

# TORQUE RIPPLE MINIMIZATION STRATEGY FOR DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING FUZZY SCHEME

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## ABSTRACT

The direct torque control (DTC) speed control scheme of an induction motor surpasses the vector control in the sense that it controls the torque directly and does not use transformations and current modulator. In the traditional direct torque control (DTC) of induction motor, the low order harmonic component of stator current is very large when the motor is running at low speed. It leads to high torque ripple of motor in low speed. To solve this problem, a new control method has been proposed in this paper. To improve the torque response and reduce the torque ripple, fuzzy logic concept has been introduced into the flux model. The simulation results depict that the proposed method not only improve the speed of torque response, but the problem of torque ripple can be effectively solved. In the whole speed range, the performance of dynamic and static is better than that of the conventional DTC.

**Keywords:** Torque Ripple; Direct Torque Control (DTC), Induction Motor, Fuzzy Logic

## I. INTRODUCTION

The induction motor due to its well known advantages of simple construction, reliability, ruggedness, and low cost has found very wide industrial applications. In recent years much research has been developed in order to find simpler control schemes of induction motors that meet the requirements like low torque ripple, low harmonic distortion and quick response [1]. Among various proposals Direct Torque control (DTC) found wide acceptance. In the 1980s, Takahashi proposed a direct torque control for an induction machine drive [2-3]. Furthermore, DTC provides very quick response with simple control structure and hence, this technique is gaining popularity in industries. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state [2-4].

The direct torque control (DTC) has the advantage of fast dynamic torque response and has good robustness to the changes of rotor parameters etc. But the torque ripple is an inadequacy of the system. The pulsation becomes more apparent especially in the low-speed operating conditions [5]. Due to this fact, some solutions have been developed in recent years.

One approach is to use a high switching frequency inverter [6]. It reduces harmonic content of the stator current, and reduces torque ripple. However, the loss of power increases and the efficiency of the inverter are reduced. Also the cost of the inverter with high frequency switching characteristics is high. Another method is to use two parallel connected inverters generate multiple non-zero voltage vector [7]. This method solved the torque ripple to some extent, but the structure of the inverter is complicated. Moreover the zero-phase sequence current needs to be monitored in this connection. In addition, there are multi-level inverter method [8] and space vector modulation method [9]. The cost and complexity will increase in the former method. The torque ripple and flux ripple can be reduced in the latter method. But it will change the switching frequency.

A DTC method with fuzzy logic controller has been presented in this paper which can dynamically adjust the torque hysteresis amplitude. The experimental results show that the program can effectively reduce the torque ripple and improve the torque control performance in the low-speed running.

## II. DTC SCHEME

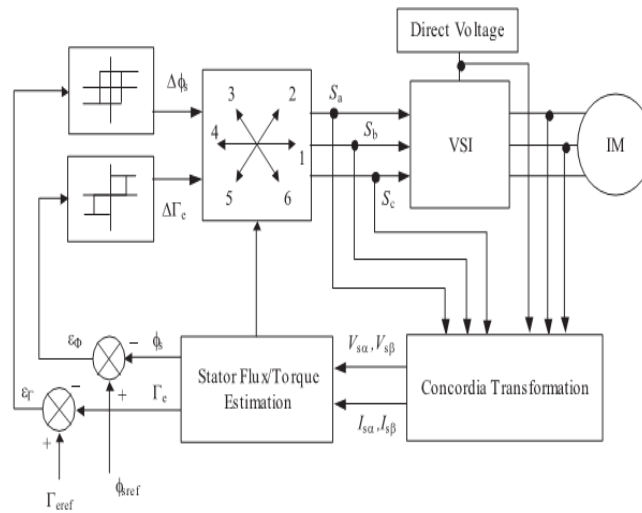
The DTC scheme is given in Fig. 1, the  $\varepsilon\phi$  and  $\varepsilon\Gamma_e$  signals are delivered to two hysteresis comparators. The corresponding digitized output variables: change of magnetic flux  $\Delta\phi$ , of mechanical torque  $\Delta\Gamma_e$  and the stator flux position sector  $s_N$  created a digital word, which selects the appropriate voltage vector from the switching table. The selection table generates pulses  $S_a$ ,  $S_b$ ,  $S_c$ , to control the power switches in the inverter.

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

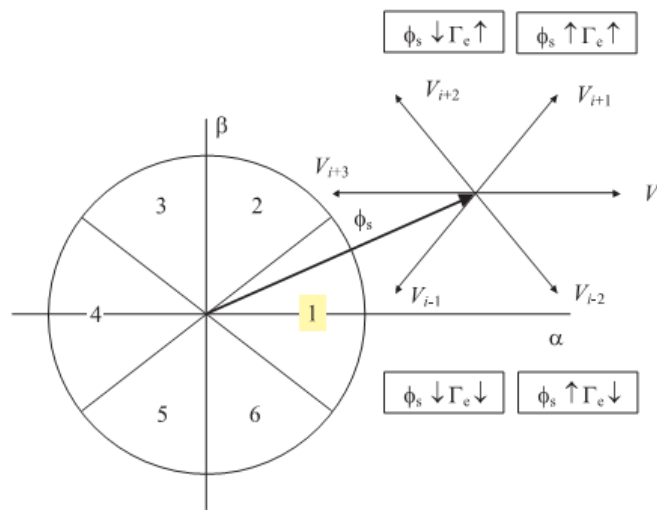
**Table1. Classical DTC switching table**

Flux $\Delta\phi$	Torque $\Delta\Gamma_e$	Sector $S_\phi$					
		$S_{\phi 1}$	$S_{\phi 2}$	$S_{\phi 3}$	$S_{\phi 4}$	$S_{\phi 5}$	$S_{\phi 6}$
1	1	$V_2$	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$
1	0	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$
1	-1	$V_3$	$V_1$	$V_2$	$V_3$	$V_4$	$V_5$
-1	1	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$	$V_2$
-1	0	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$
-1	-1	$V_5$	$V_6$	$V_1$	$V_2$	$V_3$	$V_4$

Figure 2 shows the voltage vectors which are usually employed in DTC scheme when the stator flux vector is laying in sector I. The selection of a voltage vector at each cycle period is made in order to maintain the torque and the stator flux within the limits of two hysteresis bands [10]. This simple approach allows a quick torque response to be achieved, but the steady state performance is characterized by undesirable ripple in current, flux and torque. This behavior is mainly due to the absence of information about torque and rotor speed values in the voltage selection algorithm.



**Fig.1. Block Diagram of the Induction Motor Drive System Based On DTC Scheme**



**Fig.2. Stator flux Variation (Φs Is In Section 1)**

### 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. 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 [11].

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 [11].

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. In torque hysteresis controller, an elapsing time to move from lower to upper limit, and vice versa can be changed according to operating condition [12].

Most of these methods are computationally intensive. This goal is achieved by the fuzzy controller which determinates the desired amplitude of torque hysteresis band.

#### IV. MINIMIZATION OF TORQUE RIPPLE

In the stationary stator coordinate system, the asynchronous motor electromagnetic torque (1) can be generated:

$$T_e = \frac{3}{2} n_p (i_{s\beta} \psi_{s\alpha} - i_{s\alpha} \psi_{s\beta}) \quad (1)$$

According to motor model, stator flux vector is expressed as:

$$\psi_{s\alpha} = \int (u_{s\alpha} - i_{s\alpha} R_s) dt$$

$$\psi_{s\beta} = \int (u_{s\beta} - i_{s\beta} R_s) dt$$

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2}$$

Where  $\psi_s$  the amplitude of stator flux,  $n_p$  is the number of motor pole pairs,  $R_s$  is the stator resistance,  $\psi_{s\alpha}$ ,  $\psi_{s\beta}$ ,  $u_{s\alpha}$ ,  $u_{s\beta}$ ,  $i_{s\alpha}$ ,  $i_{s\beta}$  are corresponding stator flux, stator voltage, and stator current value in the  $\alpha\beta$  coordinate system.

The dynamic compensation torque is defined as follow:

$$M = J \frac{d\hat{\omega}_r}{dt} = T_e - T_{load} \quad (2)$$

Where  $T_e$  is the motor torque,  $J$  is the transient inertia of the system;  $T_{load}$  is the torque load. The speed error signal can be expressed as  $e = \hat{\omega}_r - \omega_{ref}$ . From (1) and (2), we can get (3):

$$J \frac{d(\omega_{ref} + e)}{dt} = T_e - T_{load} \quad (3)$$

A constant speed reference signal can be expressed using the following expression:

$$\frac{d\omega_{ref}}{dt} = 0$$

If the load is constant, then it can be seen that the rate of change of speed error is closely related with the motor torque from (3).

Thus, the (3) can be reduced to:

$$\frac{de}{dt} = \frac{T_e - T_{load}}{J} \quad (4)$$

The conclusion can be drawn from the (4) that the rate of change in the speed error signal is indeed a good indicator to assess the

motor torque ripple.

## V. SPEED IDENTIFIER

For the speed sensor less DTC system, speed of observation is an important part. Based on the rotor flux error between the voltage model and the current model, the Parameter of speed can be identified by using the Model reference adaptive controller (MRAC) structure and the closed-loop feedback control theory.

It can be got from the mathematical equations of induction motor that the rotor flux has nothing to do with the rotor angular velocity in voltage model, and the rotor flux of current model is related to the rotor rotation angular velocity in the  $\alpha\beta$  coordinates. Based on inverse transformation principles in feedback model, the model reference adaptive controller about the rotor flux can be constructed by using of the voltage model and current model. The rotor speed  $\hat{\omega}_r$  can be identified through flux errors proportional-integral and feedback control in MRAC. The identifier structure was shown in Fig.3

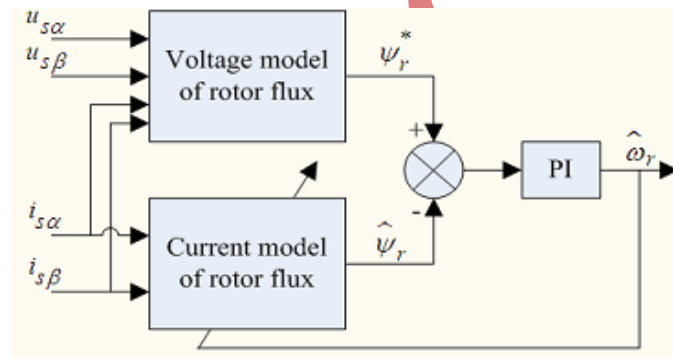


Fig.3. MRAC Speed Identifier

In Fig.3, the rotor flux reference value  $\psi_r^*$  can be acquired from the rotor flux-voltage reference model in the  $\alpha\beta$  coordinate system. The calculation process is indicated in the (5). The rotor flux estimate value  $\hat{\psi}_r$  can be acquired from the rotor flux-current adjustable model in the  $\alpha\beta$  coordinate system. The calculation process is indicated in the (6). Current model is placed on feedback channel. The rotation angular velocity can be identified by the closed loop control method for rotor flux.

$$\psi_{r\alpha}^* = \frac{L_r}{L_m} \left[ \int (u_{s\alpha} - i_{s\alpha} R_s) dt - \left( L_s - \frac{L_m^2}{L_r} \right) i_{s\alpha} \right]$$

$$\psi_{r\beta}^* = \frac{L_r}{L_m} \left[ \int (u_{s\beta} - i_{s\beta} R_s) dt - \left( L_s - \frac{L_m^2}{L_r} \right) i_{s\beta} \right]$$

$$\omega_r^* = \sqrt{(\psi_{r\alpha}^*)^2 + (\psi_{r\beta}^*)^2} \quad (5)$$

$$\hat{\psi}_{r\alpha} = \frac{1}{T_r p + 1} (L_m i_{s\alpha} - \omega_r T_r \hat{\psi}_{r\beta})$$

$$\hat{\psi}_{r\beta} = \frac{1}{T_r p + 1} (L_m i_{s\beta} - \omega_r T_r \psi_{r\alpha})$$

$$\hat{\psi}_r = \sqrt{(\psi_{r\alpha}^2) + (\psi_{r\beta}^2)} \quad (6)$$

### VI. TORQUE RIPPLE REDUCTION USING FUZZY CONTROLLER

The amplitude of torque hysteresis is not fixed. But according to the level of torque ripple, the magnitude of torque hysteresis can be adjusted by the fuzzy controller. The two inputs of the fuzzy controller are the speed error  $e_1$  and the stator current error  $e_2$ . They are decided by the following equations.

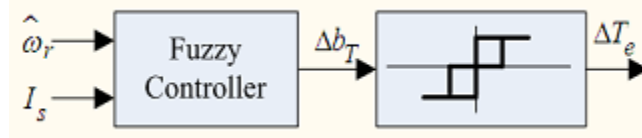


Fig.4. Torque Hysteresis Controller

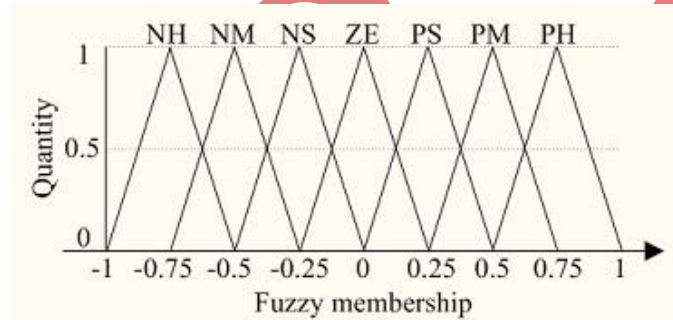


Fig.5. Input and Output Membership Function

Table2. Fuzzy Rules of Torque Hysteresis Controller

$\Delta b_T$		$e_2$						
		NH	NM	NS	ZE	PS	PM	PH
$e_1$	NH	NH	NH	NH	NH	NM	ZE	ZE
	NM	NH	NH	NH	NH	NM	ZE	ZE
	NS	NM	NM	NS	ZS	ZE	PS	PM
	ZE	NM	NM	NS	ZE	PS	PM	PM
	PS	NS	NS	ZE	PS	PS	PM	PM
	PM	ZE	ZE	PM	PH	PH	PH	PH
	PH	ZE	ZE	PM	PH	PH	PH	PH

PH: positive high; PM: positive median; PS: positive small; ZE: zero;  
 NH: negative high; NM: negative median; NS: negative small;

**Table3. Induction Motor Rated Parameter**

Parameters	Rating
Rated Power	1.5 kW
Rated Speed	1400 rpm
Pole pairs	2
Stator resistance	2.00 ohm
Rotor resistance	2.25 ohm
Stator Inductance	0.555 h
Rotor inductance	0.555 h
Mutual inductance	0.555 h
Inertia	0.025 kg.m <sup>2</sup>
Sampling time	3E-6

$$e_1(k) = \hat{\omega}(k) - \hat{\omega}(k-1) \quad (7)$$

$$e_2(k) = I_s(k) - I_s(k-1) \quad (8)$$

Where the stator current  $I_s$  can be represented as

$$I_s = \sqrt{I_{cs}^2 + I_{fs}^2}$$

The increment of the torque hysteresis amplitude can be output by the fuzzy controller. Then the required torque hysteresis amplitude can be got by (9). Finally, the torque ripple  $\Delta T$  can be suppressed.

$$b_T(k+1) = b_T(k) + \Delta b_T(k) \quad (9)$$

If setting the amplitude  $b_T$  too small, the overshoot may touch the upper boundary. Reverse voltage vector may be selected. Corresponding, the reverse voltage vector will rapidly reduce the torque. The torque ripple will be stubbornly high too.

Based on experience and simulation, the fuzzy controller is designed. For different motor speed and current values, appropriate torque hysteresis boundary can be selected in order to reduce torque and flux pulsation. The specific modus operandi of the fuzzy controller can be carried out in accordance with Table 2. The membership functions of the input  $e_1(k)$ ,  $e_2(k)$  and output  $\Delta b_T(k)$  were all chosen in the form of isosceles triangle, as shown in Fig. 5.

The semantic rules can be expressed by the following examples:

If  $e_1$  is NH or NM, and  $e_2$  is NH, then  $\Delta b_T$  is NH: this situation corresponds to the torque error has a large overshoot. To reduce the torque error, the value  $\Delta b_T$  should be significant reduced.

## VII. SIMULATION RESULTS AND ITS ANALYSIS

In this paper, the simulation about the DTC system containing the fuzzy controller was executed by using MATLAB, and the simulation results has been compared with the general DTC system. The simulation model works in low-speed (12 rd/s) status. Load torque is 18N/m. Other parameters were shown in table 3.

Since the fuzzy controller can provide suitable amplitude according to system operation station, the torque ripple was

significantly reduced as shown in Fig. 6. And the pulsation of the flux track was substantially reduced as shown in Fig. 7 when using fuzzy controller in DTC system. Fig. 8 shown that when the speed was given suddenly from 15 r/min into 100 r/min, the speed amplitude vary widely. However, the instantaneous steady state can be achieved, stability is good and fluctuation is very small. And the speed is faster than that of the traditional DTC. In point of time 5.25s, the speed was given suddenly from 100 r/min into 50 r/min. The DCT with fuzzy controller also showed better performance.

Fig.9 is the experimental trajectory of stator flux. It was drawn from the results of simulation and experiment that the DTC system with the fuzzy controller is superior to general DTC system in steady-state performance.

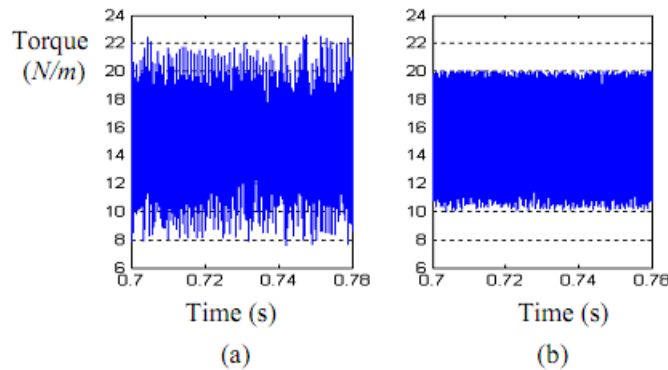


Fig.6. The waveform of torque ripple (a) in traditional DTC system (b) in the DTC system with the fuzzy controller

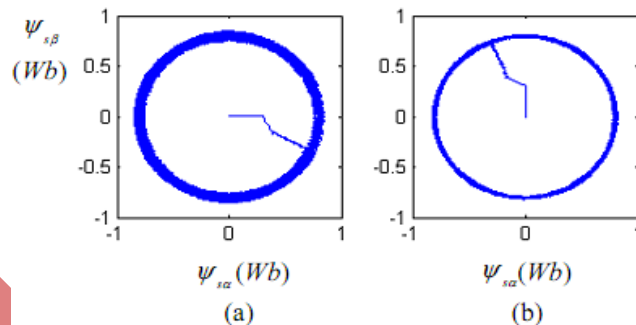


Fig.7. The simulation trajectory of stator flux (a) in traditional DTC system (b) in the DTC system with the fuzzy controller

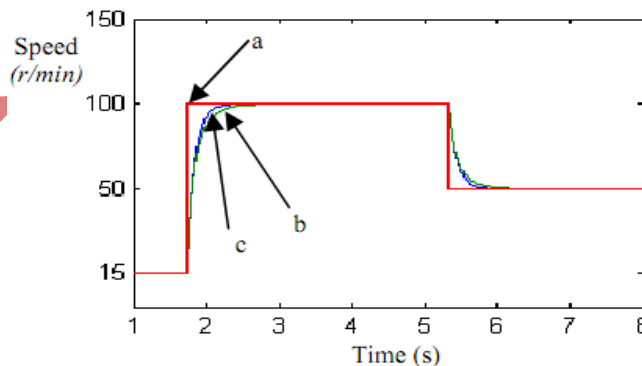
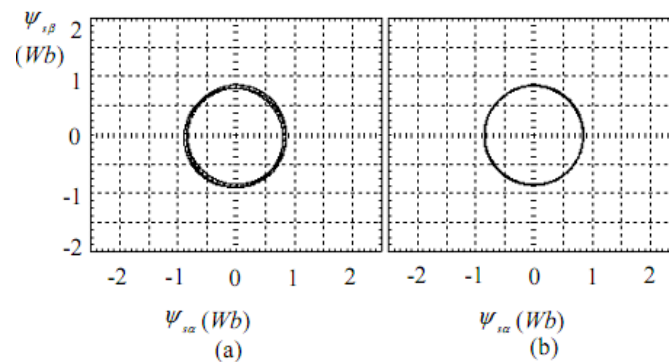


Fig.8. The waveform of speed (a) given speed (b) in traditional DTC system (c) in DTC system with the fuzzy controller



**Fig.9. The experimental trajectory of stator flux (a) in traditional DTC system (b) in DTC system with the fuzzy controller**

## VIII. CONCLUSION

DTC strategies are simple and efficient control strategies to the motor drive system. However some drawbacks associated to the high torque ripple are present in this type of control techniques. In this paper, a novel method of reducing torque ripple has been put forward by analyzing the reasons of torque ripple. It is the main character of the method that the fuzzy logic controller combines with the DTC. The speed error signal and the rate of change of current signal are the input of the fuzzy logic controller. The torque hysteresis amplitude increment is the output of the fuzzy logic controller. The controller can dynamically adjust the torque hysteresis amplitude. The simulation results show that the method can effectively improve the shortcoming that the ripple of torque in the conventional DTC system. The method provides an effective scheme for reducing motor torque ripple and noise in the low-speed operating conditions.

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