CHAPTER 2

SWITCHED RELUCTANCE MOTOR
AND ITS APPLICATION

2.1 INTRODUCTION

The concept of switched reluctance motor was established in 1838 but the motor could not realize its full potential until the modern era of power electronics and computer aided electromagnetic design. SRM’s are electrically commutated AC machines and are known as variable reluctance motor as studied by Lawrenson et al (1980). They are more than a high-speed stepper motor, lacking the usual expensive permanent magnets. It combines many of the desirable qualities of Induction-motor drives, DC commutator motor drive, as well as Permanent Magnet (PM) brushless D.C systems. SRM is rugged and simple in construction and economical when compared with the synchronous motor and the induction motor. They are known to have high peak torque-to-inertia ratios and the rotor mechanical structure is well suited for high-speed applications.

In addition to that, unipolar drive of the reluctance motor is possible and therefore, the converter requires fewer switching devices compared with the conventional inverter. From these reasons, the drive system can be more simple, economical, and reliable. It is cheap to manufacture, robust and can operate under partial failure. Its power converter has no chance for shoot-through faults. The SRM show a promise as potentially low cost electromechanical energy conversion devices because of their simple
mechanical construction. The advantages of switched reluctance motor are the production cost, efficiency and the torque/speed characteristics. Due to the above advantages and since SRM is becoming the competitor for induction and DC machines, this work aims in developing better control scheme for SRM. Once the drawback of high torque ripple is reduced this motor can be effectively and successfully implemented in market for day to day life. So this chapter presents the detail knowledge of SRM which would help to understand the control schemes which follows.

2.2 CONSTRUCTION OF SWITCHED RELUCTANCE MOTOR

The switched reluctance motor has both salient pole stator and rotor, like variable reluctance motor (Nazar 1969), but they are designed for different applications, and therefore, with different performance requirements. A stepper motor is designed to make it suitable for open loop position and speed control in lower applications, where efficiency is not an important factor. On the other hand a switched reluctance motor is used in variable speed drives and naturally designed to operate efficiently for wide range of speed and torque and requires rotor position sensing.

A switched reluctance motor is an electric motor in which the torque is produced by the tendency of its movable part to move to a position of least reluctance, which corresponds to the position of maximum inductance (Miller 1993). It is a doubly salient, singly excited motor. That is, the SRM has salient poles on both the rotor and the stator, but only the stator poles carry windings. The rotor tries to get to a position of minimum reluctance by aligning itself with the stator magnetic field. In the presence of a rotating magnetic field, the rotor tries to rotate along with the rotating magnetic field to be always in a position of minimum reluctance. Thus, exciting the stator phase windings of the motor in a particular sequence and consequently, controlling the rotating magnetic field, the movement of the rotor can be
controlled. Figure 2.1 shows a typical 6/4 SRM. It is a three-phase machine and has 6 poles on the stator and 4 poles on the rotor. The number of poles on the stator and on the rotor is usually not equal. This is to avoid the eventuality of the rotor being in a state of producing no initial torque, which occurs when all the rotor poles are locked in with the stator poles.

![Figure 2.1 Switched Reluctance Motor]

Here, the diametrically opposite stator pole windings are connected in series and they form one phase. Thus, the six stator poles constitute three phases. When the rotor poles are aligned with the stator poles of a particular phase, the phase is said to be in an aligned position. Similarly, if the interpolar axis of the rotor is aligned with the stator poles of a particular phase, the phase is said to be in an unaligned position.

In a three-phase SRM, the direction of rotation of the rotor is opposite to the direction of the switching sequence of stator poles. A unique feature of SRM is that it can be operated with reduced power output, even when there is a loss of one of the phases.
2.3 MATHEMATICAL MODEL OF THE SRM

Let us consider an elementary reluctance machine as shown in Figure 2.2. The machine is single phase exited; that is, it carries only one winding on the stator. The excited winding is wound on the stator and the rotor is free to rotate.

The flux linkage is

\[ \lambda (\theta) = L(\theta)i \]  \hspace{1cm} (2.1)

where \( i \) is the independent input variable, i.e. the current flow through the stator. The general torque expression is given by

\[ T_e = \left[ \frac{\partial W'}{\partial \theta} \right]_{i=\text{constant}} \]  \hspace{1cm} (2.2)

where \( W' \) is the co-energy which is varying with respect to position of the motor. At any position the co-energy is the area below the magnetization curve as shown in the Figure 2.3 and Figure 2.4. In other words, the definite integral

\[ W' = \int_0^i \lambda (\theta, i) \, di \]  \hspace{1cm} (2.3)
Where \( \lambda(\theta, i) \) is the flux linkage with respect to angular position \( \theta \) and current ‘i’. So the torque equation becomes

\[
T_e = \int_0^i \frac{\partial \lambda(\theta, i)}{\partial \theta} \, di
\]  

(2.4)

The mechanical work done

\[
\Delta W_m = \Delta W^2
\]  

(2.5)

Where \( W_m \) is the mechanical energy and \( W \) is the stored magnetic energy. At any rotor position \( \theta \), the co-energy and the stored magnetic energy are equal and is given by

\[
W_f = W' = \frac{1}{2} L(\theta) i^2
\]  

(2.6)

**Figure 2.3 Flux Linkage Chart**

The instantaneous torque reduces to

\[
T_e = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta}
\]  

(2.7)

As most SRM is multiphase, the torque equation becomes a summation of torques produced by each phase. For \( m \) phases, the total torque is given by
Where $T_{ej}$ is the torque due to single phase.

### 2.4 SRM PRINCIPLE OF OPERATION

SRM differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles. Figure 2.5 illustrates a typical 3-Phase SRM with a six stator / four rotor pole configuration. The rotor of an SRM is said to be at the aligned position with respect to a fixed phase if the current reluctance has the minimum value (Corda et al 1979); and the rotor is said to be in the unaligned position with respect to a fixed phase if the current reluctance reaches its maximum value.

The motor is excited by a sequence of current pulses applied at each phase. The individual phases are consequently excited, forcing the motor to rotate. The current pulses must be applied to the respective phase at the exact rotor position relative to the excited phase. When any pair of rotor poles is exactly in line with the stator poles of the selected phase, the phase is said to
be in an aligned position; i.e., the rotor is in the position of maximum stator inductance (Figure 2.5).

**Figure 2.5 Three-Phase SRM**

The inductance profile of SRM is triangular, with maximum inductance when it is in an aligned position and minimum inductance when unaligned. Figure 2.6 illustrates the idealized triangular inductance profile of all three phases of an SRM, with phase A highlighted. The individual phases A, B, and C are shifted electrically by 120° relative to each other. The interval, during which the respective phase is powered, is called the dwell angle, \( \theta_{\text{dwell}} \). It is defined by the turn-on \( \theta_{\text{on}} \) and the turn-off \( \theta_{\text{off}} \) angles.

**Figure 2.6 Phase Energizing**
When the voltage is applied to the stator phase, the motor creates torque in the direction of increasing inductance. When the phase is energized in the minimum inductance position, the rotor tends to attain the forthcoming position of maximum inductance. This movement is defined by the magnetization characteristics of the motor.

A typical current profile for a constant phase voltage is shown in Figure 2.6. For a constant phase voltage, the phase current has its maximum value in the position when the inductance begins to increase. This corresponds to the position where the rotor and the stator poles start to overlap. When a phase is turned off, the current flowing in that phase reduces to zero. The phase current present in the region of decreasing inductance generates negative torque. The torque generated by the motor is controlled by the applied phase voltage and the appropriate definition of switching turn-on and turn-off angles. As is apparent from the description, the SRM requires position feedback for motor phase commutation. In many cases, this requirement is addressed by using position sensors, such as encoders or Hall sensors. The result is that the implementation of mechanical sensors increases costs and decreases system reliability.

When current flows in a phase, the resulting torque tends to move the rotor in a direction that leads to an increase in the inductance. Provided that there is no residual magnetization of steel, the direction of current flow is immaterial and the torque always tries to move the rotor to the position of highest inductance. Positive torque is produced when the phase is switched on while the rotor is moving from the unaligned position to the aligned position as shown in Figure 2.7.

The phase voltage of the switched reluctance motor can be written as
\[ V = iR + \frac{d\lambda}{dt} \]  

(2.9)

where \( V \) is the bus voltage, ‘\( i \)’ is the instantaneous phase current, \( R \) is the phase winding resistance and \( \lambda \) flux linking of the coil. Ignoring stator resistance, the above equation can be written as

\[ V = L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} * \omega \]  

(2.10)

where \( \omega \) is the rotor speed and \( L(\theta) \) is the instantaneous phase resistance. The rate of flow of energy can be obtained by multiplying the voltage with current and can be written as

\[ Vi = Li \frac{di}{dt} + i^2 \frac{dl}{d\theta} * \omega \]  

(2.11)

![Diagram](image.png)

**Figure 2.7 Inductance Profile of One Phase SRM**

The equation given above can also be given in the form

\[ P = \frac{d}{dt} \left( \frac{1}{2} Li^2 \right) + \frac{1}{2} i^2 \frac{dl}{d\theta} * \omega \]  

(2.12)
where, the first term of the above equation represents the rate of increase in the stored magnetic field energy while the second term is the mechanical output. Thus, the instantaneous torque can be written as

\[
T(\theta, i) = \frac{1}{2} i^2 \frac{dL}{d\theta}
\]  

(2.13)

Thus positive torque is produced when the phase is switched on during the rising inductance. Consequently, if the phase is switched on during the period of falling inductance, negative torque will be produced.

2.5 FLUX LINKAGE CHARACTERISTICS OF SRM

The double saliency structure of the SRM causes its highly nonlinear motor characteristics of the motor. Compared with the other types of motor, the relationship between the electrical torque and stator current of the SRM appears to be more complex. Generally the generated electric torque can be approximated by a high order polynomial of the stator current with an order equal to or larger than two. Even for the simplest case in the linear flux region, the electrical torque is not a linear function of the stator current as stated by Miller et al (1980). That is one main reason why the control of the SRM is so challenging.

The flux linkage \( \lambda \) of a SRM (Figure 2.8) is a function of both \( i \) and the rotor position \( \theta \). For fixed rotor position \( \theta \), the flux linkage \( \lambda \) is a purely linear function of the stator current \( i \) only under the case when there is no saturation effect. Generally, when the stator current is under certain value, the relationship between \( \lambda \) and \( i \) appear to be linear. For fixed stator current \( i \), \( \lambda \) is a periodic function of rotor position with period equal to \( 2\pi / N_r \) and is bounded between the aligned and unaligned position.
2.6 SPEED TORQUE CHARACTERISTICS OF SRM

Generally, a control scheme is based on the torque-speed characteristics of a motor. Figure 2.9 describes the three basic modes of operation of switched reluctance motor based on the torque-speed characteristic. Currents in the stator circuits are switched on and off in accordance to the rotor position. With this simplest form of control, the switched reluctance motor inherently develops the torque speed characteristics typical to that of a DC machine.
This first mode is the natural one with fixed supply voltage and fixed switching angles. The operating region is the constant torque region, below rated speed. Base speed ($\omega_b$) is defined as the highest speed at which maximum current can be supplied to the motor ($I_{\text{max}}$) at rated voltage, with fixed switching angles. There is, of course, a family of characteristics for varying supply voltages. At a given speed the flux is proportional to the voltage $V$, and the torque varies with the current squared. The chopping voltage control is able to control an SRM drive only in the mode below rated speed where the generated voltage, being larger than the back-EMF, forces the drive states on the sliding surface.

If fixed switching angles are maintained at speeds above $\omega_b$, the torque falls as $1/\omega$. This is the second important mode of operation, when the machine speed is above base speed ($\omega_b$). A control alternative for the switched reluctance motor is to reduce the conduction angle $\theta_c = \theta_{\text{off}} - \theta_{\text{on}}$ at constant voltage. In this mode, the voltage generated is fully applied across the phase till $\theta_{\text{off}}$ and the current decreases. There is a practical limitation for increasing the conduction angle. If it is increased the turn-off angle corresponds to the next cycle turn-on angle, then the flux level would not return to zero at the end of each pulse. In this case, the net flux in the phase winding would increase until the machine gets continuously saturated. This corresponds to a rotor speed $\omega_p$, above which the fall of the torque production is $1/\omega^2$.

2.7 CONVERTER TOPOLOGY

As the torque is independent of the direction of phase current, the unipolar controller circuits can be used. Although, the SRM could be operated with alternating (but non-sinusoidal) current, unidirectional (DC) current has the added advantage of reducing the hysteresis losses. As the phases are independent, the SRM controller (Sood 1992) differs from the AC inverter, in which the motor windings are connected between the midpoints of adjacent inverter phase legs. Also, in an AC inverter the upper and lower leg switches
must be prevented from switching on simultaneously to avoid the shorting of the DC supply, by an additional control circuitry, which is not needed in SRM controller. Vukosavic et al (1990) proposed a comparative evaluation of the various converter configurations for SRM drives like,

- Two transistors per phase circuit.
- N+1 transistor for n phase motor.
- Bifilar winding arrangement.
- Split link converter circuit.
- C-dump converter circuit.

### 2.7.1 Two Transistors per Phase Circuit

The two transistors per phase circuit given by Pollock et al (1988) are the commonly used because of their maximum control flexibility. Though single ended converters can be used, the favorite choice is the two-transistor forward converter topology (asymmetric half-bridge), Figure 2.10 which has two power switches connected to either end of the power rails and in series with the phase winding for fluxing the machine. Two diodes are connected parallel to the switches to provide the return path.

![Figure 2.10 Unipolar Converters with Two Switches per Phase](image)

**Figure 2.10 Unipolar Converters with Two Switches per Phase**
The upper and lower phase-leg switches are switched ON together at the start of each conduction period or working stroke. At the commutation point, they are switched off. During the conduction period either or both of them can be chopped according to control strategy at low speeds as the self-EMF of the motor is much smaller than the supply voltage. But at high speeds, both transistors remain ON throughout the conduction period. Generally, it is convenient to use one transistor primarily for ‘commutation’ and the other for ‘regulation’ or ‘chopping’. At the end of the conduction period when both switches are OFF, any stored energy that is not converted to mechanical work is returned to the supply by the current freewheeling through the diodes. When the diodes are forward biased, they connect the negative of the supply voltage across the winding to reduce the flux linkage quickly to zero. The hysteresis type current regulation is used in this circuit, where the chopping frequency varies with pole alignment.

2.7.2 C-Dump Converter

The C-dump converter designed by Hava et al (1991) for variable reluctance motor is as shown in Figure 2.11 is 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 \( D_t \) and sent to the DC source. Assume that \( T_1 \) is turned on to energize phase A and when the phase A current exceeds the reference, \( T_1 \) is turned off. This enables the diode \( D_1 \) to get forward biased, and the current path is closed through \( C_d \) which increases the voltage across it. This has the effect of reducing the phase A current, and, when the current falls below the reference by \( \Delta_i \) (i.e., current window), \( T_1 \) is turned on to maintain the current close to its reference. When the current has to be cut 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 is converted into mechanical energy.
This converter has the advantage of minimum switches with single switch per phase (Krishnan 1990) 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 \( D_r \), thereby decreasing the efficiency of the motor drive.

The energy recovery circuit is activated only when \( T_1 \), \( T_2 \), \( T_3 \), or \( T_4 \) 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 \( T_r \).

2.8 DESIGN OF NEW CONVERTER TOPOLOGY

To combine the advantages of C Dump converter and two transistors per phase scheme, a new converter topology was designed with four controlled switches and diodes are shown in Figure 2.12. The front-end consists of a Single Ended Primary Inductor Conductor (SEPIC) DC/DC converter.
converter comprised of inductors L₁ and L₂, switch Q₁, intermediate capacitor C₁, diode D₁ and output capacitor C₂. Switches Qₐ, Qₕ and Qₖ respectively control the current through the phases A, B and C. The diodes Dₐ, Dₕ and Dₖ serve to freewheel the winding currents during current regulation and phase commutation. The voltage of capacitor C₁ is used for current control and to demagnetize the phases during turn-off.

It uses two separate control voltages for magnetization and demagnetization. The converter operation can be explained for a single phase, say phase A, in four states:

State 1: Magnetization. Qₐ is on, impressing the Vc₂ Voltage across the winding.

State 2: Forced demagnetization. Qₐ is off. Dₐ conducts. The intermediate capacitor C₁ helps in the demagnetization of the winding magnetic energy through Q₁.

State 3: Discharging of C₁. When Q₁ is on, C₁ discharges which builds the current in L₂. Note that the AC line contributes to the L₂ current.

State 4: Charging of C₂. Q₁ is off. D₁ conducts, transferring the energy stored in L₂ to C₂.

Figure 2.12 Schematic of Proposed Converter Operating From an AC Supply
At low speeds, when the back-EMF is low, the switching frequency increases to regulate the phase current. By bucking the input voltage to lower levels at the output $V_{dc}$, the switching frequency and hence the losses at low speeds are minimized. At higher speeds, because of the high back EMF voltage, the SEPIC front-end boost the available input voltage to maintain current regulated operation of the drive. This feature makes the proposed topology particularly suitable for low voltage DC applications such as automotive circuits.

For AC applications, it is desired to obtain improved power factor. The front-end converter could be designed to operate either in Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM). For low power levels, it is preferable to operate the SEPIC front-end in DCM. The converter works as a voltage follower and the power factor is maintained nearly unity.

Hysteresis control of the switches helps to regulate the phase currents to their reference values. Position inputs from an encoder are used to generate the commutation signals for the inverter. For ideal voltage follower operation, the intermediate capacitor voltage should follow the half-sinusoidal input voltage, and goes to zero in each half-cycle. For proper demagnetization of the phases the intermediate capacitor voltage has to be greater than the phase back-EMF, for a SRM load. This causes a distortion of the input current waveform around the zero-crossings of the input voltage. However, the input current shaping is achieved at no cost to the drive, and a high power factor is still obtained. There is a practical limit to the power level up to 450W which DC/DC converters can be operated in DCM. Beyond about 450W, CCM operation is necessary.
2.8.1 Analysis of Operation

The operation of SEPIC with input output isolation is considered to derive the values of the circuit parameters. The average output current is the average diode current. Its peak value is given by

\[ i_{0, pk} = \frac{V_i}{L_{eq}} dT_s \]  

(2.14)

where, \[ L_{eq} = \frac{L_1L_2}{L_1 + L_2} \]  

(2.15)

Its average value in a switching period is given by

\[ i_{o, avg} = \frac{i_{0, pk} t_{\text{don}}}{2T_s} \]

\[ = \frac{V_i d^2 T_s}{2L_{eq} v} \]

\[ = \frac{V_i d^2 T_s \sin^2 (\omega t)}{2L_{eq} v} \]  

(2.16)

and the average for half of a line period becomes

\[ I_{o, avg} = \frac{1}{\pi} \int_0^\pi i_{o, avg} d\omega t \]

\[ = \frac{V_i d^2 T_s}{4L_{eq} v} \]  

(2.17)
Considering 100% of efficiency, \( V_1 I_1 = V_1 I_{avg} \) \hspace{1cm} (2.18)

Using the above equations and solving for \( I_1 \)

\[
i_1 = \frac{V_1 d^2 T_s}{2L_{eq}} = I_1 \sin \omega t \hspace{1cm} (2.19)
\]

where,

\[
I_1 = \frac{V_1^2 d^2 T_s}{2L_{eq}} \hspace{1cm} (2.20)
\]

**DCM operation** To operate in DCM mode the inequalities

\[
t_{on} + t_{don} < T_s \hspace{1cm} (2.21)
\]

\[
d \left(1 + \frac{n}{M} \sin \omega t \right) < 1 \hspace{1cm} (2.22)
\]

are to be satisfied. So

\[
d = \sqrt{2M \sqrt{K_a}} \hspace{1cm} (2.23)
\]

where \( K_a \) is the conduction parameter of the SEPIC.

\[
K_a = \frac{2L_{eq}}{RT_s} \hspace{1cm} (2.24)
\]

The \( K_{a,\text{crit}} \) (Critical conduction parameter) to ensure DCM operation can be given by

\[
K_{a,\text{crit}} = 0.5/(M + 1)^2 \hspace{1cm} (2.25)
\]
The equivalent inductance $L_{eq}$ is obtained using (2.15) and is given by

$$L_{eq} = \frac{RT_s K_a}{2}$$  \hspace{1cm} (2.26)

Therefore, $L_1$, $L_2$ & $C_1$ can be obtained considering the specified maximum current ripple:

$$L_1 = \frac{V_d T_s}{I_{rip}} \quad L_2 = \frac{L_1 L_{eq}}{L_1 - L_{eq}}$$  \hspace{1cm} (2.27)

$$C_1 = \frac{1}{\omega^2 (L_1 + L_2)}$$  \hspace{1cm} (2.28)

2.8.2 Design Examples

Two design examples are considered: One for the DCM case rated 200 W, and the other operating in CCM rated 500 W. The component values are:

Peak value of voltage $V_1 = 50$ V

Input voltage $V_{ac} = 50 \sin (2\pi 50t)$ V

DC bus voltage $V_{dc} = 25$ V

Switching frequency of $Q_1$, $f_s = 25$ kHz

Voltage conversion ratio $M = 25/50 = 0.5$

Critical conduction parameter $K_{a,\text{crit}} = 0.228$

$K_a = 0.16$ is chosen to ensure DCM operation

Duty cycle of $Q_1$, $d = \sqrt{2M\sqrt{K_a}} = 0.271$

Equivalent inductance $L_{eq} = RT_s K_a/2 = 28.8 \mu$H
Input current ripple $I_{\text{rip}} = 20\% I_1 = 0.8\ A$

$L_1 = 700\ \mu H, L_2 = 30\ \mu H$

$C_1 = 1/ (\omega^2 (L_1+L_2)) = 5.8\ \mu F.$

The actual value of $C_1$ should be higher to minimize the voltage ripple caused by the freewheeling phase currents and is determined by simulation to be $8\ \mu F.$ The following component values are used for the CCM design with the same input and DC bus voltages and switching frequency as the DCM design:

$L_1 = 980\ \mu H,$

$L_2 = 325\ \mu H,$

$C_1 = 8\ \mu F.$

### 2.8.3 Simulation Results

The proposed converter topology is simulated using PSPICE. The input current plotted in Figure 2.13(a) is seen to follow the input voltage waveform. Figure 2.13(b) shows the intermediate capacitor voltage waveform. This voltage is limited to the peak phase back-EMF value which results in some distortion of the input current around the zero-crossing of the input voltage. The phase currents are shown in Figure 2.13(c).

The waveforms in CCM mode of operation are shown in Figure 2.14(a)-(c).
Figure 2.13 Waveforms in DCM: (a) Input Voltage and Current Waveforms, (b) Input and Intermediate Capacitor Voltages and (c) Phase Currents
Figure 2.14 Waveforms in CCM. (a) Input Voltage and Current, (b) $V_s$ and $V_{C1}$, and (c) Phase Currents
2.9 SWITCHED RELUCTANCE MOTOR ADVANTAGES

With the construction so simple, SRM has many advantages as stated by Krishnan (2001). Some of them are

- Windings are on the stator only, with no windings or magnets on the rotor, thus saving materials on the rotor.
- The windings are concentric around a pole, leading to a greater manufacturing economy compared to distributed windings on AC machines or even DC machines.
- The concentric windings also reduce the end-turn buildup, thus minimizing the inactive part of the materials and resulting in lower resistance and copper losses compared to the distributed winding structure of other machines.
- The rotor is the smallest of any machine and has the lowest moment of inertia, thus giving a large acceleration rate for the motor.
- It is a brushless machine, like other AC machines, and therefore is superior from the maintenance point of view compared to DC machines.
- Because the rotor does not have windings or magnets, it is highly mechanically robust and therefore naturally suited for high-speed operation.
- Since the major sources of heat are on the stator, cooling is simpler as the stator is easier to access than the rotor. The rotor losses are much smaller when compared to the stator, unlike the case of DC and induction machines. Permanent magnet synchronous and brushless DC machines would be comparable in this respect.
- Skewing is not required to decrease cogging torque or
crawling torque, as it is for induction and permanent magnet synchronous and brushless DC machines. This machine does not produce cogging or crawling torques.

- The power density is comparable to and even slightly higher than that for induction machines but is lower than that of the permanent magnet synchronous and brushless DC machines with high-energy, rare-earth magnets. This statement is true only for low speeds (i.e., below 20,000 rpm); for higher speeds, the switched reluctance motor offers equivalent or higher power density.

- As the windings are electrically separate from each other and as they have negligible mutual coupling, electrical fault in one phase does not affect other phases, in general. Such a feature is unique to the switched reluctance motor.

- The induced EMF is a function of the phase current; hence, when there is no current in the winding, there is no induced EMF in the SRM, and a phase winding fault cannot be sustained if the input current is cut off. Such is not the case for induction or permanent magnet synchronous and brushless DC machines. This leads to higher reliability in an SRM compared to any other electrical machine.

- The freedom to choose any number of phases is inherent in the SRM and lends itself to high reliability if one or more phases fail during operation as the phases are electrically independent.

- The machine is an inherent position transducer, as its inductance is uniquely dependent on rotor position and excitation current. During the inactive period of each phase winding, the rotor position can be extracted by measuring the
inductance. Such a feature is difficult to exploit with induction and permanent magnet synchronous machines as there is no inactive period for the windings. The rotor position information is extracted in these machines in other ways, but all of the methods are fraught with complexities in implementation and signal processing. Extraction of discrete rotor position information is possible with a permanent magnet brushless DC machine because there is an inactive period for each winding in this machine, but a direct relationship between rotor position and a measurable quantity such as inductance is not available with the brushless DC machine as it is in the case of the SRM.

2.10 SRM DISADVANTAGES

Though SRM has multiple advantages over other machines, it also has certain drawbacks as stated below

- Torque ripple is high but can be reduced by controlling the overlapping phase currents.
- Acoustic noise is high, but its causes are being studied and some recommendations have resulted in considerable noise reduction compared to the first-generation machines.
- Friction and windage losses are high due to the salient rotor at high speeds. They can be reduced by making the rotor surface smooth by filling in the rotor interpolar space with inert material.
- The SRM requires an electronic power converter to run and does not have line-start capability; therefore, it is difficult to compete in an application requiring this aspect, where an
induction motor is an asset. Permanent magnet synchronous and brushless DC machines have the same disadvantages of the SRM in this regard.

- Position information is required to control the SRM, as is the case for permanent magnet synchronous and brushless DC machines. Induction and DC machines are exceptions to this rule. To compete for applications requiring no position sensor and absolutely low cost, the SRM must incorporate sensorless position control. Induction and DC machines are superior in this regard, at least for low-performance applications.

2.11 SUMMARY

This chapter explains the construction, operation and application of SRM drives. It also describes the various converter topologies that can be implemented for SRM. The third chapter deals with control techniques for AC drives.