CHAPTER 6

DTC FOR CSI FED IM DRIVES

6.1 INTRODUCTION

Variable speed drives are used in all industries to control precisely the speed of electric motors driving loads ranging from pumps and fans to complex drives on paper machines, rolling mill cranes and similar drives. The most modern method for these drives is direct torque and stator flux vector control method usually called DTC. It has been realized in an industrial way by ABB, by using the theoretical background proposed by Blashke (1971) and Depenbrock (1988). This solution is based both on field oriented control (FOC) as well as on the direct self-control theory. The idea is that motor flux and torque are used as primary control variables which is contrary to the way in which traditional AC drives control input frequency and voltage, but is in principle similar to what is done with a DC drive, where it is much more straightforward to achieve.

Casadei et al (2006) has described that by controlling motor torque directly, DTC provides dynamic speed accuracy equivalent to closed loop AC and DC systems and torque response times that are 10 times faster. It is also claimed that the DTC does not generate noise like that produced by conventional PWM AC drives. This work describes a new modular approach to implement DTC method on a CSI fed IM drive, the simulation
implementation procedure. The dynamic response of the drive is analyzed and presented.

### 6.2 MODELING OF IM USING A MODULAR APPROACH

In recent years, the control of high-performance IM drives for general industrial applications and area of production has received a lot of research interests. IM modeling has continuously attracted the attention of researchers not only because such motor are made and used in larger numbers i.e. (80% of all the loads), but also due to their varied modes of operation both under steady state and dynamic state. Load characteristics have been known to have a sufficient effect on the system performance and transient stability. Because of the uncertainty of the actual load characteristics, dynamic models are used for accurate and precise result. Several efforts have been made to develop a method for constructing improved load models. One of the modes used for this work demonstrates the validity of a load modeling process based on the components that make up the dynamic load model. The basic purpose of using dq model approach is to control the motor parameters independently i.e. torque and flux of the IM.

The IM d-q or dynamic equivalent circuit is shown in Figure 6.1. One of the most popular IM models derived from this equivalent circuit is the model detailed in Krause et al (1965). According to his model, the modeling equations in flux linkage form are as follows

\[
\frac{d\lambda_{qs}}{dt} = \omega_b \left[ v_{qs} - \frac{\omega_e}{\omega_b} \lambda_{ds} + \frac{R_s}{x_{ls}} (\lambda_{qm} + \lambda_{qs}) \right] \quad (6.1)
\]

\[
\frac{d\lambda_{ds}}{dt} = \omega_b \left[ v_{ds} + \frac{\omega_e}{\omega_b} \lambda_{qs} + \frac{R_s}{x_{ls}} (\lambda_{dm} + \lambda_{ds}) \right] \quad (6.2)
\]
\[
\frac{d\lambda_{qr}}{dt} = \omega_b \left[ v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b} \lambda_{dr} + \frac{R_r}{x_{lr}} (\lambda_{qm} - \lambda_{qr}) \right] \tag{6.3}
\]

\[
\frac{d\lambda_{dr}}{dt} = \omega_b \left[ v_{dr} - \frac{(\omega_e - \omega_r)}{\omega_b} \lambda_{qr} + \frac{R_r}{x_{lr}} (\lambda_{dm} - \lambda_{dr}) \right] \tag{6.4}
\]

\[
\lambda_{qm} = x_{ml} \left[ \frac{\lambda_{qs}}{x_{ls}} + \frac{\lambda_{qr}}{x_{lr}} \right] \tag{6.5}
\]

\[
\lambda_{dm} = x_{ml} \left[ \frac{\lambda_{ds}}{x_{ls}} + \frac{\lambda_{dr}}{x_{lr}} \right] \tag{6.6}
\]

Figure 6.1 d-q axis equivalent circuit of IM
The stator, rotor current equations are as follows

\[ i_{qs} = \frac{1}{x_{ls}} (\lambda_{qs} - \lambda_{qm}) \]  
\[ i_{ds} = \frac{1}{x_{ls}} (\lambda_{ds} - \lambda_{dm}) \]  
\[ i_{qr} = \frac{1}{x_{lr}} (\lambda_{qr} - \lambda_{qm}) \]  
\[ i_{dr} = \frac{1}{x_{lr}} (\lambda_{dr} - \lambda_{dm}) \]

and the electromagnetic torque equation can be written as

\[ T_e = \frac{3}{2} \left( \frac{P_a}{2} \right) \frac{1}{\omega_b} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \]  
\[ T_e - T_l = J \left( \frac{P_a}{2} \right) \frac{d\omega_r}{dt} \]

For a squirrel cage IM as in the case of this work, when \( v_{qr} \) and \( v_{dr} \) in Equation (6.3) and (6.4) are set to zero, then the IM model can be represented with five differential equations as seen below. To solve these equations, they have to be rearranged in the state-space form, where \( \lambda_{qs}, \lambda_{ds}, \lambda_{qr}, \lambda_{dr}, \omega_r \) are the state variables. In this case, state-space form can be achieved by inserting Equations (6.5) and (6.6) in Equations (6.1 to 6.4) and collecting similar terms together so that each state derivative is a function of the other state variables and model inputs. The modeling Equations (6.1 to 6.4 and 6.12) of an IM in state-space form are given as follows.
\[ \frac{d\lambda_{qs}}{dt} = \omega_b \left[ v_{qs} - \frac{\omega_e}{\omega_b} \lambda_{ds} + \frac{R_s}{x_{ls}} \left( \frac{x_{ml}^*}{x_{lr}} \lambda_{qr} + \left( \frac{x_{ml}^*}{x_{ls}} - 1 \right) \lambda_{qs} \right) \right] \quad (6.13) \]

\[ \frac{d\lambda_{ds}}{dt} = \omega_b \left[ v_{ds} - \frac{\omega_e}{\omega_b} \lambda_{qs} + \frac{R_s}{x_{ls}} \left( \frac{x_{ml}^*}{x_{lr}} \lambda_{dr} + \left( \frac{x_{ml}^*}{x_{ls}} - 1 \right) \lambda_{ds} \right) \right] \quad (6.14) \]

\[ \frac{d\lambda_{qr}}{dt} = \omega_b \left[ -\frac{(\omega_e - \omega_r)}{\omega_b} \lambda_{dr} + \frac{R_r}{x_{lr}} \left( \frac{x_{ml}^*}{x_{ls}} \lambda_{qs} + \left( \frac{x_{ml}^*}{x_{lr}} - 1 \right) \lambda_{qr} \right) \right] \quad (6.15) \]

\[ \frac{d\lambda_{dr}}{dt} = \omega_b \left[ \frac{(\omega_e - \omega_r)}{\omega_b} \lambda_{qr} + \frac{R_r}{x_{lr}} \left( \frac{x_{ml}^*}{x_{ls}} \lambda_{ds} + \left( \frac{x_{ml}^*}{x_{lr}} - 1 \right) \lambda_{dr} \right) \right] \quad (6.16) \]

\[ \frac{d\omega_r}{dt} = \left( \frac{P}{2J} \right) (T_e - T_L) \quad (6.17) \]

### 6.3 DESIGN OF DIRECT TORQUE CONTROLLER

The DTC method is developed from Babaei et al (2010). From Krause et al (1965), in the stationary reference frame, the stator voltage and flux equation can be written as

\[ v_s = R_s i_s + \frac{d\lambda_s}{dt} \quad (6.18) \]

\[ \lambda_s = \int (v_s - R_s i_s) \, dt = \lambda_{\alpha s} + j \lambda_{\beta s} \quad (6.19) \]

\[ |\lambda_s| = \sqrt{\lambda_{\alpha s}^2 + \lambda_{\beta s}^2} \quad (6.20) \]

\[ \angle \phi_s = \tan^{-1} \left( \frac{\lambda_{\beta s}}{\lambda_{\alpha s}} \right) \quad (6.21) \]
where $R_s$ is the stator resistance, and $\lambda_s$ is the stator flux vector in the stationary reference frame. $|\lambda_s|$ and $\angle \varphi_s$ are the amplitude and position of stator flux vector, respectively. The relation between torque, stator current vector, and stator flux vector of the IM is given in Equation (6.11).

In DTC of CSI fed IM, it is desirable to determine the stator current reference so that the torque and stator flux follow their reference values Babaei et al (2010). The proposed DTC system is based on the Stator Flux Oriented (SFO) reference frame. In this rotating reference frame, it is written as

$$\lambda_{qs} = 0 \text{ and } \lambda_{ds} = |\lambda_s| \angle \varphi_s \quad (6.22)$$

Where $d$ and $q$ are the real and imaginary axes in the SFO reference frame. Therefore, the torque Equation (6.11) is rewritten as

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{1}{\omega_b} (\lambda_{ds} i_{qs}) \quad (6.23)$$

Where, $i_{qs}$ is the imaginary part of the stator current vector in the SFO reference frame. Therefore, if $|\lambda_s^*|$ and $T_e^*$ are stator flux magnitude and torque references respectively, the imaginary part of the stator current reference vector which leads to torque and stator flux magnitude references is as follows:

$$i_{qs}^* = \frac{2}{3} \frac{1}{P} \frac{T_e^*}{|\lambda_s^*|} \quad (6.24)$$

Because of the existence of a capacitor in the control system and its corresponding losses, when Equation (6.24) is used to control the torque for all rotor speeds, the control system will not be accurate enough.
Figure 6.2 q axis reference current calculator

In order to have a more accurate torque control, the block diagram shown in Figure 6.2 is used to calculate \( i_{qs}^* \). This block diagram is a combination of Equation (6.24) and a simple PI controller. This controller removes the steady-state error and leads to an accurate control. The coefficients of this controller must be small enough so that it remains stable and the ripples in \( i_{qs}^* \) are limited, because a ripple of \( i_{qs}^* \) results in a ripple of the generated torque. If only a PI is used, \( i_{qs}^* \) will have a large value of ripple, and the torque response time will be very large. Therefore, in order to have a faster transient response of torque, it is necessary to use Equation (6.24). In DTC method with VSI, the real part of voltage vector \( (v_d) \) in the stator flux reference frame leads to direct control of stator flux magnitude.

Therefore, using the real part of the stator current vector in the stator flux reference frame, it is possible to control the flux magnitude indirectly. In order to obtain the real part of the stator current reference, a simple PI controller is used. The input of this PI controller is the error that resulted from the comparison between the reference stator flux magnitude and the estimated flux value. In order to control the motor current in all cases, especially in the starting mode, the output of this PI controller must be limited between proper values. The output signal of the PI controller is the real part
of reference stator current $i_{ds}^{*}$. Therefore, the stator current reference vector
that leads to control the IM stator flux and torque is as follows:

$$i_{s(dq)}^{*} = i_{ds}^{*} + j i_{qs}^{*}$$ (6.25)

$$|i_s^{*}| = \sqrt{i_{ds}^{*2} + i_{qs}^{*2}}$$ (6.26)

The obtained reference current vector is in the stator flux reference
frame. In order to generate it by SVM of the CSI, it must be transferred to the
stationary reference frame. To do that, the stator flux position is used to
transfer this vector from the stator flux reference frame to the stationary
reference frame as follows:

$$i_{s(\alpha\beta)}^{*} = i_{\alpha}^{*} + j i_{\beta}^{*} = (i_{ds}^{*} + j i_{qs}^{*}) e^{j\varphi_s}$$

$$= |i_s^{*}| \angle \left( \varphi_s + \tan^{-1}\left( \frac{i_{qs}^{*}}{i_{ds}^{*}} \right) \right)$$ (6.27)

This reference current vector must be generated in the CSI first and
then applied to the motor after removing its harmonics with filtering
 capacitor. This current has a nearly sinusoidal waveform that leads to a nearly
sinusoidal voltage in motor terminals after feeding the motor and passing
through motor impedances. The speed and stator flux control of an IM with
DTC method is shown in Figure 6.3. Separate PI controllers are used to
control the speed and flux. The input to the speed controller is the error
caused by comparing the reference speed and the rotor speed. The output of
this controller is the imaginary part of stator current vector $i_{qs}^{*}$, which is
limited to a proper value.
6.4 DESIGN OF CLOSED LOOP TORQUE AND FLUX CONTROLLER

From the concepts of Bin Wu (2006) and Babaei et al (2010), the DTC-SVM schemes are proposed here in order to improve the classical DTC. The DTC-SVM strategies operate at a constant switching frequency. In the control structures, SVM algorithm is used. The type of DTC-SVM strategy depends on the applied flux and torque control algorithm. Basically, the controllers calculate the required stator current vector which is realized by SVM technique.

The classical DTC algorithm is based on the instantaneous values and directly calculates the digital control signals for the inverter. The control algorithm in DTC-SVM methods is based on averaged values whereas the switching signals for the inverter are calculated by space vector modulator. In this thesis, the implementation of DTC-SVM with closed loop torque and flux control in SFO is presented in Figure 6.3.
6.4.1 Design of Estimators

The vector control methods of IM require feedback signals. The information is about flux, torque and mechanical speed in drives operated without mechanical sensor. Different methods are used to obtain these state variables of IM. In this thesis, the mathematical model of IM is used to obtain the state variables.

6.4.1.1 Stator Flux Vector Estimator

The motor flux is the main component to calculate torque and speed. Therefore, accuracy of the estimation flux is very important. Flux estimation is a significant task in implementing high-performance motor drives. The flux vector estimator algorithms can be divided into two groups in terms of the input signal. The currents and voltages are the input signals to the voltage models, while the currents and speed or position information are input signals to the current models. Obviously, for sensor less control structures, general voltage models with many different modifications and improvements are used. The stator flux can be directly obtained from the motor model Equation (2.1) as follows:

\[ v_s^s = R_s i_s^s + \frac{d\lambda_s^s}{dt} \]  \hspace{1cm} (6.30)

\[ \lambda_s^s = \int (v_s^s - R_s i_s^s) \, dt \]  \hspace{1cm} (6.31)

This is a classical voltage model of stator flux vector estimation, which obtains flux by integrating the motor back emf. This method is sensitive for stator resistance. However, the implementation of pure integrator is difficult because of DC drift, initial value problems. Due to this, the estimator based on pure integrator in control structure becomes a
disadvantage. Using a pure integrator to estimate the stator flux, it is not possible to magnetize the machine if a zero torque command is applied. Moreover, the dynamic performance is lower and torque oscillations are bigger than in another stator flux estimation method. Many different stator flux estimation algorithms based on the voltage model, which do not approach the pure integrator are available. A simple method, which eliminates problems with initial conditions and DC drift appearing in pure integrator, is used here. In this case, Equation (6.31) can be transformed as follows:

$$\frac{d\lambda_s^s}{dt} = v_s^s - R_s i_s^s$$  \hspace{1cm} (6.32)

### 6.4.1.2 Torque Estimator

The IM output torque is calculated based on Equation (6.11), which for stationary coordinates system can be written as follows

$$T_e = \frac{3}{2} \frac{p}{2} (\lambda_{as}i_{as} - \lambda_{\beta s}i_{\beta s})$$  \hspace{1cm} (6.33)

It can be seen that the calculated torque depends on the current measurement accuracy and stator flux estimation method.

### 6.4.1.3 Rotor Speed Estimator

The IM mechanical speed can be calculated in different ways; here, from Equation (6.11), the speed is defined as the difference between developed electromagnetic torque and load torque. The electromagnetic torque can be calculated from Equation (6.33) and the rotor speed can be easily estimated through a pure integrator for the applied load torque.
The above estimation methods, implemented in DTC-SVM control structure are shown in Figure 6.3. The simulation circuit and results are presented in the following section.

6.5 SIMULATION IMPLEMENTATION OF DTC

In this section, a modular simulink implementation of an IM model is described in step by step Approach. With the modular system, each block solves one of the model equations. Due to this approach, all the machine parameters are accessible for control and verification purposes Khaligh et al (2005). When the equations are known, any drive or control algorithm can be modeled in simulink. However, the equations by themselves are not always enough as some experience in solving the differential equation is required.

The developed simulation model is shown in Figure 6.4. In the figure, induction motor block solves the flux linkage Equations (6.1) to (6.4) to get instantaneous dq stator currents. Equations (6.11) and (6.12) are used to obtain the instantaneous developed motor torque and motor speed respectively. The mechanical speed of the rotor is compared to its command value and the speed error is fed into a PI controller which generates the command torque value. This torque reference is compared with the estimated torque to generate a command torque to select an optimum switching state. Similarly, the flux command for switching state selection is generated by comparing the reference flux with estimated flux. The flux and torque estimators are realized from Equations (6.32) and (6.33) respectively. The flux angle is used to select the switching sector. The SVM switching states for CSI presented in the Table 2.2 is used here to generate the firing pulse to the inverter. The theoretical concepts of DTC method for CSI fed IM drive discussed in Sections 6.2 to 6.4 are verified using the simulations and the detailed simulation results are presented in the next section.
Figure 6.4 Simulation implementation of DTC method
6.6 SIMULATION RESULTS

**Figure 6.5** Speed, torque response of DTC drive when change in speed command at no load

**Figure 6.6** Speed, torque response of DTC drive when change in speed command at constant load
Figure 6.7 Speed, torque response of DTC drive when change in speed command at full load

Figure 6.8 Speed, torque and current response of DTC drive when change in torque command at full load
Figure 6.9  Dynamic performance of the DTC drive when change in speed command

Figure 6.10  Dynamic response of the DTC drive when step increase in torque command
Figure 6.11 Dynamic response of the DTC drive when step decrease in torque command

Figure 6.12 Dynamic response of the DTC drive when step decrease in -ve torque command
Table 6.1  Dynamic performance of DTC drive: Step change in motor speed

<table>
<thead>
<tr>
<th>Motor parameters</th>
<th>Step change in speed command from 0 to rated speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No load</td>
</tr>
<tr>
<td></td>
<td>( t_r ) (ms)</td>
</tr>
<tr>
<td>Motor current</td>
<td>23</td>
</tr>
<tr>
<td>Motor speed</td>
<td>315</td>
</tr>
<tr>
<td>Motor torque</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 6.2  Dynamic performance of DTC drive: Step change in motor torque

<table>
<thead>
<tr>
<th>Motor parameters</th>
<th>Step change in torque Command from no load to full Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( t_r ) (ms)</td>
</tr>
<tr>
<td>Motor current</td>
<td>18</td>
</tr>
<tr>
<td>Motor speed</td>
<td>270</td>
</tr>
<tr>
<td>Motor torque</td>
<td>38</td>
</tr>
</tbody>
</table>

The proposed DTC System with CSI fed IM shown in Figure 6.4 is simulated in MATLAB/simulink. Simulated motor parameters are presented in the Table A1.1. The simulation results of the proposed system are shown in Figures 6.5 to 6.12. Figures 6.5 and 6.6 show motor speed and torque operated under no load and constant load respectively. It is realized that the proposed drive makes the motor speed follow the reference speed as quickly
as possible. Figures 6.10 to 6.12 show the dynamic performance of DTC drive when there is a change in the torque command. The torque response rate of the developed motor torque is less than 0.15 seconds. The tabular presentation of the dynamic performance is also presented for easy analysis in the Tables 6.1 and 6.2. It is evident from the obtained simulation results that the proposed DTC drive has the good instantaneous load tracking capability under variable loading conditions with wide range of speed control.

6.7 CONCLUSION

Khaligh et al (2005) has presented a modular approach for IM model and implemented it for IFOC. Babaei et al (2010) has proposed closed loop torque and flux control systems for CSI fed IM, simulated them in MATLAB/simulink and then compared them with closed loop torque and flux control systems with VSI fed IM. In this work, closed loop torque and flux control systems for CSI fed IM are developed and used to investigate the stability of the drive during step change in speed and torque. The IM is modeled based on a modular approach. The simulink model is developed and simulated using MATLAB.

Figures 6.5 to 6.12 show the dynamic performance of the drive system during step change in speed and torque under different loading conditions, similar to the wave forms obtained by Babaei et al (2010). In the proposed method, torque ripple is reduced (approximately 10%). In addition, in this work, the IM is modeled based on modular approach in which all the machine parameters are easily accessible for control and verification purposes. This turns out to be a complicated process in dynamic equation modeling done by Babaei et al (2010).
The tabular presentation of simulated results Table 6.1 and 6.2 are also presented for stability analysis. From the simulation results, it is evident that during step change in speed command, the transient response in current, speed and torque in terms of rise time and settling time are high compared to the transient response during the step change in torque command, while there is an increase in maximum overshoot in full load case.

6.8 SUMMARY

This chapter contains a review of the theoretical concepts used in simulation and implementation of DTC for CSI fed IM drives. A new modular approach is described to model the IM in which all the motor parameters are accessible for control and verification purposes. The conventional DTC algorithm is based on the instantaneous values and is directly calculated using digital control signals for the inverter.

But, the control algorithm in this work is based on averaged values whereas the switching signals for the inverter are calculated by space vector modulator. This type of method depends on the applied flux and torque control algorithm. The flux and torque controllers calculate the required current vector which is realized by space vector modulation technique. The speed controller design, design of flux, torque, and speed estimators are presented and implemented in simulations.

The most important contributions in this chapter are:

- Modeling and simulation implementation of IM using modular approach which solves all the model equations individually.
- Torque, rotor speed and Stator flux vector estimator in terms of motor currents is developed.

- DTC Scheme with Closed Loop Torque and Flux Control in Stator Flux Coordinates is implemented.

- Dynamic performances of the proposed IM drive for different loading conditions are analyzed.