Improved Direct Torque Control of Induction Motor Drive under Low Speed Operation

T.Vinay Kumar
Department of Electrical Engineering
National Institute of technology
Warangal, A.P., India
tvinay.nitw@gmail.com

S.Srinivasa Rao
Department of Electrical Engineering
National Institute of technology
Warangal, A.P., India
srivasaraao_nitw@yahoo.co.in

Abstract—This paper presents a modified two level inverter topology to improve the low speed performance of the direct torque controlled (DTC) three phase induction motor drive. Proposed method is based on current ripple principle. In this technique, the inverter switching states are derived as a function of rotor speed. This method gives low ripple in flux and torque at low speed operation when compared with conventional DTC. Simulation results of proposed methods are presented and compared with conventional DTC method.

Keywords- Direct torque control, Induction motor, Voltage source inverter.

I. INTRODUCTION

In conventional DTC, electromagnetic torque and stator flux are independently and directly controlled by selection of optimum inverter switching modes. The selection of optimum inverter switching modes is made to limit the electromagnetic torque and flux errors within the torque and flux hysteresis bands [1-3]. Conventional DTC produces high ripple in torque and flux due to non-linear hysteresis controllers. Switching frequency in conventional DTC is not constant and also only one voltage space vector is applied for the entire sampling period [4]. Hence the motor torque may exceed the upper/lower torque limit even though the error is small [5]. In order to overcome this problem SVM-DTC method was proposed [6]. By using space vector modulation technique in DTC, the sampling frequency is maintained constant and torque ripple is reduced with low switching losses [7]. The disadvantage of SVM-DTC is design of flux and torque PI controllers are complex and also parameter sensitive. In [8], dithering technique was proposed to decrease the parameter sensitivity and also decreases the torque and flux ripple. But it requires high sampling frequency triangle signal. The torque calculation method was proposed to predict and increase the switching frequency of basic DTC without using any PWM technique [9-10]. But it requires more mathematical calculation and also increases the parameter sensitivity. The discrete SVM DTC was proposed to improve the basic DTC performance [11], but it requires high sampling frequency.

The alternate option is to minimize the torque and flux ripple problem using multilevel inverters. The three level neutral clamped inverters are suggested by some researchers for high voltage, high power applications with less harmonic output with optimum switching frequency [12]. But they suffer with fluctuating neutral point due to DC capacitor currents. In order to eliminate the neutral point fluctuations a cascaded two-level inverter topology was proposed in [13 -14]. But it increases the controller complexity. However, the basic DTC method is simple and has high dynamic torque performance than other techniques, but it suffers from two problems viz. switching frequency varies with hysteresis band and motor speed, high flux and torque ripple at low speed range because of small back EMF.

In order to improve the performance of basic DTC at low speed operation, a modified two-level inverter with two extra power electronic switches were added in the three phase bridge topology is proposed. In this technique inverter switching states are function of the rotor speed unlike basic DTC.

II. CONTROL METHOD

A. Machine Modeling

By referring to a synchronous reference frame, denoted by the superscript ‘e’, the mathematical equations of induction motor can be rewriting as follows [4]:

Stator voltage equation:

\[ u_s^e = \frac{di_s^e}{dt} + j\omega_s^e \psi_s^e \] (1)

Rotor voltage equation:

\[ 0 = \frac{di_r^e}{dt} + j(\omega_e - \omega_r)\psi_r^e \] (2)

Stator flux equation:

\[ \psi_s^e = L_s^e i_s^e + L_m^e i_r^e \] (3)

Rotor flux equation:

\[ \psi_r^e = L_r^e i_r^e + L_m^e i_s^e \] (4)

Mechanical equation:

\[ T_e - T_i = J\omega_e / dt \] (5)

\[ T_e = (3p/2)(\psi_s^e i_{sq}^e - \psi_q^e i_{sd}^e) \] (6)
B. Proposed DTC of induction motor drive

The main drawback of conventional DTC is that it produces high torque and flux ripple at low speed operation. In order to eliminate the drawbacks of basic DTC at low speeds, a modified inverter topology is used along with DTC for less flux and torque ripples when compared with conventional inverter topology.

The block diagram of a proposed DTC of induction motor drive is as shown in Fig. 1. From (1), it can be written as $d\psi_s^a/dt = u_s^a - i_s^aR_s$ (stationary reference frame). If voltage drop in stator resistance is neglected, then the stator flux linkage vector is given by $d\psi_s^a/dt = u_s^a$, this equation is replaced by $\Delta\psi_s^a = u_s^a\Delta t$ where $\Delta t$ is the sampling period. Here, $u_s^a$ is the voltage space vector that may occupy any of the eight space positions as shown in Fig. 3.

In $\Delta\psi_s^a = u_s^a\Delta t$, it is observed that the stator flux linkage will move fast, if active switching vectors are applied to voltage source inverter (VSI). If null switching vectors are applied to VSI, then the stator flux linkage space vector will stop. From Fig. 2, stator flux magnitude $\psi_s$ is directly controlled by voltage switching state. For example, if stator flux vector is in sector I, for increasing the stator flux from $\psi_s$ to $\psi_s^+$, it is necessary to select $U_2$ voltage vector. For a six-pulse voltage source inverter, the stator flux linkage space vector traces a hexagonal path with constant speed.

In $\Delta\psi_s^a = u_s^a\Delta t$, it is observed that the stator flux linkage will move fast, if active switching vectors are applied to voltage source inverter (VSI). If null switching vectors are applied to VSI, then the stator flux linkage space vector will stop. From Fig. 2, stator flux magnitude $\psi_s$ is directly controlled by voltage switching state. For example, if stator flux vector is in sector I, for increasing the stator flux from $\psi_s$ to $\psi_s^+$, it is necessary to select $U_2$ voltage vector. For a six-pulse voltage source inverter, the stator flux linkage space vector traces a hexagonal path with constant speed.

![Figure 1. Proposed direct torque control of induction motor drive for low speed operation.](image)

![Figure 2. Stator flux vector number and relation between flux, torque and inverter switching states.](image)

![Figure 3. Space Vector Voltages and Switching Pattern](image)

Fig. 3 shows that the voltage switching states of modified inverter topology. The magnitude of stator flux linkage space vector which lies in $k^{th}$ sector can be increased by using switching vector $u_{k}, u_{k+1}$ and $u_{k-1}$. However, its magnitude can be decreased by using switching vector $u_{k+2}, u_{k-2}$ and $u_{k+3}$, where $k=1,2,\ldots,6$ affects the electromagnetic torque as well. Generally, in a symmetrical three phase induction motor, the instantaneous electromagnetic torque is proportional to the cross product of the stator flux linkage space vector and the rotor flux linkage space vector.
\[ T_e = (3p/2)|\psi_s| |\psi_r| \sin \delta \]  

where, \( \psi_s \) is the stator flux linkage space vector, \( |\psi_r| \) is the rotor flux linkage space vector referred to stator and \( \delta \) is the angle between the stator and rotor flux linkage space vector. From Fig. 2, \( \delta \) is directly controlled by voltage switching state. For example, if stator flux vector is in sector I, then select \( U_2 \) voltage vector to increase the load angle from \( \delta \) to \( \delta + \Delta \delta \).

The required flux linkage locus is obtained by applying a switching sequence of null and active switching vectors as shown in Table I and Table II based on the location of the flux vector and rotor speed.

### TABLE I. VOLTAGE SWITCHING TABLE FOR HIGH AND MEDIUM SPEED OPERATION (>25% OF RATED SPEED)

<table>
<thead>
<tr>
<th>( \psi_s ) error</th>
<th>( T_e ) error</th>
<th>Sector Number(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>1   U_2</td>
<td>U_3</td>
<td>U_4</td>
</tr>
<tr>
<td>0   U_0</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>-1  U_6</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>0   U_0</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>1   U_5</td>
<td>U_6</td>
<td>U_7</td>
</tr>
<tr>
<td>0   U_0</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>1   U_5</td>
<td>U_6</td>
<td>U_7</td>
</tr>
</tbody>
</table>

### TABLE II. VOLTAGE SWITCHING TABLE FOR LOW SPEED OPERATION (<25% OF RATED SPEED)

<table>
<thead>
<tr>
<th>( \psi_s ) error</th>
<th>( T_e ) error</th>
<th>Sector Number(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>1   U_20</td>
<td>U_30</td>
<td>U_40</td>
</tr>
<tr>
<td>0   U_2</td>
<td>U_3</td>
<td>U_4</td>
</tr>
<tr>
<td>-1  U_6</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>0   U_0</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>1   U_5</td>
<td>U_6</td>
<td>U_7</td>
</tr>
<tr>
<td>0   U_0</td>
<td>U_1</td>
<td>U_2</td>
</tr>
<tr>
<td>1   U_5</td>
<td>U_6</td>
<td>U_7</td>
</tr>
</tbody>
</table>

### C. At high and medium speed operating condition

The modified two-level inverter configuration for high and medium speed operation is shown in Fig. 4. At high and medium speed operation (>25% of rated speed), \( S_{HS} \) switch is in ‘OFF’ condition and \( S_{LS} \) switch is in ‘ON’ condition. In this switching condition, the choice of selecting voltage vector is in between \( V_1 \) to \( V_6 \) and null vector \( V_0 \). In this region, \( \alpha - \beta \) plane of the voltage vector is divided into six sectors as shown in Fig. 2. The selection of voltage vectors depends on the flux error, torque error and also sector number. From Fig. 2, the stator flux vector is assumed to be in sector I. It is evident that \( V_1, V_2 \) and \( V_6 \) voltage vectors increases the stator flux magnitude for any position in sector I, and also that \( V_0, V_3 \) and \( V_4 \) voltage vectors decreases the stator flux magnitude for any position in sector I. Positive torque errors are compensated by selecting \( V_2 \) and \( V_3 \) voltage vectors in sector I, negative torque errors are compensated by selecting \( V_3 \) and \( V_6 \) voltage vectors in sector I.

### D. At low speed operating condition

At low speed operation (<25% of rated speed), \( S_{HS} \) switch is in ‘OFF’ condition and \( S_{LS} \) is in ‘ON’ condition. In this switching condition the choice of voltage vector is selected between \( V_{20} \) to \( V_{60} \) and null vector \( V_0 \). From Fig. 2, the stator flux vector is assumed to be in sector I. It is evident that \( V_{10}, V_{20} \) and \( V_{60} \) voltage vectors increases the stator flux magnitude for any position of in sector I, and also that \( V_{10}, V_{30} \) and \( V_{50} \) voltage vectors decreases the stator flux magnitude for any position in sector I. Positive torque error can be compensated by selecting \( V_{20} \) and \( V_{30} \) voltage vectors in sector I and negative torque error can be compensated by selecting \( V_{30} \) and \( V_{50} \) voltage vectors in sector I. Selection of \( V_1 \) to \( V_6 \) voltage vector is not preferable due to large flux and torque ripple in this range of operation.

The modified inverter switching states and the corresponding DC link voltage for two-level inverter are as shown in Table III.
TABLE III. SWITCHING STATES FOR PHASE ‘A’ LEG FOR MODIFIED INVERTER

<table>
<thead>
<tr>
<th>Switches</th>
<th>High Speed</th>
<th>Low Speed</th>
<th>Leg ‘a’ voltage (Sa+ ON and Sa- OFF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_H 1</td>
<td>1</td>
<td>0</td>
<td>V_{DC}</td>
</tr>
<tr>
<td>S_L 3</td>
<td>0</td>
<td>1</td>
<td>V_{DC}/2</td>
</tr>
</tbody>
</table>

E. Optimum flux and torque ripple

The method of achieving optimum flux and torque ripple is based on reduction of current ripple, because flux and torque ripple is function of change in current ripple (voltage vector). This current ripple principle is useful for low speed operation condition. From [15],

\[
\psi_r = (L_r / L_m)\psi_s - (L_r L_m - L_m^2 / L_m)i_s
\]

(d.w.t (8)),

\[
d\psi_r / dt = (L_r / L_m) d\psi_s / dt - \sigma d_i_s / dt
\]

\[
di_s / dt = [k_1 V_s - jk_2 \psi_r \omega_r]
\]

Where \(k_1 = L_r / \sigma L_m\) and \(k_2 = 1 / \sigma\). From (8), \(\psi_r\) is the rotor flux, \(L_r\) is the rotor leakage inductance, \(L_m\) is the mutual inductance between stator and rotor, \(L_s\) is the stator self inductance. From (10), \(k_1 V_s\) is the applied voltage vector and \(jk_2 \psi_r \omega_r\) is back EMF of the stator winding. The rate of change of stator current depends on applied voltage and speed of rotor flux. The magnitude of the back EMF (\(jk_2 \psi_r \omega_r\)) depends on the speed of rotor flux and independent of rotor flux. Fig. 6 to Fig. 8 gives the variation of the current ripple for different operating speeds.

III. SIMULATION RESULTS

From the developed mathematical model, simulations were carried out on a 3hp induction motor drive system for forward motoring operation using MATLAB/SIMULINK.

![Figure 6. Incremental change in stator current to increase flux and torque at high speed operation.](image)

![Figure 7. Incremental change in stator current to increase flux and torque at low speed operation.](image)

![Figure 8. Incremental change in stator current to increase the flux and torque at low speed operation.](image)

![Figure 9. Torque responses of the IM drive for a step change in load from 0.3 to 0.8 N-m at speed of 120 rpm. (a) Conventional DTC. (b) Proposed DTC.](image)
Figure 10. Steady-state speed response of the IM drive on no-load at 119.25rpm. (a) Conventional DTC. (b) Proposed DTC.

Figure 11. Steady-state torque response of the IM drive on no-load at 119.25rpm. (a) Conventional DTC. (b) Proposed DTC.

Fig. 12. Steady-state stator flux-linkage response of the IM drive, at 40% rated load and speed of 119.25 rpm. (a) Conventional DTC. (b) Proposed DTC.

Figure 13. Steady-state stator flux-linkage upper case response of the IM drive, at rated load and speed of 119.25rpm. (a) Conventional DTC. (b) Proposed DTC.
From Fig. 9, it is observed that the dynamic response of the proposed method is similar to conventional DTC. From Fig. 10 and Fig. 11, it is observed that the profile of steady speed response is improved and also torque ripple is reduced in the proposed DTC when compared with conventional DTC. From Fig. 12 to Fig. 13, it is noticed that the flux ripple is reduced in the proposed DTC.

IV. CONCLUSION

In this paper, a modified inverter topology was presented for direct torque and flux control of three phase induction motor drive to improve its performance at low speed operation. Simulations are carried out using MATLAB/SIMULINK for modified DTC and conventional. From the simulation results, it is observed that in proposed DTC technique, the speed, flux and torque ripple are less than the conventional DTC at low speed operation.

REFERENCES


