Direct Torque Control of Induction Drive Using Fuzzy Controller

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Abstract—**In this study the direct torque control of the induction drive with a fuzzy controller was investigated. The objective of this research was the reduction of the stator current and electromagnetic torque pulsations. The principles of the fuzzy controller development for the induction drive with a direct torque control and the obtained computer model were presented, and the simulation results were compared to the results of the induction drive under the traditional direct torque control. The implementation of the applied fuzzy controller allowed us to achieve the pulsations of the torque twice lower, the stator current, flux and the maximum overshoots were lowered.**

Index Terms—**Variable speed drives, induction motors, direct torque control, fuzzy control.**

I. INTRODUCTION

The method of the direct torque control (DTC) was introduced in 1986. The advantages of this method are concerned with a very fast and accurate response to the torque control signal and the available comparative simplicity of the control algorithm with a few input variables such as motor torque, flux magnitude and flux sector [1].

DTC for induction machines (IM) simplify the overall drive technology, because the controller is directly connected to the drive circuitry of the switches, which eliminates the modulator [2], [3]. Provided the torque and flux controllers produce good results, DTC is rather robust to the motor parameters and external disturbances. The other advantage of DTC based controllers is the possibility to avoid the coordinate transformation in calculations, and eliminate current regulation and voltage modulation blocks in the controller. The established disadvantages of DTC are highlighted at the start-up and in low speed region or the high ripple and slow response to the saltatory torque changes [2]–[4]. To improve the performance the fuzzy logics is successfully implemented in various control systems and the electric drive control [5], therefore there arises the necessity for testing it in DTC.

II. DIRECT TORQUE CONTROL

The structural scheme of the basic functional blocks used

for the implementation of the direct torque fuzzy control (DTFC) of the induction motor drive is presented in Fig. 1. The motor is powered from the voltage source inverter (VSI), and the inverter switching mode selection (the fuzzy controller output signals S_A, S_B, S_C in Fig. 1) can be used for the stator flux and electromagnetic torque direct control.
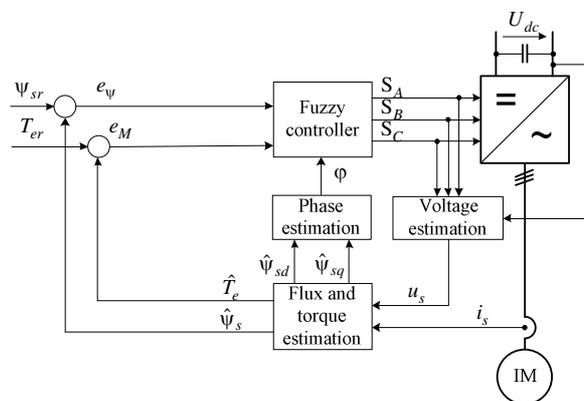

Fig. 1. DTFC scheme for induction motor drives.

The output voltage vector of the pulse width modulated voltage source inverters can be expressed by (1)

$$U_s = \sqrt{\frac{2}{3}} U_0 \left(C_1 + C_2 e^{j\frac{2\pi}{3}} + C_3 e^{j\frac{4\pi}{3}} \right), \qquad (1)$$

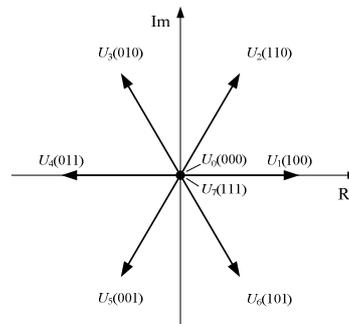where C_1, C_2, C_3 are Boolean functions of the inverter switching state.

Fig. 2. Voltage space vectors generated by three-phase inverter.

There are obtained 8 switching combinations, 2 zero voltage vectors and 6 non-zero voltage vectors [4], [6] as

shown in Fig. 2.

The information in terms of the electromagnetic torque and stator flux is derived from the measured stator currents and phase voltages.

The Park's transformation is applied as in (2), (3):

$$\begin{cases} i_{sd} = \dfrac{2}{3} i_A - \dfrac{1}{3} i_B - \dfrac{1}{3} i_C, \\ i_{sq} = -\dfrac{1}{\sqrt{3}} i_B + \dfrac{1}{\sqrt{3}} i_C, \end{cases} \quad (2)$$

$$\begin{cases} u_d = \dfrac{2}{3} u_A - \dfrac{1}{3} u_B - \dfrac{1}{3} u_C, \\ u_q = -\dfrac{1}{\sqrt{3}} u_B + \dfrac{1}{\sqrt{3}} u_C, \end{cases} \quad (3)$$

where i_{sd} – stator current in d axis, i_{sq} – stator current in q axis, u_{sd} – stator voltage in d axis, u_{sq} – stator voltage in q axis.

The only parameter of the motor required in the DTC algorithm is the stator resistance R_s the accurate knowledge of which is crucial for high performance low-speed operation of the drive [6].

The components of the stator flux are calculated:

$$\begin{cases} \hat{\psi}_{sd} = \int (u_{sd} - R_s \cdot i_{sd}) dt; \\ \hat{\psi}_{sq} = \int (u_{sq} - R_s \cdot i_{sq}) dt. \end{cases} \quad (4)$$

The magnitude and phase of the stator flux vector are given by:

$$\hat{\psi}_s = \sqrt{\psi_{sd}^2 + \psi_{sq}^2}, \quad (5)$$

$$\varphi = \tan^{-1} \left(\frac{\psi_{sq}}{\psi_{sd}} \right). \quad (6)$$

The electromagnetic torque expression is

$$\hat{T}_e = \frac{3}{2} p (\hat{\psi}_{sd} i_{sq} - \hat{\psi}_{sq} i_{sd}), \quad (7)$$

where p is the number of pole pairs.

III. FUZZY CONTROLLER

The concept of the controller remains the same as in case of the traditional DTC. The fuzzy controller combines the functions of the flux and torque controllers as well as the vector switching table, thus the structural scheme of the direct torque fuzzy controller resembles mostly the traditional DTC.

The stator flux magnitude and the developed torque depend on the space vectors of the stator voltage, and could be directly controlled by selecting the proper inverter states [6]. As the selected inverter has six switches, the fuzzy controller has six outputs directly controlling each switch separately. The output signal values are limited to 0 and 1.

The inputs for both traditional and fuzzy control are the phase angle φ and deviation of the stator flux and the

electromagnetic torque:

$$e_\psi = \psi_{sr} - \hat{\psi}_s, \quad (8)$$

$$e_T = T_{er} - \hat{T}_e, \quad (9)$$

where ψ_{sr} – reference value of the stator flux, $\hat{\psi}_s$ – estimated magnitude of the stator flux, T_{er} – reference value of the torque, $\hat{T}_e$ – estimated value of the torque.

The regulations and rules referring the fuzzy control basically are identical to the classical DTC vector switching table. Only the addition regulations for handling large deviations of the stator flux are added (Table I). This approach also solves the problem of starting the engine when the flux is too low or there is none.

This table ensures the selection of the optimal vector. The output is based on the deviation of the stator flux, electromagnetic torque and phase. The membership functions are the following: PL – positive large, PS – positive small, NS – negative small, NL – negative large, P – positive, Z – zero, N – negative. From S.1 to S.6 there are the membership functions which are equivalent to the sectors of phase. This expression is possible due to only eight vectors that are allowed to be used for a three-phase inverter.

TABLE I. RULES FOR FUZZY CONTROLLER.

e_ψ	e_M	Phase φ					
		S. 1	S. 2	S. 3	S. 4	S. 5	S. 6
PL	any	U_1	U_2	U_3	U_4	U_5	U_6
PS	P	U_2	U_3	U_4	U_5	U_6	U_1
	Z	U_7	U_0	U_7	U_0	U_7	U_0
	N	U_6	U_1	U_2	U_3	U_4	U_5
NS	P	U_3	U_4	U_5	U_6	U_1	U_2
	Z	U_0	U_7	U_0	U_7	U_0	U_7
	N	U_5	U_6	U_1	U_2	U_3	U_4
NL	any	U_4	U_5	U_6	U_1	U_2	U_3

The concept of the direct torque fuzzy control for the voltage source inverter is shown in Fig 3. It consists of three major blocks: a fuzzification block, rule base and defuzzification block [7].
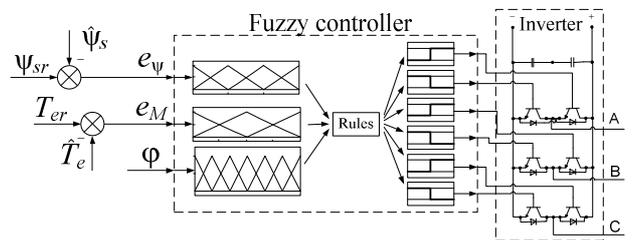

Fig. 3. Fuzzy controller.

DTFC fuzzy controller is based on Mamdani model with defuzzification using the mean of maximum (mom) method [8] as it allows the discrete output signals, unlike Sugeno model which cannot guarantee the safe use of the inverter. The membership functions of the controller inputs are shown in Fig. 4–Fig. 6.

As seen in Fig. 6 the phase is divided into 6 sectors. Note that there are two membership functions for sector 4 (S 4.1 and S 4.2). That is because the phase signal range is [–180° 180°] and the sector borders on both extremes are [–180° –

120°] and [120° 180°]. Obviously, that creates 8 additional rules and the total amount goes up to 56 rules instead of 48 linguistic rules of Table I.
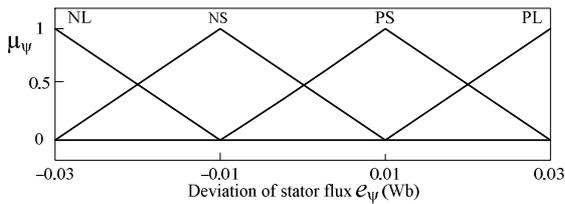

Fig. 4. Membership functions of stator flux deviation fuzzification block.
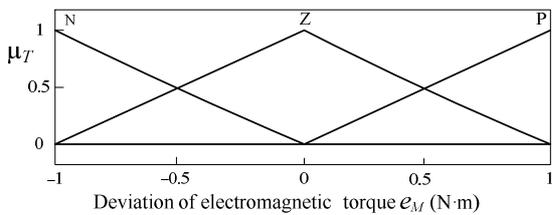

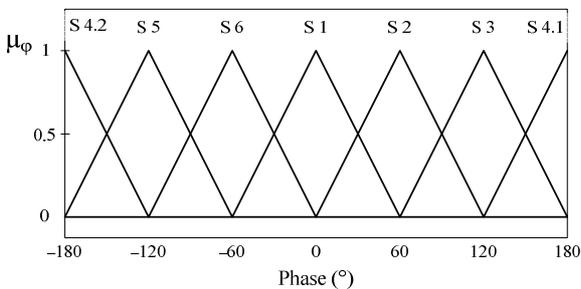Fig. 5. Membership functions of torque deviation fuzzification block.

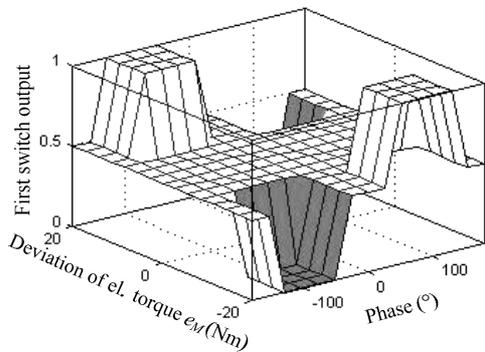Fig. 6. Membership functions of phase fuzzification block.

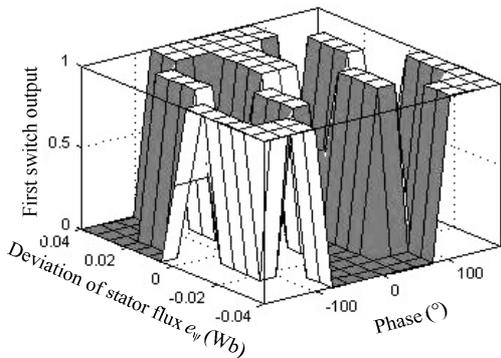Fig. 7. First switch output dependence from deviation of electromagnetic torque and phase.

Fig 8. First switch output dependence from deviation of stator flux and phase.

The controller first output dependence from the deviation of the electromagnetic torque, the deviation of the stator flux and phase inputs are presented in three-dimensional figures (Fig. 7 and Fig. 8).

IV. RESULTS OF MODELING

Both the traditional and fuzzy direct torque control types are simulated under the same conditions. The parameters of the induction motor used for modelling are presented in Table II.

TABLE II. PARAMETERS OF INDUCTION MOTOR.

P_n	U	f	
4000 W	400 V	50 Hz	
R_s	L_s	R_r	L_r
1.405 Ω	5.839 mH	1.395 Ω	5.839 mH
L_m	J	k_{tr}	p
0.1722 H	0.0131 kg·m^2	2.985 mN·m·s	2

Speed response of the modelled DTFC induction drive is given in Fig. 9. The motor starts with the speed ramp and reaches the given steady state value 800 rpm in 0.2 s. A mechanical load equal to 12 N·m is applied to the motor at 0.25 s from the motor start. This impact creates a negative speed ripple equal to 5 % of the steady-state value. At 0.3 s of the motor run the load is changed to the opposite – 12 N·m value. Because the total change of the load is double, it invokes the speed overshoot close to 10 %.
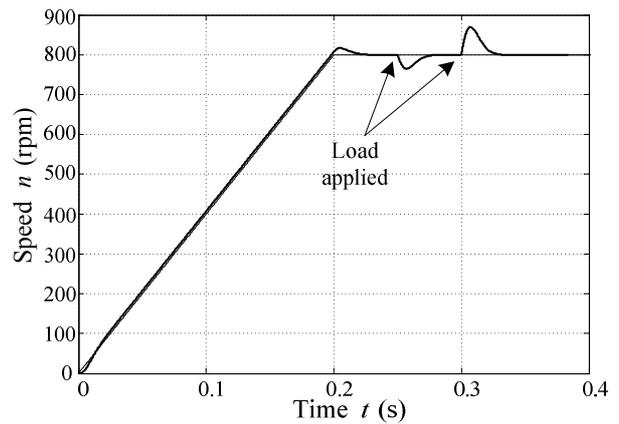

Fig. 9. Speed of DTFC induction drive.

The motor torque response is presented in Fig. 10. When load torque is applied, DTFC drive adopts to the new load after 0.05 s.
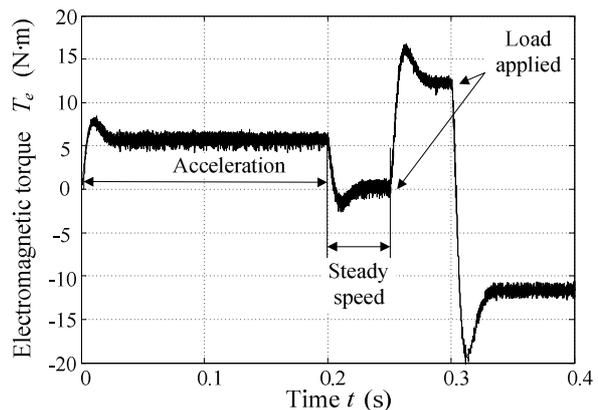

Fig. 10. Electromagnetic torque of DTFC induction drive.

Torque overshoot at fuzzy control is 1.9 % which is quite insignificant, yet the overall torque ripples are nearly halved in comparison to the traditional DTC (Fig. 11).

The results of the stator current are almost identical to those of the electromagnetic torque in the sense that the ripples receded and response difference of the traditional and fuzzy systems is negligible.
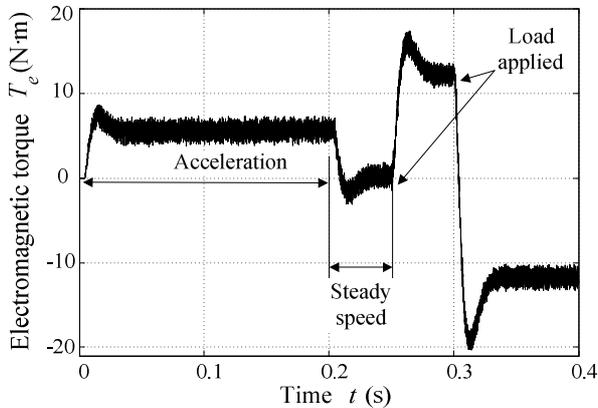

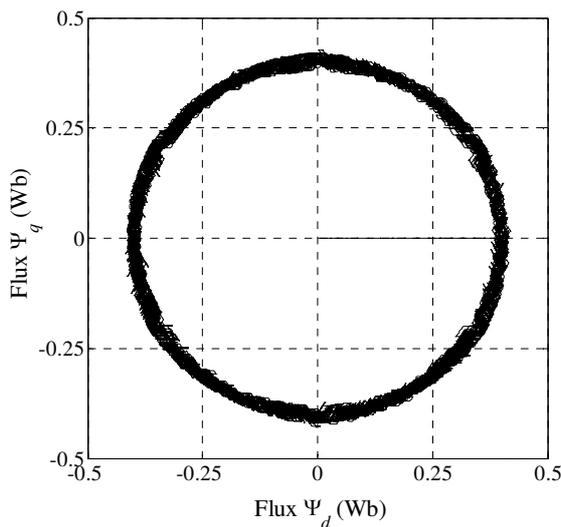Fig. 11. Electromagnetic torque of traditional DTC induction drive.

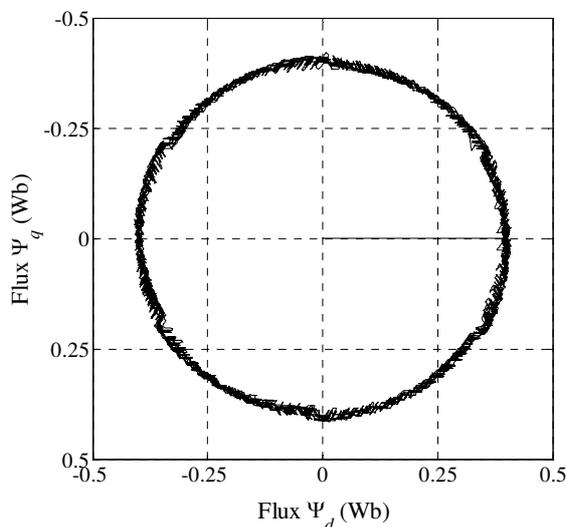Fig. 12. Stator flux trajectory of traditional DTC.

Fig. 13. Stator flux trajectory of DTFC.

The stator flux follows the circular trajectory as shown in Fig. 12. The straight line starting in the centre corresponds to the gaining of the nominal flux since the initial value is zero. In addition, the average ripples are halved and flux overshoot is lowered by 48.5 % (Fig. 13).

The use of the fuzzy controller in DTC drive reduces the flux and electromagnetic torque ripples in the steady state and provides fast response to the speed and load torque changes.

V. CONCLUSIONS

The simulation models of DTFC and DTC have been elaborated and considered. Based on the simulation it is possible to implement fuzzy logics in the control algorithm requiring fast response.

The direct torque fuzzy control reduces the electromagnetic torque overshoot by 1.9 % and the stator flux overshoot by 48.5 %. The ripples of the torque, the stator current and flux during the steady state have been halved. DTFC drive responded to the applied load in less than 0.05 seconds.

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