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Direct Torque Control Of IM Drives Using Fuzzy Logic Controller

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Abstract:

This study deals with the direct torque control (DTC) of the induction motor. This type of control allows decoupling control between the flux and the torque without the need for a transformation of coordinates. However, the DTC scheme has a high ripple for both electromagnetic torque and stator flux and a distortion of the stator current. To solve these problems, we have developed a new approach of DTC scheme making use of fuzzy logic.

Key words: Induction machine, Direct torque control, Fuzzy logic

1.Introduction

For high power industrial applications it is desirable to use AC motor drive instead of DC. But due to inherent torque coupling present in AC motor, the dynamic response becomes sluggish. In order to improve the performance of AC motor, we follow motion control techniques so that AC motor can provide a good dynamic torque response as it is obtained from DC motor drives.

In recent years, an advanced control method called direct torque control has gained importance owing to its capability to produce fast torque control of induction motor. Conventional DTC does not require any mechanical sensor or current regulator and coordinate transformation is not present, thus reducing the complexity. Fast and good dynamic performances and robustness have made DTC popular and is now used widely in all industrial applications (Nasir Uddin, 2012). Despite these advantages it has some disadvantages such as high torque ripple and slow transient response to step changes during start up. The major problem in a DTC-based motor drive is the presence of ripples in the motor-developed torque and stator flux. Generally, there are two main techniques to reduce the torque ripples. The first one is to use a multilevel inverter which will provide the more precise control of motor torque and flux. However, the cost and complexity of the controller increase proportionally. The other method is space vector modulation. Its drawback is that the switching frequency still changes continuously. Advantages of intelligent controllers such as fuzzy logic, neural network, Neuro-fuzzy, etc., are well known as their designs do not depend on an accurate mathematical model of the system and they can handle non-linearity of arbitrary complexity. Among different intelligent algorithms, fuzzy logic is the simplest, which does not require intensive mathematical analysis. For this purpose, we follow artificial intelligent techniques such as neural network, fuzzy logic. In this study, the Fuzzy Logic (FL) method, which is based on the language rules, is employed to solve this non-linear issue.

2.Materials And Methods

2.1.Mathematical Model Of Induction Motor

A three phase two poles symmetrical induction motor with sinusoidally distributed stator windings and short circuited rotor windings is considered. The effect of magnetic saturation, iron losses and eddy currents are neglected. By considering the stationary reference frames fixed on the stator, the mathematical equations of the IM can be written as follows (Bujat al., 1997). [1]

Stator and rotor voltage equations

$$V_s = R_s I_s + \frac{d\psi_s}{dt} \quad (1)$$

$$0 = R_r I_r + \frac{d\psi_r}{dt} - j\omega\psi_r \quad (2)$$

Stator and rotor flux equations

$$\psi_s = L_s I_s + M I_r \quad (3)$$

$$\psi_r = L_r I_r + M I_s \quad (4)$$

Mechanical dynamic equation

$$J \frac{d\Omega}{dt} = T - f\Omega - T_l \quad (5)$$

$$\text{Electromagnetic torque } T = \rho \frac{M}{L_r} (\psi_{dr} I_{qs} - \psi_{qr} I_{ds}) \quad (6)$$

2.2.Space Vector

Space vector notation allows the transformation of the natural instantaneous value of a three phase system onto a complex plane located in the cross section of the motor. In this plane, the space vector rotates with an angular speed equal to the angular frequency of the three phase supply system.

A three-phase symmetric system represented in a neutral coordinate system by phase quantities, such as voltages, currents or flux linkages can be replaced by one resulting space vector of respectively, voltage, current and flux-linkage. A space vector is defined as:

$$K = \frac{2}{3} (1K_A(t) + aK_B(t) + a^2K_C(t)) \quad \text{Where } K_A(t), K_B(t), K_C(t) \text{ are the arbitrary phase quantities in a system of natural coordinates, satisfying the condition } K_A(t) + K_B(t) + K_C(t) = 0.1, a, a^2 \text{ are the complex unit vectors, with a phase shift } 2/3 \text{ is the normalization factor.} \quad (7)$$

coordinates, satisfying the condition $K_A(t) + K_B(t) + K_C(t) = 0.1$, a, a^2 are the complex unit vectors, with a phase shift $2/3$ is the normalization factor.

2.3.Direct Torque Control

Direct Torque Control (DTC) is one of the methods used in variable frequency drives to control the torque (and thus finally the speed) of three phase AC electric motors. The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits.

The direct torque control method was introduced in the middle of 80's by Isao Takahashi and Toshihiko Noguchi (1980). The principles of DTC method is to select one of the inverters namely 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 basic DTC scheme is shown in Figure.1.

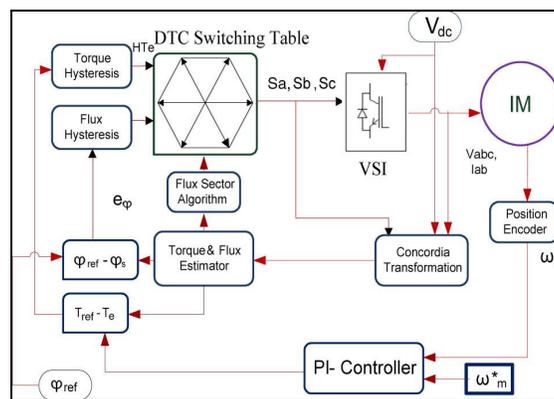


Figure 1: Conventional DTC Scheme For IM Drive

The DTC switching table produces the logic signals $S_a, S_b,$ and S_c based on the three inputs (output digit of torque hysteresis controller, output digit of flux linkage hysteresis controller, and sector number) where stator flux linkage space vector is positioned. These logic signals are used to trigger the switches of the three-phase voltage source inverter (VSI).

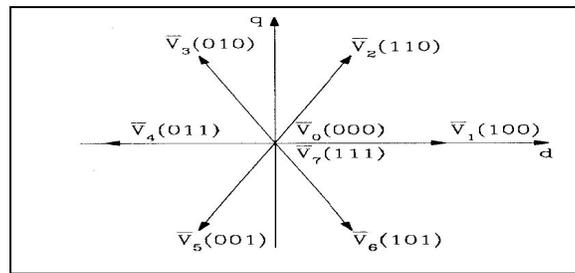


Figure 2: Voltage Vectors

The possible six active combinations of these logic signals and the corresponding active input voltage vectors of the inverter (V1 to V6) are shown in Figure.2. The three phase output voltage of VSI, which is the input to the stator of IM, is given by

$$V_{sa} = \frac{V_{dc}}{3} (2S_a - S_b - S_c) \quad (8a)$$

$$V_{sb} = \frac{V_{dc}}{3} (2S_b - S_c - S_a) \quad (8b)$$

$$V_{sc} = \frac{V_{dc}}{3} (2S_c - S_a - S_b) \quad (8c)$$

Where V_{dc} is the dc link inverter voltage. By concordia transformation

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (9)$$

Stator flux linkage ϕ_s can be obtained from stator voltage vector

$$\phi_s = \frac{1}{T_N} \left(\int_0^t (V_s - R_s I_s) dt + \phi_{s0} \right) \quad (10)$$

Neglecting stator resistance R_s , it may be simplified as

$$\Delta\phi_s = V_s \Delta t \quad (11)$$

$\Delta\phi_s$ is the change in stator flux caused by the application of an inverter voltage vector V_s . ϕ_{s0} is the stator flux linkage at $t=0$. The change in stator flux $\Delta\phi_s$ has the same direction as that of the applied voltage. For DTC scheme the estimated electromagnetic torque

$$\text{developed and stator flux linkages are given by } T_e = \frac{3}{2} P [\phi_{s\alpha} I_{s\beta} - \phi_{s\beta} I_{s\alpha}] \quad (12) \quad \phi_s = \sqrt{(\phi_{s\alpha}^2 + \phi_{s\beta}^2)} \quad (13)$$

$I_{s\alpha}$ and $I_{s\beta}$ are the direct and quadrature components of stator current, respectively. These estimated values of torque and flux are compared with the corresponding command/reference values, and the error signals are delivered to the respective hysteresis controllers. On the basis of the magnitude of the error signals and allowable bandwidth, each hysteresis controller produces a digit. Then, the position of the stator flux-linkage space vector is evaluated as

$$\theta_s = \tan^{-1}(\phi_{s\beta} / \phi_{s\alpha}) \quad (14)$$

Therefore, two digits produced by hysteresis controllers and one by flux position are collectively used to trigger the switches of the VSI which selects the appropriate voltage vector by using the classical DTC look up table. Thus, the selection table generates pulses S_A , S_B , S_C to control the power switches in the inverter.

2.4. Torque Ripple Analysis

Under the influence of any active VSI voltage vector, the motor torque keeps on increasing or decreasing until it touches the boundary defined by torque hysteresis bands. The torque ripple is only affected by the width of the torque hysteresis band and is almost independent of the width of the flux hysteresis band. Torque ripple changes proportionally with change in the torque hysteresis bandwidth. However, due to the discrete nature of the control system, there might be still torque ripple even with the zero bandwidth of the hysteresis controller. On the other hand, if the bandwidth decreases, frequency increases, which proportionally increases its switching losses. Consequently, the bandwidth of the torque hysteresis controller must be optimized in such a way that the torque ripple level and switching frequency of the inverter are within acceptable limits (Nasir Uddin, 2012). A too small band may result in the selection of reverse voltage vector instead of zero vectors to reduce the torque. The selection of reverse voltage vector may then causes torque undershoots. Hence, the torque ripple will become higher than those specified by the hysteresis controller band limits.

2.5. Torque Ripple Minimization

In order to reduce the ripples in the output, intelligent controllers are used. Some of the intelligent controllers are fuzzy logic, neural network, Neuro fuzzy etc. Advantages of intelligent controllers are well known as their designs do not depend on an accurate mathematical model of the system and they can handle non linearity of arbitrary complexity. Among different intelligent algorithms, Fuzzy Logic is the simplest and it does not require intensive mathematical analysis.

3. Principle Of Fuzzy Direct Torque Control

The Fuzzy Logic system involves three steps fuzzification, application of Fuzzy rules and decision making and defuzzification, (Guohanin and Zhiewei Xu, 2010). Fuzzification involves mapping input crisp values to Fuzzy variables. Fuzzy inference consists of Fuzzy rules and decision is made based on these Fuzzy rules. These Fuzzy rules are applied to the fuzzified input values and Fuzzy outputs are calculated. In the last step, a defuzzifier converts the Fuzzy outputs back to the crisp values.

The Fuzzy controller is designed to have three Fuzzy input Variables and one output variable for applying the Fuzzy control to direct torque Control of Induction Motor, there are three variable input Fuzzy Logic variables - the stator flux error, electromagnetic torque error, and angle of flux stator (Sweety Jose et al., 2011)



Figure 3: Fuzzy Logic Controller

The membership functions of these Fuzzy sets are triangular with two membership function N, P for the flux-error, three membership functions N, Z, P for the torque-error, six membership variables for the stator flux position sector and eight membership functions for the output commanding the inverter (Jalluri and Sanker Ram, 2012). The inference system contains thirty six Fuzzy rules which are framed in order to reduce the torque and flux ripples. Each rule takes three inputs, and produces one output, which is a voltage vector. Each voltage vector corresponds to a switching state of the inverter. The switching state decides the pulse to be applied to the inverter. The Fuzzy inference uses Mamdani's procedure for applying Fuzzy rules which is based on min-max decision.

Depending on the values of flux error, torque error and stator flux position the output voltage vector is chosen based on the Fuzzy rules (Sweety Jose et al., 2011). Using Fuzzy Logic controller the voltage vector is selected such that the amplitude and flux linkage angle is controlled. Since the torque depends on the flux linkage angle the torque can be controlled and hence the torque error is very much reduced.

4. Results And Discussion

4.1. Simulation Results

The performance of the conventional DTC scheme for IM drive has been investigated extensively at different operating conditions. Sample simulation results are presented below. The nominal IM parameters, used for simulation and real-time application, are given in the Appendix.

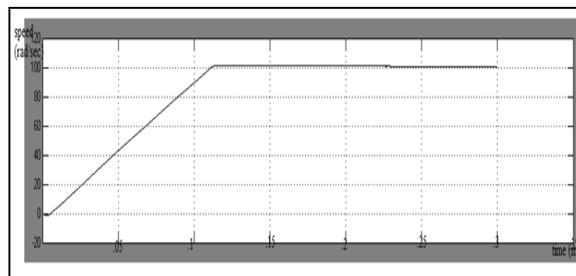


Figure 4: Steady State Speed Response

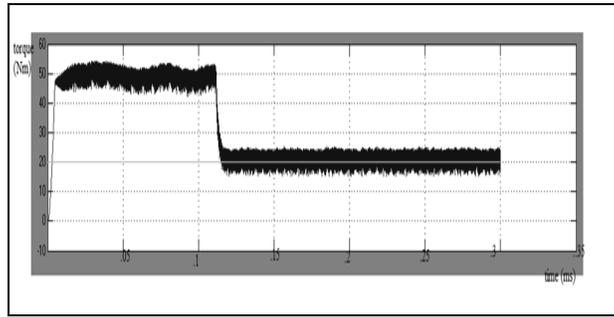


Figure 5: Steady State Torque Response

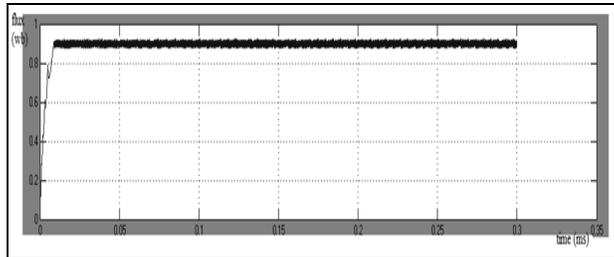


Figure 6: Steady State Flux Response

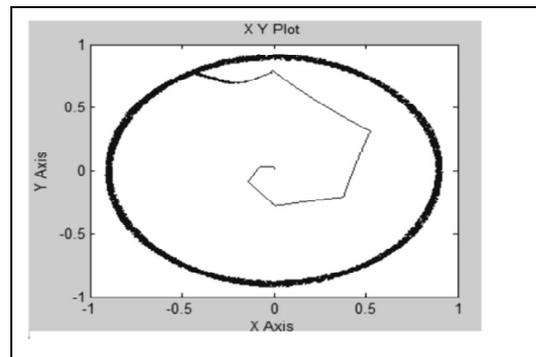


Figure 7: Stator Flux Circle

From the steady-state speed responses of conventional DTC scheme, we found that it has approximate average speed ripples of 0.02 rad/s with some very big abrupt peaks. By using the proposed DTC scheme, the speed response is very smooth, and there are almost negligible ripples. From the steady state torque response, we found that there are ripples. In particular the negative torque ripple is very big in the conventional DTC scheme.

5. Conclusion

In this study, a new strategy to control the voltage source inverter with the DTC concept was developed. The DTFC scheme is proposed to reduce the ripples that can be seen in electromagnetic torque and stator flux and also improve the form of the stator current. The DTFC scheme achieved on the basis of the conventional DTC scheme has also shown through the different simulations its effectiveness, and superiority to the conventional DTC scheme.

6. Appendix

IM parameters used for experiment: $L_{ls} = 0.0154$ H, $L_{lr} = 0.0154$ H, $L_m = 0.2655$ H, $P = 2$, $R_s = 6.5 \Omega$, $R_r = 3.4 \Omega$, $J = 0.0012$ kg·m², $B^m = 0.0001$ Nm/rad/s, and $HP = 1/3$. Torque hysteresis controller parameters: $HBTU = 0.1$, $HBTL = -0.1$, $KU = 1$, and $KL = 2$.

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