CHAPTER 2
CURRENT SOURCE INVERTER FOR IM CONTROL

2.1 INTRODUCTION

AC drives are mainly classified into direct and indirect converter drives. In direct converters (cycloconverters), the AC power is fed directly to the AC motor. The maximum output frequency of the cycloconverter is about one third of the supply frequency. It has principally been used for applications in which motor size is large and the speed of the operation is low. In indirect converters the AC power variation process is carried out in two stages. In the first stage, the AC power, using either a diode or SCR bridge rectifier, is rectified and in second stage rectified power is converted to a variable AC power by means of an inverter. This connection between the converters is known as a DC link. DC link AC converters are divided into VSI and CSI. They are in fact duals of each other. CSI supplies a controlled current to the motor whereas VSI controls, voltage at the motor terminals.

A VSI consists of a controlled rectifier, an inductor, a capacitor which forms a filter, and an inverter. Because of the large capacitor, VSI provides a constant voltage to the load and the output voltage waveforms are not affected by the load. CSI on the other hand, consists of a rectifier, an inductor and an inverter. The presence of inductor ensures that CSI provides constant torque to the load and the output current waveforms are not affected by the load. CSI has a stiff DC current at its input source, so, it has received considerable interest in the applications which require control over the torque.
This chapter contains a review of theoretical concepts of CSI fed IM drives. In the first section, mathematical model of IM is described. When an electrical motor is viewed as a mathematical system with inputs and outputs, it can be analyzed and described in multiple ways, considering different reference frames and state-space variables. New mathematical models have to be implemented for the three-phase IM in order to analyze its operation both dynamically and in steady-state. In the second section, the DC link frequency converters, VSI and CSI, commonly used in IM drives are reviewed. The distinction is based on the inverter switching constraints; in VSIs, the DC voltage is converted into AC output voltage, whereas in CSIs, DC current is converted into AC output current. In this work, CSI is preferred to control IM. So, CSI topologies are presented in detail. In the third section, a brief description of the four control methods such as V/f, IOL, FOC, and DTC are presented with their salient features.

2.2 MATHEMATICAL MODEL OF IM

In general, IM is used to transform electrical energy to mechanical energy. It consists of electric circuitry, electromagnetic circuitry and electro mechanic circuitry. The main objective of the motor modeling is to build a simple but competent model that describes these circuits and their interconnections. The main path in the model is in relation between the voltage and/or current or the stator phases in input where as the magnetic flux inside the motor and electromagnetic torque in the output. As mentioned earlier, the squirrel cage IM is prepared for industry applications. The IM can either be supplied by a voltage source or a current source. These sources are assumed to be ideal; this means that they can supply any desired voltage or current without losses. According to Krause et al (1965), the basic equations of the IM are the stator voltage equation (2.1), the rotor voltage
equation (2.2), the equations of the flux linkages of the stator and the rotor winding systems, (2.3) and (2.4), and the torque equation (2.5).

\[ v_s^S = R_s i_s^S + \lambda_s^S \quad (2.1) \]
\[ v_r^r = 0 = R_r i_r^r + \lambda_r^r \quad (2.2) \]
\[ \lambda_s^a = \lambda_m^a + L_{ls} i_s^a \quad (2.3) \]
\[ \lambda_r^a = \lambda_m^a + L_{lr} i_r^a \quad (2.4) \]
\[ T_e = \left[ C \left( \frac{\pi}{2} \right) \lambda_m^a \right]^T i_s^a \quad (2.5) \]

The equations are given in vector format. Every vector variable has two components: The first component is parallel to the reference frame axis or ‘d’ axis and the second component is perpendicular to the reference axis or ‘q’ axis. The symbols are \( v \)-voltage, \( i \)-current, \( \lambda \)-flux linkage, \( R \)-resistance and \( L \)-leakage inductance; subscript \( s \) indicates the stator winding system, \( r \), the rotor winding system; superscript ‘s’ indicates the stator reference frame (stator coordinates), ‘r’, the rotor reference frame and ‘a’, any arbitrary reference frame; \( \lambda_m \) is the magnetic flux in the air gap of the motor: the air gap flux; \( T_e \) is the electromagnetic torque; \( C \left( \frac{\pi}{2} \right) \) is a rotation matrix over \( \frac{\pi}{2} \) radians; the dot \( ( \cdot ) \) indicates a time derivative. Equation (2.1) is restricted to the stator reference frame because of the differential of the stator flux vector where as the Equation (2.2) is restricted to the rotor reference frame because of the differentiation. The flux equations and the torque equation can be defined in any reference frame, denoted by superscript ‘a’.
It is evident from the equations (2.1 to 2.5) that the motor voltage, flux, and torque can be controlled easily by controlling the current of the motor. So, the CSI is the right choice to control the motor directly because the inputs of the current fed IM model are the stator currents. Before these equations are completed to obtain the IM model, the reference frame of the model in relation to the problem being investigated is chosen. In order to evaluate the usefulness of each reference frame, the above equations are simulated using MATLAB 7.6 software to predict the transient performance of an IM.

![Simulated results of ‘a’ phase and d-axis stator currents in different rotating reference frames]

Figure 2.1 shows the transient performance of ‘a’ phase and d-axis stator currents in each reference frame when there is a step change in the reference torque from 0 to full load at 1.4 seconds. From Figure 2.1 (a), it is evident that in stator or stationary reference frame stator d-axis current behaves exactly the same way as do the stator ‘a’ phase current of the motor.
If the stationary reference frame is used, then the stator d-axis current identical to the stator phase current. This would be useful when interest is specifically confined to stator variables, for example, variable speed stator-fed IM drives. Similarly, if the rotor reference frame is used then the rotor d-axis current will behave in exactly the same as the rotor ‘a’ phase current. This would be useful when interest is confined to rotor variables only, as for example in variable speed rotor-fed IM drives. From Figure 2.1 (b), it is evident that in rotor rotating reference, frame stator d-axis current does not behave as the stator phase current. From Figure 2.1 (c), it is apparent that in synchronously rotating reference frame, stator d-axis current behaves like DC quantity. If the synchronously rotating reference frame is used, then the stator and rotor current behave like DC quantity. Thus, the controller design is simple and is widely used in AC drives.

![Simulated results of q-axis stator current and d-axis rotor flux in different rotating reference frames](image)

**Figure 2.2** Simulated results of q-axis stator current and d-axis rotor flux in different rotating reference frames
Figure 2.2 shows the transient performance of q-axis stator current and d-rotor flux in each reference frame when there is a step change in the reference torque from 0 to full load at 1.4 seconds. From Figures 2.2 (a) and 2.2 (b), it is apparent that there is a coupling effect between stator q-axis current and rotor d-axis flux. So, independent control is difficult. Figure 2.2 (c) shows that the rotor d-axis flux and stator q-axis current (control variables) have linear relationship with torque (speed). Thus, it is useful in the Rotor Flux Oriented (RFO) Control methods.

![Figure 2.2](image)

**Figure 2.2** Simulated results of q-axis stator current and d-axis stator flux in different rotating reference frames

Figure 2.3 shows the transient performance of q-axis stator current and d-stator flux in each reference frame when there is a step change in the reference torque from 0 to full load at 1.4 seconds. Figures 2.3 (a) and 2.3 (b) state that there is a coupling effect between stator q-axis current and stator
d-axis flux and so independent control is difficult. From Figure 2.2 (c), it is evident that the stator d-axis flux and stator q-axis current (control variables) have linear relationship with torque (speed). It is used in the Stator Flux Oriented (SFO) Control methods.

2.3 CURRENT SOURCE INVERTER

CSI research in motor control applications has predominantly focused on use with IM. Only a few applications of the CSI are related to other types of ac motors such as Synchronous Motor (SM) and brushless Permanent Magnet Synchronous Motor (PMSM). Generally, the CSI fed drives have a distinct advantage over VSI fed drives: the electrical apparatus is current sensitive, and torque is directly related to the current rather than the voltage. Hence, control of current ensures the direct and precise control of electromagnetic torque and drive dynamics. The operation is explained in the following sections.

2.3.1 CSI: PWM Switching

The power electronic switching is presented for VSIs, with reference to Ahmet M. Hava et al (1999), Holmes et al (2003), since this theory forms the basis of progression to CSI switching and control schemes. VSI schemes can be modified and adapted for application to CSI. CSI switching and pre-charge algorithms are presented and discussed and the mapping of VSI to CSI logic is presented for ease of comparison.

The circuit of the VSI illustrated in Figure 2.4 consists of six semiconductor switches (S1 to S6) with gate-turn off control and their associated freewheel diode is usually incorporated within the device package in modern devices. Gate drive and snubber circuitry are not shown for simplicity. The six devices create three separate phase legs (a, b and c) within
the inverter, the centre point of each leg being a connection point for the load being driven.

The switch activation signals g1 to g6 for switches S1 to S6 can be applied either at the output frequency for six-step operation or using a high frequency PWM scheme. Six-step operation is switching at the frequency of the inverter output, i.e. each switch turns on and off once during the output period, $2\pi$ radians (0.02 Seconds), and has an ‘on’ duration of $\pi$ radians (0.01 Seconds). Each phase leg is offset by $\pi/3$ radians creating six equal intervals (I to VI) during one output period.

The switching order of VSI topology is S1, S2, S3, S4, S5, S6. Here, one switch from each leg always conducts except for a small period of time to allow the conducting switch to turn off before the switch from the same leg is turned on. The delay period is known as the blanking time that prevents both switches in a leg conducting simultaneously, shorting the DC link and causing a shoot-through fault, where current rises rapidly and is likely to cause device(s) with the inverter to fail. Figure 2.5 details the simulated gating control signals for each switch (excluding blanking time) along with the resulting output voltage, $V_{an}$, referred to as the load star point.
Figure 2.5 Simulated gating signals for VSI six-step switching

Figure 2.6 CSI topology
The circuit of the CSI, detailed in Figure 2.6, consists of six semiconductor switches (S1 to S6), with gate-turn off control, and six diodes. Gate drive and snubber circuitry are not shown. The six device pairs create three separate phase legs (a, b and c) within the inverter, the centre point of each leg being a terminal for the load being driven.

![CSI Circuit Diagram](image)

**Figure 2.7 Practical implementation of a CSI**

In practical systems, the constant current source is replaced by a DC voltage supply and a DC link inductor, as detailed in Figure 2.7. Switch activation signals g1 to g6 for switches S1 to S6 can be applied either at the output frequency for six-step operation, or using a high frequency PWM scheme. Six-step operation of a CSI is similar to a VSI system with each switch operating once during the output period, $2\pi$ (0.02 seconds), except with an ‘on’ duration of $2\pi/3$ radians. Each phase leg is offset by $\pi/3$ radians, creating six equal intervals (I to VI) during one output period.

The switching order is the number order of the switches and results in there always being one switch from top row and one switch from the bottom row conducting at all times. Figure 2.8 details the simulated gating
control signals for each switch along with the resulting output voltage, $V_{an}$, for a static load referred to as the load star point. In CSI, maintaining a constant $I_{DC}$ from a DC supply voltage control is desirable, which in turn controls the current in the inductor. Six-step switching in a CSI results in the same low frequency harmonics problems as the six-step switched VSI.

![Figure 2.8 Simulated gating signals for CSI six-step switching](image)

### 2.3.2 CSI: Carrier Based PWM Switching

Bin Wu et al's (1992) solution to the harmonics problems, when controlling the DC link voltage, is to use PWM, turning each switch within the inverter on and off multiple (usually thousands) of times within one period, effectively reducing harmonic content in output voltage while maintaining a fixed DC link voltage. The system will now be free mostly from all the problems related to variable DC link voltage systems. In this section, implementation of PWM switching to a CSI is briefly discussed. By
using this PWM scheme, the low frequency harmonics are eliminated. By modulating the first and last $\pi/3$ radians or $60^\circ$ (of a half cycle), the low frequency harmonics can be reduced to such a level that they can be considered to have been eliminated.

![Simulated gating signals for CSI PWM switching](image)

**Figure 2.9 Simulated gating signals for CSI PWM switching**

The order of harmonics eliminated is directly related to the number of pulses per half cycle, for example, three pulses result in the lowest harmonic being eliminated, while seven pulses result in the elimination of the lowest three harmonics. Implementation is usually achieved by a trapezoid-triangle comparison, detailed in Figure 2.9 (g1 to g6 are gating signals for
switches S1 to S6), resulting in PWM operation for electrical angles 0 to $\pi/3$ and $2\pi/3$ to $\pi$, with a continuous high for $\pi/3$ to $2\pi/3$ for S1. S4 repeats this pattern for $\pi$ to $2\pi$ and each phase leg is offset by $2\pi/3$. It is noted that switching does not remain to be $120^\circ$ duration for the six-step CSI and the rule that there are always (and only) two simultaneously active switches is no longer true. The modulation index $m_\alpha$ is again calculated as the ratio of amplitude of the reference wave or modulated wave, $V_m$, and the amplitude of the carrier wave, $V_c$, as in Equation (2.6). Controlling the magnitude of the output current still requires a controlled current source as the supply to the inverter.

$$m_\alpha = \frac{V_m}{V_c} \quad (2.6)$$

### 2.3.3 CSI: SVM Switching

Space Vector Modulation (SVM) is an advanced modulation technique that is normally implemented using microprocessors or DSP controllers based on the eight possible switch combinations of VSI Ahmet M. Hava et al (1999), Bin Wu (2006). Of the combinations, six ($\bar{V}_1$ to $\bar{V}_6$) are ‘on’ (active) states and two ($\bar{V}_0$ and $\bar{V}_7$) are ‘off’ (zero) states, with zero state being all the top or bottom switches conducting, shorting the connected load.

The eight states can be represented as stationary vectors on the d-q plane, as shown in Figure 2.10. An output reference vector can be formed by the addition of two or more vectors where the amplitude of each vector can be controlled by the time over which it is applied. Table 2.1 details the switching states and space vector for VSI.
Figure 2.10 VSI space vector diagram

Table 2.1 VSI switching states and space vectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Switching State</th>
<th>On-State Switch</th>
<th>Inverter PWM Voltage</th>
<th>Space Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero States</td>
<td>[135] $S_1, S_3, S_5$</td>
<td>0 0 0</td>
<td>$V_{AN}$ $V_{BN}$ $V_{CN}$</td>
<td>$V_7 = 0$</td>
</tr>
<tr>
<td></td>
<td>[462] $S_4, S_6, S_2$</td>
<td>0 0 0</td>
<td></td>
<td>$V_0 = 0$</td>
</tr>
<tr>
<td>Active States</td>
<td>[162] $S_1, S_6, S_2$</td>
<td>$V_d$ 0 0</td>
<td></td>
<td>$V_1 = \frac{2}{3} V_d e^{j0}$</td>
</tr>
<tr>
<td></td>
<td>[132] $S_1, S_3, S_2$</td>
<td>$V_d$ $V_d$ 0</td>
<td></td>
<td>$V_2 = \frac{2}{3} V_d e^{j\frac{\pi}{2}}$</td>
</tr>
<tr>
<td></td>
<td>[432] $S_4, S_3, S_2$</td>
<td>0 $V_d$ 0</td>
<td></td>
<td>$V_3 = \frac{2}{3} V_d e^{j\frac{2\pi}{3}}$</td>
</tr>
<tr>
<td></td>
<td>[435] $S_4, S_3, S_5$</td>
<td>0 $V_d$ $V_d$</td>
<td></td>
<td>$V_4 = \frac{2}{3} V_d e^{j\frac{3\pi}{3}}$</td>
</tr>
<tr>
<td></td>
<td>[465] $S_4, S_6, S_5$</td>
<td>0 0 $V_d$</td>
<td></td>
<td>$V_5 = \frac{2}{3} V_d e^{j\frac{4\pi}{3}}$</td>
</tr>
<tr>
<td></td>
<td>[165] $S_1, S_6, S_5$</td>
<td>$V_d$ 0 $V_d$</td>
<td></td>
<td>$V_6 = \frac{2}{3} V_d e^{j\frac{5\pi}{3}}$</td>
</tr>
</tbody>
</table>
Table 2.2 CSI switching states and space vectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Switching State</th>
<th>On-State Switch</th>
<th>Inverter PWM Current</th>
<th>Space Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero States</td>
<td>[14] S₁, S₄</td>
<td>0 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[36] S₂, S₆</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[52] S₅, S₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active States</td>
<td>[61] S₆, S₁</td>
<td>l₅d − l₅d 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[12] S₁, S₂</td>
<td>l₅d 0 − l₅d</td>
<td></td>
<td>l₅ = 2√3/3 l₅d e^{jπ/6}</td>
</tr>
<tr>
<td></td>
<td>[23] S₂, S₃</td>
<td>0 l₅d − l₅d</td>
<td></td>
<td>l₅ = 2√3/3 l₅d e^{jπ/2}</td>
</tr>
<tr>
<td></td>
<td>[34] S₃, S₄</td>
<td>−l₅d l₅d 0</td>
<td></td>
<td>l₅ = 2√3/3 l₅d e^{j7π/6}</td>
</tr>
<tr>
<td></td>
<td>[45] S₄, S₅</td>
<td>−l₅d 0 l₅d</td>
<td></td>
<td>l₅ = 2√3/3 l₅d e^{j3π/2}</td>
</tr>
<tr>
<td></td>
<td>[56] S₅, S₆</td>
<td>0 −l₅d l₅d</td>
<td></td>
<td>l₅ = 2√3/3 l₅d e^{j11π/6}</td>
</tr>
</tbody>
</table>

Figure 2.11 CSI space vector diagram
Current Source Space Vector Modulation (CS-SVM), like Voltage Source Space Vector Modulation (VS-SVM), is based upon the possible switch combinations. For a CSI too, there are six active states ($\bar{I}_1$ to $\bar{I}_6$) but three zero states ($\bar{I}_7$, $\bar{I}_8$, $\bar{I}_9$). In this case, the zero states are the activation of both the switches within one leg so as to ensure a continuous current through the DC link inductor, Bin Wu (2006). As earlier, they can be represented as stationary vectors on the d-q plane, as shown in Figure 2.11. The CSI space vector mapping shows a 30° phase lag on the vectors as vector $\bar{I}_1$ results in the maximum line-to-line voltage $V_{ac}$, which lags $V_a$ by 30°. The 30° phase shift can be implemented in the control system when determining the output vector. This allows direct mapping of the active vectors with those from the VSI, i.e. $\bar{I}_1 = \bar{V}_1$, etc. The mapping of the zero vectors, assuming that minimum switch transition is to be implemented, is based upon the current interval of the presently located reference vector, as each interval has a common switch in the two active vectors that mark the boundaries. Table 2.2 details the switching states and space vector for CSI.

Table 2.3 VSI to CSI control signal mapping

<table>
<thead>
<tr>
<th>Sector (Interval)</th>
<th>Active VSI Vector</th>
<th>VSI Active Switches</th>
<th>VSI Logic</th>
<th>CSI Active Switches from VSI Logic (Without Inversion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\bar{V}_1+\bar{V}_2$</td>
<td>$1 \bar{3} \bar{5} + 1 \bar{3} \bar{5}$</td>
<td>$1.\bar{5}$</td>
<td>$1.2$</td>
</tr>
<tr>
<td>II</td>
<td>$\bar{V}_2+\bar{V}_3$</td>
<td>$1 \bar{3} \bar{5} + \bar{1} \bar{3} \bar{5}$</td>
<td>$\bar{5}.3$</td>
<td>$2.3$</td>
</tr>
<tr>
<td>III</td>
<td>$\bar{V}_3+\bar{V}_4$</td>
<td>$\bar{1} \bar{3} \bar{5} + \bar{1} \bar{3} \bar{5}$</td>
<td>$\bar{3}.\bar{1}$</td>
<td>$3.4$</td>
</tr>
<tr>
<td>IV</td>
<td>$\bar{V}_4+\bar{V}_5$</td>
<td>$\bar{1} \bar{3} \bar{5} + \bar{1} \bar{3} \bar{5}$</td>
<td>$\bar{1}.5$</td>
<td>$4.5$</td>
</tr>
<tr>
<td>V</td>
<td>$\bar{V}_5+\bar{V}_6$</td>
<td>$\bar{1} \bar{3} \bar{5} + 1 \bar{3} \bar{5}$</td>
<td>$5.\bar{3}$</td>
<td>$5.6$</td>
</tr>
<tr>
<td>VI</td>
<td>$\bar{V}_6+\bar{V}_1$</td>
<td>$1 \bar{3} \bar{5} + 1 \bar{3} \bar{5}$</td>
<td>$\bar{7}.1$</td>
<td>$6.1$</td>
</tr>
</tbody>
</table>
Table 2.4 CSI null vector mapping

<table>
<thead>
<tr>
<th>Interval</th>
<th>Active CSI Vectors</th>
<th>Null Vector</th>
<th>Active Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$I_1 + I_2$</td>
<td>$I_9$</td>
<td>2.5</td>
</tr>
<tr>
<td>II</td>
<td>$I_2 + I_3$</td>
<td>$I_7$</td>
<td>3.6</td>
</tr>
<tr>
<td>III</td>
<td>$I_3 + I_4$</td>
<td>$I_8$</td>
<td>1.4</td>
</tr>
<tr>
<td>IV</td>
<td>$I_4 + I_5$</td>
<td>$I_9$</td>
<td>2.5</td>
</tr>
<tr>
<td>V</td>
<td>$I_5 + I_6$</td>
<td>$I_7$</td>
<td>3.6</td>
</tr>
<tr>
<td>VI</td>
<td>$I_6 + I_1$</td>
<td>$I_8$</td>
<td>1.4</td>
</tr>
</tbody>
</table>

In this work, a new truth table which is used to determine the individual switch mappings required to convert VS-SVM to CS-SVM, is developed. This allows standard controllers to implement CS-SVM by including low cost programmable logic devices with VS-SVM. Tables 2.3 and 2.4 detail the control signal mapping for VSI to CSI and Null vector mapping respectively.

2.4 CONTROL METHODS OF IM

This section overviews the most significant control methods of the IM (Scalar Control (V/f), IOL, FOC, DTC) and presents a brief analysis of the major advantages and drawbacks of Bimal K. Bose (2002).

2.4.1 Scalar Control

It is aimed at controlling the induction machine at quasi-steady state by varying the amplitude of the fundamental supply voltage and its frequency. The amplitude of the fundamental voltage is computed from the stator pulsation by adopting an empirical function that compensates the stator resistive drop and keeps the magnitude of the flux approximately constant.
However, this procedure is not valid during transient conditions and so the most crucial variables (torque and flux) cannot be adequately regulated in these situations. Besides, this absence of regulation depends on the transient duration related to load characteristics. In this work, a vector based V/f control for CSI fed IM drive is discussed. The dynamic performance of the drive is obtained from the developed simulation circuits. The open and closed loop performances are presented in the tabular form for easy comparison.

2.4.2 Field Oriented Control

Blaschke (1972) introduced FOC method which is firmly established on rigorous mathematical formalisms involving dynamical modeling of the machine and requires co-ordinate transformations over a rotating reference frame (dq axis). If this frame is oriented along with the rotor flux vector, both torque and rotor flux magnitude can be controlled independently by regulating the stator current components of the d and q axis, respectively. Usually, linear PI regulators are employed within both torque and flux control loops. In this work, an IFOC method for CSI fed IM drive is discussed. A RFO controller is designed and the simulation results are obtained. The dynamic performance of a drive is presented in a tabular form for easy analysis.

Advantages

- True decoupling between torque and flux control.
- Flux level imposition in a wide range of speed, including at standstill.
- Phase currents magnitude is kept moderate.
- Effective torque control either in motor or regenerative operations.
Disadvantages

- Rotor flux observation is sensitive to the rotor time constant.
- The optimal tuning of the PI regulators may be difficult.
- It is still a linear control method.

2.4.3 Input Output Linearization Control

A disadvantage of the FOC is that the method assumes that the magnitude of rotor flux is regulated to a constant value. Therefore, the rotor speed is only asymptotically decoupled from the rotor flux. Riccardo Marino et al (1996) developed an input output decoupling controller (used voltage commands) which decouples the control of the magnitude of the rotor flux from the regulation of the rotor speed.

This method can also be called as Feedback Linearization Control (FLC) because the speed and rotor flux amplitude are decoupled by feedback. In this work, an IOL control method is described for CSI fed IM drives which provides state feed backward as well as feed forward control to drive. The modeling and simulation procedures of the drive systems are presented along with simulation results.

Advantages

- True decoupling between speed and flux control.

Disadvantages

- It is implemented in a state feedback fashion and needs more complex signal processing.
2.4.4 Direct Torque Control

In the mid 1980s, there was a trend towards the standardization of the control systems on the basis of the FOC philosophy based on which appeared the innovative studies of Depenbrock (1988) and of Takahashi et al (1986) that depart from the idea of coordinate transformation and the analogy with dc motor control. These innovators proposed to replace the decoupling control with the bang-bang control that adequately meets the on–off operation of the inverter semiconductor power devices. This control strategy is commonly referred to as DTC and since 1985, it has been continuously developed and improved by many other researchers. In this work, the DTC method is described for CSI fed IM drives. A modular based approach is used to develop the IM model. The closed loop torque and flux control is used to design the DTC.

Advantages

- True decoupling between torque and flux control, with sinusoidal current absorption.
- Simplicity in analog implementations, with high robustness.
- Unbeatable torque dynamics with no overshoots.

Disadvantages

- The switching frequency is much higher at very low speed operation.
- It is difficult to guarantee absence of harmonics at a given frequency.
- Torque ripple is typically higher compared to other vector control methods.
2.5 CONCLUSION

The basic IM equations from Krause et al (1965) are simulated for three different reference frames using MATLAB7.6 software and the results obtained are compared with each reference frame. From the comparison, it is observed that: If the stator rotating reference frame is used, the stator d-axis current is identical to that of the stator ‘a’ phase current as shown in Figure 2.1(a), useful in stator fed IM drives. Similarly, in rotor reference frame, rotor d-axis current is identical to the rotor ‘a’ phase current and useful in rotor fed IM drives. If the synchronous reference frame is used, then the stator d-axis current behaves like DC quantity as shown in Figure 2.1(c). From Figures 2.2(c) and 2.3(c), it is evident that synchronous reference frame is useful in RFO and SFO drive control methods. In this thesis, synchronous reference frame is preferred to model the IM in V/f, IOL control methods. RFO control is used in IFOC method and SFO is used in DTC method. The gating signal generation concepts obtained from Ahmet M. Hava et al (1999), Holmes et al (2003) and Bin Wu et al (1992), are simulated and the resultant gating signals are shown in Figures 2.7 and 2.8. The VSI, CSI SVM switching states and space vector Tables 2.1 and 2.2 are presented in Bin Wu (2006). In this chapter, a mapping of VSI to CSI SVM switching logic is presented in Table 2.3. The CSI active switches presented in that table is same as the active switches presented in Table 2.2. So, the CS-SVM can be easily implemented from VS-SVM with low cost programmable logic devices.

2.6 SUMMARY

Background theory of IM modeling is briefly explained with the simulated results. The VSI and CSI gating signal generations are also presented with simulated waveforms. A new mapping technique of the VSI switching logic to CSI switching logic is presented in Table 2.3 for easy
implementation. The important IM control methods are briefly described with their advantages and disadvantages.

The most important contributions in this chapter are:

- The IM dynamic modeling with different reference frames are described with simulated graphical representations.
- The application of CSI to control AC motor is briefly discussed with simplified diagrams.
- The control signal generation for CSI is explained with simulated waveforms.
- The development of CS-SVM from VS-SVM principle is presented.