Construct a Fuzzy Rule Table with the Direct Torque Control Principle

Nguyen Hoang Viet and Pham Duc Dai

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Nguyen Hoang Viet
Faculty of Electrical and Electronics Engineering
Thuyloi University
Hanoi, Vietnam
viethn@tlu.edu.vn

Pham Duc Dai
Faculty of Electrical and Electronics Engineering
Thuyloi University
Hanoi, Vietnam
daipd@tlu.edu.vn

***Abstract*— Direct torque control (DTC) is one of the popular induction motor control structures in the industry. This control structure is simple, flexible, and high performance. However, large torque ripple and poor performance in low speed regions are disadvantages of this structure. Therefore, overcoming these disadvantages of the DTC structure is always an issue of concern in the field of motor control.**

In order to address the drawbacks of the conventional DTC structure, this paper investigates the DTC structure employing a fuzzy controller (FDTC). The fuzzy controller in this structure will replace the stator flux controller, torque controller, and switching table in the classic DTC structure. The paper proposes fuzzy rules are built based on the principle of direct torque control and are derived from the DTC table in 12 sectors. This ensures the stability and robustness of the FDTC control structure. Simulation results on Matlab/Simulink show that the fuzzy rules suggested in this paper, when combined with the FDTC structure, perform exceptionally well and the torque ripple and stator flux ripple are significantly reduced compared to the traditional DTC structure. Furthermore, even at low speeds, FDTC has a strong dynamic responsiveness.

Keywords— ***Direct torque control, Fuzzy control, Torque ripple, Flux stator ripple***

I. Introduction

After it was first introduced in 1986, the direct torque control principle gained traction and became a key concept in the field of induction motor control [1], [2]. By using this principle, the stator flux and electromagnetic torque can be controlled independently through direct selection of the inverter's output voltage vector. Based on this idea, a direct torque control (DTC) structure with excellent performance has been developed. However, this structure's drawbacks include a significant torque ripple and poor performance in low speed areas. In this scenario, the DTC structure's drawbacks can be addressed by using a fuzzy controller. Direct torque control and fuzzy controller topologies have been discussed in the literature [3] – [7]. A fuzzy controller was utilized in place of the stator flux controller, torque controller, and switching table in a traditional DTC structure. Simulation results show that the dynamic response of the control system is improved. The PI speed controller can also be replaced by a fuzzy controller to improve torque ripple and maintain good performance at low speed ranges [8].

The most important part of the fuzzy controller in the FDTC structure is the fuzzy rule table which plays an important role in improving the performance and stability of the system. The construction of fuzzy rules with different numbers of membership functions and different numbers of fuzzy rules has not been specifically analyzed and is still largely based on experience. This paper presents a method for constructing an FDTC structure based on the direct torque control concept. Fuzzy rule tables are constructed from DTC tables in 12 sectors. This ensures the stability and robustness of the FDTC structure equivalent to the traditional DTC structure. Additionally, the author suggests using twelve fuzzy subsets to determine the fuzzy stator flux vector position variable, five fuzzy subsets to determine the fuzzy torque error variable, and five fuzzy subsets to determine the fuzzy torque error variable. This quantity of fuzzy subsets for fuzzy variables will guarantee the FDTC structure performs well. Simulation results show that the FDTC structure using these fuzzy rule tables still has good performance like the DTC structure while the torque ripple and stator flux ripple are reduced, good performance in the low speed region is still guaranteed.

II. The Direct Torque Control Principle and Vector Table in 12 Sector

The principle of direct torque control is derived from the electromagnetic torque equation and stator voltage equation of the induction motor (IM) model [1]. From this principle, the vector cases that increase and decrease the stator torque and flux in 12 sectors are established and it is the premise to build a fuzzy logic set according to the DTC principle.

A. *The Direct Torque Control Principle*

From the electromagnetic torque equation (1), the concept of direct torque control is developed [1], [2].

$$T_e = \frac{3}{2} p_b \frac{L_M}{L_r L_s - L_M^2} \psi_s \psi_r \approx K \psi_s \psi_r \delta \tag{1}$$

The rotor flux vector typically rotates at a slower speed than the stator flux vector. Consequently, the rotor flux can be regarded as constant while the stator flux varies over a small sampling cycle. From expression (1), to control the electromagnetic torque, a simple solution is to keep the stator flux constant and adjust the angle δ, which is the angle between the stator flux vector and the rotor flux vector. Therefore, the two issues that make up the concept of direct torque control are controlling the angle δ of the stator flux vector and maintaining the stator flux vector modulus at a fixed value. Note that angle δ control is also electromagnetic torque control.

If the stator resistance is ignored, the stator voltage equation [2] is given in equation (2).

$$\boldsymbol{u_s} = \frac{d\boldsymbol{\psi_s}}{dt} \tag{2}$$

Application of the Euler approximation technique to equation (2).

$$\boldsymbol{\psi_{sk+1}} = \boldsymbol{\psi_{sk}} + \boldsymbol{u_{sk}} T_s \tag{3}$$

Where $\boldsymbol{\psi}_{sk+1}$, $\boldsymbol{\psi}_{sk}$ are the stator flux vector at time *k+1* and time *k*, $\boldsymbol{u}_{sk}$ is the stator voltage at time *k* and T_s is the sampling cycle.

Equation (3) can be expressed as a sum of two vectors as shown in Fig.1.

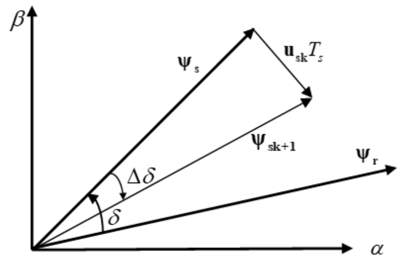

Fig. 1. The relationship between vector stator voltage and vector stator flux

Based on Fig.1, the following four significant rules may be made:

- The angle between the stator voltage vector and the stator flux vector must be larger than 90 degrees to increase the modulus of the stator flux vector.
- The angle between the stator voltage vector and the stator flux vector must be less than 90 degrees to reduce the modulus of the stator flux vector.
- The stator voltage vector has a phase sooner than the stator flux vector to increase torque.
- The stator voltage vector has a phase later than the stator flux vector to decrease torque.

The above four rules are derived from the direct torque control principle and are the basis for building the switching table in the DTC structure.

B. The DTC Table in 12 Sector

In this paper, a voltage source inverter (VSI) is used to control the IM motor. The VSI inverter generates eight vectors including six active vectors $(\boldsymbol{v_1}, \dots, \boldsymbol{v_6})$ and two zero vectors $(\boldsymbol{v_0}, \boldsymbol{v_7})$.

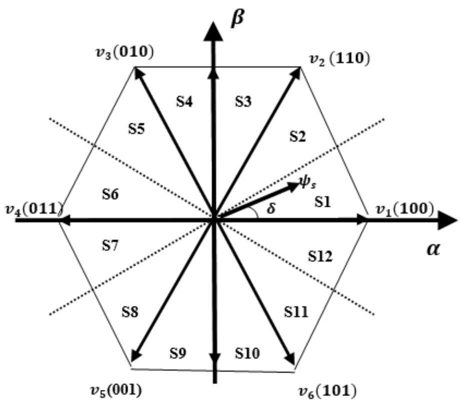

Fig. 2. The 12 sector in the coordinate system (αβ)

The positions of six active vectors and 12 sectors from S_1 to S_{12} on the coordinate plane (αβ) are described in Figure 2.

Table I provides the DTC table in the 12 sectors [2] that illustrates how the VSI inverter's output vectors change stator torque and flux using the four rules mentioned in the previous section.

TABLE I. THE DTC TABLE IN 12 SECTOR

	$\boldsymbol{\psi_s} \downarrow$		$\boldsymbol{\psi_s} \uparrow$	
	$T_e \uparrow$	$T_e \downarrow$	$T_e \uparrow$	$T_e \downarrow$
S1	$\boldsymbol{v_2}$	$\boldsymbol{v_1, v_6}$	$\boldsymbol{v_3, v_4}$	$\boldsymbol{v_5}$
S2	$\boldsymbol{v_2, v_3}$	$\boldsymbol{v_1}$	$\boldsymbol{v_4}$	$\boldsymbol{v_5, v_6}$
S3	$\boldsymbol{v_3}$	$\boldsymbol{v_2, v_1}$	$\boldsymbol{v_4, v_5}$	$\boldsymbol{v_6}$
S4	$\boldsymbol{v_3, v_4}$	$\boldsymbol{v_2}$	$\boldsymbol{v_5}$	$\boldsymbol{v_1, v_6}$
S5	$\boldsymbol{v_4}$	$\boldsymbol{v_2, v_3}$	$\boldsymbol{v_5, v_6}$	$\boldsymbol{v_1}$
S6	$\boldsymbol{v_4, v_5}$	$\boldsymbol{v_3}$	$\boldsymbol{v_6}$	$\boldsymbol{v_2, v_1}$
S7	$\boldsymbol{v_5}$	$\boldsymbol{v_3, v_4}$	$\boldsymbol{v_1, v_6}$	$\boldsymbol{v_2}$
S8	$\boldsymbol{v_5, v_6}$	$\boldsymbol{v_4}$	$\boldsymbol{v_1}$	$\boldsymbol{v_2, v_3}$
S9	$\boldsymbol{v_6}$	$\boldsymbol{v_4, v_5}$	$\boldsymbol{v_2, v_1}$	$\boldsymbol{v_3}$
S10	$\boldsymbol{v_1, v_6}$	$\boldsymbol{v_5}$	$\boldsymbol{v_2}$	$\boldsymbol{v_3, v_4}$
S11	$\boldsymbol{v_1}$	$\boldsymbol{v_5, v_6}$	$\boldsymbol{v_2, v_3}$	$\boldsymbol{v_4}$
S12	$\boldsymbol{v_2, v_1}$	$\boldsymbol{v_6}$	$\boldsymbol{v_3}$	$\boldsymbol{v_4, v_5}$

In Sector 1, four cases of electromagnetic torque and stator flux control are considered.

- Vector $\boldsymbol{v_2}$ is chosen to raise electromagnetic torque and decrease stator flux.
- Vectors $\boldsymbol{v_1}$ and $\boldsymbol{v_6}$ are chosen to decrease electromagnetic torque and decrease stator flux.
- Vectors $\boldsymbol{v_3}$ and $\boldsymbol{v_4}$ are chosen to raise electromagnetic torque and stator flux.
- Vectors $\boldsymbol{v_5}$ are chosen to decrease electromagnetic torque and raise stator flux.

The remaining cases can be deduced similarly. This switching table is the basis for forming fuzzy rules in the next section.

III. THE DIRECT TORQUE CONTROL AND FUZZY LOGIC CONTROLLER STRUCTURE

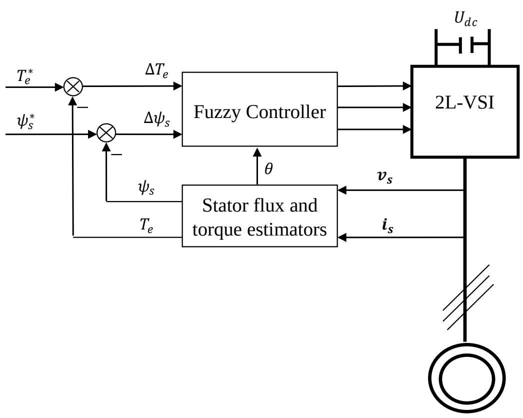

Fig. 3. The Fuzzy controller – DTC (FDTC) structure

The direct torque control and fuzzy logic structure are depicted in Fig.3. The switching table and hysteresis controllers in the DTC structure are replaced by a fuzzy logic controller. The fuzzy controller includes three inputs: torque error, stator flux error, and stator flux vector position. The voltage vector corresponding to the switching state used to control the VSI inverter is the fuzzy logic controller's output.

The speed controller can use a PI controller like the DTC structure. The torque estimation and stator flux estimation algorithms are used the same as in the DTC structure.

A. Fuzzification of Input and Output Fuzzy Variables

The three inputs of the fuzzy controller are defined as follows.

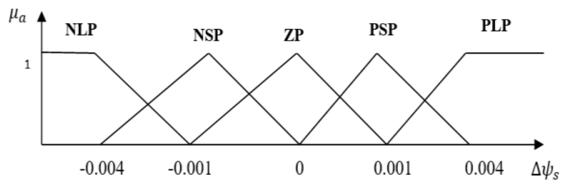

Fig. 4. The membership function of $\Delta\psi_s$

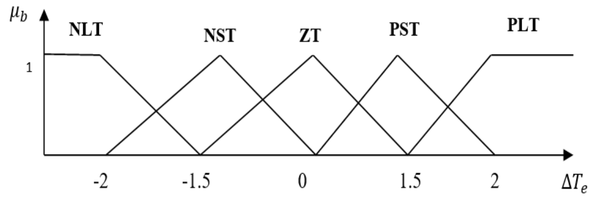

Fig. 5. The membership function of ΔT_e

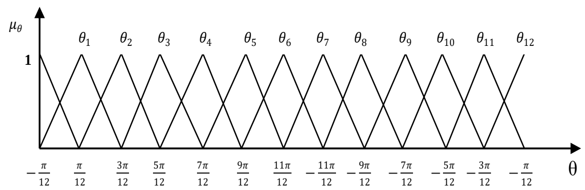

Fig. 6. The membership function of θ

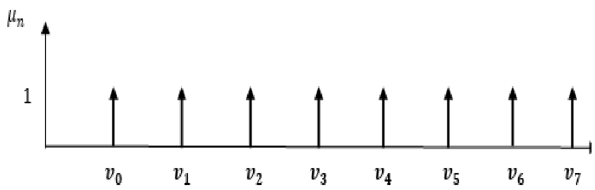

Fig. 7. The membership function of v_{out}

- The stator flux error,

$$\Delta\psi_s = \psi_s^* - \psi_s \tag{4}$$

The fuzzy stator flux error variable uses five fuzzy subsets NLP (negative large error), NSP (negative small error), ZP (zero error), PSP (positive small error), and PLP (positive large error).

- The torque error,

$$\Delta T_e = T_e^* - T_e \tag{5}$$

The fuzzy torque error variable uses five fuzzy subsets (negative large error), NST (negative small error), ZT (zero error), PST (positive small error), and PLT (positive large error).

- The stator flux vector position is expressed through an angle θ,

$$\theta = arctan\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right) \tag{6}$$

The fuzzy angle variables use 12 fuzzy subsets as θ_i, *i=1,...,12*.

The output of the fuzzy controller is the voltage vector of the VSI inverter, v_{out}. The fuzzy output variables use 8 fuzzy subsets $\boldsymbol{v_n}$, *n=0,...,7*.

The membership distribution of fuzzy variables is given in Fig. 4 to Fig. 7.

B. Fuzzy Rules for Direct Torque Control

Each fuzzy rule used in the fuzzy controller has the following general form.

***R**m: IF* $\Delta\psi_s$ *is* a_m, ΔT_e *is* b_m, θ *is* θ_i *THEN* $\boldsymbol{v_{out}}$ *is* $\boldsymbol{v_n}$

Where $a_m = \{NLP, NSP, ZP, PSP, PLP\}$, $b_m = \{NLT, NST, ZT, PST, PLT\}$, θ_i and $\boldsymbol{v_n}$ represent fuzzy subsets.

There are a few principles that must be followed to create a fuzzy rule table from a general fuzzy rule.

- If the stator flux error is NSP or NLP, the stator flux must be reduced.
- If the stator flux error is PSP or PLP, the stator flux must be increased.
- If the stator flux error is ZP, the stator flux is kept constant.
- If the torque error is NST or NLT, the torque must be reduced.
- If the torque error is PST or PLT, the torque must be increased.
- If the torque error is ZT, the torque is kept constant.

From the rules given above combined with Table I, the fuzzy rule tables with fuzzy sets θ_1 and θ_2 are established as in Table II and Table III. The selection of vectors $\boldsymbol{v_1}$ and $\boldsymbol{v_6}$ reduces the torque and stator flux when the stator flux vector is in sector S1. But compared to vector $\boldsymbol{v_1}$, vector $\boldsymbol{v_6}$ significantly lowers torque. The remaining cases are analyzed similarly. The numbers in the fuzzy rule table are the index *n* of $\boldsymbol{v_n}$.

TABLE II. THE FUZZY RULE TABLE WITH FUZZY SUBSET θ_1

	NLP	NSP	ZP	PSP	PLP
NLT	5	5	5	6	6
NST	5	5	1	1	1
ZT	0	0	0	0	0
PST	3	3	3	2	2
PLT	4	4	4	2	2

TABLE III. THE FUZZY RULE TABLE WITH FUZZY SUBSET θ_2

	NLP	NSP	ZP	PSP	PLP
NLT	5	5	5	1	1
NST	6	6	6	1	1
ZT	7	7	7	7	7
PST	4	4	2	2	2
PLT	4	4	4	3	3

By similar analysis, the fuzzy rule tables in the remaining sectors corresponding to θ_i have the general form given in Table IV.

TABLE IV. THE FUZZY RULE TABLE WITH FUZZY SUBSET θ_i

	NLP	NSP	ZP	PSP	PLP
NLT	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
NST	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}
ZT	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}
PST	a_{41}	a_{42}	a_{43}	a_{44}	a_{45}
PLT	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}

If the angle θ_i with i is an odd number, the elements in the general fuzzy rule table are calculated according to equations (7) to (20).

$$a_{11} = a_{12} = a_{13} = a_{21} = a_{22} = Mod(4 + j, 6) \quad (7)$$
$$a_{14} = a_{15} = Mod(5 + j, 6) \quad (8)$$
$$a_{23} = a_{24} = a_{25} = Mod(6 + j, 1) \quad (9)$$
$$a_{31} = a_{32} = a_{33} = a_{34} = a_{35} = 0 \quad (10)$$
$$a_{41} = a_{42} = a_{43} = Mod(2 + j, 6) \quad (11)$$
$$a_{44} = a_{45} = a_{54} = a_{55} = Mod(1 + j, 6) \quad (12)$$
$$a_{51} = a_{52} = a_{53} = Mod(3 + j, 6) \quad (13)$$

Where $j = Div(i, 2) + 1$

If the angle θ_i with i is an even number, the elements in the general fuzzy rule table are given as follows.

$$a_{11} = a_{12} = a_{13} = Mod(4 + k, 6) \quad (14)$$
$$a_{14} = a_{15} = a_{24} = a_{25} = Mod(6 + k, 6) \quad (15)$$
$$a_{21} = a_{22} = a_{23} = Mod(5 + k, 6) \quad (16)$$
$$a_{31} = a_{32} = a_{33} = a_{34} = a_{35} = 7 \quad (17)$$
$$a_{41} = a_{42} = a_{51} = a_{52} = a_{53} = Mod(3 + k, 6) \quad (18)$$
$$a_{43} = a_{44} = a_{45} = Mod(1 + k, 6) \quad (19)$$
$$a_{54} = a_{55} = Mod(2 + k, 6) \quad (20)$$

Where $k = Div(i, 2)$

When fuzzy rules are written in the form of a general fuzzy rule table, programming is easier to do. Twelve fuzzy rule tables are used to create a total of 400 fuzzy rules.

The fuzzy rule tables in this paper are established similarly to the switching tables in the classic DTC structure. Therefore, the FDTC structure has the stability and durability of the classic DTC structure.

C. *Fuzzy interface*

Madani's Max-Min method is the fuzzy interface utilized in this paper.

$$\alpha_m = Min\{\mu_{a_m}(\Delta\psi_s), \mu_{b_m}(\Delta T_e), \mu_{\theta_i}(\theta)\} \quad (21)$$

The m^{th} fuzzy rule

$$\mu_{R_m} = Min\{\alpha_m, \mu_n(\boldsymbol{v_n})\} \quad (22)$$

The output membership function is given as follows.

$$\mu_n(\boldsymbol{v_{out}}) = \max_{1 \le m \le 400}(\mu_{R_m}) \quad (23)$$

The inverter will be controlled by the voltage vector associated with the membership function with the highest value.

IV. SIMULATION RESULTS

The simulation results of the two structures, DTC and FDTC, in two scenarios, at high speed, and at low speed, will be compared in this section. The induction motor used in the simulation has the parameters given in Table V. The sampling time is selected as $T_s = 10\mu s$.

TABLE V. THE PARAMETER OF INDUCTION MOTOR

Parameters	Symbol	Value
Rated power (kW)	P_n	2.2
Rated speed (rpm)	n_n	1450
Number of pole pairs	p	2
Moment of inertia (kgm^2)	J	0.01
Stator resistance (Ω)	R_s	3.32
Rotor resistance (Ω)	R_r	2.11
Stator inductance (H)	L_s	0.24169
Rotor inductance (H)	L_r	0.24169
Mutual inductance (H)	L_M	0.2373

A. *Induction Motor Runs at High Speed*

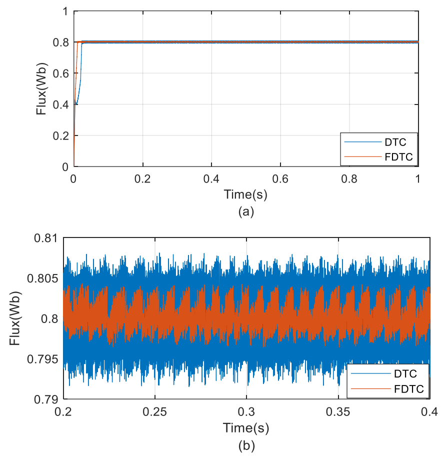

Fig. 8. a) The stator flux response of DTC and FDTC structures at 600 rpm, b) The stator flux ripple of DTC and FDTC structures at 600 rpm

In this scenario, the stator flux reference is set at 0.8Wb. At first, the induction motor operates without any load until 0.7(s) then it starts to operate with a 9Nm load. The reference value of speed is set at 600rpm.

The blue and red lines in the simulation results represent the torque and flux responses of the DTC and FDTC structures, respectively.

Fig. 8(a) and Fig. 9(a) are the stator flux and torque responses of the two structures DTC and FDTC at 600rpm. The simulation results indicate that while the stator flux response of the FDTC structure is faster than that of the DTC structure, the torque response of the two structures, DTC and FDTC, is the same. Furthermore, the FDTC structure's torque ripple and stator flux ripple are less than those of the traditional DTC structure. These findings demonstrate that the FDTC structure outperforms the DTC structure.

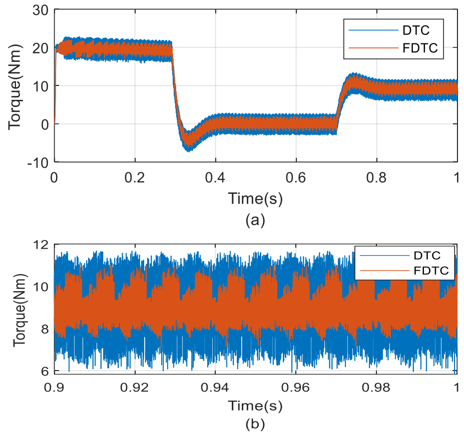

Fig. 9. a) The torque response of DTC and DTC structures at 600 rpm, b) The torque ripple of DTC and DTC structures at 600 rpm

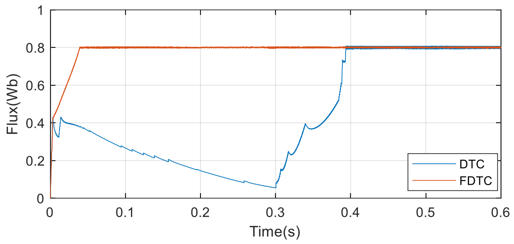

Fig.10. The stator flux response of DTC and FDTC structures at 20 rpm

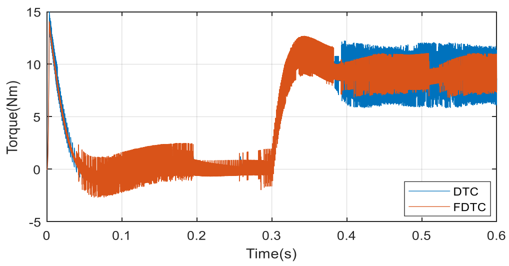

Fig.11. The torque response of DTC and FDTC structures at 20 rpm

B. Induction Motor Runs at Low Speed

In this scenario, the motor is considered to operate at 20rpm, the initial load torque is maintained at 0Nm, and at 0.2s the load torque increases to 5Nm. The stator flux still has a reference value of 0.8Wb.

Figures 10 and 11 show the simulation results at a low speed of 20 rpm. At this speed, the DTC control structure cannot adjust the flux when the motor is in the no-load mode but the FDTC structure still maintains good performance. The superiority of using the fuzzy rules developed in this research on the FDTC structure is further demonstrated by these results.

V. Conclusions

The paper applies fuzzy control techniques to the DTC structure to control induction motors with a fuzzy rule table built on the direct torque control principle. These fuzzy rules ensure the stability of the motor control system because the vectors used always satisfy the direct torque control principle. The FDTC structure performs significantly better than the conventional DTC structure, according to simulation findings, thanks to the fuzzy principles defined in this study. The FDTC structure has a superior flux response compared to the DTC structure. The FDTC structure's torque ripple and magnetic flux ripple are both smaller than the DTC structure's. In the low speed region, the FDTC structure retains good performance even when the induction motor is running at no load.

This study's fuzzy rules can be simply extended to motor control systems that use multi-level inverters with a high number of output voltage vectors. However, the computational burden of the fuzzy controller will increase significantly, limiting the applicability of this structure.

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