Improvement Of Direct Torque Control Of Induction Motor Drives Using Neuro-Fuzzy Controller

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Abstract— Direct torque control (DTC) is an advanced and simple control method for induction motor drive has many advantages over other variable frequency control methods, but it has a common disadvantage of high torque ripple. This paper introduces design and analysis for DTC of induction motor drives using the switching table, hysteresis controllers and flux and torque estimator. This paper also proposes improvement of the conventional DTC using the improvement of the switching table and the application of the artificial intelligent techniques to minimize the torque, flux and current ripples and to get better performance of the motor. At the end of this paper there is a comparison between the conventional DTC and the proposed one.

Keywords— Induction Motor Drive; Direct Torque Control (DTC); switching table; flux and torque estimator; artificial neural networks (ANN); Fuzzy logic control (FLC).

I. INTRODUCTION

In many variable speed drive applications (e.g. traction drives for electric vehicles), torque control is required or desired, but precise, closed-loop control of speed is not necessary. Torque control provides greatly improved transient response, avoidance of nuisance over-current trips, and elimination of load dependent controller parameters[1]. DTC was introduced by Takahashi (1984) in Japan and then in Germany by Depenbrock (1985)[2].

DTC method is characterised by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technique for the inverter is not needed. The main advantages of DTC are absence of coordinate transformation and current regulator, absence of separate voltage modulation block[3].

Common disadvantages of conventional DTC are high torque ripple. It also needs flux and torque estimators and therefore, accurate machine parameters are required. For that reason the application of artificial neural network and fuzzy logic control attracts the attention of many scientists from all over the world. The reason for this trend is the many advantages which the architectures of ANN have over traditional algorithmic methods [3],[4].

II. STRATEGY OF DIRECT TORQUE CONTROL

DTC technique can be easily implemented using two hysteresis controllers (one for flux and the other for torque), torque and flux estimators and a switching table to select the proper voltage vector[5]. The basic functional blocks used to implement the DTC scheme are represented in Fig.1.

The torque control of the inverter fed machine is carried out by hysteresis control of magnitude of stator flux and torque that selects one of the six active and two zero inverter voltage vector \( V_{n}(t) \)[6]. The use of a switching table for voltage vector selection provides fast torque response, low inverter switching frequency and low harmonic losses without the complex field orientation by restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made[5].

In a voltage fed three phases, the switching commands of each inverter leg are complementary. So for each leg a logic state \( C_l \) (l=a,b,c) can be defined ; \( C_l \) is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be close (first)[7]. The following equation give the voltage vectors:
Eight switching states can be taken according to equation (1): two zero voltage vectors and six non-zero voltage vectors show by Fig. 2[7].

\[ V_s = \frac{2}{3} U_0 \left[ C_1 + C_2 e^{\frac{j\pi}{3}} + C_3 e^{\frac{j2\pi}{3}} \right] \] (1)

In Fig. 2 the stator flux is represented by the direct axis and the torque is represented by the quadrature axis. It can be seen that selecting the proper voltage vector results in maintaining the torque and stator flux within the limits. The switching table proposed by Takahashi is given by Table 1:

### TABLE I. SWITCHING TABLE FOR CLASSICAL DTC

<table>
<thead>
<tr>
<th>Sector</th>
<th>( H_{\psi} )</th>
<th>( H_{Te} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></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>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td></td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td></td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td></td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td></td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
</tr>
</tbody>
</table>

The voltage vector table receives the flux level \( H_{\psi} \), the torque level \( H_{Te} \) and the sector number and generates appropriate control for the inverter from a look-up table as in Table 1[6].

Table 1 can be simply modified by applying zero voltage vectors \((V_0, V_7)\) for the torque decrease states (-1), and this modification will result in decreasing the torque ripple largely. A considerable reason for this decrease is that applying the zero voltage vectors result in reducing the inertia of the motor at this instant and this result in reducing the torque with a percent which is more suitable than the percent given by applying the vectors in Table 1 for the torque decrease states[8]. Table 2 illustrates this modification.

### TABLE II. SWITCHING TABLE FOR MODIFIED CLASSICAL DTC

<table>
<thead>
<tr>
<th>Sector</th>
<th>( H_{\psi} )</th>
<th>( H_{Te} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></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>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td></td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td></td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
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<tr>
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<td>0</td>
<td></td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
</tr>
</tbody>
</table>

### III. DIRECT TORQUE CONTROL USING FUZZY LOGIC

Fuzzy logic controller can be used to replace the switching table of the conventional DTC, and this result in improving the performance of the motor and reducing the torque ripple. Fig. 3 shows block diagram for DTC of I.M using fuzzy logic controller.

**A. Design of DTC using fuzzy logic**

A designer of Fuzzy logic controller must choose memberships for input and output variables and put the rules for the control process. Figure 4 shows functional block diagram for fuzzy logic controller; in this diagram the decision making is made according to fuzzified inputs and rule base which the designer put according to data base, then the output is defuzzified.
B. Input and Output variables

Flux error, torque error and flux position are the input variables of fuzzy logic controller and the stator voltage vector \( (V_0 - V_7) \) is the output variable. Figures 5-8 show memberships for the inputs and output variables.

Fig. 5. Membership for the flux error

Fig. 6. Membership for the torque error

Fig. 7. Membership for the flux position

Fig. 8. Membership for the stator voltage vector

C. Rule base

As shown in figure 4 decision making is made according to the inputs and the rule base. A designer of FLC puts the rules according to data base for the control method used for the system to be controlled. The rules of DTC using fuzzy logic is put according to figure 2 and table 2 mentioned above.

IV. ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANN) are, as their name indicates, computational networks which attempt to simulate, in a gross manner, the networks of nerve cell (neurons) of the biological (human or animal) central nervous system[9]. Neural networks are composed of simple elements called neurons operating in parallel. As in nature, the connections between elements largely determine the network function[10].

![Multiple Layer Neural Network](image)

\[
a_i = f \left( \sum_{j=1}^{R} w_{ij} p_j + b_i \right)
\]

where;

\( R \) : number of elements in input vector.
\( S \) : number of neurons.

A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between elements. Typically, neural networks are adjusted, or trained, so that a particular input leads to a specific target output[10]. Neural networks have self-adapting compatibilities which makes them well suited to handle non-linearities, uncertainty and parameter variations. Neural networks are capable of generalization in regions of the input space, where little or no training data are available[11].

![Basic principle of operation for the ANN](image)

A neural network is designed and trained so that it can replace the conventional PI speed controller to get the desired response. Network given is feed forward with one input, three hidden and one output layer. The hidden layers have 'log-sigmoid', 'tan-sigmoid' and 'pure line' as transfer functions. The training is done using Levenberg–Marquardt Back-propagation Algorithm with 20 neurons in each hidden layer using Matlab simulink.
V. SIMULATION OF DIRECT TORQUE CONTROL

A. Model and Parameters

Figure 11 shows simulink model of DTC for induction motor drive, while Tables III, IV. and V. show the parameters of the induction motor, DTC and speed controller respectively.

![Simulink model of DTC](image)

**Figure 11. Simulink model of DTC**

**TABLE III. PARAMETERS FOR INDUCTION MOTOR**

<table>
<thead>
<tr>
<th>Rated voltage</th>
<th>Rated power</th>
<th>Rated frequency</th>
<th>Pole pairs</th>
<th>Stator resistance</th>
<th>Stator inductance</th>
<th>Rotor resistance</th>
<th>Rotor inductance</th>
<th>Mutual inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>VA</td>
<td>Hz</td>
<td>2</td>
<td>0.435</td>
<td>2</td>
<td>0.816</td>
<td>2</td>
<td>69.3</td>
</tr>
</tbody>
</table>

**TABLE IV. PARAMETERS FOR DIRECT TORQUE CONTROL**

<table>
<thead>
<tr>
<th>Sampling time</th>
<th>Hysteresis torque band width</th>
<th>Hysteresis flux band width</th>
<th>Max. switching frequency</th>
<th>Initial flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 µs</td>
<td>0.5 N.m</td>
<td>0.01 Hz</td>
<td>20 KHz</td>
<td>0.3 wb</td>
</tr>
</tbody>
</table>

**TABLE V. PARAMETERS FOR SPEED CONTROLLER**

<table>
<thead>
<tr>
<th>Upper limit torque</th>
<th>Lower limit torque</th>
<th>Sampling time</th>
<th>Cut off frequency</th>
<th>KI</th>
<th>Kp</th>
<th>Ramp 2 speed</th>
<th>Ramp 1 speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.8 N.m</td>
<td>-17.8 N.m</td>
<td>7*20 µs</td>
<td>100 Hz</td>
<td>10</td>
<td>5</td>
<td>1800 r.p.m</td>
<td>-1800 r.p.m</td>
</tr>
</tbody>
</table>

The following simulation results is drawn in per unit values for a base values of 12.5 N.m for the torque , 1705 r.p.m for the speed ,0.3 wb for flux and 25A for the stator current.
B. Results

Fig. 12. Electromagnetic torque for classical DTC

Fig. 13. Rotor speed for classical DTC

Fig. 14. Torque for modified classical Fuzzy DTC

Fig. 15. Torque in (p.u) for Neuro-Fuzzy DTC

Fig. 16. Stator flux circle for classical DTC

Fig. 17. Stator flux circle for modified fuzzy DTC

Fig. 12 shows electromagnetic torque in per unit for the classical DTC which has an unaccepted ripple value of torque (0.38 p.u.). Fig. 14 shows electromagnetic torque in (p.u) for modified classical Fuzzy DTC the ripple value of torque is reduced and became 0.175 p.u. which is an accepted. Also, it is clear the fast dynamic response of the torque and the under and over shoots presented in the torque results. Fig. 15 shows electromagnetic torque in (p.u) for Neuro-Fuzzy DTC, here the under and over shoots are reduced.

Fig. 18. Stator current in per unit for classical DTC

Fig. 19. Stator current for the modified fuzzy DTC

Fig. 18 shows Stator current for classical DTC which has a large value of ripple, while Fig. 19 shows Stator current for modified fuzzy DTC which has a minimum value of ripple.
VI. CONCLUSION

This paper proposes improvement of DTC using FLC as switching state selector based on modified classical DTC and neural speed controller. It can be seen from the simulation results above for the simulation model given and the parameters mentioned above that flux, torque and current ripples is reduced remarkably for the proposed method. The simulation results show that the torque has very good dynamic response for the mentioned DTC methods. Applying ANN to replace conventional PI speed controller result in reducing the over and under shoots and lead to swift speed response as shown in simulation results. Therefore using the proposed method results in improving the motor performance.

REFERENCES


