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Direct Torque Control of Three phase Induction Motor drive using Fuzzy Logic controllers for low Torque ripple

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Abstract— **This paper presents an improved Direct Torque Control (DTC) based on fuzzy logic technique. The major problem that is usually associated with DTC drive is the high torque ripple. To overcome this problem a torque hysteresis band with variable amplitude is proposed based on fuzzy logic. The fuzzy proposed controller is shown to be able to reducing the torque and flux ripples and to improve performance DTC especially at low speed. The validity of the proposed methods is confirmed by the simulative results.**

Keywords- Direct torque control, induction motor, fuzzy logic, torque ripple minimization.

I. INTRODUCTION

Fuzzy logic is recently getting increasing emphasis in drive control applications. Recent years, fuzzy logic control has found many applications in the past two decades. This is so largely increasing because fuzzy logic control has the capability to control nonlinear uncertain systems even in the case where no mathematical model is available for the control system [1]. So, the development of high performance control strategies for AC servo system drives resulted in a rapid evolution. To overcome the disadvantages of vector control technique, in the middle of 1980's, a new quick response technique for the torque control of induction motors was proposed by Takahashi as direct torque control (DTC) [2]. DTC provides very quick response with simple control structure and hence, this technique is gaining popularity in industries [2]. Though, DTC has high dynamic performance, it has few drawbacks such as high ripple in torque, flux, current and variation in switching frequency of the inverter. The effects of flux and torque hysteresis band amplitudes in the induction motor drive performance have been analyzed in [3].

Since DTC was first introduced, several variations to its original structure were proposed to overcome the inherent disadvantages in any hysteresis-based controller, such as variable switching frequency, high sampling requirement for digital implementation, and high torque ripple[22]-[23]. To solve this problem, various techniques have been proposed.
Including the use of variable hysteresis bands [17], predictive control schemes [24], space vector modulation techniques [25] and intelligent control methods [18]. This paper proposes a novel scheme to improve the drive performance. Fuzzy direct torque control (DTC) is used to improve dynamic response performance and decrease the torque ripples.

II. DTC STRUCTURES

The basic model of DTC induction motor scheme is shown in Fig. 1. At each sample time, the two stator currents i_{sa} and $i_{sb}$and the DC bus voltage $V_{dc}$are sampled. Using the inverter voltage vector, the α,β components of the stator voltage space vector in the stationary reference frame are calculated as follows.

$$\begin{cases} V_{s\alpha ref} = \frac{2}{3}V_{dc}\left(S_a - \frac{S_b+S_c}{2}\right) \\ V_{s\beta ref} = \frac{1}{\sqrt{3}}V_{dc}(S_b - S_c) \end{cases} \tag{1}$$

The α,β components of the stator current space vector are calculated using

$$\begin{cases} I_{s\alpha} = i_{sa} \\ I_{s\beta} = \frac{i_{sa}+2i_{sb}}{\sqrt{3}} \end{cases} \tag{2}$$

The stator flux is a function of the rotor flux which is provides from the flux observer.

$$\begin{cases} \varphi_{s\alpha} = \sigma L_s I_{s\alpha} + \frac{M}{L_r}\varphi_{r\alpha} \\ \varphi_{s\beta} = \sigma L_s I_{s\beta} + \frac{M}{L_r}\varphi_{r\beta} \end{cases} \tag{3}$$

Then the magnitude of the stator flux is calculated by

$$|\varphi_s| = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \tag{4}$$

The electromagnetic torque is calculated by

$$T_e = \frac{3}{2}p(\varphi_{s\alpha}I_{s\beta} - \varphi_{s\beta}I_{s\alpha}) \tag{5}$$

where p is the number of pole pairs.

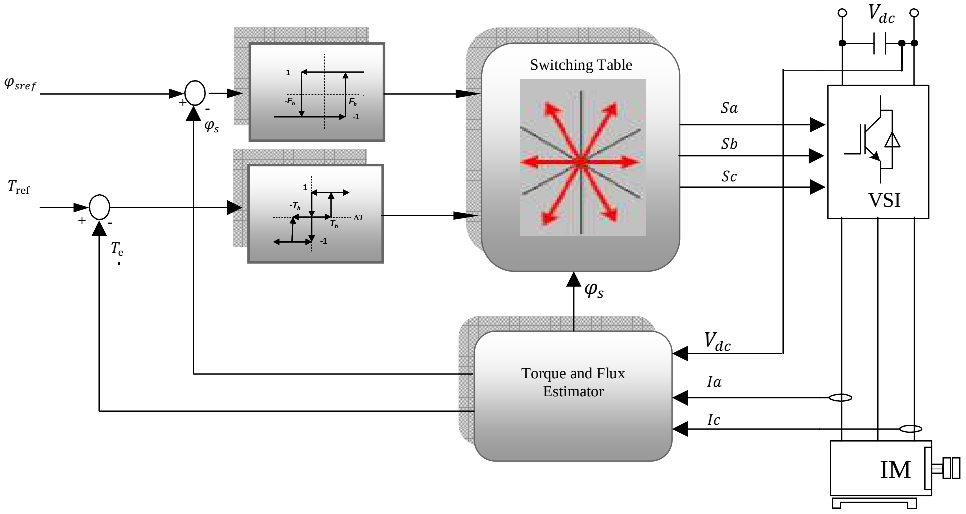


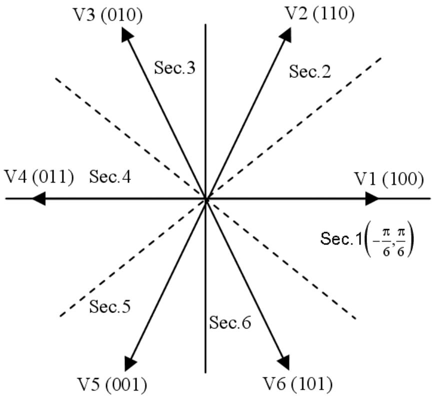
Figure.1. Block diagram of classical direct torque control

The torque and flux errors are defined as

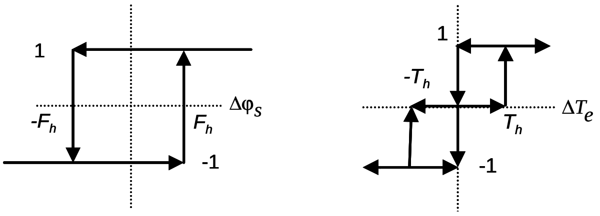
$$\begin{cases}\Delta\varphi_s = |\varphi_{sref}| - |\varphi_s| \\ \Delta T_e = T_{ref} - T_e\end{cases} \tag{6}$$

The inverter switching states are determined by the torque and flux errors according to the sector determined.

As shown in Fig. 2, a switching table is used for the inverter control such that the torque and flux errors are kept within the specified bands.



(a) Output voltage vectors.



(b) Flux comparator. (c) Three-level torque comparator.

Figure 2. DTC definition of the voltage vectors and comparators.

Three-level torque and two level flux hysteresis controllers are used according to the outputs of the torque controller and the sector information, appropriate voltage vectors for both the inverters are selected from a switching table as it is shown in Table 1.

Table 1. Classical DTC Switching table.

		Sector 6	Sector 5	Sector 4	Sector 3	Sector 2	Sector 1
		$\left(-\frac{\pi}{2},-\frac{\pi}{6}\right)$	$\left(-\frac{\pi}{6},,\frac{\pi}{6}\right)$	$\left(\frac{\pi}{6},\frac{\pi}{2}\right)$	$\left(\frac{\pi}{2},\frac{5\pi}{6}\right)$	$\left(\frac{5\pi}{6},\frac{7\pi}{6}\right)$	$\left(\frac{7\pi}{6},\frac{9\pi}{6}\right)$
Decrease Flux	Increase Torque	100	110	010	011	001	101
	Decrease Torque	011	001	101	100	110	010
Increase Flux	Increase Torque	110	010	011	001	101	100
	Decrease Torque	001	101	100	110	010	011

III. Torque ripple analysis

Since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux, torque and flux ripples compose a real problem in DTC induction motor drive.

Many solutions were proposed to improve performances [7, 9–17].

According to the principle of operation of DTC, the torque presents a pulsation that is directly related to the amplitude of its hysteresis band. The torque pulsation is required to be as small as possible because it causes vibration and acoustic noise [15].

A small flux hysteresis bands should be preferred when high-switching speed semi- conductor devices are utilized because their switching losses are usually negligible with respect on state losses. In this way the output current harmonic can be strongly reduced [15].

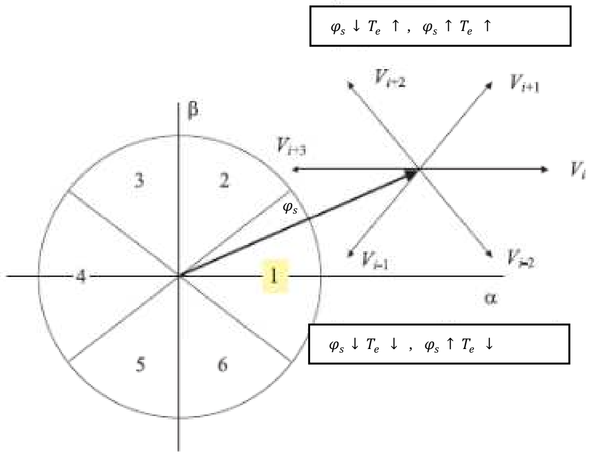


Figure. 3. Stator flux variation (φ_s is in section 1)

The hysteresis band has to be set large enough to limit the inverter switching frequency below a certain level that is usually determined by thermal restriction of power devices. Since the hysteresis bands are set to cope with the worst case, the system performance is inevitably degraded in a certain operating range, especially in a low speed region [17]. In torque hysteresis controller, an elapsing time to move from lower to upper limit, and vice versa can be changed according to operating condition [17].

IV. DESIGN OF FLC FOR TORQUE RIPPLE OPTIMIZATION

The principle of fuzzy logic direct torque control (DTC) is similar to traditional DTC. The difference is using a fuzzy logical controller to replace the torque hysteresis loop controller. As shown in Figure4.

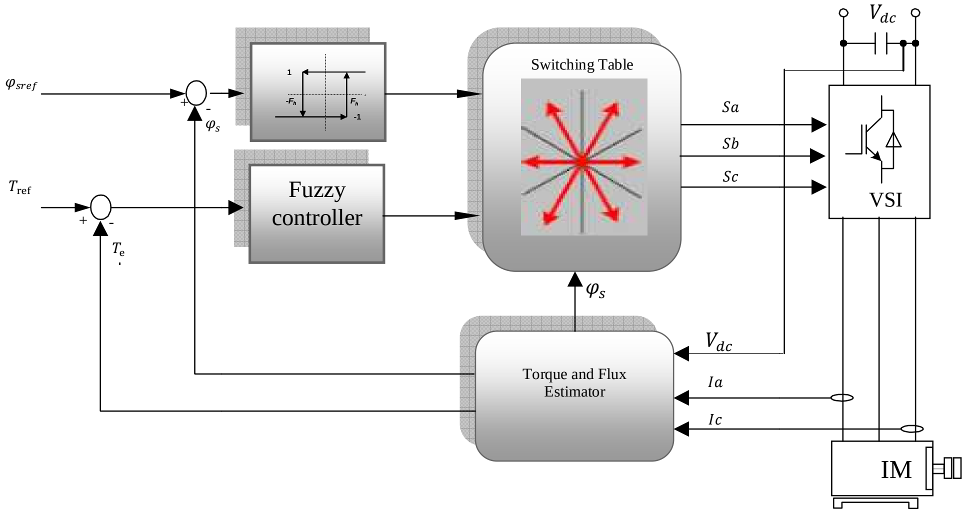


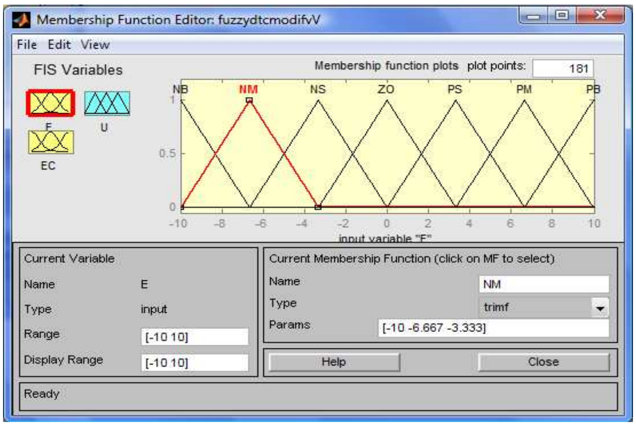
Figure4. Fuzzy logic DTC scheme

In this paper, a Mamdani-type FLC is developed to adapt the torque hysteresis band in order to reduce the ripples in the motor-developed torque [23]–[25]. In conventional DTC technique, the amplitude of the torque hysteresis band is fixed. However, in this proposed scheme, the FLC controls the upper and lower limits of the torque hysteresis band on the basis of its feedback inputs. The fuzzy systems are universal function approximators [24]. The FLC is used as a nonlinear function approximator producing a suitable change in the bandwidth of the torque hysteresis controller in order to keep the torque ripples minimum.

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule U(EC; E) . The shapes of membership functions are refined trough simulation and testing. The rules sets are shown in Table 2. Figure 5 and 6 shows the membership functions of input and output variables respectively. The rules were formulated using analysis data obtained from the simulation of the system using different values of torque hysteresis band.

Table 2. Fuzzy rules of torque hysteresis controller

EC U E	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	ZO
NM	PB	PB	PM	PM	PS	ZO	ZO
NS	PB	PM	PM	PS	ZO	ZO	NS
ZO	PM	PS	PS	ZO	NS	NS	NM
PS	PS	ZO	ZO	NS	NM	NM	NB
PM	ZO	ZO	NS	NM	NM	NB	NB
PB	ZO	NS	NM	NB	NB	NB	NB



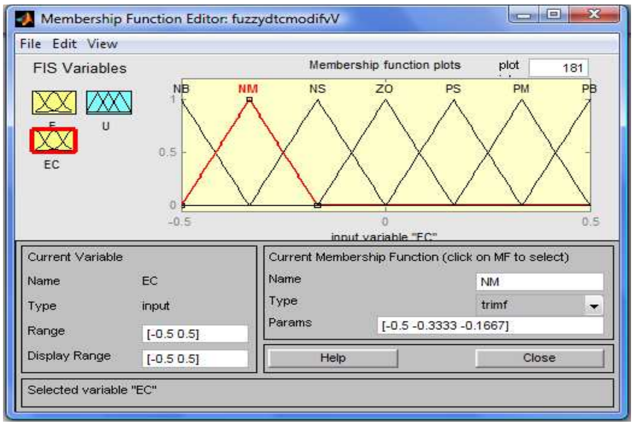
plot points: 181

Current Variable
Name E
Type input
Range [-10 10]
Display Range [-10 10]

Current Membership Function (click on MF to select)
Name NM
Type trimf
Params [-10 -6.667 -3.333]

Ready

a)



plot 181

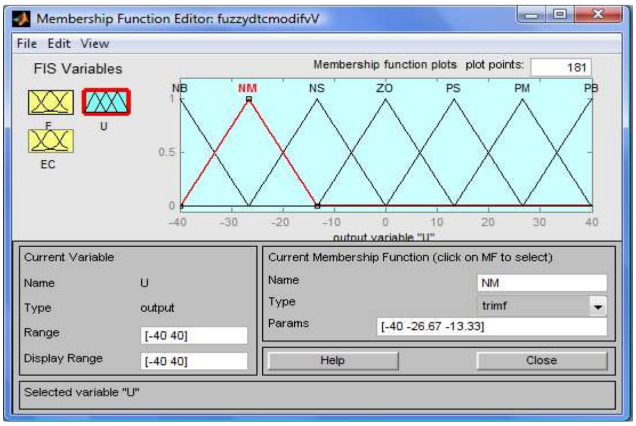
Current Variable
Name EC
Type input
Range [-0.5 0.5]
Display Range [-0.5 0.5]

Current Membership Function (click on MF to select)
Name NM
Type trimf
Params [-0.5 -0.3333 -0.1667]

Selected variable "EC"

b)

Figure.4. Input variables membership functions



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Current Variable
Name U
Type output
Range [-40 40]
Display Range [-40 40]

Current Membership Function (click on MF to select)
Name NM
Type trimf
Params [-40 -26.67 -13.33]

Selected variable "U"

Figure.5. Output variable membership function

V. SIMULATION RESULT

The simulations of the DTC induction motor drive were carried out using the Matlab/Simulink simulation package. A 3-phase, 4 pole, induction motor with parameters of Rs=0.728; Rr=0.706; Ls=0.0996; Lr=Ls; Lm=0.0969; Lds=Ls-Lm; Ldr=Lr-Lm; C and J=0.062Kg.m2 are considered.

Stator flux linkage comparing curves are shown in Figure 6 and Figure 7.

Compared with two groups of flux waveform, the flux track amplitude of traditional DTC model is volatile. At certain parts, there is a clear deviation, flux required for a longer time to reach steady-state, the fuzzy logic DTC flux track has always maintained a very good round, flux is required for a short time to reach steady-state, and flux amplitude fluctuation is small.

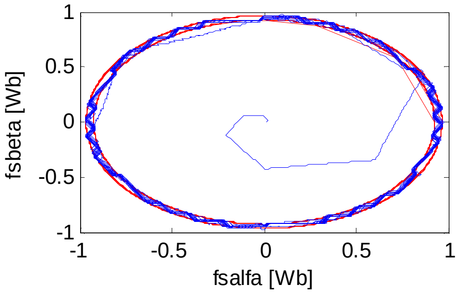

Figure.6. Stator flux circle based Classical DTC

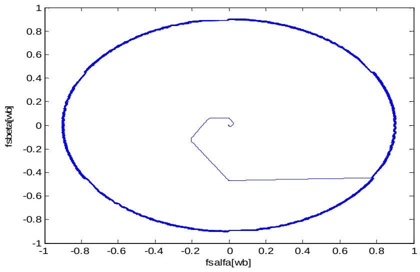

Figure.7. Stator flux circle based on Fuzzy DTC

Torque response comparing curves are shown in Figure 8 and Figure 9.see Figures the torque ripple is significantly reduced when fuzzy controller is in use. The fuzzy controller provides the desired amplitude according to the torque ripple level and operating condition, as it is shown in paper.

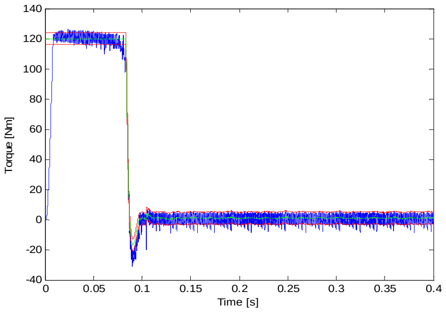

Figure.8. Torque response based Classical DTC

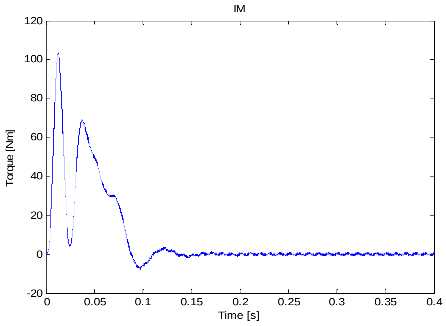

Figure.9. Torque response based Fuzzy DTC

Figures10 and 11 shows the stator flux responses of both the conventional and Fuzzy DTC schemes. It is found that the proposed variable band torque hysteresis controller-based DTC scheme exhibits smooth response and lesser ripple in flux as compared to the conventional DTC scheme.

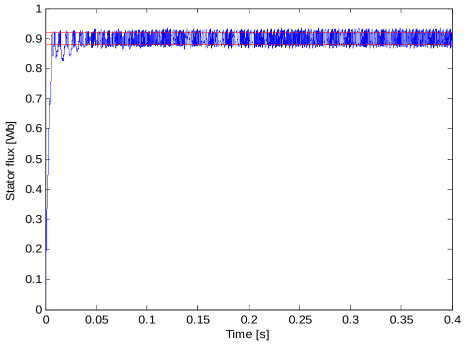

Figure.10. Steady-state stator flux-response based Classical DTC

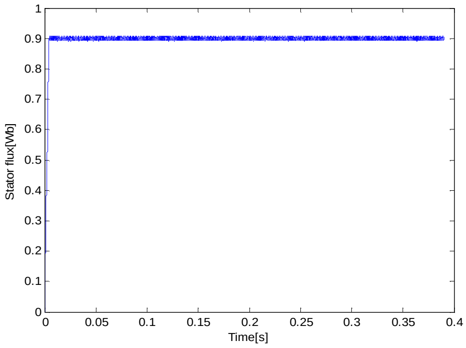

Figure.11. Steady-state stator flux-response based Fuzzy DTC

Steady state current comparing curves are shown in Figure 12 and Figure 13.

Compared with Steady state current waveform, traditional DTC model maintaining the current waveform of Sine, but there is a little large pulsation, there are some harmonics which will lead to torque ripple in the wave form; while the fuzzy logic DTC current waveform is relatively smooth, so, effectively reduces the harmonic.

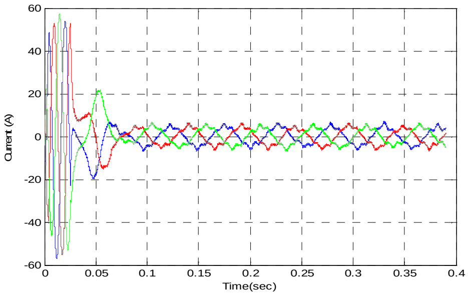

Figure12. Steady-state stator current based on Classical DTC

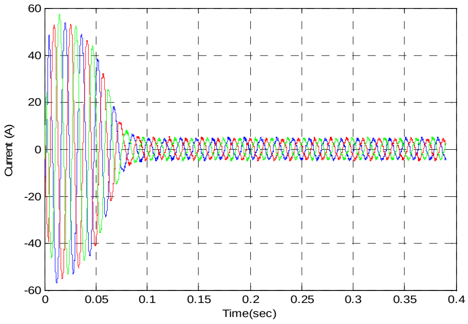

Figure13. Steady-state stator current based on fuzzy logic DTC

VI. CONCLUSION

The present paper has presented a sensorless speed DTC drive with fuzzy controller. This controller determinates the desired amplitude of torque hysteresis band. It is shown that the proposed scheme results in improved stator flux and torque responses under steady state condition. The main advantage is the improvement of torque and flux ripple characteristics at low speed region, this provides an opportunity for motor operation under minimum switching loss and noise.

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