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Torque and Flux Ripple Minimization of Induction Motor Using Fuzzy Logic Controller

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Abstract: This paper proposes design and simulation of Direct Torque Control of Induction Motor drive system is to minimize stator current distortion, electromagnetic torque and flux ripples. In this paper, Fuzzy Logic Controllers are proposed to replace the classical PI torque and flux controllers to achieve desired torque and flux with zero steady state error and also with good dynamic tracking and fast response. Fuzzy based torque and flux controllers are designed to optimize the stator voltages in d-q reference frame that applied to SVPWM-Direct Torque Control. From the output of SVPWM-DTC based motor control signal is developed, hence the speed of IM is regulated. Simulation and the performance of the proposed FLC are analyzed. Simulation results showed that a significant improvement in dynamic torque and speed response in both steady and transient states and also a considerable reduction in Total Harmonic Distortion (% THD).

Keywords: Induction Motor (IM), Direct Torque Control (DTC), Field Oriented Control (FOC), Space Vector Modulation (SVM), Fuzzy Logic Controller (FLC), Fuzzy Logic Direct Torque Control (FLDTC), etc.

1.0 Introduction

In recent years, the variable speed operation of the induction motor is achieved by modern inverters. Fast switching frequency inverters are now available at relatively low cost, at the same time the modern induction machines are now replacing DC motors in industrial applications. Where a fast speed and torque responses in four quadrants is required. One of the best suitable and more reliable techniques to effectively control the speed of induction motor is the Direct Torque Control (DTC) technique proposed by Takahashi and M. Depenbrock [1]. In last two decades the use of AC drives with DTC technique have gradually increased due to its advantages over the Field Oriented Control (FOC) techniques, good dynamic performance, precise and quick response of stator flux and electromagnetic torque, robust against machine parameter variations, no current control loop and simplicity of the algorithm [3, 4].A classical or conventional DTC drive system, which is based on a fixed hysteresis bands for both torque and flux controllers, suffers from a varying switching frequency, which is a function of the motor speed; stator fluxes and stator voltage; it is also not constant in steady state. Variable switching frequency is undesirable at low speed operation; an appreciable level of noise is present which is mainly due to the low inverter switching frequency. The high frequency is limited by the switching characteristics of the power semiconductor devices. Therefore, there will be large torque ripples and distorted wave forms in currents and fluxes. Several solutions have been proposed to keep constant switching frequency like in [2-8]. In order to improve the dynamic performance of the classical DTC scheme, a new modified DTC with a Space Vector Modulation (SVM) based Fuzzy Logic Controller (FLC) is proposed. In this technique is to ensure a constant switching frequency and the use of FLC is to obtain a decoupled between torque ad flux. This present paper deals the development of a Fuzzy Logic Direct Torque Control (FLDTC), expected to improve the dynamic performance compared to the Conventional DTC system. To overcome the disadvantages of the Classical DTC method such as, starting problems, distorted current waveform, Variable switching frequency, high torque and flux ripples and sluggish response. This new proposed FLDTC system is designed and proved by means of simulation in MATLAB/SIMULINK. This paper has Section 2 Mathematical model of asynchronous drive, Section 3 DTC basic concepts and its principles, Torque and Stator flux control, Section 4 Basic switching table and selection of voltage vectors, Section 5 Fuzzy Logic DTC controller and Simulation results, Section 6 Conclusion and Future work.

2.0 Mathematical Model of Induction Motor

The mathematical model of induction motor is the analysis of dynamic d-q equivalent circuits. The dynamic behavior of asynchronous drive is complex to the coupling effect between the stator and rotor phases. The figure.1 below shows the dynamic d-q equivalent circuits of an asynchronous drive. The different parameters of asynchronous drive are also shown in the figure.1

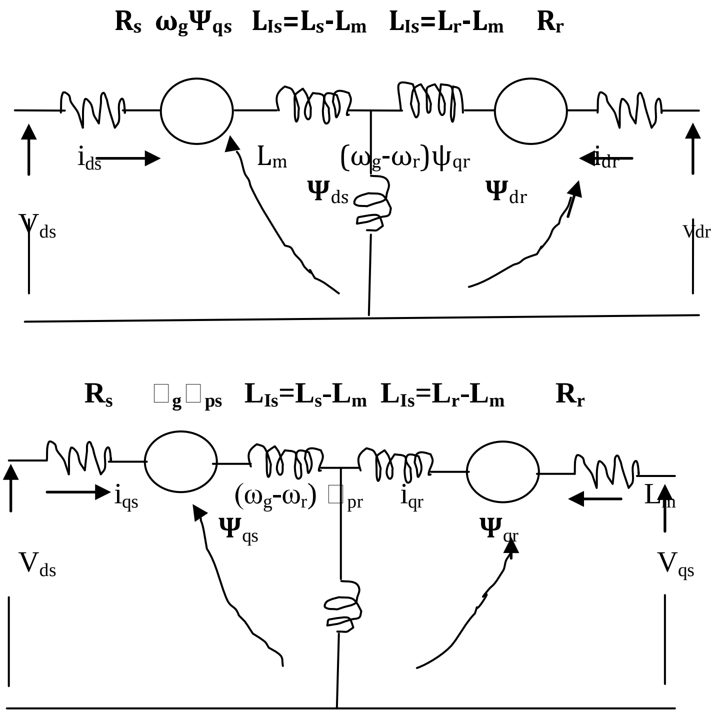


Figure.1 Dynamic d-q equivalent circuits of an asynchronous drive (a) d-axis, (b) q-axis

The flux linkage expressions in terms of the currents can be written from figure as follows:

$$\Psi_{qs} = L_s i_{qs} + L_m (i_{qs} + i_{qr}) \quad (2.1) \qquad \Psi_{qr} = L_r i_{qs} + L_m (i_{qs} + i_{qr}) \quad (2.2)$$

$$\Psi_{qm} = L_m (i_{qs} + i_{qr}) \quad (2.3) \qquad \Psi_{ds} = L_s i_{ds} + L_m (i_{ds} + i_{dr}) \quad (2.4)$$

$$\Psi_{dr} = L_r i_{ds} + L_m (i_{ds} + i_{dr}) \quad (2.5) \qquad \Psi_{dm} = L_m (i_{ds} + i_{dr}) \quad (2.6)$$

The electrical transient model in terms of voltages and currents can be given in matrix forms as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{dr} \end{bmatrix} \quad \textbf{(2.7)}$$

Whereas S is the Laplace operator, dѠ/dt. The speed ω_r in the above equations is related to the torque by the following mechanical dynamic equation,

$$\mathbf{T_e = T_L + J \frac{d\omega_m}{dt} = T_L + \frac{2}{P} J \frac{d\omega_r}{dt}} \quad \textbf{(2.8)}$$

Where J = combined rotor and load inertia, and ω_m = mechanical speed. The torque equation in stationary reference frame can be written as:

$$\mathbf{T_e = \frac{3}{2} \frac{P}{2} \Psi_s X i_s} \quad \textbf{(2.9)}$$

In terms of stator and rotor currents, the torque can be written as:

$$\mathbf{T_e = \frac{3}{2} \frac{P}{2} L_m (i_{rd}\, i_{sq} - i_{rq}\, i_{sd})} \quad \textbf{(2.10)}$$

3.0 DTC basic concepts and its principles

The control techniques of asynchronous machine drive including Scalar control, Vector or Field Oriented Control (FOC), Direct Torque and Flux Control (DTC (or) DTFC) or Direct Self Control (DSC) and Adaptive control. Scalar control is based on the steady state motor model while Vector control is based on dynamic model of motor. Scalar control, as the name indicates is due to magnitude variation of the control variables only, and disregards the coupling effect in the machine. For example, the voltage of a machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. Scalar controls are easy to implement and have been widely used in industry. Scalar control techniques with voltage fed and current – fed inverters etc.

In the mid 1980s, an advanced Scalar Control technique, known as Direct Torque and Flux Control (DTFC or DTC) or Direct Self-control (DSC) was introduced for voltage-fed PWM inverter drives. The DTC proposed by **Takashi** and **M. Depenbrock** for variable load and speed asynchronous motor drives. It was a good alternative to the other type of vector control which known as FOC [5] due to some well known advantages, such as simple control structure, robust and fast torque response without co-ordinate transformation PWM pulse generation and current regulators moreover, DTC minimizes the use of motor parameters. Besides these advantages, DTC scheme [6] still had some disadvantages like high torque and current ripples, possible problems during starting and low speed operation, variable switching frequency.

3.1 Torque expression with stator and rotor fluxes

The torque expression given in equation is

$$\mathbf{T_e = \frac{3}{2}\,\frac{P}{2}\,(\Psi_{ds}{}^{s}\, i_{qs}{}^{s} - \Psi_{qs}{}^{s}\, i_{ds}{}^{s})} \qquad \textbf{(3.1)}$$

The above equation can be expressed in the vector form is

$$\mathbf{T_e = \frac{3}{2}\,\frac{P}{2}\;\Psi_s \;X\; \Psi i_s} \qquad \textbf{(3.2)}$$

Where $\Psi_s = \Psi_{ds}{}^{s}{}_{-\,j\,\Psi qs}{}^{s}$ and $\Psi I_s = i_{qs}{}^{s} - i_{ds}{}^{s}$. In this equation, ΨI_s is to be replaced by rotor flux Ψ_r. In
the complex form, Ψ_s and Ψ_r can be expressed as functions of currents as

$$\mathbf{\Psi s = L_s\, I\Psi_s + L_m\, I\Psi_r} \qquad \textbf{(3.3)}$$

$$\mathbf{\Psi s = Lr\, I\Psi_r + L_m\, I\Psi_s} \qquad \textbf{(3.4)}$$

Eliminating I_s from Equation (3.3), we get

$$\mathbf{\Psi s = \frac{Lm}{Lr}\,\Psi_r + L_s{}'\, I\Psi_s} \qquad \textbf{(3.5)}$$

Where $L_s{}^{'} = L_s\, I_r - L_m{}^{2}$. The corresponding expression of I_s is

$$\mathbf{I\Psi_s = \frac{1}{Ls'}\;\Psi_s - \frac{Lm}{LrLs'}\,\Psi_r} \qquad \textbf{(3.6)}$$

Substituting Equations (3.6) in (3.1) and simplifying yields

$$\mathbf{T_e = \frac{3}{2}\,\frac{P}{2}\;\frac{Lm}{LrLs'}\,\Psi_r \;X\; \Psi_s} \qquad \textbf{(3.7)}$$

That is, the magnitude of torque is

$$\mathbf{T_e = \frac{3}{2}\,\frac{P}{2}\;\frac{Lm}{LrLs'}\,|\Psi_r|\;|\;\Psi_s\;|\;\sin\gamma} \qquad \textbf{(3.8)}$$

Where, γ is the angle between the fluxes. Figure shows the phasor diagram for equation (3.7), indicating the vectors Ψ_s, Ψ_r and Ψ_s for positive developed torque. If the rotor flux remains constant and the stator flux is changed incrementally by stator voltage V_s as shown, and the corresponding change of γ angle is Δγ, the incremental torque ΔT_e expression is given as

$$\Delta T_e = \frac{3}{2}\,\frac{P}{2}\,\frac{Lm}{LrLs'}\,|\Upsilon_r|\;|\,\Psi_s+\Delta\,\Psi_s|\,\sin\gamma \qquad (3.9)$$

3.0 Basic switching table and selection of voltage vectors

The basic working principle of switching table of DTC concept [7] is shown in figure.3. The reference stator flux ψ_{sref}, and torque T_{eref} are compared with the actual value of ψ_s and T_e in hysteresis flux and torque controller respectively. The hysteresis flux controller is a two-level comparator while the hysteresis torque controller is a three level comparator.

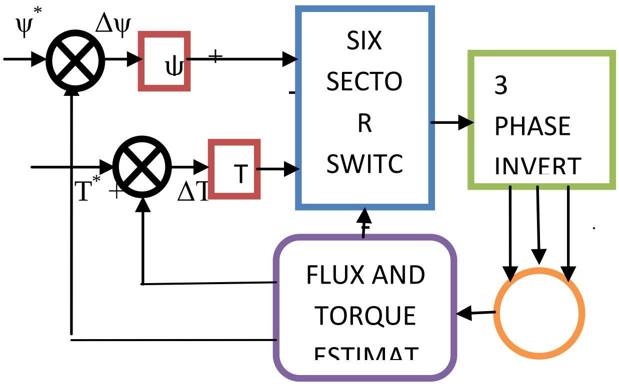


Figure 3 shows block diagram of DTC Switching table concept

The output signal of hysteresis flux controller is define as given below

$$\Psi_{serr}=1,\ \text{for}\ \Psi_s < \Psi_{sref} - H_\psi \qquad (4.1)$$
$$\Psi_{serr}= -1,\ \text{for}\ \Psi_s < \Psi_{sref} + H_\psi \qquad (4.2)$$

and output signal of hysteresis torque controller are define as given below

$$T_{eerr}=1,\ \text{for}\ T_e < T_{eref} - H_m \qquad (4.3)$$
$$T_{eerr} = -1,\ \text{for}\ T_e = T_{eref} \qquad (4.4)$$
$$T_{eerr}= -1,\ \text{for}\ T_e < T_{eref} + H_m \qquad (4.5)$$

Where 2 H□ is the flux tolerance band and 2 H_m is the torque tolerance band.On the basis of the torque and flux hysteresis status and stator flux switching sector which is indicated by

$$\alpha = \angle\,\varphi_s^s = \tan^{-1}(\varphi^s_{qs}/\ \varphi^s_{ds}) \qquad (4.6)$$

Switching table output is a setting of switching devices of the inverter: hence DTC technique [8] selects the inverter voltage vector to apply the asynchronous machine from table.2 and Figure 4 shows the relationship between the inverter voltage vector and stator flux switching sector in which six active switching vectors are: V_1= [1 0 0], V_2= [1 1 0], V_3= [0 1 0], V_4= [0 1 1], V_5 = [0 0 1], V_6= [1 0 1] and two zero switching vectors are: V_0= [0 0 0], V_7= [1 1 1] and also

-30° < α (1) < 30°, 30° < α (2) < 90°, 90° < α (3) < 150°, 150° < α (4) < 210°, 210° < α (5) < 270°, 270° < α (6) < 330°.

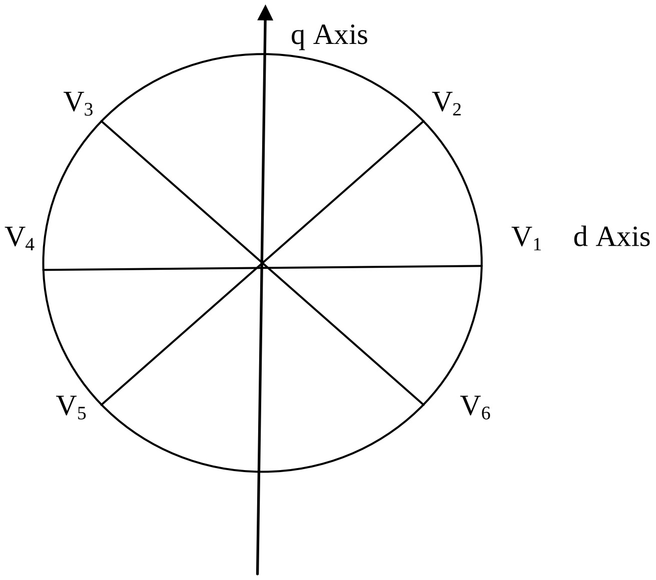


Figure 4 shows switching vectors

$H_{\square}$	H_{Te}	α (1)	α (2)	α (3)	α (4)	α (5)	α (6)
1	1	110	010	011	001	101	100
	0	000	111	000	111	000	111
	-1	101	100	110	010	011	001
-1	1	010	011	001	101	100	110
	0	111	000	111	000	111	000
	-1	001	101	100	110	010	011

Table 2 switching table of inverter voltage vectors

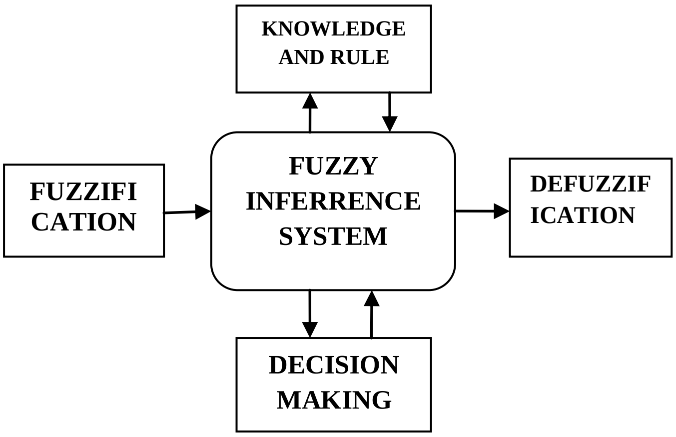
5.0 Fuzzy Logic DTC Controllers

5.1 Concepts of Fuzzy Logic Controller

Fuzzy logic becomes one of the most successful of recent technology for developing sophisticated control system. Several papers show, both in simulations and experimental results, that fuzzy logic control yields superior results with respect to those obtained by conventional control algorithms thus, in industrial electronics the FLC control [9] has become an attractive solution in controlling the electrical motor drives with large parameter variations.

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore traditional methods become infeasible in these systems. However fuzzy logics linguistic terms provide a feasible method for defining the operational characteristics of such system / Fuzzy logic controller can be considered as a special class of symbolic controller. The fuzzy logic controller has three main components

- Fuzzification
- Fuzzy inference system
- Defuzzification



Fuzzification

Fuzzification is a process of making crisp quantity fuzzy. We do this by simply recognizing that many of quantities that we consider to be crisp and deterministic are actually not deterministic at all. They carry considerable uncertainty. If the form of uncertainly happens to arise because of imprecision ambiguity, or vagueness, then the variable is probably fuzzy can be represented by a membership function. The different shapes of membership functions are triangular, trapezoidal, bell shape, curved or other variations etc.

Fuzzy inference System

Fuzzy inference system is the process of formulating the mapping from a given input to an output using FL. The mapping then provides a basis from which decisions can be made. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems differ the way outputs are determined.

Defuzzification

The output of the fuzzy inference mechanism is fuzzy variables. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values, so that the actual system can use these variables [10]. This conversion is called defuzzification.

5.2 Principles of fuzzy controller

The fuzzy logic controller is one of the controller methods in Artificial Intelligence (AI) techniques. In this paper a Mamdani type of controller is used to regulate the speed of the asynchronous drives. In this section, a fuzzy approach is proposed to reduce the torque ripples and oscillation in speed. In this controller requires three inputs and one single output. The inputs are represented as error of torque, the error in stator and the stator flux angle. Figure 5 illustrates the proposed fuzzy controller of the DTC for asynchronous drives.

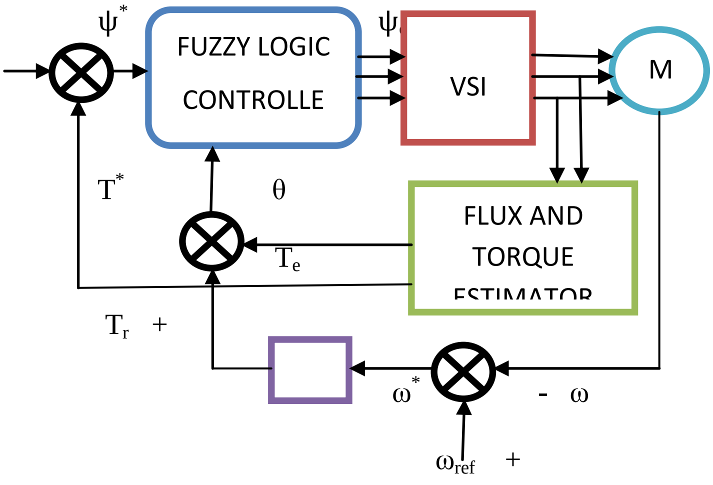


Figure 5 block diagram of basic fuzzy logic controller

The fuzzy logic controller performance is based on the shape of the membership function and the fuzzy reasoning rules. A fuzzy logic controller converts a linguistic control strategy into an automatic control strategy and the rules are constructed by expert knowledge. The input torque and change in torque error have been placed to the fuzzy logic controller. Then the output of the fuzzy logic control of change in torque.

The table 3 shows the rules for torque and hysteresis of fuzzy logic controller.

$\Delta T_e(K)$ **$\Delta T_e^*(K)$**	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

Table 3 Rules for fuzzy logic controller

5.3 Fuzzy logic simulation results

To minimize the amplitude of torque hysteresis band of torque ripple level using fuzzy logic control [11]. The FLC is easily implemented and to observe the better performance for reducing the torque, flux and current ripple and maintaining the good torque response.

6.0 Conclusion

In this work an more improvements in torque and Stator flux ripple minimization was achieved with the FLDTC than the CDTC. The performance has been tested by simulation results using Matlab/Simulink. The results are as fast stator flux response in transient state, Reduction of torque and current ripples in transient and steady state response, reduction of speed ripple in steady state and transient response.

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