOR SRM DRIVES

Since the torque in SRM drives is independent of the excitation current polarity, the SRM drives require only one switch per phase winding. This is contrary to the ac motor drives where at least two switches per phase are required for current control. Moreover, the windings are not in series with the switches in ac motor drives, leading to irreparable damage in shoot-through faults. The SRM drives always have a phase winding in series with a switch.

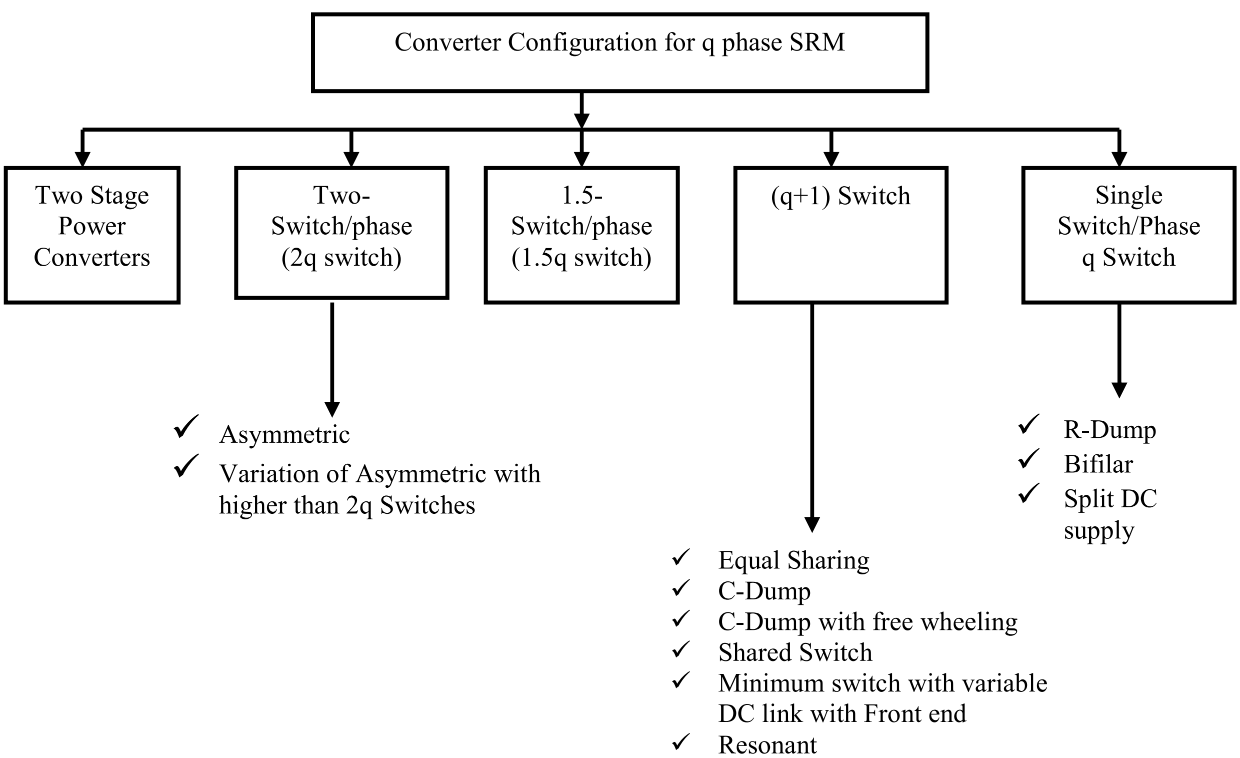
In case of a shoot-through fault, the inductance of the winding limits the rate of rise in current and provides time to initiate protective relaying to isolate the faults. The phases of the

SRM are independent and, in case of one winding failure, uninterrupted operation of the motor drive operation is possible, although with reduced power output.

3.10.1 CONVERTER CONFIGURATIONS

The mutual coupling between phases is negligible in SRMs. This gives complete independence to each phase winding for control and torque generation. While this feature is advantageous, a lack of mutual coupling requires a careful handling of the stored magnetic field energy. The magnetic field energy has to be provided with a path during commutation of a phase; otherwise, it will result in excessive voltage across the windings and hence on the power semiconductor switches leading to their failure. The manner in which this energy is handled gives way to unique but numerous converter topologies for SRM drives. The energy could be freewheeled, partially converting it to mechanical/electrical energy and partially dissipating it in the machine windings. Another option is to return it to the dc source either by electronic or electromagnetic means. All of these options have given way to power converter topologies with q, $(q+1)$, $1.5q$, and $2q$ switch topologies, where q is the number of machine phases.

3.10.1.1 Classification of Converter Configurations



3.10.2 ASYMMETRIC BRIDGE CONVERTER

Figure 3.5a shows the asymmetric bridge converter considering only one phase of the SRM. The rest of the phases are similarly connected. Turning on transistors T_1 and T_2 will circulate a current in phase A of the SRM. If the current rises above the commanded value, T_1 and T_2

are turned off. The energy stored in the motor winding of phase A will keep the current in the same direction until it is depleted. Hence, diodes D_1 and D_2 will become forward biased leading to recharging of the source. That will decrease the current, rapidly bringing it below the commanded value. This operation is explained with the waveforms of Figure 3.5b. Assuming that a current of magnitude Ip is desired during the positive inductance slope for motoring action, the A -phase current command is generated with a linear inductance profile. Here, phase advancing both at the beginning and during commutation are neglected. The current command i_a^* is enforced with a current feedback loop where it is compared with the phase current, i_a. The current error is presumed to be processed through a hysteresis controller with a current window of Δi. When the current error exceeds $-\Delta i$, the switches T_1 and T_2 are turned off simultaneously. Hysteresis current controller is considered here due to its simplicity in concept and implementation. At that time, diodes, D_1 and D_2 take over the current and complete the path through the dc source.

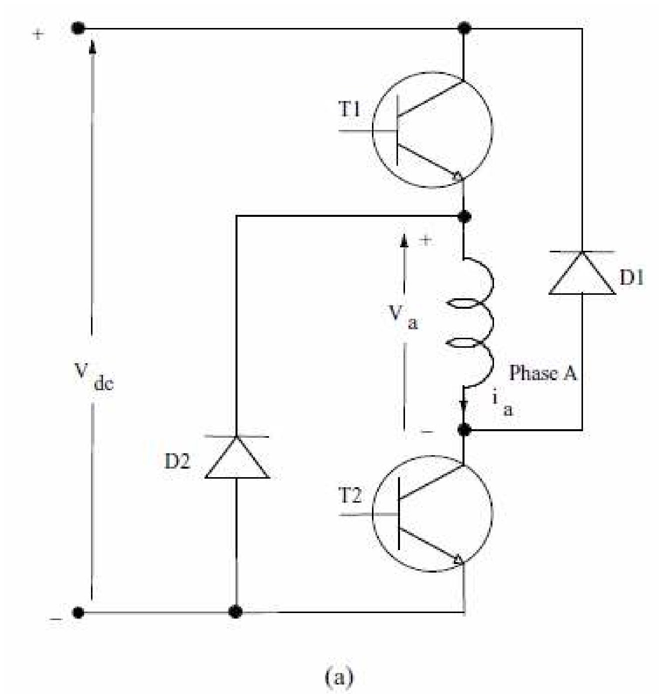


FIGURE 3.5 (a) Asymmetric converter for SRM with freewheeling and regeneration capability.

Note that the voltage of phase A is then negative and will equal the source voltage, Vdc. During this interval, the energy stored in the machine inductance is sent to the source, thus exchanging energy between the load and source repeatedly in one cycle of a phase current. After the initial startup, during turn-on and turn-off of T_1 and T_2, the machine phase winding experiences twice the rate of change of dc link voltage, resulting in a higher deterioration of the insulation. This control strategy (strategy I) hence puts more ripples into the dc link capacitor, thus reducing its life and also increasing the switching losses of the power switches due to frequent switching necessitated by energy exchange. These can be ameliorated with an alternate switching strategy.

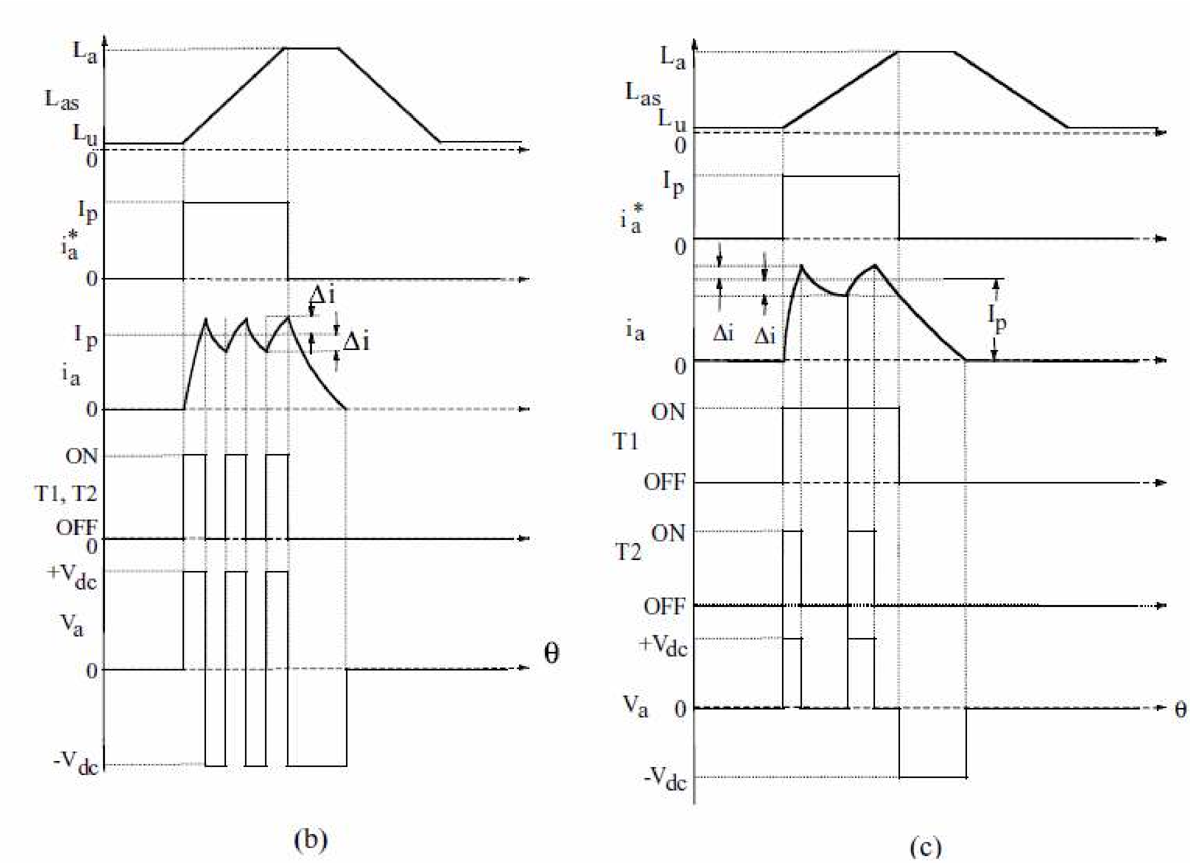


FIGURE 3.5 (b) Operational waveforms of the asymmetric bridge converter (strategy I); (c) Operational waveforms of the asymmetric bridge converter (strategy II).

The energy stored in the phase *A* can be effectively circulated in itself by turning off, say, T_2 only (strategy II). In that case, the current will continue to flow through T_1, phase *A*, and D_1, the latter having forward biased soon after T_2 is turned off. The voltage across the winding becomes zero if the diode and transistor voltage drops are neglected as shown in Figure 4.2c. That will take the phase current from $Ip + \Delta I$ to $Ip - \Delta i$ in a time greater than had it been forced against the source voltage using the previous strategy. This particular fact reduces the switching frequency and hence the switching losses. When the current command goes to zero, both T_1 and T_2 are turned off simultaneously. During this interval, the voltage across the winding is $-V_{dc}$ as long as D_1 and D_2 conduct (i.e., until i_a goes to zero) and thereafter the winding voltage is zero. The voltage across T_2 during its off time and when T_1 is on is equal to the source voltage, V_{dc}. Hence, the power switches and diodes have to be rated to a minimum of source voltage at least. The current ratings of the switches are equal to or less than $I_p/\sqrt{q}$ by interchanging the off times between $T1$ and $T2$ in one cycle of phase conduction. Similarly, the current rating of the diodes can be evaluated. While such a self-circulation will keep the current going for a longer time compared to recharging the source voltage, it has the advantage of converting the stored energy to useful mechanical work.

While this form of control can be used for current control, the recharging of the source is advantageous when the current has to be turned off rapidly. Such an instance arises when the inductance profile becomes flat or is starting to have a negative slope. Any further conduction of current in such regions entails a loss of energy or production of negative torque, thus reducing the average motoring torque. Note that this converter requires two transistors and two diodes for each phase, resembling the conventional ac motor drives.

3.10.3 SINGLE-SWITCH-PER-PHASE CONVERTERS

Single-switch-per-phase converters are appealing due to their compactness of converter package and hence a possible reduction in their cost compared to other converters. They also have the disadvantage of being unable to apply zero voltage across the machine phase during current conduction. Such an operational constraint increases the circulation of energy between the machine and dc link, resulting in higher losses and reduced system efficiency

3.10.3.1 R-DUMP

Figure 3.6 shows a converter configuration with one transistor and one diode per phase of the SRM. When T_1 is turned off, the current freewheels through D_1, charging C_s, and later flows through the external resistor R. This resistor partially dissipates the energy stored in phase A. This has the disadvantage that the current in phase A will take longer to extinguish compared to recharging the source. The energy, in addition, is dissipated in a resistor, thus reducing the overall efficiency of the motor drive.

Figure 3.6b shows the timing waveforms of the circuit in detail. The hysteresis current controller turns off T_1 when the phase current exceeds the current command, by Δi. Turning off T_1 will reduce the current, which in turn induces an emf in the winding to sustain i_a in the same direction. This emf forward biases diode D_1. The voltage across the resistor R is $i_a R$. Note that the voltage across the resistor has a positive polarity with respect to the positive rail of the source voltage. The voltage across T_1 during off time is then the sum of the source voltage and the voltage drop across the resistor is expressed as:

$$V_{T1} = V_{dc} + i_a R \qquad (3.15)$$

Design considerations such as the turn-off transient voltage have to be included in the rating of the switch T_1. The selection of R not only determines the power dissipation but also the switch voltage. A lower value of R increases the fall time of the current. If the current comes under the negative slope region of the phase inductance, negative torque will be generated, decreasing the average motoring torque. A high value of R increases the voltage drop across the winding and hence across T_1.

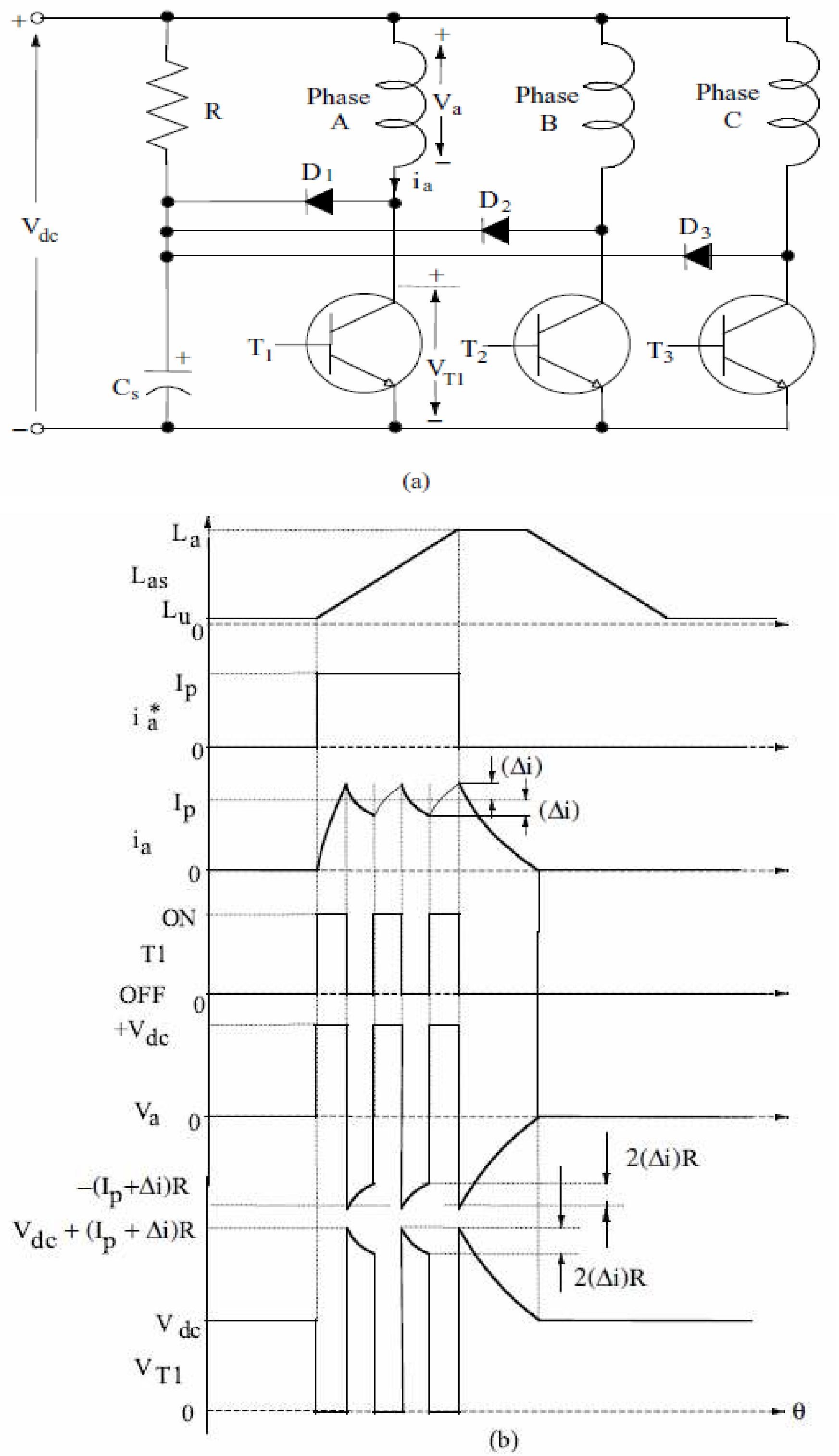


FIGURE 3.6 (a) Converter for SRM with freewheeling path; (b) operational waveforms of R-dump converter

3.10.3.2 BIFILAR TYPE

Figure 3.7a shows a converter configuration with one transistor and one diode per phase but regenerating the stored magnetic energy to the source. This is achieved by having a bifilar winding with the polarity as shown in the figure. When the phase-*A* current is turned off by removing the base drive signal to T_1, the induced emf in the winding is of such polarity that

D_1 is forward biased. This leads to the circulation of current through D_1, the bifilar secondary winding, and the source, thus transferring energy from the machine winding to the source.

The various timing waveforms of the circuit are shown in Figure 3.7b. During current turn-off, the applied voltage across the bifilar secondary winding is equal to the dc link voltage. The voltage reflected into the main winding is dependent upon the turns ratio of the windings. Considering the turns ratio between the main winding in series with the power switch and the auxiliary winding in series with the diode as a, the voltage across the power switch is

$$V_{T1} = V_{dc} + aV_{dc} = (1 + a)V_{dc} \qquad (3.16)$$

This shows that the voltage across T_1 can be very much greater than the source voltage. One switch per phase comes with a voltage penalty on the switch. The volt ampere (VA) capability of the switch will not be very different for one switch compared to two switches per phase circuit. The disadvantage of this drive is that the SRM needs a bifilar winding and such a form of winding is not economical for large motors. Also, the bifilar windings require additional slot volume, reducing the power density of the SRM.

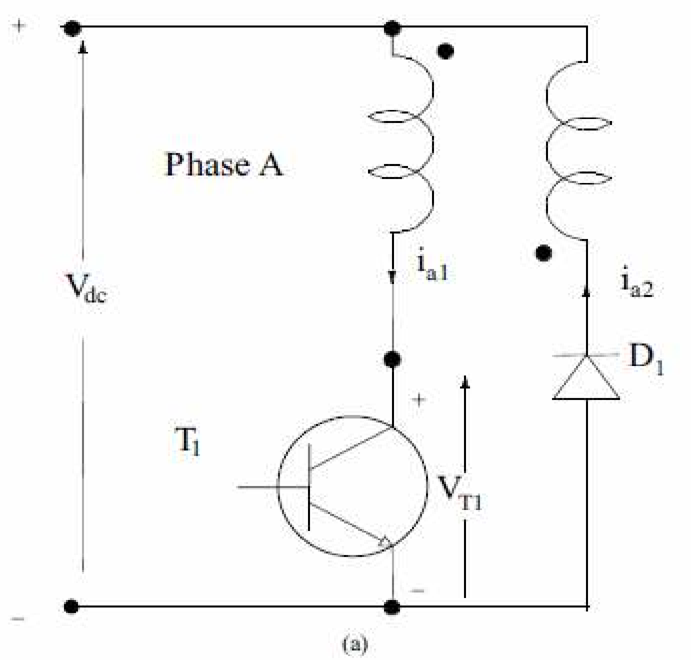


FIGURE 3.7 (a) Converter for an SRM with bifilar windings

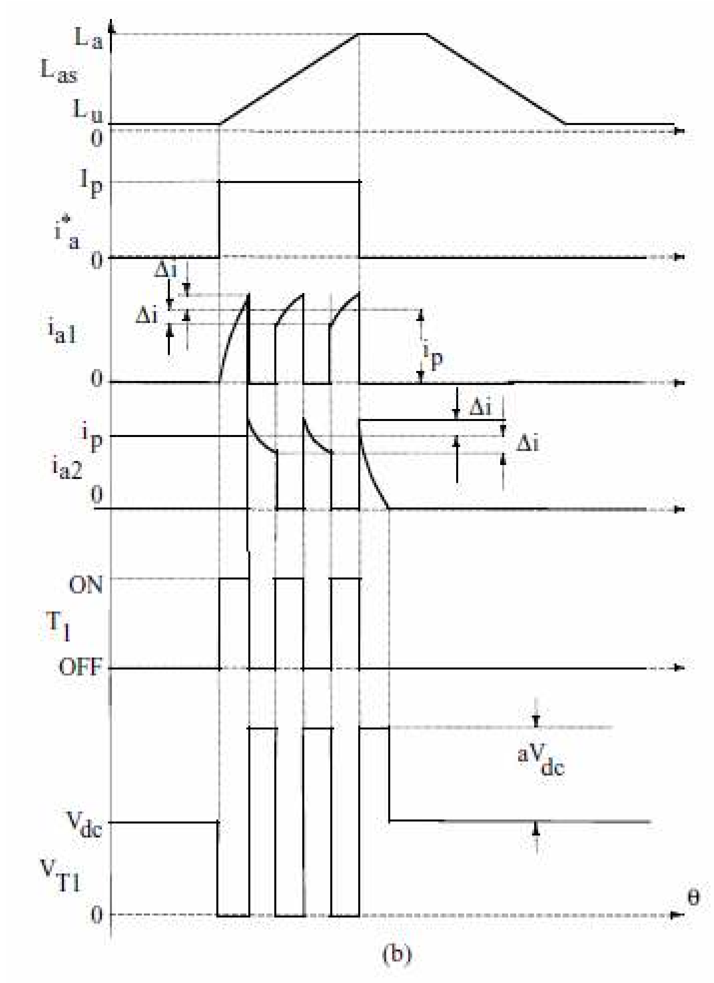


FIGURE 3.7 (b) operational waveforms of bifilar converter.

3.10.3.3 SPLIT DC SUPPLY CONVERTER

A split dc supply for each phase allows freewheeling and regeneration, as shown in Figure 3.8a. This topology preserves one switch per phase; its operation is as follows. Phase *A* is energized by turning on T_1. The current circulates through T_1, phase *A*, and capacitor C_1. When T_1 is turned off, the current will continue to flow through phase *A*, capacitor C_2, and diode D_2. In that process, C_2 is being charged up and hence the stored energy in phase *A* is depleted quickly. Similar operation follows for phase *B*. The operation of this circuit for phase *A* is shown in Figure 3.8b. A hysteresis current controller with a window of Δi is assumed. The phase voltage is V_{dc} /2 when *T*1 is on, and when it is turned off with a current established in phase *A*, the phase voltage is $-V_{dc}/2$. The voltage across the transistor T_1 during the on time is negligible, and it is V_{dc} when the current is turned off. That makes the switch voltage rating at least equal to the dc link voltage. As the stator current reference, goes to zero, the switch T_1 is turned off regardless of the magnitude of i_a. When the winding current becomes zero, the voltage across T_1 drops to 0.5 V_{dc} and so also does the voltage across D_2. Note that this converter configuration has the disadvantage of derating the supply dc voltage,

V_{dc}, by utilizing only half its value at any time. Moreover, care has to be exercised in balancing the charge of C_1 and C_2 by proper design measures.

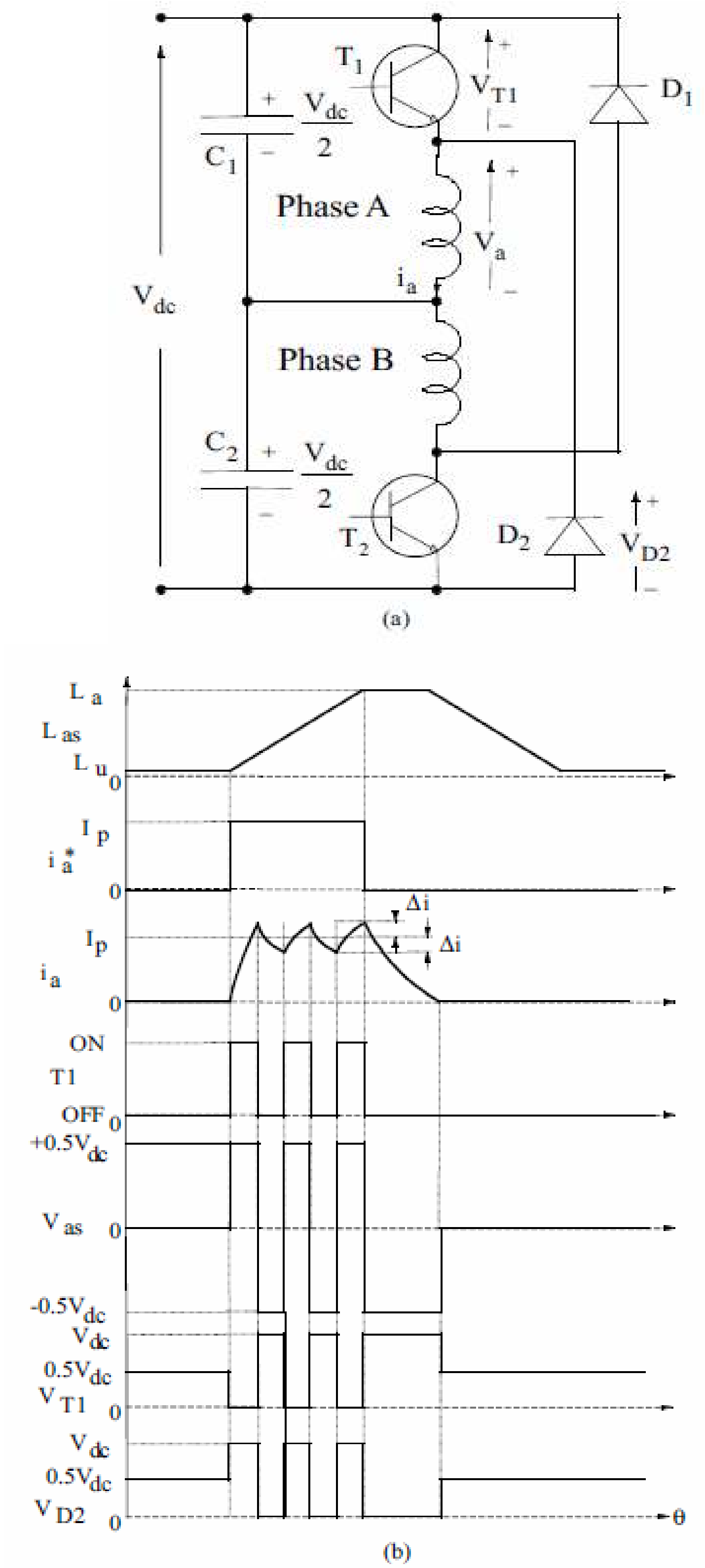


FIGURE 3.8 (a) Converter for SRM with split dc supply; (b) Operational waveforms of split dc supply converter.

For balancing the charge across the dc link capacitors, the number of machine phases has to be even and not odd. In order to improve the cost-competitive edge of the SRM drive, this converter was chosen in earlier integral horse power (hp) product developments, but its use in fractional hp SRM drives supplied by a single phase 120-V ac supply is much more justifiable; the neutral of the ac supply is tied to the midpoint of the dc link and so capacitors can be rated to 200 V dc, thus minimizing the cost of the converter.

3.10.4 (q + 1) SWITCH AND DIODE CONFIGURATIONS

3.10.4.1 C-DUMP CONVERTER

The C-dump converter is shown in figure 3.9 with an energy recovery circuit. The stored magnetic energy is partially diverted to the capacitor C_d and recovered from it by the single quadrant chopper comprising of T_r, L_r, and D_r and sent to the dc source. Assume that T_1 is turned on to energize phase *A* and when the *A*-phase current exceeds the reference, T_1 is turned off. This enables the diode D_1 to be forward biased, and the current path is closed through C_d which increases the voltage across it. This has the effect of reducing the *A*-phase current, and, when the current falls below the reference by Δi (i.e., current window), T_1 is turned on to maintain the current close to its reference. When current has to be turned off completely in phase *A*, T_1 is turned off, and partially stored magnetic energy in phase *A* is transferred to energy dump capacitor, C_d. The remaining magnetic energy in the machine phase has been converted to mechanical energy. Figure 3.9(b) shows the variables of interest in this converter.

This converter has the advantage of minimum switches allowing independent phase current control. The main disadvantage of this circuit is that the current commutation is limited by the difference between voltage across C_d, v_o, and the dc link voltage. Speedy commutation of currents requires larger v_o, which results in increasing the voltage rating of the power devices. Further, the energy circulating between C_d and the dc link results in additional losses in the machine, T_r, L_r, and D_r, there by decreasing the efficiency of the motor drive.

The energy recovery circuit is activated only when T_1, *T2, T3 orT4* switches are conducting to avoid freewheeling of the phase currents. The control pulses to T_r end with the turn-off of the phase switches. The control pulse is generated based on the reference and actual value of *E* with a window of hysteresis to minimize the switching of T_r.

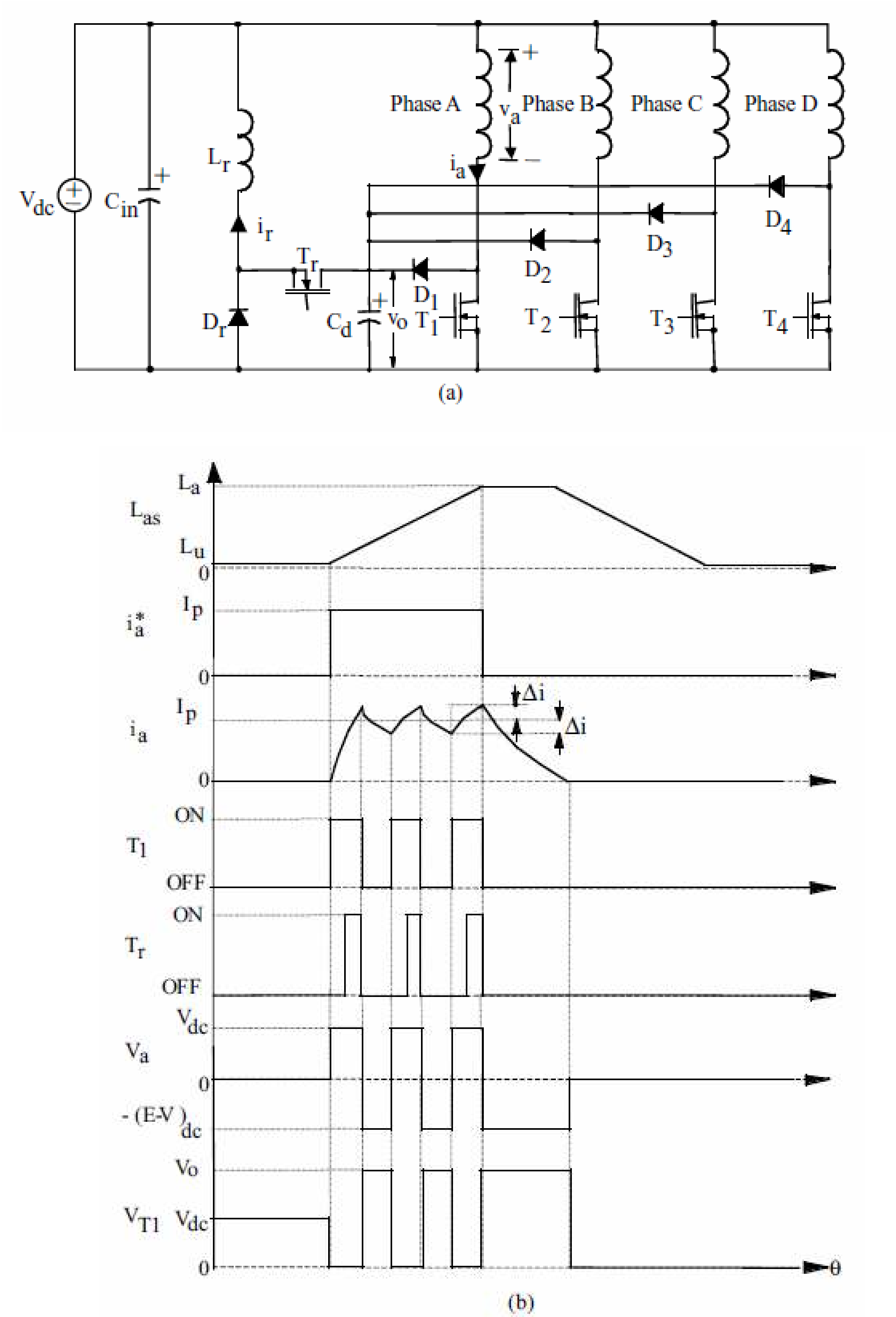


FIGURE 3.9 (a) C-dump converter with energy recovery circuit;
(b) Waveforms of C-dump converter with energy-recovery circuit.

3.11 MICROPROCESSOR BASED CONTROL OF SRM

This section describes a general purpose microprocessor controlled closed loop-switched reluctance motor (SRM) drive system. The system is designed to drive a four phase SRM with minimum number of switches, while achieving maximum flexibility. This section also describes the hardware for driving the motor, the techniques used to measure control parameters and how they are fed to the microprocessor. The operation of the microprocessor software to provide the user interface and control on the operation is given in detail.

The main objective of this microprocessor based control of SRM is to develop Software controllability of various modes of operation; here a microprocessor based control philosophy is adopted to achieve flexibility of adapting the controller-driver for various applications.

3.11.1 System Concept

Figure 3-10 shows the principal block diagram of the system concept for the switched reluctance motor.

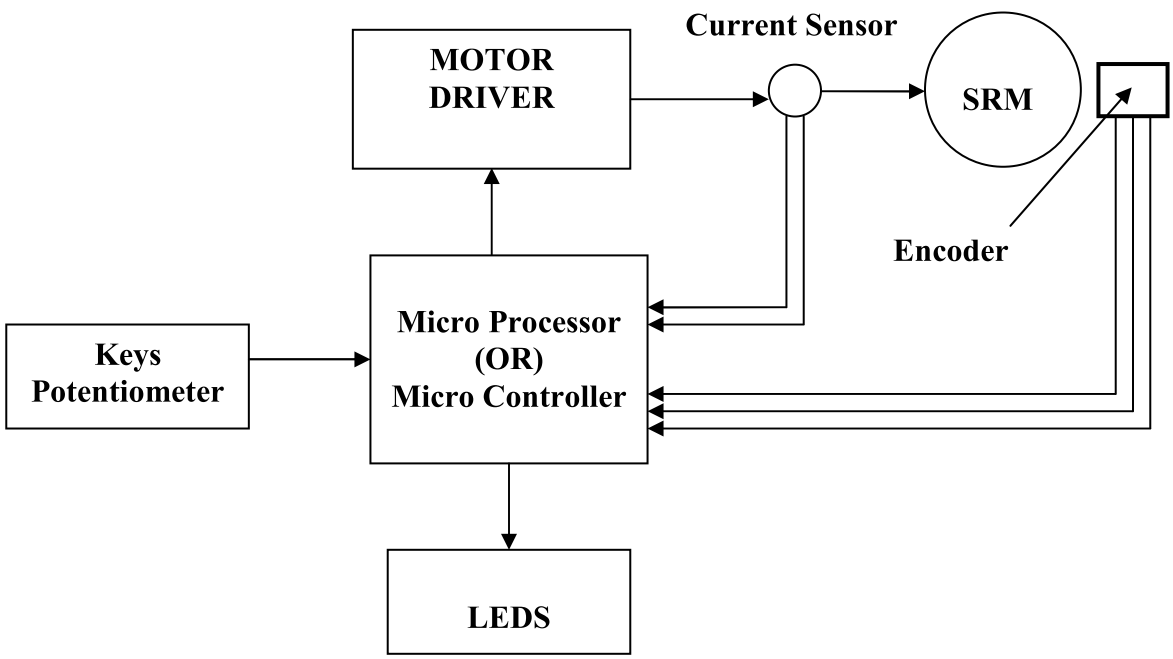


Figure 3.10 Principle Block Diagram of Microprocessor based SRM

This system can be designed to drive a SR motor. The application should meet the following performance specifications:

- ✓ Speed control of SR motor with encoder position sensor
- ✓ Variable line voltage up to rated 42V DC
- ✓ Control techniques incorporates
  - ❖ Voltage SRM control with speed closed loop.
  - ❖ Motor starts from any position with rotor alignment.
  - ❖ Two directions of rotation.
  - ❖ Motoring mode.
  - ❖ Minimal speed 600 rpm (can be set by user).
  - ❖ Maximal speed depended on line voltage 4320 rpm (can be set by user).

❖ Encoder position reference for commutation.

✓ User Interface (start/stop switch, right/left switch, potentiometer for speed adjustment, LED indicators).

✓ DC-Bus over current protection.

3.11.2 System Configuration

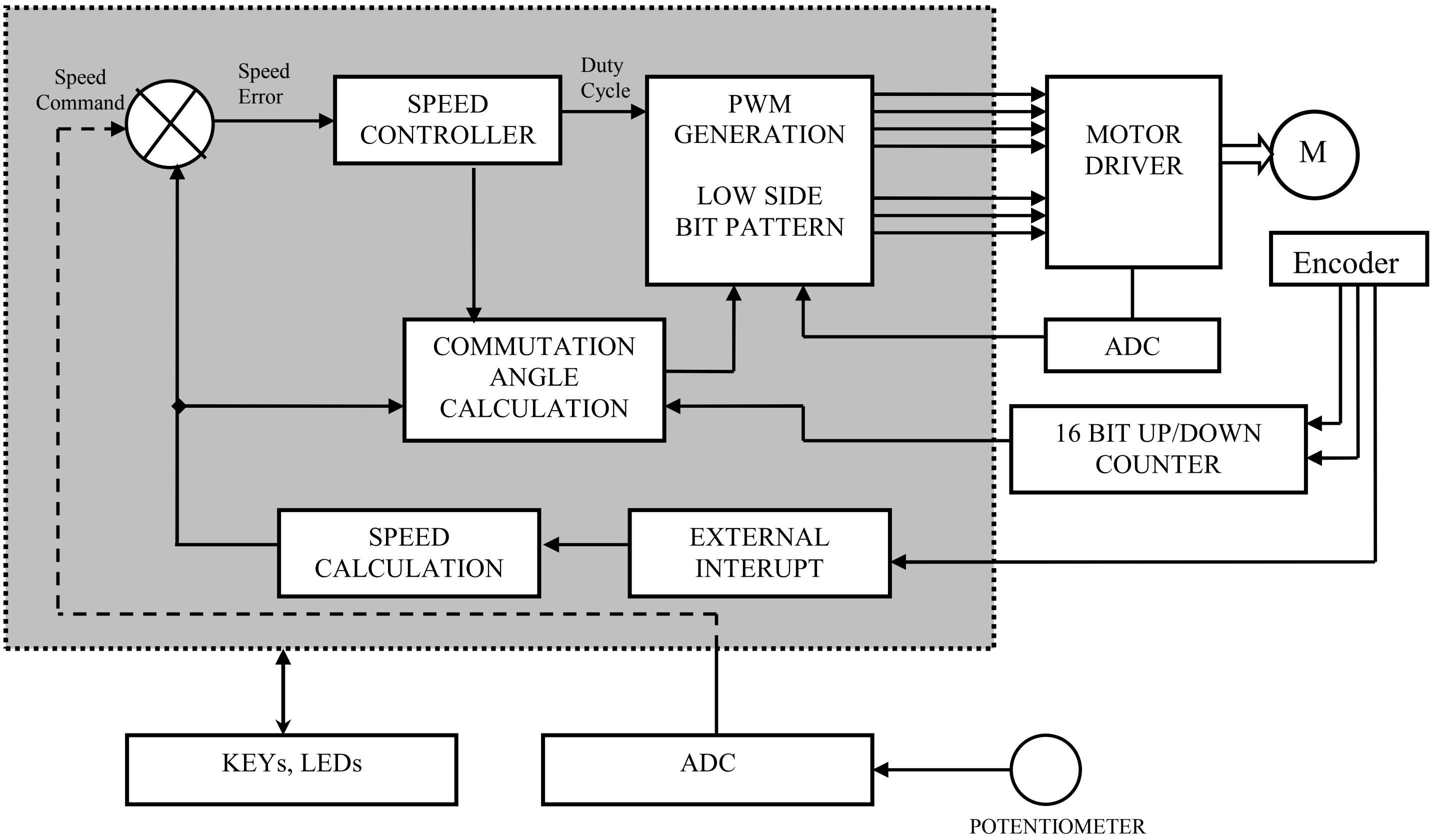


Figure 3.11 Microprocessor Based Control of SR motor

The microprocessor runs the main control algorithm. It generates 4-Phase PWM output signals for the SR motor power stage according to the user interface input and feedback signals. The required speed is set by a potentiometer, furthermore a start/stop and right/left switch is provided. When the start command is given the start-up sequence with the rotor alignment is performed and the motor is started in the desired direction. The rotor position is evaluated using the external encoder and the commutation angle is calculated. When the actual position of the motor is equal to the reference position, the commutation of the phases in the desired direction of rotation is done; the actual phase is turned off and the following phase is turned on. For the speed calculation no additional velocity sensor is needed, motor speed is derived from the position information. The reference speed is calculated from user defined potentiometer value. The speed error between commanded speed and actual speed is used in the speed controller to manipulate the voltage applied to each phase winding and the firing angles. As mentioned earlier PWM Voltage regulation is used in low- and mid speed regions, whereas advancing the turn-on angle in the single-pulse control comes active in the high speed area. The control algorithm is build up in such a matter, when the PWM regulation reaches its limits the single-pulse regulation takes over. Then during the PWM cycle, the actual phase current is compared with the absolute maximum value for the rated current. As soon as the actual current exceeds this value the PWM duty cycle is restricted. The procedure is repeated for each commutation cycle of the motor.

3.12 Torque–Speed Characteristics

The torque–speed plane of an SRM drive can be divided into three regions as shown in Fig. 3.12. The constant torque region is the region below the base speed ω_b, which is defined as the highest speed when maximum rated current can be applied to the motor at rated voltage with fixed firing angles. In other words, ω_b is the lowest possible speed for the motor to operate at its rated power.

Region 1

In the low-speed region of operation, the current rises almost instantaneously after turn-on, since the back-emf is small. The current can be set at any desired level by means of regulators, such as hysteresis controller or voltage PWM controller.

As the motor speed increases, the back-emf soon becomes comparable to the DC bus voltage and it is necessary to phase advance-the turn-on angle so that the current can rise up to the desired level against a lower back-emf. Maximum current can still be forced into the motor by PWM or chopping control to maintain the maximum torque production. The phase excitation pulses are also needed to be turned off a certain time before the rotor passes alignment to allow the freewheeling current to decay so that no braking torque is produced.

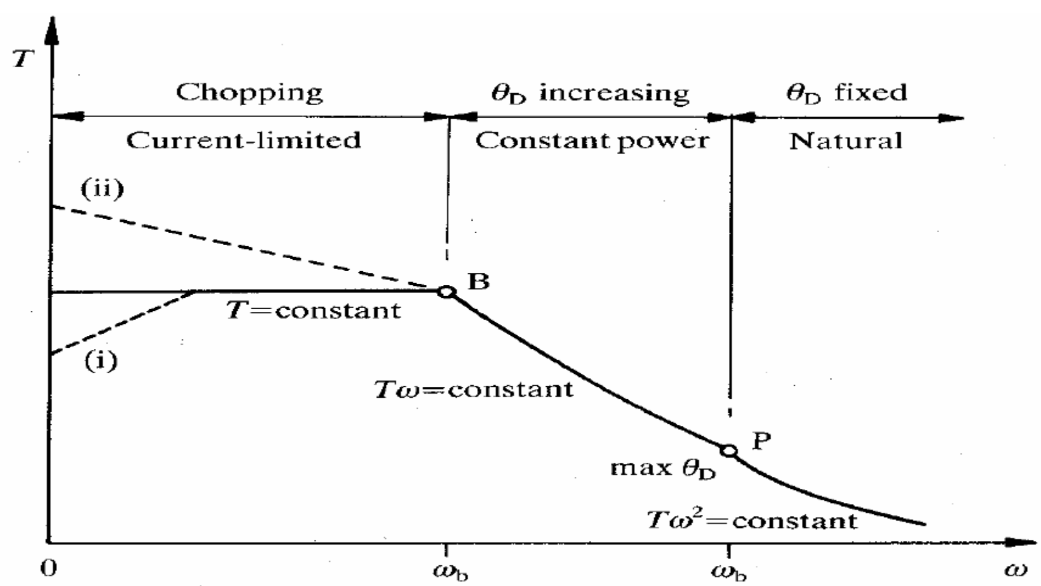


Fig 3.12 Torque Speed Characteristics of SRM

Region 2

When the back-emf exceeds the DC bus voltage in high-speed operation, the current starts to decrease once pole overlap begins and PWM or chopping control is no longer possible. The natural characteristic of the SRM, when operated with fixed supply voltage and fixed conduction angle θ_{dwell} (also known as the dwell angle), is that the phase excitation time falls off inversely with speed and so does the current. Since the torque is roughly proportional to the square of the current, the natural torque–speed characteristic can be defined by $T \alpha\ 1/\omega^2$. Increasing the conduction angle can increase the effective amps delivered to the phase. The torque production is maintained at a level high enough in this region by adjusting the conduction angle θ_{dwell} with the single-pulse mode of operation. The controller maintains the torque inversely proportional to the speed; hence, this region is called the constant power region. The conduction angle is increased by advancing the turn-on angle until the θ dwell reaches its upper limit at speed ω_p. The medium speed range through which constant power operation can be maintained is quite wide and very high maximum speeds can be achieved.

Region 3

The θ_{dwell} upper limit is reached when it occupies half the rotor pole-pitch, i.e., half the electrical cycle. θ_{dwell} cannot be increased further because otherwise the flux would not return to zero and the current conduction would become continuous. The torque in this region is governed by the natural characteristics, falling off as $1/\omega^2$. The torque–speed characteristics of the SRM are similar to those of a DC series motor, which is not surprising considering that the back-emf is proportional to current, and the torque is proportional to the square of the current.

3.13 SR MOTOR CONTROL

For motoring operation the pulses of phase current must coincide with a period of increasing inductance, i.e. when a pair of rotor poles is approaching alignment with the stator poles of the excited phase. The timing and dwell of the current pulse determine the torque, the efficiency, and other parameters. In d.c. and brushless d.c. motors the torque per ampere is more or less constant, but in the SR. motor no such simple relationship emerges naturally. With fixed firing angles, there is a monotonic relationship between average torque and r.m.s. phase current, but in general it is not very linear. This may present some complications in feedback-controlled systems although it does not prevent the SR motor from achieving 'near-servo quality' dynamic performance, particularly in respect of speed range, torque/inertia, and reversing capability.

At low speeds the self-e.m.f. of the winding is small and the current must be limited by chopping or p.w.m. of the applied voltage. The regulating strategy employed has a marked effect on the performance and the operating characteristics.

3.13.1 Hysteresis Type Regulator

Figure 3.13(a) shows schematically the method of control. As the current reference increases, the torque increases. At low currents the torque is roughly proportional to current squared, but at higher currents 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 characteristic as indicated in Fig. 3.14. With loads whose torque increases monotonically with speed, such as fans and blowers, speed adjustment is possible without tachometer feedback, but in general feedback is needed to provide accurate speed control. In some cases the pulse train from the shaft position sensor may be used for speed feedback, but only at relatively high speeds. At low speeds a larger number of pulses per revolution is necessary, and this can be generated by an optical encoder or resolver, or alternatively by phase-locking a high-frequency oscillator to the pulses of the commutation sensor (Bose 1986). Systems 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. Shunts or Hall-effect sensors can be used, or alternatively, 'Sensefets' with in-built current sensing. Much of the published literature on SR drives describes this form of control.

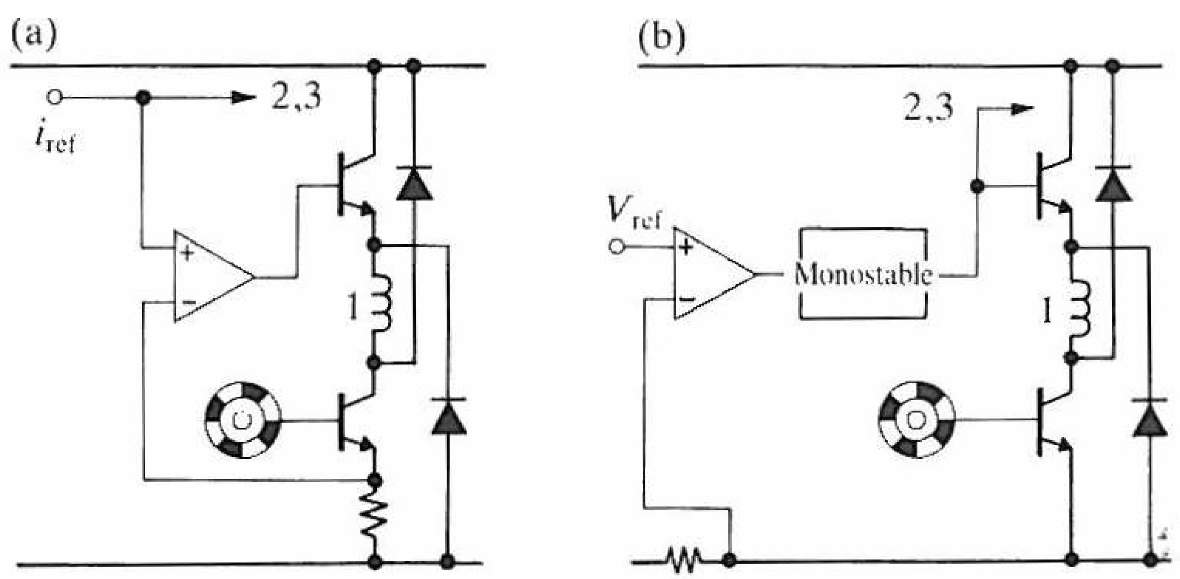


Fig 3.13 Schematic of Current regulated for one Phase

(a) Hysteresis Type (b) Voltage PWM Type (duty-cycle control)

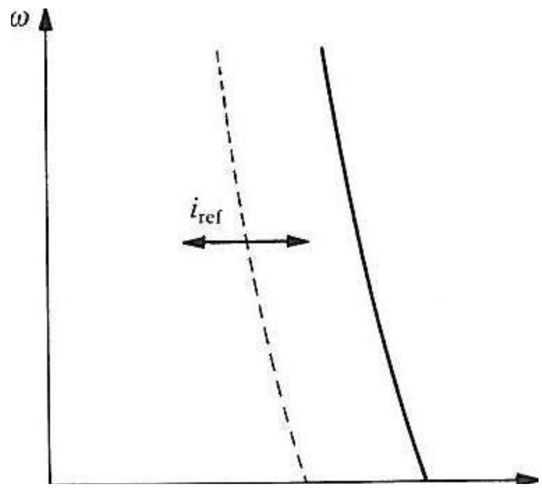


Fig. 3.14. Constant-torque characteristic obtained with regulator of Fig. 3.13(a)

3.13.2 Voltage PWM Type

Figure 3.13(b) shows an alternative regulator using fixed-frequency p.w.m. of the voltage with variable duty-cycle. Current feedback can be added to the circuit of Fig. 7.20(b) to provide a signal which, when subtracted from the voltage reference, modulates the duty cycle of the p.w.m. and 'compounds' the torque-speed characteristic. It is possible in this way to achieve under-compounding, over-compounding, or flat compounding just as in a d.c. motor with a wound field. For many applications the speed regulation obtained by this simple scheme will be adequate. For precision speed control, normal speed feedback can be added. The current feedback can also be used for thermal over current sensing.

A desirable feature of both the 'hysteresis-type' current-regulator and the voltage p.w.m. regulator is that the current waveform tends to retain much the same shape over a wide speed range. When the p.w.m. duty cycle reaches 100 per cent the motor speed can be increased by increasing the dwell (the conduction period), the advance of the current-pulse relative to the rotor position, or both. These increases eventually reach maximum practical 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 obtained, as in the synchronous reluctance motor and induction motor, because there is not the limitation imposed by fixed excitation as in PM motors.

TWO MARKS QUESTIONS AND ANSWERS

1. Define Switched Reluctance Motor

SRM is a doubly salient and singly excited motor. That means both the stator and rotor has salient poles but only one usually stator carries the winding which operates based on the reluctance principle.

2. Write two distinguished points between Switched Reluctance and stepper motor.

- The SRM motor is normally operated with shaft position feed back to synchronize the commutation of the phase currents with precise rotor positions, where as stepper motor is normally run in open loop, i.e. without shaft position feedback.
- SRM is normally designed for efficient conversion of significant amounts of power, stepper motors are more usually designed to maintain step integrity in position controls.

3. Write the advantages of SRM.

- Machine construction ***is simple and low-cost because*** of the ***absence of rotor winding*** and permanent magnets.
- There are ***no shoot-through faults between the DC buses*** in the SRM drive converter because ***each rotor winding is connected in series with converter*** switching elements.
- ***Bidirectional currents are not necessary***, which facilitates ***the reduction of the number of power switches*** in certain applications.
- The bulk of the losses appear in the stator, which is relatively ***easier to cool***.
- The torque–speed characteristics of the motor ***can be modified to the application requirement more easily*** during the design stage than in the case of induction and PM machines.
- The starting torque can be ***very high without the problem of excessive in-rush current*** due to its higher self-inductance.
- The open-circuit voltage and short-circuit current at faults ***are zero or very small***.
- The maximum permissible ***rotor temperature is higher***, since there are no permanent magnets.
- There is ***low rotor inertia and a high torque/inertia ratio***.
- Extremely ***high speeds with a wide constant power region*** are possible.
- There are independent stator phases, ***which do not prevent drive operation*** in the case of loss of one or more phases.

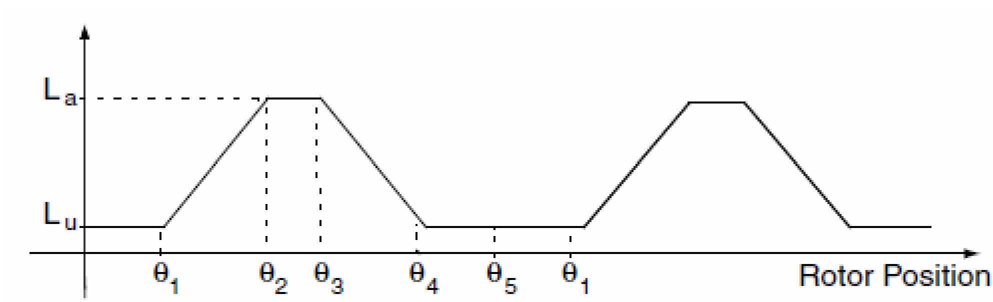
4. **List the disadvantages of SRM.**
   - The SRM also comes with a few disadvantages among ***which torque ripple and acoustic noise are the most critical***. The higher torque ripple also ***causes the ripple current in the DC supply*** to be quite large, ***necessitating a large filter capacitor***. The doubly salient structure of the SRM also causes ***higher acoustic noise compared with other machines***.
   - The absence of permanent magnets ***imposes the burden of excitation on the stator windings and converter***, which increases the ***converter KVA requirement***. Compared with PM brushless machines, the ***per unit stator copper losses will be higher, reducing the efficiency and torque per ampere***. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRMs.
5. **Define aligned and unaligned inductance**
   - The inductance measured at the position as the conjunction of any rotor inter pole axis with the axis of the stator poles of the phase is called as unaligned inductance.
   - The inductance measured at the position as the conjunction of any rotor pole axis with the axis of the stator poles of the phase is called as aligned inductance.
6. **Write the instantaneous torque equation of switched reluctance motor.**

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

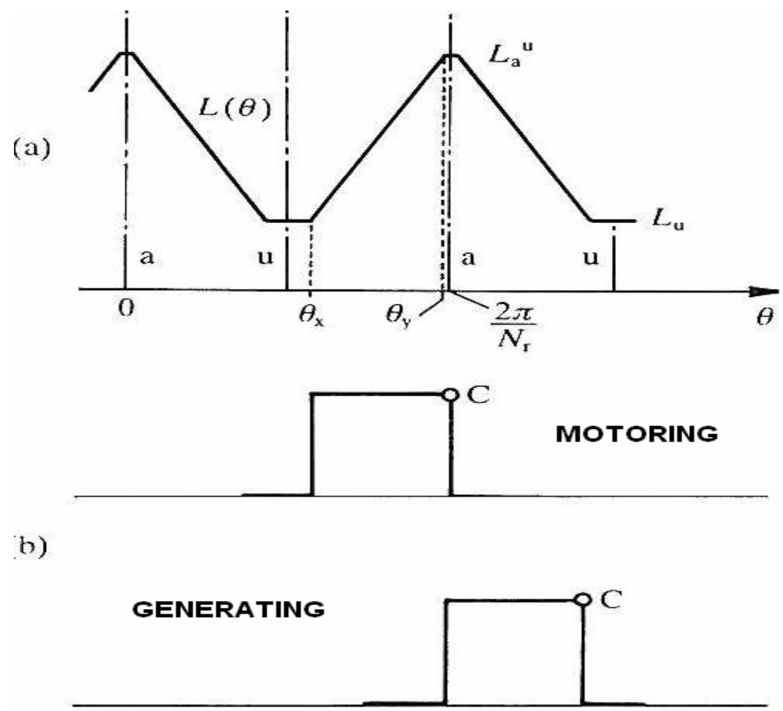
Where

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

7. **Draw the inductance variation with respect to the rotor position in SRM.**



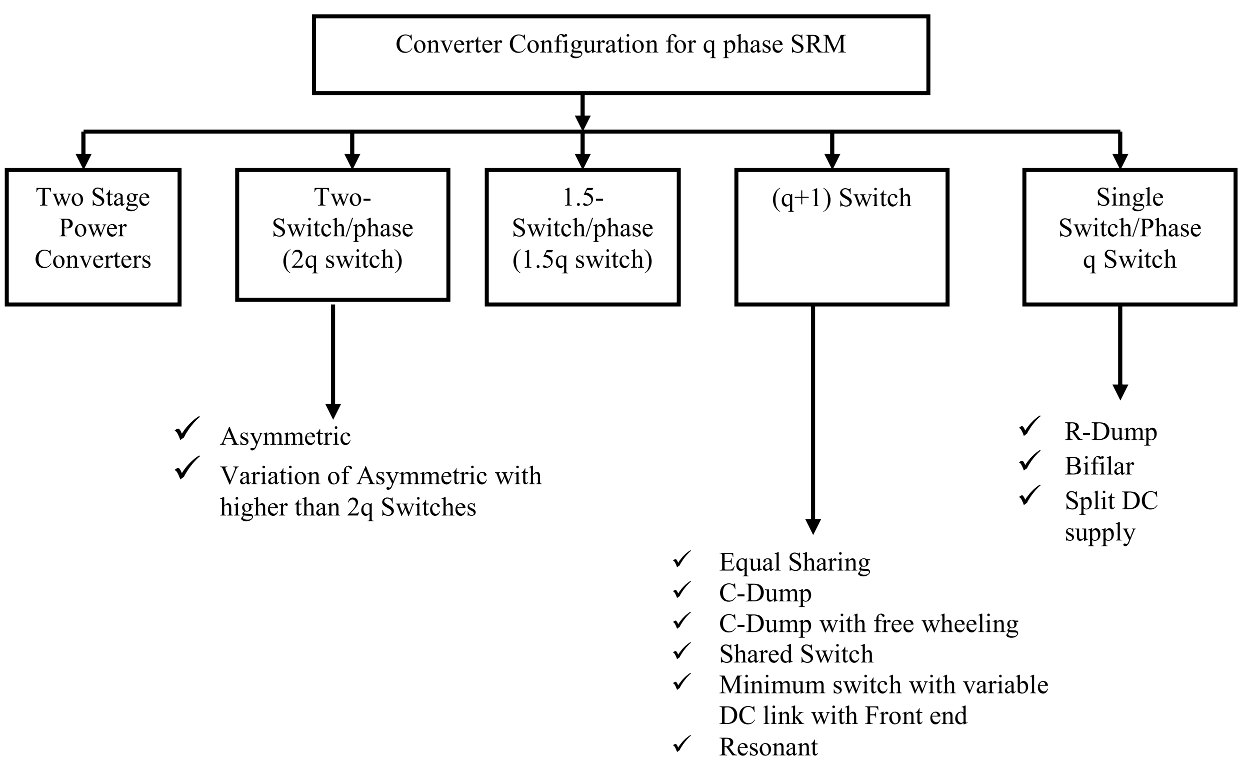
8. Draw the ideal current wave form for motoring and generating



9. Bring out the requirements to get the maximum torque per ampere.

- Unsaturated aligned inductance should be as large as possible by implying a small air gap with wide slots.
- Smallest possible unaligned inductance can be achieved by a large inter polar arc on the rotor, narrow stator poles and deep slotting on both stator and rotor
- The highest possible saturation flux density.

10. What are the types of converters used to drive SRM?



11. Which makes the SRM to use unipolar controller circuit?

The torque is independent of the direction of the phase current which can therefore be unidirectional. This permits the use of unipolar controller circuit for SRM.

12. Write the advantages of 2n transistor converter circuit

- This circuit provides the maximum control flexibility and efficiency, with a minimum of passive components.
- By controlling the upper and lower transistors independently all possible firing angles can be used.
- In small drives PWM control over the entire speed range is possible.

13. How the phase windings of the SRM are connected with the converter circuit and compare it with the normal inverter with windings.

The phase winding is connected in between the two control switches on the same leg. But in inverter the windings are connected from the mid points of adjacent phase legs. No simultaneous switching ON process of the switches in the same leg.

14. State the advantages and limitations of bifilar winding converter circuit.

Advantages:

To reduce the number of switching devices bifilar winding is used.

Limitation:

- Double the numbers of connections are used.
- Poor utilization of copper
- Voltage spikes due to imperfect coupling

15. What is C dump converter circuit?

One capacitor is used in the circuit with one more phase to bleed the stored energy in the capacitor.

16. What are the types of control method used to control SRM?

(a) Hysteresis Type

(b) Voltage PWM Type (duty-cycle control)

17. Draw the torque speed characteristics of SRM