DIRECT TORQUE CONTROL OF INDUCTION MOTOR SIMULATION USING CONVENTIONAL METHOD

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ABSTRACT

This paper proposes direct torque control of induction motor simulation using conventional method. Direct Torque Control (DTC) is a control technique used in AC drive systems to obtain high performance torque control and thereby controlling the speed of induction motor. The principle is based on simultaneous decoupling of stator flux and electromagnetic torque of AC drive system. DTC drives use hysteresis comparators and they suffer from high torque ripple and variable switching frequency problem. The performance of this method is demonstrated by simulation using MATLAB/Simulink software.

Keywords: Direct Torque Control, Induction Motor

I. INTRODUCTION

Induction Motors (IM) are widely used in industrial, commercial and domestic applications as they are low-cost, rugged and easy to maintain. Induction motors demand better control platform that is precise, quick torque and flux response, large torque at low speed, wide speed range. Though DC motor provides desired performance, its maintenance is high and is unsafe in explosive environment. In 1970s, Field Oriented Control (FOC) platform proved its effectiveness for torque and speed control of induction motor. Hence the scheme proves itself superior to the DC machine. The problem faced by FOC scheme is complexity in its implementation due to dependence of machine parameters, reference frame transformation. Later DTC was introduced. Direct torque control (DTC) method is used to control the torque (finally speed) in variable frequency drives of three-phase AC electric motors. From the measured voltage and current of the motor an estimate of the motor's magnetic flux and torque is calculated. Integrating the stator voltages, stator flux linkage is estimated. Cross product of measured motor current vector and estimated stator flux linkage vector results in estimated torque. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed limits, the transistors of the variable frequency drive are turned OFF and ON in such a way that the flux and torque errors will return in their tolerant bands as fast as possible. Thus direct torque control is one form of the hysteresis control. The method requires only the stator resistance to estimate the stator flux and torque.
The basic DTC scheme consists of two comparators with specified bandwidth, switching table, voltage source inverter, flux and torque estimation block[1]. Like every control method has some advantages and disadvantages, DTC method has too. Some of the advantages are lower parameters dependency, making the system more robust and easier implements and the disadvantages are difficult to control flux and torque at low speed, current and torque distortion during the change of the sector, variable switching frequency, a high sampling frequency needed for digital implementation of hysteresis controllers, high torque ripple. The torque ripple generates noise and vibrations, causes errors in sensorless motor drives, and associated current ripples are in turn responsible for the EMI. The reason of the high current and torque ripple in DTC is the presence of hysteresis comparators together the limited number of available voltage vectors.

If a higher number of voltage vectors than those used in conventional DTC is used, the favorable motor control can be obtained[2]. Because of complexity of power and control circuit, this approach is not satisfactory for low or medium power applications. This method is used in a variable-speed asynchronous motor drive. In this control scheme, a d-q coordinate’s reference frame locked to the stator flux space vector is used to achieve decoupling between the motor flux and torque. They can be thus independently controlled by stator d-axis voltage and q-axis voltage. This paper proposes a novel control method of DTC based on SVPWM to give a constant torque switching frequency and reduces the torque ripple. This method is used in a variable-speed asynchronous motor drive. In this control scheme, a d-q coordinate’s reference frame locked to the stator flux space vector is used to achieve decoupling between the motor flux and torque. They can be thus independently controlled by stator d-axis voltage and q-axis voltage.

II. PRINCIPLE OF DIRECT TORQUE CONTROL

The basic principle of DTCs is to directly select stator voltage vectors according to the torque and flux errors which are the differences between the references of torque and stator flux linkage and their actual values[3]. The basic functional blocks used to implement the DTC control platform is shown in Fig.1. The governing equation for torque for this scheme is due to the interaction of stator and rotor fields. Torque and stator flux linkage are computed from measured motor terminal quantities i.e. stator voltages and current. An optimal voltage vector for the switching of VSI is selected among the six non-zero voltage vectors and two zero voltage vectors by the hysteresis control of stator flux and torque.
A. Torque and Flux Estimator

The terminal voltages and currents are used to calculate feedback flux and torque from the machine. The sector number is also calculated by the block used to compute the sector in which the flux vector lies. The phase voltage and currents in stationary reference are given by the following equations:

\[ V_{sa} = V_a \quad \text{and} \quad V_{sb} = \frac{-1}{\sqrt{3}}(V_a + 2V_b) \]  
\[ I_{sa} = I_a \quad \text{and} \quad I_{sb} = \frac{-1}{\sqrt{3}}(I_a + 2I_b) \]  

The stator flux components are given by:

\[ \Psi_{sa} = \int (V_{sa} - R_s I_{sa}) dt \]  
\[ \Psi_{sb} = \int (V_{sb} - R_s I_{sb}) dt \]  

The magnitude of the stator flux can be estimated from the components of the stator flux as given by the equation:

\[ \Psi_s = \sqrt{\Psi_{sa}^2 + \Psi_{sb}^2} \]  

The flux components are used to obtain flux vector zone. Torque can be calculated by using the flux components, current components and IM number of and is given by equation:

\[ T_e = \frac{3}{2} \left( \frac{P}{2} \right) \left( \Psi_{sa} I_{sb} - \Psi_{sb} I_{sa} \right) \]
B. Torque and Flux Controller

1) Torque Hysteresis Controller
The Torque hysteresis controller is a three level controller and is shown in Fig. 2. It means the torque control loop has three levels of digital outputs. The torque error $\Delta T_e$ is given to the torque hysteresis controller and the output is torque error status ($dT_e$) which can have three values -1, 0 or 1. The width of the hysteresis band is $2\Delta T_e$. Torque error status is given to the switching table for optimum voltage vector selection for the inverter.

$$\Delta T_e = T_{eref} - T_e$$

**Fig. 2** Torque Hysteresis Controller

Torque error $\Delta T_e = T_{eref} - T_e$........................(7)

$|dT_e| = +1$ if $|T_e| < |T_{eref} - |\Delta T_e||$: Torque to be increased

$|dT_e| = -1$ if $|T_e| > |T_{eref} + |\Delta T_e||$: Torque to be decreased

$|dT_e| = 0$ if $|T_{eref} - |\Delta T_e|| \leq |T_e| \leq |T_{eref} + |\Delta T_e||$: Torque to remain unchanged.

2) Flux Hysteresis Controller
The flux hysteresis controller is a two level controller and is shown in Fig. 3. So the flux control loop has two digital outputs. The stator flux error $\Delta \Psi$ given to the flux hysteresis controller and the output is flux error status ($d\Psi$), which can have two values 0 and 1. The width of the hysteresis band is $2\Delta \Psi$. Flux error status is given to the switching table for optimum voltage vector selection for the inverter.

$$\Delta \Psi = \Psi_{sref} - \Psi_s$$

**Fig. 3** Flux Hysteresis controller

Stator flux error $\Delta \Psi = \Psi_{sref} - \Psi_s$..........................(8)

The flux is controlled according to the following equations
\[ |d\Psi_s| = 1 \text{ if } |\Psi_s| \leq |\Psi_{sref}| - |\Delta \Psi_s|: \text{ flux to be increased} \]
\[ |d\Psi_s| = 0 \text{ if } |\Psi_s| \geq |\Psi_{sref}| + |\Delta \Psi_s|: \text{ flux to be decreased} \]

C. Switching Selection
A high performance torque control can be established due to the decoupled control of stator flux and torque in DTC. Fig.4 shows an example of stator flux located in sector-1 (S(1)) with the corresponding optimum switching voltage vectors for anti-clockwise and clockwise rotation of the shaft. Optimum switching vector selection table given by Table.1 shows the optimum selection of the switching vectors in all sectors of the stator flux plane. This table is based on the value of stator flux error status, torque error status and orientation of stator flux for counter clockwise rotation of the shaft.

![Fig.4 Optimum Switching Voltage Vector in Sector-1 for (a) Anti-Clockwise and (b) Clockwise Rotation](image)

<table>
<thead>
<tr>
<th>d\Psi</th>
<th>dT_e</th>
<th>S(1)</th>
<th>S(2)</th>
<th>S(3)</th>
<th>S(4)</th>
<th>S(5)</th>
<th>S(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>V_2</td>
<td>V_3</td>
<td>V_4</td>
<td>V_5</td>
<td>V_6</td>
<td>V_1</td>
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<tr>
<td>0</td>
<td>V_7</td>
<td>V_0</td>
<td>V_7</td>
<td>V_0</td>
<td>V_7</td>
<td>V_0</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>V_6</td>
<td>V_1</td>
<td>V_2</td>
<td>V_3</td>
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<td>V_6</td>
<td>V_1</td>
<td>V_2</td>
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<tr>
<td>0</td>
<td>V_0</td>
<td>V_7</td>
<td>V_0</td>
<td>V_7</td>
<td>V_0</td>
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<tr>
<td>-1</td>
<td>V_5</td>
<td>V_6</td>
<td>V_1</td>
<td>V_2</td>
<td>V_3</td>
<td>V_4</td>
<td></td>
</tr>
</tbody>
</table>

In stationary reference frame the stator flux equation can be written as:
\[ \Psi_s = \int V_s - i_s R_s dt \] ....................................................(9)
If the stator resistance drop is neglected for simplicity, the stator flux varies along the direction of applied voltage vector and the equation is reduced to
\[ \Psi_s = \int V_s \Delta t \] .................................(10)

which means, by applying stator voltage vector \(V_s\) for a time increment \(\Delta t\), \(\Psi_s\) can be changed incrementally. The command value of the stator flux \(\Psi_s^*\) follows a circular trajectory, the plane of stator flux is divided into six sectors as shown in Fig.5. Each sector has a different set of voltage vector to increase or decrease the stator flux. The command flux vector rotates in anticlockwise direction in a circular path and the actual stator flux vector \(\Psi_s\) tracks the command flux in a zigzag path but constrained to the hysteresis band which is shown in fig.5. In general, the active forward voltage vector \(V_{s,k+1}\) and \(V_{s,k+2}\) are applied to increase or decrease the stator flux respectively when the stator flux lies in sector \(k\). The radial voltage vectors \(V_{s,k}\) and \(V_{s,k+3}\) which quickly affect the flux are generally avoided. The active reverse voltage vectors \(V_{s,k-1}\) and \(V_{s,k-2}\) are used to increase or decrease the stator flux in reverse direction. The stator flux vector change due to stator voltage vector is quick whereas change rotor flux is sluggish because of its large time constant \(T_r\). That is why \(\Psi_s\) movement is jerky and \(\Psi_r\) moves uniformly at frequency \(\omega_e\) as it is more filtered. However, the average speed of both remains the same in steady state condition. The flux increment vector corresponding to each of the six inverter voltage vectors are shown in Fig.5. The flux can be increased by the \(V_1\), \(V_2\) and \(V_6\) vectors and it can be decreased by the \(V_3\), \(V_4\) and \(V_5\) vectors. Similarly torque is increased by the \(V_2\), \(V_3\) and \(V_4\) vectors and decreased by the \(V_1\), \(V_5\) and \(V_6\) vectors. The zero vector short circuits the machine terminals and keeps the flux and torque unaltered.

III. SIMULATION AND RESULTS

The DTC and SVM-DTC scheme for induction motor are simulated using MATLAB/Simulink and their results have been compared. Fig.8 shows the Simulink model of conventional control of induction motor. The motor parameters used for simulation are given in Table 2.
Fig. 8. Simulink Model Using Conventional Method

Table 2 Motor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>350V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Stator Resistance, $R_s$</td>
<td>1.115Ω</td>
</tr>
<tr>
<td>Rotor Resistance, $R_r$</td>
<td>1.083Ω</td>
</tr>
<tr>
<td>Stator self Inductance, $L_s$</td>
<td>0.005974H</td>
</tr>
<tr>
<td>Rotor self Inductance, $L_r$</td>
<td>0.005974H</td>
</tr>
<tr>
<td>Mutual Inductance, $L_m$</td>
<td>0.2037H</td>
</tr>
<tr>
<td>Moment of Inertia, $J$</td>
<td>0.02 Kg.m²</td>
</tr>
</tbody>
</table>

Simulation Results

Conventional control method was simulated and stator currents, rotor speed and torque are obtained. Fig. 10, shows variation of stator currents with time using conventional method. Stator current in phase b is varying between 15.4943A to -16.1464A in conventional method. Fig.11 shows speed and torque response of induction motor. It is clear that induction motor is taking 0.5 seconds time to settle to a constant speed and there are large variations in torque with time and variation is between 5.5121 and 2.1268 Nm in the conventional method.
Fig. 10. Stator Currents Using Conventional Method
Fig. 11. Speed and Torque Response Using Conventional Method

IV. CONCLUSION
This project has reviewed control strategy for induction motor drives. The DTC represents a very good alternative to Field Oriented Control (FOC). In conclusion, it is believed that the DTC principle will continue to play a strategic role in the development of high performance drives.

REFERENCES