CHAPTER 4

CONTROL TECHNIQUES FOR SRM DRIVE

4.1 INTRODUCTION

The switched reluctance machine has strong similarity to series excited DC and synchronous reluctance machines, but in control it is very remotely connected to these machines and therefore analogous control development is not possible. The fact that the machine inductance is not only a function of the rotor but also the excitation current even for a fraction of the rated current complicates the development of control strategies for SRM drive systems. In contrast, for all other electrical machines, it is known that control strategies are derived based on the machine parameters, being constant for most of the excitation range. This may confound design of the drive system control for SRM initially, but by classifying the control requirement as low or high performance based on torque ripple and speed of response specification, it may be found that a majority of the applications fall into the low-performance category. Only a small fraction of the applications or a small fraction of the motor drives required the demand of high performance. The main objective here is implement the various control techniques to SRM and to analyze the nature of its performance with regard to torque, current, speed and flux. In this regard current control, speed control, direct torque control for SRM is implemented.

The concept of control from the machine characteristics of inductance vs. rotor position for a fixed excitation used the variables of
control such as advance rise angles, commutation angles and their
dependence on machine inductance, speed, and the requirement to maximize
torque etc. The heart of any motor drive’s control system is current control.
Two types of current controllers are developed, one based on the linearized
model of an SRM delivering a reasonable performance and the other based
on decoupling and linearization to give high performance. For the high-
performance current controller design, factors such as mutual coupling of the
phases and nonlinearity of the system are included one at a time. Systematic
design derivation, implementation, and verification of the current controller
are developed. In most of the DC drives, torque control is synonymous with
current control. Because of its nonlinearity, the SRM is significantly different
in this regard. Multiphase switching is mandatory for minimization of torque
ripple and to deliver high and quickly responsive torque performance. Also
torque control based on torque distribution functions guarantee a linear torque
amplifier out of the SRM drive throughout its excitation range.

4.2 CONTROL PRINCIPLE

With control of torque, speed control becomes a simple task. Analogous to other motor drives, the speed controller chosen here for illustration is proportional plus integral. The derivation of the speed controller is achieved using a symmetric optimum technique. The current, torque, and speed controller performances are illustrated amply with dynamic simulation results, and, wherever possible, linear control system techniques are used to bring out the vast knowledge base of linear control systems to bear on the design.

Given the inductance profile (Lee 2000) as shown in Figure 4.1 for motoring operation, the phase windings are excited at the onset of increasing inductance. The torque production for motoring and regeneration is also shown in Figure 4.1. The torque shown is for only one phase. An average
torque will result due to the combined instantaneous values of electromagnetic torque pulses of all the machine phases. The machine produces discrete pulses of torque and, by proper design of overlapping inductance profile; it is possible to produce a continuous torque. In actual practice, it will result in reduced power density of the machine and increased complexity of control of the SRM drive.

It can be seen that the average torque is controlled by adjusting the magnitude of winding current, \( i_p \), or by varying the dwell angle, \( (\theta_d) \). To reduce the torque ripples, it is advisable to keep the dwell angle constant and vary the magnitude of the winding current. The latter approach requires a current controller in the motor drive which incidentally also ensures a safe operation.

![Diagram](image)

**Figure 4.1 Motoring and Regenerative Actions of SRM**

To ensure instantaneous torque production it is essential that the desired current comes on at the instant of increasing inductance. From a
practical point of view, the current cannot instantaneously rise or fall in a Resistor-Inductor (RL) circuit.

![Diagram of current control](image)

**Figure 4.2 Current Control of the SRM Drive**

This necessitates advanced application of voltage for starting the current and advanced commutation to bring the current to zero before a negative sloping inductance profile is encountered. Hence, the actual current waveforms are likely to be shown as in Figure 4.2. The voltage to the phase winding is applied in advance by $\theta_a$ degrees and the current turn-off is initiated in advance by $\theta_{co}$. Note that $\theta_a$ and $\theta_{co}$ are dependent on the magnitude of the peak winding current $i_p$ and the rotor speed. The current is maintained at $i_p$ by switching on or off the transistors. The actual current is
allowed to deviate by ±Δi, and this window is adjusted to ensure minimum switching frequency and minimum turn-on and turn-off losses.

4.3 CLOSED-LOOP, SPEED-CONTROLLED SRM DRIVE

A closed-loop, speed-controlled SRM drive is shown in Figure 4.3. The speed error is processed through a Proportional plus Integral (PI) controller and a limiter is used to yield the torque command, $T_e^*$. From the torque command, the current command is obtained using the torque constant, $K_t$. This torque constant is for the linearized inductance vs. rotor position characteristics for a particular value of current. The current command is added and subtracted from the hysteresis window, $\Delta i$, to obtain the $i_{\text{max}}$ and $i_{\text{min}}$ that determine the switching of the phase and main switches of any converter. The currents are injected into respective windings based on their position information obtained from an encoder or a resolver or position estimator. The rise and fall angles are calculated from the magnitude of the stator current, rotor speed, and minimum and maximum inductances. The rise and fall angles are incorporated with the rotor position information in the switch control signal generator block shown in the block diagram.

Figure 4.3 shows the block diagram of such an SRM controller, and the detailed implementation schematic is given. The inputs to the controller are speed reference $\omega_m^*$, motor winding currents $i_a$, $i_b$, $i_c$, rotor position ($\theta$) and rotor speed $\omega_m$. The motor currents can be detected through the use of Hall sensors. The rotor position information can be obtained from transducers or by estimation.

The speed command is processed through a soft-start circuit to provide a controlled acceleration/deceleration. The speed controller accepts the speed and its processed command value to find the current command with
a proportional integral amplification of the speed error. The current command, \(i^*\), is compared with the motor currents and their errors are merged with a triangular carrier frequency to generate the required pulse width modulation control signals. These control signals are steered to the corresponding base/gate of the power switches by the switch-select generator which has the actual rotor position information. The switch select generator is implemented with a read-only memory.

Figure 4.3 Closed-loop SRM drive

4.3.1 Current Loop

Three identical current loops, one for each phase, are suggested (Bae 1996) for implementation. Each loop consists of the following

i) Current error signal generator

ii) PWM circuit

iii) Converter

iv) Current feedback circuit
Current Comparator

The current error is obtained by using an operational amplifier as an inverting adder, the output of which is given as:

\[ i_e = K_i(i^* - i) \]  \hspace{1cm} (4.1)

where, \( K_i \) is the gain of current loop. To obtain a high speed of response, the instrumented value is in the range of 30 to 70. \( i^* \) is the commanded current, and \( i \) is the actual winding current. Hall-effect current sensors with galvanic isolation are used for sensing the winding currents, and a circuit is built to process this feedback signal. In order to maintain a desired current in the phase windings, the PWM technique is used in the current loops. Each loop has a comparator to compare the amplitude of the current error with the carrier signal of the triangular waveform at 3 kHz. When the carrier amplitude is higher than the current error, the output is low and the switch is turned off. This is shown using the input and output waveforms of the comparator.
4.3.3 Speed Control Loop

The output of the soft-start circuit, which is a ramp circuit, provides the modified speed reference. A speed error is generated by subtracting the speed from its reference value. The speed error is amplified by a proportional plus integral (PI) controller. The speed reference is enforced by this controller and speed feedback. The PI controller is synthesized with analog circuitry and uses an operational amplifier. The PI controller output is current command given by

\[ i^* = K_p (\omega_m - \omega_m) + K_i \int (\omega_m - \omega_m) dt \] (4.2)

where \( \omega_m \) and \( \omega_m \) are the modified speed reference and speed.

4.4 DIRECT TORQUE CONTROL

In recent years the high performance induction machine drives market has been dominated by the rotor flux orientated vector control technique. This offers similar dynamic torque control performance to that of the DC machines, giving fast, near step changes in machine torque. However, there has been growing interest in the DTC technique, which offers simpler control architecture with a similar dynamic performance to vector control claimed. More than a decade ago, DTC was introduced to give fast and good dynamic torque response. DTC can be considered as an alternative to the Field-Oriented Control (FOC) technique.

4.5 FIELD ORIENTED CONTROL Vs DIRECT TORQUE CONTROL

The application of the field oriented control method for variable speed induction motor drives leads to a complex control system structure. Generally, a closed loop field oriented control system consists of the following components:
• PID controller for motor flux and torque
• Current and/or voltage decoupling network
• Complex coordinate transformation
• Two axis to three axis converter
• Voltage or current modulator
• Flux and torque estimator
• PID (sliding mode) speed controller

In a DTC system, as introduced by Takahashi and Depenbrock in the mid 1980’s, the components 1-5 are replaced by two hysteresis comparators and a selection table. It has been shown that with this greatly simplified control structure, the drive performance can be significantly improved when compared to field oriented control.

Table 4.1  Comparison between Field Oriented Control and Direct Torque Control

<table>
<thead>
<tr>
<th>S. No</th>
<th>Features</th>
<th>Field Oriented Control</th>
<th>Direct Torque Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Coordinate reference axis</td>
<td>Synchronous rotating d-q</td>
<td>Stationary d-q</td>
</tr>
<tr>
<td>2.</td>
<td>Controlled variables</td>
<td>- Torque</td>
<td>- Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Rotor flux</td>
<td>- Stator flux</td>
</tr>
<tr>
<td>3.</td>
<td>Control variables</td>
<td>- Stator currents</td>
<td>- Stator voltage space vector</td>
</tr>
<tr>
<td>4.</td>
<td>Sensed variables</td>
<td>- Rotor mechanical speed</td>
<td>- Stator voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stator currents</td>
<td>- Stator currents</td>
</tr>
</tbody>
</table>
### Table 4.1 (Continued)

<table>
<thead>
<tr>
<th>S. No</th>
<th>Features</th>
<th>Field Oriented Control</th>
<th>Direct Torque Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>Estimated variables</td>
<td>- Slip frequency</td>
<td>- Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Rotor flux position $\theta_e$</td>
<td>- Stator flux</td>
</tr>
<tr>
<td>6.</td>
<td>Regulators</td>
<td>- Three-phase current regulators (hysteresis)</td>
<td>- Torque regulator (hysteresis)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Stator flux regulator (hysteresis)</td>
</tr>
<tr>
<td>7.</td>
<td>Torque control</td>
<td>- Indirectly controlled by stator currents</td>
<td>- Directly controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- High dynamics</td>
<td>- High dynamics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Torque ripple</td>
<td>- Controlled torque ripple</td>
</tr>
<tr>
<td>8.</td>
<td>Flux control</td>
<td>- Indirectly controlled by stator currents</td>
<td>- Directly controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Slow dynamics</td>
<td>- Fast dynamics</td>
</tr>
<tr>
<td>9.</td>
<td>Parameter sensitivity</td>
<td>Sensitive to variations of rotor time constant $\zeta_r$</td>
<td>Sensitive to variations of stator resistance</td>
</tr>
<tr>
<td>10.</td>
<td>Implementation complexity</td>
<td>- High complexity</td>
<td>- Medium complexity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Calculations requiring trigonometric functions complexity</td>
<td></td>
</tr>
</tbody>
</table>

### 4.6 PRINCIPLE OF DTC

On the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. The DTC scheme as initially proposed is very simple; in its basic configuration. It consists of a pair of hysteresis comparators, torque and flux calculator, a
lookup table, and a Voltage-Source Inverter (VSI). The configuration is much simpler than the FOC system due to the absence of frame transformer, pulse-width modulator, and a position encoder.

Figure 4.5 Structure of DTC Technique

Since it was introduced in 1986, a large number of technical papers have appeared in the literature, mainly seeking to improve the performance of DTC of induction machine drives. Two of the major issues which are normally addressed in DTC drives are the variation of the switching frequency of the inverter used in the DTC drives with operating conditions and the high torque ripple. It is shown that the switching frequency is highly influenced by the motor speed, which is mainly due to the torque slope that depends on speed. The DTC system comprises three basic functions, namely:

A motor model estimates the actual torque, stator flux and shaft speed by means of measurements of two motor phase currents, the intermediate circuit DC voltage and information on the state of the power switches. Calculations are performed every 25 microseconds and these include corrections for temperature and saturation effects. The parameters of
the motor model are established by an identification run, which is made during commissioning.

A two level hysteresis controller, where the torque and flux references are compared with the actual values calculated from the motor model. The magnitude of the stator flux is normally kept constant and the motor torque is controlled by means of the angle between the stator and rotor flux.

Optimal switching logic that translates the controller outputs into the appropriate commands to the power switching devices. There are six voltage vectors and two different kinds of zero-voltage vectors available in the two level voltage source inverter and the optimum switching logic determines the required selection every 25 microseconds.

4.7 DRIVE CONTROL

DTC provides only effective torque control and estimates the motor quantities. In order to make a practical drive, speed control functions must be added. Typical additional functions are:

Torque reference chain: The input of the torque chain is either the torque reference from the speed controller or an external torque reference. The torque reference is modified in order to keep the DC intermediate circuit voltage and electrical frequency limited. The inverter is protected from overload by limiting the torque although short time overloads are allowed. Torque reference is also limited in order to prevent the motor torque from exceeding the pullout torque.

Speed control: In many applications, speed control is the most important task of the inverter drive. Quality parameters of the process often depend on the function of the speed controller. In a DTC inverter, speed control is not an inner part of the inverter control as in traditional inverters.
Output of the speed control is an external reference to the torque control. This enables consideration of more process requirements in the speed controller design. The basic algorithm of the speed controller is PID plus an acceleration compensator. The compensator is very useful in order to minimize the control deviation in the acceleration and deceleration of inertia because the PID controller can be tuned to act more as a load compensator. The PID controller and acceleration compensator are tuned by an automatic tuning method, which is based on the identification of the mechanical time constant of the drive. The time constant can be identified during commissioning or normal operation.

**Flux reference:** An absolute value of the stator flux can be given as a reference value to the DTC block. The ability to control and modify flexibly the absolute value of stator flux reference provides an easy way to realize many inverter functions. For example, flux reference control is utilized in flux optimization, field weakening control, etc.

**Switching frequency reference:** The switching frequency is controlled to match the limitations of the power modules (e.g. 1.5 to 3.5 KHz). The method is based on the modification of the hysteresis parameters as a function of electrical frequency.

### 4.8 PERFORMANCE OF DTC DRIVE

#### 4.8.1 Benefits of DTC

- The drive performance described above is realized without tachogenerator or encoder. Hence, the motor is robust, cabling to the motor is reduced and a cost competitive drive is obtained by obviating the need to provide and fit an encoder.

- The performance is superior to that from a DC thyristor drive and it can therefore be used on those applications previously
reserved for DC. The low maintenance and robustness of an AC motor reduces running costs and the AC drive runs at a power factor better than 0.97 at all speeds and loads and has therefore minimum impact on the supply system.

- Harmonic currents are less than those produced by a DC drive. Furthermore, harmonic current can be virtually eliminated by using a second DTC converter as the supply rectifier. The frequent calculation of optimum switching means that the drive can respond rapidly to external influences in addition to process requirements. For example, riding through a loss of supply.

- DTC enables the inverter to be switched on to a rotating motor irrespective of the direction of rotation and motor flux levels; this can be useful for such simple applications as a fan drive. Noise levels of DTC controlled drives are an improvement compared to conventional PWM; the noise tends to be “white noise” without the noise from the pulse width modulation and fundamental frequencies which can be intrusive.

- A Common Drive Control (CDC) is available for all drives (AC and DC) to provide additional programmable features and a high-speed interface to an over-riding control system.

- No need of complex reference frame transformation.

- Current controllers are not required.

- PWM unit is not required.

- Precise position of rotor magnet is not mandatory only 60 degree sector wise information is needed.
4.8.2 Problems Associated with DTC

- Difficulty in controlling torque and flux at very low speed.
- High current and torque ripple.
- Variable switching frequency behavior.
- High noise level at low speed.
- Lack of direct current control.

Table 4.2 Benefits of Direct Torque Control Technique

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip-less drive</td>
<td>Process changes will not affect performance. Drive will not trip.</td>
</tr>
<tr>
<td>Flash start</td>
<td>Can start into a motor that is running at any speed without waiting for the flux to decay.</td>
</tr>
<tr>
<td>Smooth recovery</td>
<td>No process interruptions after short supply outages.</td>
</tr>
<tr>
<td>Flux braking</td>
<td>Full control during deceleration between speeds. Reduced need for brake chopper.</td>
</tr>
<tr>
<td>Auto tuning</td>
<td>Less commissioning time. Easy retrofit to existing motor.</td>
</tr>
<tr>
<td>Low Noise</td>
<td>Acoustic noise more acceptable; and easier to screen.</td>
</tr>
<tr>
<td>Accurate temperature calculation</td>
<td>Improved motor protection</td>
</tr>
</tbody>
</table>
4.8.3 Possible Solutions for Improvement in DTC Technique

- Use of improved switching tables
- Use of comparators with and without hysteresis, at two or three levels.
- Implementation of DTC schemes for constant switching frequency operation with PWM or SVM techniques.
- Use of variable duty ratio control.
- Increasing the number of phases.
- Introduction of fuzzy or neuro-fuzzy techniques.

4.9 DIRECT TORQUE CONTROL FOR SRM

In this section, the DTC scheme that was applied to the SRM will be discussed. In the SRM, the motor phases are driven by switched currents which are nonsinusoidal and normally highly nonlinear. Furthermore, the phases of the motor are excited completely independently of each other. Thus, conventional AC machine rotating field theory cannot be directly applied to the SRM. Re-examining the torque equation of the SRM, a new control technique can be found which uses a similar philosophy as the conventional DTC of AC machines. As in conventional DTC, the control scheme directly controls the amplitude of the flux and torque within hysteresis bands. However, the motor phase switching strategy is based instead on the nonuniform torque characteristics of the SRM.

4.9.1 Torque Expression

In any type of electromechanical device, on energy balance can be used to drive the mechanical work in terms of the input energy, dissipated energy, and the stored energy. In a reluctance device, the mechanical work
required to move the permeable material is equal to the supplied electrical input energy minus the energy dissipated in the resistance of the coil minus stored field energy. This is expressed mathematically as given in

\[ \text{d}w_m = \text{d}e - \text{d}w_f \quad (4.3) \]

where \( \text{d}w_m \) = differential output of mechanical energy, \( \text{d}e \) = differential input of electrical energy, \( \text{d}w_f \) = differential increase in stored magnetic energy.

For one of the phase of an SRM, the electrical energy of the coil is

\[ \text{d}e = (v - ir)idt = eidt \quad (4.4) \]

The motor torque output can be found using the motor electromagnetic equation

\[ v = Ri + \frac{d\psi(i,\theta)}{dt} \quad (4.5) \]

where, \( \psi(i,\theta) \) is the nonlinear function of phase linkage which is a function of rotor position \( \theta \) and current \( i \). The nonlinear flux linkage term can be expanded into partial fractions such that

\[ v = Ri + \frac{\partial\psi(\theta,i)}{\partial i} \frac{di}{dt} + \frac{\psi(\theta,i)}{\partial \theta} \frac{d\theta}{dt} \quad (4.6) \]

The power flow equation can be written as

\[ vi = R^2i + i\frac{\partial\psi(\theta,i)}{\partial i} \frac{di}{dt} + i\frac{\psi(\theta,i)}{\partial \theta} \frac{d\theta}{dt} \quad (4.7) \]

From equation (4.7) the field energy can be separated into its constituent components to give
\[ \text{dw}_f = \left. \frac{\partial w_f}{\partial i} \right|_{\theta = \text{con}} di + \left. \frac{\partial w_f}{\partial \theta} \right|_{i = \text{con}} d\theta \]  \hspace{1cm} (4.8)

Form the consideration of the stored field energy it can be shown that

\[ \text{de} = i \left. \frac{\partial \psi(\theta, i)}{\partial i} \right|_{\theta = \text{con}} di + i \left. \frac{\partial \psi(\theta, i)}{\partial \theta} \right|_{i = \text{con}} d\theta \]  \hspace{1cm} (4.9)

\[ \text{dw}_f = i \left. \frac{\partial \psi(\theta, i)}{\partial i} \right|_{\theta = \text{con}} di \]  \hspace{1cm} (4.10)

By substitution of (4.9), (4.10) in (4.4), we get

\[ \text{dw}_m = i \left. \frac{\partial \psi(\theta, i)}{\partial \theta} \right|_{\theta = \text{con}} d\theta - \left. \frac{\partial w_f}{\partial \theta} \right|_{\theta = \text{con}} d\theta \]  \hspace{1cm} (4.11)

The instantaneous torque is defined by

\[ T = \frac{\text{dw}_m}{d\theta} \]  \hspace{1cm} (4.12)

Substituting (4.11) into (4.12) the expression for instantaneous torque production of an SRM phase can be written as

\[ T = i \left. \frac{\partial \psi(\theta, i)}{\partial \theta} \right|_{\theta = \text{con}} - \left. \frac{\partial w_f}{\partial \theta} \right|_{\theta = \text{con}} \]  \hspace{1cm} (4.13)

Due to saturation in SRM, the influence of the second term (4.13) is small therefore

\[ T \approx i \left. \frac{\partial \psi(\theta, i)}{\partial \theta} \right|_{\theta = \text{con}} \]  \hspace{1cm} (4.14)
The approximate torque equation (4.14) is sufficient to control the general characteristics (increase or decrease) of the torque production and not magnitude of the torque. The current is always positive as SRM is unipolar. Hence, the sign of the torque is directly related to the sign of $\frac{\partial \psi}{\partial \theta}$. In other words to produce positive torque the stator flux amplitude must be increasing with respect to rotor position, whereas to produce a negative torque, the change in stator flux should decrease with respect to the rotor position movement.

The new SRM control technique is defined as follows

i) The stator flux linkage vector of the motor is kept at a constant amplitude

ii) The torque is controlled by accelerating or decelerating the stator flux vector.

This is similar to conventional DTC except that it is dependent on stator current. The stator current is found to have a first order delay relative to the change of stator flux $\frac{\partial \psi}{\partial \theta}$. The current equation in the time domain can be found as

$$\frac{di}{dt} = e^{-\frac{\partial \psi}{\partial \theta}} \frac{d\theta}{dt} \frac{\frac{\partial \psi}{\partial \theta}}{\frac{\partial \psi}{\partial i}}$$ (4.15)

Now putting $\frac{d\theta}{dt} = \omega$ where $\omega$ is the speed of the rotor $\frac{\partial \psi}{\partial i} = l$ where $l$ is the incremental inductance, we can write the equation for current in the time domain as
\[ i = \frac{e^{-\frac{\partial \psi}{\partial \theta}} \omega}{sl} \]  

(4.16)

Therefore, it can be seen that the current has a first order delay relative to changes in the applied voltage and the change in flux with respect to rotor position \( \frac{\partial \psi}{\partial \theta} \). Thus, it can be assumed that the current is relatively constant during the control of the flux acceleration and deceleration. This allows the control method to control torque, based only on the change in the value of the flux acceleration and deceleration without consideration of the current change.

4.9.2 Voltage Vectors for SRM

Similar to the AC drives equivalent space voltage vectors can be defined for SRM. The voltage space vector for each phase is defined as lying on the center axis of the stator pole because the flux linkage for current and voltage applied to a motor phase will have a phasor direction in line with the center of the pole axis as shown in Figure 4.6. This does not need any change in the physical winding topology.

![Figure 4.6 Definitions of Phase Voltage Vectors In Three Phase SRM](image)
In SRM, each motor phase can have three possible voltage states for a unidirectional current as shown in Figure 4.7. The voltage state for a given phase is defined as $S_q=1$ when both devices in a motor phase are turned on. In this case positive voltage is applied to the motor phase. When current is flowing and one device is turned off, a zero voltage loop occurs and the state is defined as $S_q=0$. Finally when both devices are turned off, there are no current or freewheeling current flows through the diodes. In this case negative voltage is experienced by the motor phase and the state is defined as $S_q=-1$. So with each phase having three possible states (0, 1, -1) unlike conventional DTC for AC drives with two states, a total of 27 possible configuration is possible. But only six equal magnitude voltage vectors separated by $\pi/3$ radians is considered as DTC allows no other states to be chosen by the controller.

![Figure 4.7 SRM Phase Voltage States](image)

One out of the six states is chosen to keep torque and flux within the hysteresis bands. Let the stator flux vector be located in the $K^{th}$ sector ($K = 1, 2, 3, 4, 5, 6$). In order to increase the amplitude of the stator flux, the voltage vector $V_k$, $V_{k+1}$, $V_{k-1}$ can be applied and $V_{k+2}$, $V_{k+3}$, $V_{k-2}$, can be applied to decrease the flux. $V_k$ and $V_{k+3}$ are zero space vectors. As in conventional DTC, the control scheme of SRM is based on the results as follows.
The motor is solicited only through the converter component of voltage space vectors along the same flux.

ii) The motor torque is affected by the component of the voltage space vector orthogonal to the stator flux.

iii) The zero space vectors do not affect the space vector of the stator flux.

So the stator flux when increased by $V_{k+1}$ and $V_{k-1}$ vectors and decreased by $V_{K+2}$ and $V_{K-2}$ affects the torque. As $V_{k+1}$ and $V_{k+2}$ vector advance the stator flux linkage in the direction of rotation they tend to increase the torque. But $V_{k-1}$ and $V_{K-2}$ decelerates the flux in opposite direction and decrease the torque. So the switching table becomes as Table 4.3.

**Table 4.3 General Selection Table of Direct Torque Control**

<table>
<thead>
<tr>
<th>Voltage Vector</th>
<th>Increase</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator flux</td>
<td>$V_k, V_{k+1}, V_{k-1}$</td>
<td>$V_{k+2}, V_{k-2}, V_{k+3}$</td>
</tr>
<tr>
<td>Torque</td>
<td>$V_{k+1}, V_{k+2}$</td>
<td>$V_{k-1}, V_{k-2}$</td>
</tr>
</tbody>
</table>
The flux control using hysteresis is achieved by vectors $V_{k+2}$ and $V_{k+1}$ that increase the torque as shown in Figure 4.9. In conventional DTC, the stator flux vector $\psi_s$ is expressed as

$$\vec{\psi}_s = \int_0^1 (v_s - R_s \vec{i}_s) + \vec{\psi}_{s0}$$  \hspace{1cm} (4.17)$$

where, $\psi_{s0}$ is the initial value of stator flux vector. In SRM, as the motor is robust to problems of integration offset, $\vec{\psi}_{s0}$ is assumed to be zero and the individual flux linkages are calculated using equation (4.17).

**Figure 4.9 Illustration of Flux Control using Hysteresis**

The magnitude of individual phase flux linkage varies with time but the direction is always along the stator pole axis. To resolve these phase flux vectors for the three phases of SRM are transformed into a stationary orthogonal two axis $\alpha-\beta$ reference frame as shown in Figure 4.10.

**Figure 4.10 Definition of Two Frame Reference Axis for Motor Voltages**
The orthogonal flux vectors are expressed as

\[ \psi_\alpha = \psi_1 - \psi_2 \cos 60^\circ - \psi_3 \cos 60^\circ \]  
(4.18)

\[ \psi_\beta = \psi_2 \sin 60^\circ - \psi_3 \sin 60^\circ \]  
(4.19)

The magnitude of \( \vec{\psi} \) and angle \( \delta \) of the equivalent flux vector is defined as

\[ \psi_s = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \]  
(4.20)

\[ \delta = \arctan \left( \frac{\psi_\beta}{\psi_\alpha} \right) \]  
(4.21)

The actual nonuniform torque versus angle and current characteristics of the motor is shown in Figure 4.11.

Figure 4.11 Non-uniform Torque Characteristics
4.9.3 Simulation Results

To simulate the system a Matlab/ Simulink model was constructed for the SRM and the control system as in Figure 4.12. In this simulation test, the motor command flux was maintained at a constant 0.35 Wb and a motor torque reference of 40 Nm was used. The speed of the motor in this test was a constant 2800 rpm. The hysteresis bands are defined to be of ±0.01 Wb and ±0.1 Nm for the flux linkages and torque respectively. The result of the torque and flux control can be seen in Figures 4.13.

Figure 4.12 Block Diagram of DTC Algorithm
The chapter explains the closed loop current and speed control for SRM drive. The DTC as implemented to three-phase SRM drive is clearly explained with results. The fifth chapter explains the different torque ripple minimization techniques in DTC.