CHAPTER 4

THREE LEVEL SVM BASED DIRECT TORQUE
CONTROL OF INDUCTION MOTOR

4.1 INTRODUCTION

The open loop performance of induction motor with multilevel inverter is analyzed in the previous chapters. The main aim of the analysis was to identify the relation between the torque ripple and the level of inverter. From the analysis carried out, it is concluded that the THD is reduced considerably as the level of inverter is increased. However, as the level of inverter increases, the cost and complexity increase thereby restricting further study to a DTC scheme with a three level inverter along with hardware implementation.

In the present chapter, a three level SVM -DTC fed induction motor is analyzed in closed loop mode for various load conditions. The analysis is carried out for two different machines using the simulation software MATLAB.

4.2 CONVENTIONAL DTC SCHEME

The conventional DTC scheme is a closed loop control scheme with the important elements of the control structure being: the power supply circuit, a three phase voltage source inverter, the induction motor, the speed controller to generate the torque command and the DTC controller. The DTC
controller again consists of torque and flux estimation block, two hysteresis controllers and sector selection block. The output of the DTC controller is the gating pulses for the inverter.

The DTC scheme does not require coordinate transformation, feedback current control loop and PI controllers in the stationary frame of reference. So, this scheme does not suffer from parameter variations and delay in the current controllers. The torque and stator flux are controlled directly by using hysteresis comparators. Figure 4.1 shows the basic block diagram of a conventional DTC scheme.

![Figure 4.1 Block diagram of conventional DTC scheme for IM](image)

### 4.3 PRINCIPLE OF DTC SCHEME

In principle, the DTC method selects one of the inverter’s six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes. The stator flux will increase the phase angle between the stator
flux and rotor flux vectors and so the torque produced will increase. The control algorithm in DTC-SVM methods are based on averaged values of flux and torque. The switching signals for the inverter are calculated by space vector modulator.

4.4 NEUTRAL POINT CLAMPED (NPC) INVERTER

The voltage across semiconductor switches are limited by diodes connected to various DC levels in the diode clamped multilevel inverters. According to the original invention, the concept can be extended to any number of levels by increasing the number of capacitors in addition to dc link capacitors. Early descriptions of this topology were limited to three-levels where two capacitors are connected across the DC bus resulting in one additional level. The additional level was the neutral point of the dc bus, so the terminology Neutral Point Clamped inverter (NPCI) was introduced.

The functional diagram of a three level NPC converter is shown in Figure 4.2. Each leg contains four active switches S1 to S4 with parallel diodes D1 to D4. The capacitors at the DC side are used to split the DC input into two, to provide a neutral point Z. The clamping diodes can be defined as the diodes connected to the neutral point Dz1, Dz2. When switches S2 and S3 are connected, the output terminal A can be taken to the neutral through one of the clamping diodes. The voltage applied to each of the DC capacitors is E, which is equal to \( V_d/2 \). Table 4.1 shows the possible three phase switching states and inverter terminal voltage.
Table 4.1 Various switching states

<table>
<thead>
<tr>
<th>Switching state</th>
<th>Device switching status (Phase A)</th>
<th>Inverter terminal voltage $V_{AZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On  On  Off  Off</td>
<td>E</td>
</tr>
<tr>
<td>0</td>
<td>Off  On  On  Off</td>
<td>0</td>
</tr>
<tr>
<td>-1</td>
<td>Off  Off  On  On</td>
<td>-E</td>
</tr>
</tbody>
</table>

4.5 SPACE VECTOR MODULATION (SVM)

The objective of the SVPWM is to generate PWM line voltage that is in average equal to a given reference voltage. This is achieved in each sampling period by properly selecting the switch states of the inverter and the calculation of appropriate time period for each state. The selection of the states and their time periods are accomplished by the space vector (SV)
transformation. It is a sophisticated technique for generating sine wave that provides an increased voltage to the motor with a low total harmonic distortion. In SVPWM technique, instead of using a separate modulator for each of the three phases, the complex reference voltage vector is processed as a whole. SVPWM generates less harmonic distortion in the output voltages and currents in the windings of the motor and provides an efficient use of the DC supply voltage in comparison with SPWM.

SVPWM treats the sinusoidal voltage as a constant amplitude vector rotating at constant speed. This PWM technique approximates the reference voltage \( V_{\text{ref}} \) by a combination of selected patterns out of 27 switching patterns (\( V_0 \) to \( V_{26} \)) for TLDCI. In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantities either in synchronously rotating frame or stationary frame. From these two-phase components the reference vector magnitude can be found and used to modulate the inverter output. The rotating flux component can be represented as a single rotating vector. The magnitude and angle of the rotating vector at any sampling instant can be determined from the d-q components of stator phase voltages.

Table 4.2 shows the voltage space vector, switching states and their magnitudes. P type and N type represent the positive and negative group of switches. In phase A, S1 and S2 are the positive group and S3 and S4 are the negative group of switches. When S1 and S2 conduct the voltage vector is \([1]\) in phase A. When S2 and S3 conduct the voltage vector is \([0]\) whereas the vector takes a value \([-1]\) when S3 and S4 conduct.
Table 4.2 Space vectors and switching states

<table>
<thead>
<tr>
<th>Space Vector</th>
<th>Switching State [A B C]</th>
<th>Vector Classification</th>
<th>Vector Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$</td>
<td>$[1\ 1\ 1][-1\ -1\ -1][0\ 0\ 0]$</td>
<td>Zero Vector</td>
<td>0</td>
</tr>
<tr>
<td>$V_1$</td>
<td>P type [1 0 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N type [0 -1 -1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_2$</td>
<td>P type $[1\ 1\ 0]$</td>
<td>Small vector</td>
<td>$\frac{V_d}{3}$</td>
</tr>
<tr>
<td></td>
<td>N type [0 0 -1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_3$</td>
<td>P type $[0\ 1\ 0]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N type [-1 0 -1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_4$</td>
<td>$V_{4PN}$ [0 1 1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V_{4N}$ [-1 0 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_5$</td>
<td>P type $[0\ 0\ 1]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N type [-1 -1 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_6$</td>
<td>P type $[1\ 0\ 1]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N type [0 -1 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_7$</td>
<td>$[1\ 0\ -1]$</td>
<td>Medium vector</td>
<td>$\frac{V_d}{\sqrt{3}}$</td>
</tr>
<tr>
<td>$V_8$</td>
<td>$[0\ 1\ -1]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_9$</td>
<td>[-1 1 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{10}$</td>
<td>[-1 0 1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{11}$</td>
<td>[0 -1 1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{12}$</td>
<td>[1 -1 0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{13}$</td>
<td>[1 -1 -1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{14}$</td>
<td>[1 1 -1]</td>
<td>Large vector</td>
<td>$\frac{2}{3}V_d$</td>
</tr>
<tr>
<td>$V_{15}$</td>
<td>[-1 1 -1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{16}$</td>
<td>[-1 1 1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{17}$</td>
<td>[-1 -1 1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{18}$</td>
<td>[1 -1 1]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figures 4.3 and 4.4 depict the 27 switching state possible in TLDCI fed induction motor with SVM-DTC.

The voltage vector has four groups.

- **Zero vector** \( (V_0) \), representing three switching states \([1 \ 1 \ 1], [0 \ 0 \ 0] \) \& \([-1 -1 -1]\). The magnitude of \( V_0 \) is Zero.

- **Small vectors** \( (V_1 \ to \ V_6) \), all have a magnitude of \( \frac{V_d}{3} \). Each small sector has two switching states, one containing \([1]\) and the other containing \([-1]\) and they classified as \( P_\) or \( N_\) type small vector.

- **Medium vectors** \( (V_7 \ to \ V_{12}) \), whose magnitude are \( \frac{V_d}{\sqrt{3}} \)

- **Large vectors** \( (V_{13} \ to \ V_{18}) \), all have a magnitude of \( \frac{2}{3}V_d \)

![Figure 4.3 Space vector diagram of a three level inverter](image-url)
4.5.1 Design Steps for SVPWM Generation

The various steps involved in the design of SVPWM generation is discussed in the succeeding sections.

4.5.1.1 Sector determination

The value of $\theta$ is calculated from $V_d$ and $V_q$ and then the sector in which the command vector $V_{\text{ref}}$ is located is determined. If $\theta$ is between

- $0^\circ \leq \theta < 60^\circ$, then $V_{\text{ref}}$ will be in Sector_1,
- $60^\circ \leq \theta < 120^\circ$, then $V_{\text{ref}}$ will be in Sector_2,
- $120^\circ \leq \theta < 180^\circ$, then $V_{\text{ref}}$ will be in Sector_3,
- $180^\circ \leq \theta < 240^\circ$, then $V_{\text{ref}}$ will be in Sector_4,
- $240^\circ \leq \theta < 300^\circ$, then $V_{\text{ref}}$ will be in Sector_5,
- $300^\circ \leq \theta < 360^\circ$, then $V_{\text{ref}}$ will be in Sector_6.
Figure 4.5 gives the switching states associated with long, medium and small vectors involved in switching when $V_{\text{ref}}$ lies in sector _1.

### 4.5.1.2 Determination of region

![Figure 4.5 Sector_1 and its switching states for three-level inverter](image)

From the Figure 4.5 it can be observed that two additional vectors $\bar{V}_a$ and $\bar{V}_b$ are used to determine the region where $V_{\text{ref}}$ is located as given in Equations (4.1) (4.2).

\begin{align*}
\bar{V}_a &= \bar{V}_{\text{ref}} (\cos \theta - \frac{\sin \theta}{\sqrt{3}}) \quad (4.1) \\
\bar{V}_b &= 2 \bar{V}_{\text{ref}} \frac{\sin \theta}{\sqrt{3}} \quad (4.2)
\end{align*}

Using Equations (4.1) and (4.2), it is possible to specify the working region:

- If $\bar{V}_a$, $\bar{V}_b$ and $(\bar{V}_a + \bar{V}_b)$ are smaller than $0.33V_d$, then $\bar{V}_{\text{ref}}$ is placed in region _1.
• If $\tilde{V}_a$, $\tilde{V}_b$ are smaller than $0.33V_d$ and $(\tilde{V}_a + \tilde{V}_b)$ is higher than $0.33V_d$, and then $\tilde{V}_{\text{ref}}$ is placed in region_2.

• If $\tilde{V}_a$ is higher than $0.33V_d$, then $\tilde{V}_{\text{ref}}$ is placed in region_3.

• If $\tilde{V}_b$ is higher than $0.33V_d$, then $\tilde{V}_{\text{ref}}$ is placed in region_4.

4.5.1.3 Calculation of time duration

The principle of SVPWM method is based on the command voltage vector which is approximated by using three adjacent inverter voltage vectors. The duration of each voltage vector is obtained by using the voltage time equation of vectors as given in Equations (4.3) and (4.4).

\[ T_a V_1 + T_b V_2 + T_c V_0 = T_s V_{\text{ref}} \]  
\[ T_a + T_b + T_c = T_s \]  

$V_1$, $V_2$ and $V_0$ are the vectors that define a triangle region in which $\tilde{V}_{\text{ref}}$ lies. $T_a$, $T_b$ and $T_c$ are the corresponding vector durations and $T_s$ is the sampling time. The calculation of vector duration time is explained as shown in Figures 4.6 to 4.9 when $V_{\text{ref}}$ lies in different sectors and regions.
Sector_1 Region_4 (0 ≤ θ < 60°)

The relationship between voltages and time durations in region_4 of sector_1 can be expressed as shown in Equation (4.5)

\[
\tilde{V}_{14}T_a + \tilde{V}_7T_b + \tilde{V}_2T_c = \tilde{V}_{\text{ref}}T_s \tag{4.5}
\]

where

\[
\tilde{V}_{14} = \frac{2}{3}V_{de} \frac{j\pi}{3} ; \quad \tilde{V}_7 = \frac{\sqrt{3}}{3}V_{de} \frac{j\pi}{6} ; \quad \tilde{V}_2 = \frac{1}{3}V_{de} \frac{j\pi}{3}
\]

Substituting the values in Equation (4.5), one gets

\[
\frac{2}{3} \left[ \frac{\cos(\pi)}{3} + \frac{j\sin(\pi)}{3} \right] T_a + \frac{\sqrt{3}}{3} \left[ \frac{\cos(\pi)}{6} + \frac{j\sin(\pi)}{6} \right] T_b + \frac{1}{3} \left[ \frac{\cos(\pi)}{3} + \frac{j\sin(\pi)}{3} \right] T_c = \frac{V_{\text{ref}}}{V_d} [\cos(\theta) + j\sin(\theta)]T_s \tag{4.6}
\]

The real and imaginary parts are separated as shown in Equations (4.7) and (4.8)
Real part \[ T_a = \frac{1}{3}T_a + \frac{1}{2}T_b + \frac{1}{6}T_c = \frac{\bar{V}_{ref}}{V_d} \cos(\theta)T_s \] (4.7)

Imaginary part \[ T_a = \frac{\sqrt{3}}{3}T_a + \frac{\sqrt{3}}{6}T_b + \frac{\sqrt{3}}{6}T_c = \frac{\bar{V}_{ref}}{V_d} \sin(\theta)T_s \] (4.8)

Total time \[ T_s = T_a + T_b + T_c \] (4.9)

By solving Equations (4.7) to (4.9) the switching times can be calculated as shown in Equations (4.10) to (4.12)

\[ T_a = T_s[2M \sin(\theta) - 1] \] (4.10)

\[ T_b = T_s[2M \sin\left(\frac{\pi}{3} - \theta\right)] \] (4.11)

\[ T_c = T_s[2 - 2M \sin\left(\frac{\pi}{3} + \theta\right)] \] (4.12)

Where \[ M = \frac{\sqrt{3}V_{ref}}{V_d} \]

**Sector_1 Region_2** \((0 \leq \theta < 60^\circ)\)

![Figure 4.7 Sector_1 Region_2](image)
The relationship between voltages and time duration in region_2 of sector_1 can be expressed as shown in Equation (4.13).

\[ \tilde{V}_1 T_a + \tilde{V}_7 T_b + \tilde{V}_2 T_c = \tilde{V}_{\text{ref}} T_s \]  

(4.13)

where \( \tilde{V}_1 = \frac{1}{3} V_d \); \( \tilde{V}_2 = \frac{1}{3} V_{de} \); \( \tilde{V}_7 = \frac{\sqrt{3}}{3} V_{de} \)

Substituting the values in Equation (4.13), one gets

\[ \frac{1}{3} T_a + \frac{\sqrt{3}}{3} \left[ \cos\left(\frac{\pi}{6}\right) + j\sin\left(\frac{\pi}{6}\right) \right] T_b + \frac{1}{3} \left[ \cos\left(\frac{\pi}{3}\right) + j\sin\left(\frac{\pi}{3}\right) \right] T_c = \frac{V_{\text{ref}}}{V_d} [\cos(\theta) + j\sin(\theta)] T_S \]

(4.14)

The real and imaginary parts are separated as shown in Equations (4.15) and (4.16)

Real part = \( T_a + \frac{3}{2} T_b + \frac{1}{2} T_c = 3\frac{\tilde{V}_{\text{ref}}}{V_d}\cos(\theta) T_s \)  

(4.15)

Imaginary part = \( \frac{3}{2} T_b + \frac{\sqrt{3}}{2} T_c = 3\frac{\tilde{V}_{\text{ref}}}{V_d}\sin(\theta) T_s \)  

(4.16)

Total time \( T_S = T_a + T_b + T_c \)

(4.17)

By solving Equations (4.15) to (4.17) the switching time can be calculated as shown in Equations (4.18) to (4.20)

\( T_a = T_s [1 - 2M\sin(\theta)] \)  

(4.18)

\( T_a = T_s [2M\sin\left(\frac{\pi}{3} + \theta\right) - 1] \)  

(4.19)

\( T_c = T_s [2 - 2M\sin\left(\frac{\pi}{3} - \theta\right)] \)  

(4.20)
Sector _2 Region_ 2 \((60^\circ \leq \theta < 120^\circ)\)

Figure 4.8 Sector _2 Region_ 2

The relationship between voltages and time duration for region_2 of sector_2 can be expressed as shown in Equation (4.21).

\[
\tilde{V}_2 T_a + \tilde{V}_8 T_b + \tilde{V}_{14} T_c = \tilde{V}_{\text{ref}} T_s \tag{4.21}
\]

where \(\tilde{V}_2 = \frac{1}{3} V_d; \ \tilde{V}_8 = \frac{1}{\sqrt{3}} V_d e^{\frac{j \pi}{6}}; \ \tilde{V}_{14} = \frac{2}{3} V_d\)

Substituting the values in Equation (4.21), one gets

\[
\frac{1}{3} T_a + \frac{\sqrt{3}}{3} \left[ \cos\left(\frac{\pi}{6}\right) + j \sin\left(\frac{\pi}{6}\right) \right] T_b + \frac{2}{3} T_c = \frac{V_{\text{ref}}}{V_d} [\cos(\theta) + j \sin(\theta)] T_S \tag{4.22}
\]

The real and imaginary parts are separated as shown in Equations (4.23) and (4.24)

\[
\text{Real part} = \frac{1}{3} T_a + \frac{\sqrt{3}}{6} T_b + \frac{2}{3} T_c = \frac{V_{\text{ref}}}{V_d} \cos(\theta) T_S \tag{4.23}
\]
Imaginary part = \( \frac{3}{6} T_b = \frac{\bar{V}_{\text{ref}}}{V_d} \sin(\theta) T_s \) \hspace{1cm} (4.24)

Total time \( T_c = T_a + T_b + T_c \) \hspace{1cm} (4.25)

By solving Equations (4.23) to (4.25) the switching times can be calculated as shown in Figure (4.26) to (4.28)

\[
T_a = T_s [2 - 2M \sin(\frac{\pi}{3} + \theta)] \hspace{1cm} (4.26)
\]

\[
T_b = T_s [2M \sin(\theta)] \hspace{1cm} (4.27)
\]

\[
T_c = T_s [2M \sin(\frac{\pi}{3} - \theta) - 1] \hspace{1cm} (4.28)
\]

**Sector_4 region_2** \((180^\circ \leq \theta < 240^\circ)\)

![Figure 4.9 Sector_4 Region_2](image)

The relationship between voltages and times in region_2 of sector_4 can be expressed as shown in Equation (4.29).
\[ \tilde{V}_4 T_a + \tilde{V}_{10} T_b + \tilde{V}_5 T_c = \tilde{V}_{\text{ref}} T_s \]  

(4.29)

Where \[ \tilde{V}_4 = \frac{1}{3} V_d; \quad \tilde{V}_{10} = \frac{1}{\sqrt{3}} V_d e^{\frac{j \pi}{6}}; \quad \tilde{V}_5 = \frac{1}{3} V_d e^{\frac{j \pi}{3}} \]

Substituting the values in Equation (4.29), one gets

\[ \frac{1}{3} T_a + \frac{\sqrt{3}}{3} \left[ \cos \left( \frac{\pi}{6} \right) + j \sin \left( \frac{\pi}{6} \right) \right] T_b + \frac{1}{3} \left[ \cos \left( \frac{\pi}{3} \right) + j \sin \left( \frac{\pi}{3} \right) \right] T_c = \frac{\tilde{V}_{\text{ref}}}{V_d} [\cos(\theta) + j \sin(\theta)] T_S \]

(4.30)

The real and imaginary parts are expressed as shown in Equations (4.31) and (4.32)

Real part = \[ T_a + \frac{3}{2} T_b + \frac{1}{2} T_c = 3 \frac{\tilde{V}_{\text{ref}}}{V_d} \cos(\theta) T_s \]  

(4.31)

Imaginary part = \[ \frac{3}{2} T_b + \frac{\sqrt{3}}{2} T_c = 3 \frac{\tilde{V}_{\text{ref}}}{V_d} \sin(\theta) T_s \]  

(4.32)

Total time \[ T_s = T_a + T_b + T_c \]  

(4.33)

By solving Equations (4.31) to (4.33) the switching time can be calculated as shown in Equations (4.34) to (4.36)

\[ T_a = T_s [1 - 2M \sin 0] \]  

(4.34)

\[ T_b = T_s [2M \sin \left( \frac{\pi}{3} + \theta \right) - 1] \]  

(4.35)

\[ T_c = T_s [2 - 2M \sin \left( \frac{\pi}{3} - \theta \right)] \]  

(4.36)

The switching time calculation of sector _1 is shown in Table 4.3. This table is valid for all the four regions in the remaining four sectors. The Figures 4.10 and 4.11 show the switching sequence for regions 1, 2, 3 and 4 as given in Tables 4.4, to 4.7 respectively.
Table 4.3 Values of switching time calculation for different regions of Sector_1

<table>
<thead>
<tr>
<th>Region</th>
<th>Region I</th>
<th>Region II</th>
<th>Region III</th>
<th>Region IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_a$</td>
<td>$T_s [2M \sin (\frac{\pi}{3} - \theta)]$</td>
<td>$T_s [1 - 2M \sin 0]$</td>
<td>$T_s [2 - 2M \sin (\frac{\pi}{3} + \theta)]$</td>
<td>$T_s [2M \sin (\theta) - 1]$</td>
</tr>
<tr>
<td>$T_b$</td>
<td>$T_s [1 - 2M \sin (\frac{\pi}{3} - \theta)]$</td>
<td>$T_s [2M \sin (\frac{\pi}{3} + \theta) - 1]$</td>
<td>$T_s [2M \sin (0)]$</td>
<td>$T_s [2M \sin (\frac{\pi}{3} - \theta)]$</td>
</tr>
<tr>
<td>$T_c$</td>
<td>$T_s [2M \sin (0)]$</td>
<td>$T_s [2 - 2M \sin (\frac{\pi}{3} - \theta)]$</td>
<td>$T_s [2M \sin (\frac{\pi}{3} - \theta) - 1]$</td>
<td>$T_s [2 - 2M \sin (\frac{\pi}{3} + \theta)]$</td>
</tr>
</tbody>
</table>

The switching sequences for the regions 1 and 2 for different sectors are shown in Figure 4.10. The sector divisions for region_1 are represented as D1,D2,D3,D4,D5 and D6 as shown in Figure 4.10 (a). The Figure 4.10 (b) shows sector divisions for region_2 which are represented as D7,D8,D9,D10,D11 and D12.

![Diagram](image)

(a) Region_1

Figure 4.10 (Continued)
Figure 4.10 Switching sequences for Region_1 and Region_2

Table 4.4 Switching sequence for Region_1 in Sector_1

<table>
<thead>
<tr>
<th>Vectors</th>
<th>( V_0 )</th>
<th>( V_{1N} )</th>
<th>( V_{2N} )</th>
<th>( V_0 )</th>
<th>( V_{1P} )</th>
<th>( V_{2P} )</th>
<th>( V_0 )</th>
<th>( V_{1P} )</th>
<th>( V_{2P} )</th>
<th>( V_0 )</th>
<th>( V_{1N} )</th>
<th>( V_{2N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch  Time</td>
<td>( T_a/8 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/4 )</td>
<td>( T_a/8 )</td>
<td></td>
</tr>
<tr>
<td>State [A B C]</td>
<td>-1-1-1</td>
<td>0-1-1</td>
<td>00-1</td>
<td>100</td>
<td>110</td>
<td>111</td>
<td>110</td>
<td>100</td>
<td>000</td>
<td>00-1</td>
<td>0-1-1</td>
<td>-1-1-1</td>
</tr>
</tbody>
</table>

Table 4.5 Switching sequence for Region_2 in Sector_1

<table>
<thead>
<tr>
<th>Vectors</th>
<th>( V_{1N} )</th>
<th>( V_{2N} )</th>
<th>( V_0 )</th>
<th>( V_14 )</th>
<th>( V_2 )</th>
<th>( V_8 )</th>
<th>( V_{2N} )</th>
<th>( V_{1N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Time</td>
<td>( T_d/6 )</td>
<td>( T_d/3 )</td>
<td>( T_d/2 )</td>
<td>( T_d/3 )</td>
<td>( T_d/3 )</td>
<td>( T_d/2 )</td>
<td>( T_d/3 )</td>
<td>( T_d/6 )</td>
</tr>
<tr>
<td>State [A B C]</td>
<td>0-1-1</td>
<td>00-1</td>
<td>10-1</td>
<td>100</td>
<td>110</td>
<td>100</td>
<td>10-1</td>
<td>00-1</td>
</tr>
</tbody>
</table>

The switching sequence for the region_3 and region_4 for different sector is shown in Figure 4.11. The sector divisions for region_3 are represented as D13,D15,D17,D19,D21 and D23 as shown in Figure 4.11 (a). The Figure 4.11 (b) shows sector divisions for region_4 which are represented as D14,D16,D18,D20,D22 and D24.
Figure 4.11 Switching sequences for Region_3 and Region_4

Table 4.6 Switching sequence for Region_3 in Sector_1

<table>
<thead>
<tr>
<th>Vectors</th>
<th>$V_{1N}$</th>
<th>$V_{13}$</th>
<th>$V_7$</th>
<th>$V_{1P}$</th>
<th>$V_7$</th>
<th>$V_{13}$</th>
<th>$V_{IN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Times</td>
<td>$T_{a}/4$</td>
<td>$T_c/2$</td>
<td>$T_{b}/2$</td>
<td>$T_c/2$</td>
<td>$T_{b}/2$</td>
<td>$T_c/2$</td>
<td>$T_{a}/4$</td>
</tr>
<tr>
<td>State $[A B C]$</td>
<td>0-1-1</td>
<td>1-1-1</td>
<td>10-1</td>
<td>100</td>
<td>10-1</td>
<td>1-1-1</td>
<td>0-1-1</td>
</tr>
</tbody>
</table>
Table 4.7 Switching sequence for Region_4 in Sector_1

<table>
<thead>
<tr>
<th>Vectors</th>
<th>$V_{2N}$</th>
<th>$V_7$</th>
<th>$V_{14}$</th>
<th>$V_{2P}$</th>
<th>$V_{14}$</th>
<th>$V_7$</th>
<th>$V_{2N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Switching Times</strong></td>
<td>$T_c/4$</td>
<td>$T_b/2$</td>
<td>$T_a/2$</td>
<td>$T_c/2$</td>
<td>$T_a/2$</td>
<td>$T_b/2$</td>
<td>$T_c/4$</td>
</tr>
<tr>
<td><strong>State</strong></td>
<td>00-1</td>
<td>10-1</td>
<td>11-1</td>
<td>110</td>
<td>11-1</td>
<td>10-1</td>
<td>00-1</td>
</tr>
</tbody>
</table>

4.6 SIMULATION MODEL OF TLDCl FED INDUCTION MOTOR WITH DTC-SVM

The simulation model of TLDCl fed induction motor with DTC-SVM control consists of four blocks namely, Induction motor drive block, DTC-SVM block, DCI block, flux and torque estimation block as shown in Figure 4.12.

Figure 4.12 Simulation diagram of TLDCl fed IM with DTC-SVM
4.6.1 Flux and Torque Estimation Block

The flux and torque are estimated from the machine terminal voltage and current by using 3-phase to 2-phase transformation and then calculating the flux and torque from the two phase variables. The flux and torque in dq stator reference frame with d-axis fixed along a-axis are calculated based on Equation (4.39) and (4.40) as given below.

\[ \psi_{ds}^s = \int (V_{ds}^s - R_s I_{ds}^s) \]  \hspace{1cm} (4.37)

\[ \psi_{qs}^s = \int (V_{qs}^s - R_s I_{qs}^s) \]  \hspace{1cm} (4.38)

\[ \psi_s^s = \sqrt{\left(\psi_{ds}^s\right)^2 + \left(\psi_{qs}^s\right)^2} \]  \hspace{1cm} (4.39)

\[ T_e = p \frac{3}{2} \left( \psi_{ds}^s I_{qs}^s - \psi_{qs}^s I_{ds}^s \right) \]  \hspace{1cm} (4.40)

\[ \theta = \tan^{-1} \left( \frac{\psi_{qs}^s}{\psi_{ds}^s} \right) \]

p - Number of poles

\( \psi_{ds}^s \) and \( \psi_{qs}^s \) are the direct and quadrature axes components of stator flux.

\( I_{qs}^s \) and \( I_{qs}^s \) are the direct and quadrature axes components of stator current.

The implementation of the above equations is shown in Figure 4.13.
\[ T_e^* = \left( K_p + \frac{1}{T_i} \right) \Delta \omega \quad ; K_i = 1/T_i \]

\[ \Delta \omega_m = \omega_m - \omega_m^* \]

**Torque PI Controller**

The torque PI controller is shown in Figure 4.15 generates the voltage \( V_{qs}^* \) which is given in Equation (4.41).

\[ V_{qs}^* = K_p T_e \Delta T_e + \frac{1}{T_i} \int \Delta T_e \, dt \quad ; K_i = 1/T_i \]  \( (4.41) \)

\[ \Delta T_e = T_e^* - T_e \]
4.7 DESIGN OF PI CONTROLLERS

The PI controller is the one which decides the dynamic performance of the machine. The gains of PI controllers for the torque and flux loops have to be tuned properly to minimize the torque ripple.

Figure 4.15 Block diagram of PI torque controller

Figure 4.16 Block diagram of PI flux controller
The mathematical model for the induction machine with d-axis fixed along the stator flux axis is given in Equations (4.43) to (4.50)

\[ V_{ds} = R_s I_{ds} + P \psi_{ds} \]  \hspace{1cm} (4.43)
\[ V_{qs} = R_s I_{qs} + \omega \psi_{qs} \]  \hspace{1cm} (4.44)
\[ 0 = R_r I_{dr} + P \psi_{dr} - \psi_{qr} (\omega_s - p \omega_m) \]  \hspace{1cm} (4.45)
\[ 0 = R_r I_{qr} + P \psi_{qr} + \psi_{dr} (\omega_s - p \omega_m) \]  \hspace{1cm} (4.46)
\[ \psi_{ds} = L_s I_{ds} + L_m I_{dr} \]  \hspace{1cm} (4.47)
\[ \psi_{qs} = L_s I_{qs} + L_m I_{qr} = 0 \]  \hspace{1cm} (4.48)
\[ \psi_{dr} = L_r I_{dr} + L_m I_{ds} \]  \hspace{1cm} (4.49)
\[ \psi_{qr} = L_r I_{qr} + L_m I_{qs} \]  \hspace{1cm} (4.50)

where, \( V_{ds}, V_{qs} \) are stator voltages in d and q axes of rotating reference frame, \( I_{ds} \) and \( I_{qs} \) are stator currents in d and q axis respectively. \( \psi_{ds} \) and \( \psi_{qs} \) are the direct and quadrature component of stator flux. \( \psi_{dr} \) and \( \psi_{qr} \) are direct and quadrature axis components of rotor flux. \( R_s, R_r \) are the stator and rotor winding resistances. \( L_s, L_r \) and \( L_m \) are stator, rotor self and mutual inductances. \( \Psi_s \) is the stator flux. \( \omega_m \) is the angular motor speed. \( \omega_s \) is the stator flux speed. \( P \) denotes \( \frac{d}{dt} \), \( p \) represents the pole pairs.

\[ T_e = p \frac{3}{2} (\psi_{ds} I_{qs} - \psi_{qs} I_{ds}) \]  \hspace{1cm} (4.51)
Since d-axis is fixed along the stator flux $\psi_s$, the flux $\psi_{qs}$ becomes zero. Torque can be written as

$$T_e = \frac{3}{2} p \psi_{ds} \psi_{qs}$$  \hspace{1cm} (4.52)

In the present work, separate PI controllers are used for torque, flux and speed loops. Each controller is designed as discussed below.

### 4.7.1 Torque PI Controller for 3kW machine

The motor Equation from (4.43) to (4.50) can be modified and written as given in Equations (4.53) to (4.55).

$$\left( R_s L_r + R_r L_s \right) + \sigma L_s L_r \frac{d}{dt} I_{qs} = L_r V_{ds} - L_r \psi_s \omega_m + I_{ds} \sigma L_s L_r (\omega_{ss} - p \omega_m)$$  \hspace{1cm} (4.53)

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

The last term in the right side of above equation is negligibly small and it can be considered as zero compared to the values of other terms.

$$I_{ds} \sigma L_s L_r (\omega_{ss} - p \omega_m) \approx 0$$  \hspace{1cm} (4.54)

$$\left( R_s L_r + R_r L_s \right) + \sigma L_s L_r \frac{d}{dt} I_{qs} = L_r V_{ds} - L_r \psi_s \omega_m$$  \hspace{1cm} (4.55)

Under no load condition the change in motor speed can be expressed as shown in Equation (4.56).

$$\frac{d \omega_m}{dt} = \frac{3}{2} \frac{1}{J} \psi_s I_{ds}$$  \hspace{1cm} (4.56)
The current $I_{qs}$ can be expressed as shown in Equation (4.57).

$$I_{qs} = \frac{2}{3} \frac{T_e}{p \psi_S^3} \quad (4.57)$$

$$\left( R_S L_T + R_T L_S \right) \frac{d}{dt} + \sigma L_S L_T \left( \frac{d}{dt} \right)^2 I_{qs} = L_T \frac{dV_{ds}}{dt} - L_T \psi_S \frac{d\omega_m}{dt} \quad (4.58)$$

Based on the Equations (4.50), (4.52) and (4.53) the open loop transfer function can be expressed as

$$G_T(s) = \frac{As}{s^2 + Bs + C} \quad (4.59)$$

where the constants $A$, $B$ and $C$ are defined as given in Equation (4.60) to (4.62).

$$A = \frac{3p \psi_S}{2 \sigma L_S} \quad (4.60)$$

$$B = \frac{R_S L_T + R_T L_S}{\sigma L_S L_T} \quad (4.61)$$

$$C = \frac{3}{2} \frac{p^2 \psi_S^2}{\sigma L_S J} \quad (4.62)$$

The values of constants $A$, $B$ and $C$ are calculated based on the machine parameters and the values are

$A=3358e3$, $B=14495e3$, $C=52676e5$

The closed loop block diagram for torque PI Controller is shown in Figure 4.17. The parameters $K_p$ and $K_i$ of the PI controller are calculated
assuming the values of settling time $t_s$ and peak overshoot $M_p$ such that $t_s \leq 0.003$ sec and maximum peak overshoot $M_p \leq 2\%$.

$$M_p = e^{-\frac{-\xi \pi}{\sqrt{1-\xi^2}}} = 0.02$$

$$\xi = 0.707$$

$$t_s = \frac{4}{\xi \omega_n} = 0.003$$

$$\omega_n = 9.429 \text{rad/sec}$$

where $\xi$ and $\omega_n$ correspond to the damping ratio and the natural frequency of the system oscillation.

$$T_1(s) = \frac{3358s}{s^2 + 14495s + 57675}$$

$$\frac{T_e}{T_e} = \frac{3358 K_p s + 3358 K_i}{s^2 + (14495 + 3358 K_p)s + 57675 + 3358 K_i} \quad (4.63)$$

The denominator of the Equation (4.63) is a characteristic equation of the form

![Figure 4.17 Block diagram for torque PI controller](image-url)
The gains $K_p$ and $K_i$ can be calculated from the Equations (4.64)

$$s^2 + (14495 + 3358 K_p)s + 57675 + 3358 k_i = 0 \quad (4.64)$$

By substituting the values of damping ratio and natural frequency in Equation (4.65) and (4.66) the value of $K_p$ and $K_i$ are obtained as $K_p=4.312$ and $K_i =17.14$ respectively.

The response of the estimated torque when set torque $T^*_e$ is changed from 1pu to 0.8pu is given in Figure 4.18.

![Figure 4.18 Electromagnetic torque response of 3kW induction motor when $T^*_e$ is changed](image)

The settling time is found to be 0.005sec from the torque response
4.7.2 Flux PI Controller for 3kW Machine

Based on the motor Equations (4.40) to (4.47), the following Equations (4.67) can be obtained as

\[
\begin{align*}
\left( R_s L_s + \sigma L_s L_{tr} \frac{d}{dt} \right) I_{ds} &= \left[ R_s R_{tr} + \frac{d}{dt} (R_s L_s + R_{tr} L_{tr}) + \sigma L_s L_{tr} \left( \frac{d}{dt} \right)^2 \right] \psi_s + R_s I_{qs} \sigma L_s L_{tr} (\omega_s - p\omega_m) \\
\end{align*}
\]

where

\[
\sigma = 1 - \frac{L_m^2}{L_s L_{tr}}
\]

The value of the last term in Equation (4.67) becomes very small and can be written as

\[
R_s I_{qs} \sigma L_s L_{tr} (\omega_s - p\omega_m) \approx 0
\]

Then the Equation (4.67) can be written as

\[
\begin{align*}
\left( R_s L_s + \sigma L_s L_{tr} \frac{d}{dt} \right) I_{ds} &= \left[ R_s R_{tr} + \frac{d}{dt} (R_s L_s + R_{tr} L_{tr}) + \sigma L_s L_{tr} \left( \frac{d}{dt} \right)^2 \right] \psi_s \\
\end{align*}
\]

From the above equation, the simplified transfer function can be expressed as shown in Equation (4.69).

\[
G_{\psi}(s) = \frac{A_1 + s}{s^2 + B_1 s + C_1}
\]
where

\[ A_1 = \frac{R_F}{\sigma L_{\text{r}}} \]  

(4.70)

\[ B_1 = \frac{R_{\text{r}} L_s + R_s L_{\text{r}}}{\sigma L_s L_{\text{r}}} \]  

(4.71)

\[ C_1 = \frac{R_s R_{\text{r}}}{\sigma L_s L_{\text{r}}} \]  

(4.72)

For the machine under consideration, the values of \( A_1 \), \( B_1 \) and \( C_1 \) are constants which are calculated from the Equation (4.70 to 4.72) and their values are

\[ A_1 = 11795, \quad B_1 = 14495, \quad C_1 = 5.397e6 \]

The closed loop diagram for flux PI controller is shown in Figure 4.19. The values of \( \xi \) and \( \omega_n \) are 0.707 and 9.49 rad/sec based on \( t_s = 0.003s \) and \( M_p = 0.02 \).

\[ G_{\Psi}(s) = \frac{11795 + s}{s^2 + 14495s + 5397e6} \]  

(4.73)
The third order system is characterised by a general characteristic equation

\[ \frac{\psi_s}{\psi_{s*}} = \frac{K_ps^2 + s(11795K_p + K_i) + 11795K_i}{s^3 + (14495 + K_p)s^2 + s(5.397e6 + 11795K_p + K_i) + 11795K_i} \]  \hspace{1cm} (4.74)

The characteristic equation can be obtained from Equation (4.74) equating the denominator term to zero.

\[ (s + \alpha)(s^2 + 2\xi \omega_n + \omega_n^2) = 0 \]  \hspace{1cm} (4.75)

By comparing Equations (4.75) and (4.76) the values of \(K_p\) and \(K_i\) can be calculated.

\[ 14495 + K_p = 2\xi \omega_n + \alpha \] \hspace{1cm} (4.77)

\[ 5.397e6 + 11795K_p + K_i = \omega_n + 2\xi \omega_n \alpha \] \hspace{1cm} (4.78)

\[ \alpha \omega_n^2 = 11795K_i \] \hspace{1cm} (4.79)

By substituting the values of damping ratio and natural frequency in Equations (4.77) to (4.79) the values of \(K_p\) and \(K_i\) are obtained as 5 and 500.

The set flux \(\Psi_{s*}\) is changed from 1 pu to 0.8 pu and the measured flux response is given in Figure 4.20. The settling time measured from the response is 0.0015 sec. This value being less than the assumed value of 0.003 seconds validates the designed values of \(K_p\) and \(K_i\).
4.7.3 Speed PI controller for 3kW machine

The dynamics of induction motor can be expressed as shown in Equation (4.80).

\[
\frac{d\omega_m}{dt} = \frac{1}{J} [T_e - T_i] \tag{4.80}
\]

The transfer function of torque with control loop can be calculated as

\[
G'_M (s) = \frac{T_e}{T_{ec}} = G_{FM} (s)G_{Mc} (s)
\]

\[G_{FM}(s) = \text{Pre filter transfer function} = 1\]

\[G_{Mc}(s) = \text{Torque control loop transfer function.}\]
\[
G'_M(s) = \frac{A'_c}{B'_c s^2 + C'_c s + 1}
\]  
(4.81)

\[
A'_c = \frac{AK_p}{CT_i + AK_p}
\]  
(4.82)

\[
B'_c = \frac{T_i}{CT_i + AK_p}
\]  
(4.83)

\[
C'_c = \frac{T_i (AK_p + B)}{CT_i + AK_p}
\]  
(4.84)

\[B'_c \approx 0 \text{ When approximated by first order integration.}\]

\[A'_c = 0.0991\]

\[C'_c = 8.944e^{-6}\]

The transfer function can be written as

\[
G'_M(s) = \frac{A'_c}{C'_c s + 1} = \frac{0.0991}{8.944e^{-6}s + 1}
\]  
(4.85)

The block diagram of PI speed controller is shown in Figure 4.21.

\[\text{Figure 4.21 Block diagram of PI speed controller}\]
\[
\frac{\omega_m}{\omega^*_m} = 1 + \frac{0.0991K_ps + 0.0991K_i}{s^2(8.944e-6s + 1)(0.058s + 1)0.007}
\]  

(4.86)

From the above equation the value of \( K_p \), \( K_i \) for the speed PI controller are obtained as 1.77 and 12.54 respectively.

The speed response of the system when set speed \( \omega^*_m \) is changed from 1 pu to 0.8pu is shown in Figure 4.22. The settling time, from the response, is measured as 0.003sec which is the assumed settling time for the design.

![Figure 4.22 Speed response of 3kW induction motor for change in set speed](image)

**Figure 4.22** Speed response of 3kW induction motor for change in set speed

The calculated parameters of PI controller for torque, flux and speed controllers are repeated for 0.75kW induction motor and the design values of \( K_p \) and \( K_i \) are given in Table 4.8.
Table 4.8 Values of $K_p$ and $K_i$ controller of 0.75kW IM

<table>
<thead>
<tr>
<th>Controllers/Parameters</th>
<th>$K_p$</th>
<th>$K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque PI controller</td>
<td>1.5</td>
<td>100</td>
</tr>
<tr>
<td>Flux PI controller</td>
<td>4441</td>
<td>107.38</td>
</tr>
<tr>
<td>Speed PI controller</td>
<td>187.56</td>
<td>132.83</td>
</tr>
</tbody>
</table>

The responses of torque, flux and speed of 0.75kW induction motor are given in Figures 4.23 to 4.25 respectively when set values are changed from 1pu to 0.8pu. The settling times measured from the response in each case are given in Table 4.9.

![Figure 4.23 Torque response of 0.75kW induction motor for change in $T_L$](image)

Figure 4.23 Torque response of 0.75kW induction motor for change in $T_L$
Figure 4.24  Flux response of 0.75kW induction motor when set flux $\Psi_s^*$ is changed

Figure 4.25  Speed response for 0.75kW induction motor when set speed $\omega_m^*$ is changed
Table 4.9  Settling times measured from the responses of various controllers

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Settling time in sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque PI controller</td>
<td>0.005</td>
</tr>
<tr>
<td>Flux PI controller</td>
<td>0.0015</td>
</tr>
<tr>
<td>Speed PI controller</td>
<td>0.001</td>
</tr>
</tbody>
</table>

4.8  TRANSFORMATION BLOCK

The space vector modulation needs three phase sinusoidal quantity. In order to obtain the three phase variables, the control variables $V_{ds}$ and $V_{qs}$ obtained from the torque and flux PI controllers are transformed to three phase variables using the d-q transformation block as shown in Figure 4.26. The calculation of $\theta$ and identification of sector are done by the sub block shown in Figure 4.27.

![Figure 4.26 Transformation block](image)
4.9 SPACE VECTOR MODULATION BLOCK

Space vector modulation block consists of magnitude, theta and region calculations as shown in Figure 4.28. The region calculations are generated using the M-file program based on switching time calculation as presented in Table 4.3.
4.10 TRIGGERING PULSE FOR PHASE A

The generation of triggering pulse ‘ga’ for phase A using SVM technique is shown in Figure 4.29.

(a) Gate pulse for S1

(b) Gate pulse for S2

Figure 4.29 (Continued)
Simulation of DTC-SVM controlled TLDCI fed induction motor is performed using MATLAB software and the percentage of ripple present in the torque is measured. The Figures 4.30 and 4.31 show the line to line and phase voltages of a 3kW machine. Initially, the motor accelerates from standstill at no load and then it reaches steady state at $t = 0.085\text{seconds}$. 

Figure 4.29 Gate pulse for phase A using SVPWM

4.11 SIMULATION RESULTS OF TLDCI FED IM WITH DTC-SVM
The starting speed response of TLDCI fed induction motor at no load and corresponding torque oscillations under steady state are shown in Figure 4.32 and Figure 4.33 respectively.
The speed response for TLDCI fed IM with DTC-SVM for change in set speed under no load is shown in Figure 4.34. The set speed is decreased from 1500 rpm to 1200 rpm at 0.25 sec and then increased to 1400 rpm at 0.45 sec. It is observed that the speed of the motor settles to the set value within 0.02 sec for changes in set speed. The electromagnetic torque response for TLDCI fed IM with DTC-SVM for change in set speed under no load is shown in Figure 4.35. The electromagnetic torque (EMT) response is decaying oscillation and finally settles at zero average torque. The EMT response for change in torque of 15 Nm and 10 Nm applied alternately at 0.25 and 0.45 seconds are shown in Figure 4.36.
Figure 4.34 Speed response of TLDCI fed IM with DTC-SVM for change in set speed

Figure 4.35 Torque response of TLDCI fed IM with DTC-SVM for change in set speed $\omega_m^*$ at no load

Figure 4.36 Torque response of TLDCI fed IM with DTC-SVM for change in torque $T_L$
When a load of 15Nm is applied at 0.25 seconds, the speed drops to 1478 rpm and settles at 1500rpm within 0.005 seconds as shown in Figure 4.37. The corresponding torque response and the torque ripples are shown in Figures 4.38 and 4.39 respectively. It is clear that the EMT overshoots to a value of 22 Nm and then settles around 15 Nm at 0.257s. The torque ripples vary between 15.7 Nm and 14.3 Nm as seen from the Figure 4.39.

![Figure 4.37 Speed response of TLDCI fed IM with DTC-SVM when load of 15 Nm applied at 0.25 seconds with $\omega_0 = 1500$ rpm](image)

![Figure 4.38 Torque response when load is changed from 0 to 15 Nm](image)
When the machine delivers a load torque of 10Nm, the torque ripple varies between 10.6 Nm and 9.55 Nm as shown in Figure 4.40.

The Figure 4.41 gives the torque response when a load of 15Nm is applied at 0.25s and then the load is reduced to 10Nm at 0.5s with the set speed 1400rpm.
Figure 4.41 Electromagnetic torque response of TLDCI fed IM with DTC-SVM for change in load torque

The set speed of the machine was reduced to 1200rpm and the response was evaluated for change in load torques. A load of 15 Nm is applied at 0.25sec and then it is reduced to 10 Nm at 0.45 sec and the corresponding torque response is shown Figure 4.42. The electromagnetic torque reaches to a peak value of 19 Nm and then settles around 15 Nm at 0.257s. The torque ripple varies between 15.8 Nm and 14.3 Nm as depicted in Figure 4.43.

Figure 4.42 Electromagnetic torque response of TLDCI fed IM with DTC-SVM for load of 15Nm and 10Nm
Figure 4.43 Torque ripples of TLDCI fed IM with DTC-SVM at 15Nm

The Figure 4.44 gives the torque ripple for a load of 10Nm at 1200 rpm. In this condition, the torque ripples are varying between 10.8 Nm and 9.5 Nm.

Figure 4.44 Torque ripples of TLDCI fed IM with DTC-SVM at 10Nm

Dynamic performance of 0.75kW is also carried out using simulation software. The speed responses is shown in Figures 4.45 when 5Nm load torque is applied at 0.25 seconds and the steady state line current waveform is shown in Figure 4.46. The Figure 4.47 shows the torque response of the induction motor at set speed 1500rpm for change in load torque at 0.25 and 0.45 seconds. Figure 4.48 shows the torque ripple for a load torque of 5Nm which varies between 5.6 and 4.5Nm. The measured ripple content is about 21.78%.
Figure 4.45 Speed response of 0.75kW IM when load applied at 0.25 seconds

Figure 4.46 Phase A current of 0.75kW IM for load torque of 5Nm

Figure 4.47 Electromagnetic torque response for 0.75kW IM when load is changed at 0.25 and 0.45 seconds
The torque ripples at various speeds and loads for both the machines are shown in Table 4.10.

**Table 4.10 Values of torque ripple at various conditions**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Synchronous Speed (rpm)</th>
<th>Load Torque (Nm)</th>
<th>Torque ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00 kW</td>
<td>1000</td>
<td>10</td>
<td>14.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>11.6%</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>10</td>
<td>12.80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>9.9%</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>10</td>
<td>10.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>9.33%</td>
</tr>
<tr>
<td>0.75 kW</td>
<td>1000</td>
<td>5</td>
<td>24.3%</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>5</td>
<td>22.34%</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>5</td>
<td>21.78%</td>
</tr>
</tbody>
</table>
4.12 CONCLUSION

The performance of TLDCI fed IM with DTC-SVM is simulated using MATLAB software for 3kW and 0.75kW machines. Space vector modulation with twenty seven switching states and the relevant voltage vectors are generated using M-file program. The dynamic performance of TLDCI fed IM with DTC-SVM with PI controllers for different load torques and set speeds are measured. The torque ripples are also calculated for different load torques with various set speeds. From the simulation study it is observed that torque ripple increases when the set speed is decreased for a given load torque. The torque ripple also decreases when the load torque is increased for given set speed.

The next chapter deals with the hardware implementation of TLDCI fed 0.75kW IM with DTC-SVM to validate the results obtained by simulation.