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Direct Torque Control for Induction Motor Using Fuzzy Logic

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Abstract

In this paper we propose an approach to improve the direct torque control (DTC) of an induction motor (IM). The proposed DTC is based on fuzzy logic technique switching table, is described compared with conventional direct torque control (DTC). To test the fuzzy control strategy a simulation platform using MATLAB/SIMULINK was built which includes induction motor d-q model, inverter model, fuzzy logic switching table and the stator flux and torque estimator. The simulation results verified the new control strategy.

Keywords: DTC, *Fuzzy logic, induction motor, switching table.*

1. Introduction

Advanced control of electrical machines requires an independent control of magnetic flux and torque. For that reason it was not surprising, that the DC-machine played an important role in the early days of high performance electrical drive systems, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively. The introduction of Field Oriented Control [1] meant a huge turn in the field of electrical drives, since with this type of control the robust induction machine can be controlled with a high performance. Later in the eighties a new control method for induction machines was introduced: The Direct Torque Control (DTC) method is characterised by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technique for the inverter is not needed. However if the control is implemented on a digital system (which can be considered as a standard nowadays); the actual values of flux and torque could cross their boundaries too far [2] [3], which is based on an independent hysteresis control of flux and torque. The main advantages of DTC are absence of coordinate transformation and current regulator absence of separate voltage modulation block.

Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. These are disadvantages that we want to remove by using and implementing modern resources of artificial intelligence like neural networks, fuzzy logic and genetic algorithms. In the following, we will describe the application of fuzzy logic in DTFC control [9].

Fuzzy control is a way for controlling a system without the need of knowing the plant mathematic model. It uses the experience of people's knowledge to form its control rule base. There has appeared many applications of fuzzy control on power electronic and motion control in the past few years. A fuzzy logic controller was reported being used with DTC [7]. However there arises the problem that the rule numbers it used is too many which would affect the speed of the fuzzy reasoning. This paper we propose an approach to improve the direct torque control (DTC) of an induction motor (IM). The proposed DTC is based on fuzzy logic technique switching table and the platform to perform the simulation by using SIMULINK.

2. Direct Torque Control with Three-Level Inverter

The basic functional blocks used to implement the DTC scheme are represented in Figure 1. The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator [1]. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration

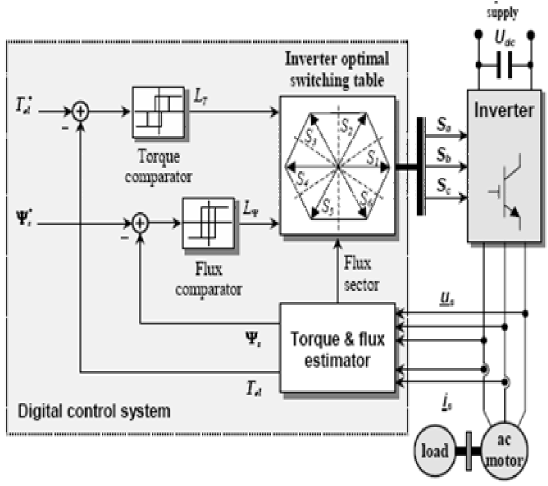


Figure 1. Basic direct torque control scheme for ac motor drives

Vector model of inverter output voltage: In a voltage fed three phase, the switching commands of each inverter leg are complementary. So for each leg a logic state C_i (i=a,b,c) can be defined. C_i is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be close (first).

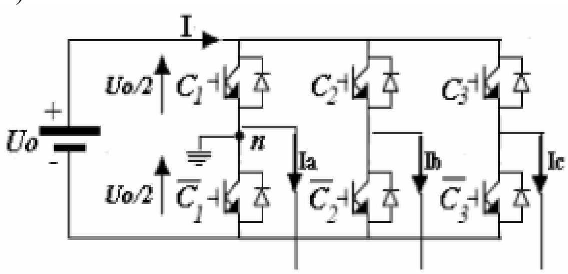


Figure 2. Three phase voltage inverter

Since three are 3 independent legs there will be eight different states, so 8 different voltages. Applying the vector transformation described as:

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

As it can be seen in second, there are six non-zero voltage vectors and two zero voltage vectors which correspond to (C_1, C_2, C_3)= (111)/ (000) as shown by Figure.3 [1] [2].

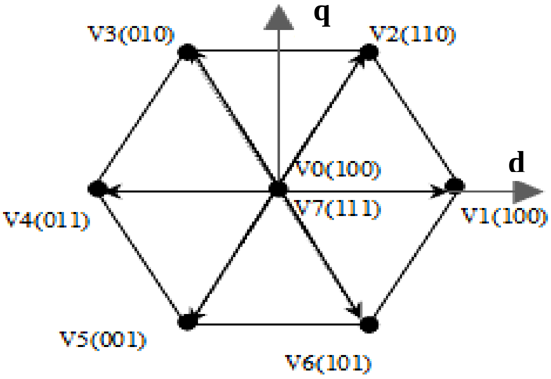


Figure 3. Partition of the d, q plane into 6 angular sectors

Stator flux control: Stator voltage components (V_{sd},V_{sq}) on perpendicular (d,q) axis are determined from measured values (U_o and I_{sabc}). Boolean switching controls (C_1,C_2 ,C_3,) by, [1][2]:

$$\begin{cases} V_{Sd} = \sqrt{\frac{2}{3}} U_0 \left(C_1 - \frac{1}{2}(C_2 + C_3) \right) \\ V_{Sd} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \end{cases} \quad (2)$$

and stator current components (I_{sd},I_{sq}) :

$$\begin{cases} I_{Sd} = \sqrt{\frac{2}{3}} Isa \\ I_{Sd} = \frac{1}{\sqrt{2}} (Isb - Isc) \end{cases} \quad (3)$$

The stator resistance can be assumed constant during a large number of converter switching periods Te. The voltage vector applied to the induction motor remains also constant during one period Te. The stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance as given by equations (4):

$$\overline{\varphi}_S = \int_0^t (\overline{V}_S - R_S \overline{I}_S) dt \ , \quad (4)$$

During the switching interval, each voltage vector is constant and (4) is then rewritten as in (5):

$$\varphi_S(t) \approx \varphi_{S0} + V_s T_e \ , \quad (5)$$

In equation; φ_{s0} stands for the initial stator flux condition.

In fact, we have $\frac{d\varphi_S}{dt} \approx V_s$ .The following Figure 4 is established for the case V_s=V_3.

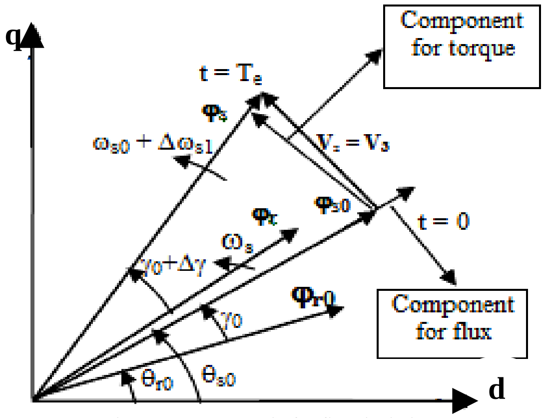


Figure 4. An example for flux deviation

Neglecting the stator resistance, (5) implies that the end of the stator flux vector will move in the direction of the applied voltage vector, as shown in Figure.4. Is the initial stator flux linkage at the instant of switching. To select the voltage vectors for controlling the amplitude of the stator flux linkage, the voltage vector plane is divided into six regions, as shown in Figure.3. In each region, two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the amplitude of, respectively. For instance, vectors and are selected to increase and decrease the amplitude of when is in region one and is rotating in a counter-clockwise direction. In this way, can be controlled at the required value by selecting the proper voltage vectors. Figure 3 shows how the voltage vectors are selected for keeping within a hysteresis band when is rotating in the counter-clockwise direction. [3] [7].

Stator flux and torque estimation: The magnitude of stator flux, which can be estimated as following [1] [6].

$$\begin{cases} \overline{\varphi}_{Sd} = \int_0^t (\overline{V}_{Sd} - R_S \overline{I}_{Sd})\,dt \\ \overline{\varphi}_{Sq} = \int_0^t (\overline{V}_{Sd} - R_S \overline{I}_{Sd})\,dt \end{cases} \qquad (6)$$

The stator flux linkage phasor is given by

$$\varphi_S = \sqrt{\varphi_{Sd}^2 + \varphi_{Sq}^2} \qquad (7)$$

By comparing the sign of the components stator flux (φ_{sd}, φ_{sq}), the relationship between these components and the amplitude of flux, the number (N) of the zone in which flux is can be obtained, [2] [5]. Electromagnetic torque calculation uses flux components (6), current components (3) and *P*, pair-pole number of the induction machine:

$$\Gamma_{em} = p(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}) \qquad (8)$$

3. Stator Flux and Electromagnetic Torque

The calculated magnitude of stator flux and electric torque are compared with their reference values in their corresponding hysteresis comparators as are shown in Figure.5 and 6, respectively. Finally, the outputs of the comparators with the number of sector at which the stator flux space vector is located are fed to a switching table to select an appropriate inverter voltage vector. The selected voltage vector will be applied to the induction motor at the end of the sample time [1].

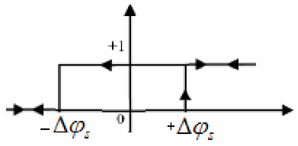


Figure 5. Stator flux hysteresis comparator

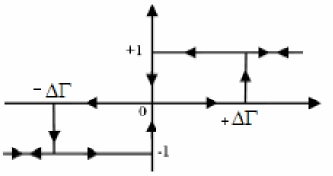


Figure 6. Torque hysteresis comparator

As shown in Figure 3, eight switching combinations can be selected in a voltage source inverter, two of which determine zero voltage vectors and the others generate six equally spaced voltage vectors having the same amplitude. According to the principle of operation of DTC, the selection of a voltage vector is made to maintain the torque and stator flux within the limits of two hysteresis bands. The switching selection table for stator flux vector lying in the first sector of the d-q plane is given in Table. I [1][2].

Sector		1	2	3	4	5	6
Flux	**Torque**						
$\Delta\varphi = 1$	$\Delta\Gamma = 1$	V_2	V_3	V_4	V_5	V_6	V_1
	$\Delta\Gamma = 0$	V_7	V_0	V_7	V_0	V_7	V_0
	$\Delta\Gamma = -1$	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\varphi = 0$	$\Delta\Gamma = 1$	V_3	V_4	V_5	V_6	V_1	V_2
	$\Delta\Gamma = 0$	V_0	V_7	V_0	V_7	V_0	V_7
	$\Delta\Gamma = -1$	V_5	V_6	V_1	V_2	V_3	V_4

Table I: the switching table for DTC basis

4. Principal of Fuzzy Direct Torque Control

The principal of direct torque control using fuzzy logic (FDTC). The fuzzy controller is designed to have three fuzzy state Variables and one control variable for achieving direct torque Control of the induction machine[13], there are three variable input fuzzy logic controllers, the stator flux error, electromagnetic torque error, and angle of flux stator respectively the output it is the voltage space vector shown Figure 7.

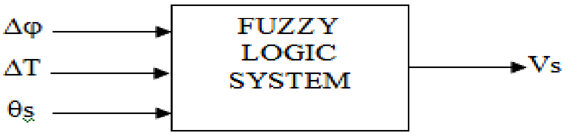


Figure 7. Switching table in fuzzy logic

Flux linkage errors: The errors of flux linkage is related value of stator's flux φ_{sref} and real value of stator's φ_s, they are subject to equation

$$\Delta\varphi_s = \varphi_{sref} - \varphi_s \quad (9)$$

voltage vector shall cause different affection to stator's flux in different flux position; show figure 3 given that stator's flux θ locates in domain θ_1.then V_4 will make flux increase rapidly, V_3 will make flux decrease rapidly, V_5 and V_6 will make flux increase slowly; and V_1 and V_2 will make flux decrease slowly, we use the three following linguistic terms: negative value, zero value and positive value denoted respectively N, Z and P. Three fuzzy sets are then defined by the delta and trapezoidal membership functions as given by Figure.8, [13].

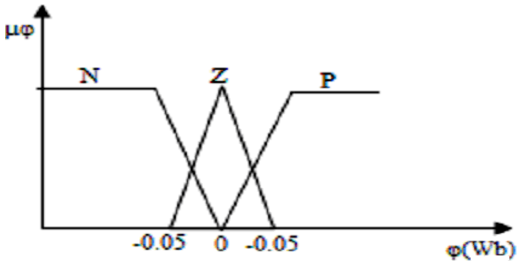


Figure 8. Membership functions for flux error

Electromagnetic torque errors: Error of torque ΔΓ is related to desired torque value $\Delta\Gamma_{ref}$ and real torque value ΔΓ ; they are subject to equation (10)

$$\Delta\Gamma = \Gamma_{ref} - \Gamma\,, \qquad (10)$$

In domain θ_1, V_2 and V_6 will make torque increase rapidly, V_1 and V_5 will make torque increase rapidly, V_4 will make torque increase slowly, V_3, V_0 and V_7 will make torque increase slowly [13]. Therefore, these rules may be described by language variable, i, e. Positive Large (LP), Positive Small (PS), Negative Small (NS), and Negative

Large (NL), their membership function's distribution is shown as Figure 9. [12],

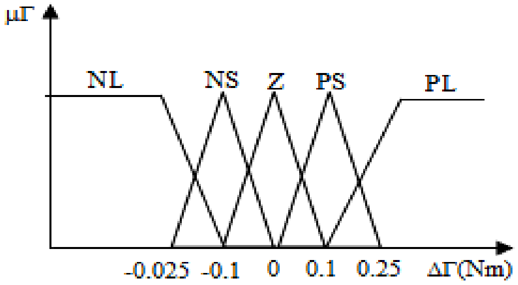


Figure 9. Membership functions for Torque error

Angle of flux linkage θ_s: The angle of flux linkage θsis an angle between stator's flux φ_s and a reference axis is defined by equation:

$$\theta_s = \arctan \frac{\varphi_{ds}}{\varphi_{qs}}, \qquad (11)$$

In (6), (φ_{sd},φ_{sq}) are the component of flux linkage φ_s in the plan (d,q) on the basis of voltage vector shown as Figure.3, fuzzy variable may be described by 12 language value ($\theta_1 \rightarrow \theta_{12}$),it's the membership function's distribution is shown Figure.8 [13].

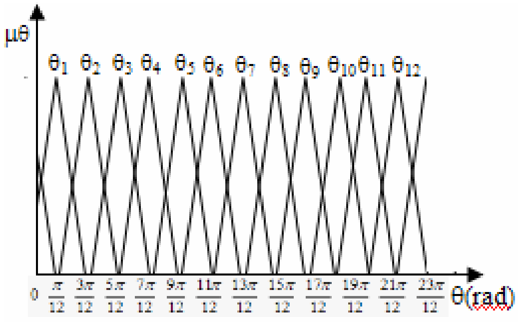


Figure 10. Membership functions for flux position

The control variable: The control variable is the inverter switching state (n). In a six step inverter, seven distinct switching states are possible [13], [8]. The switching states are crisp thus do not need a fuzzy membership distribution. Each control rule can be described using the state variables $\Delta\varphi$, $\Delta\Gamma$ and θ_s and the control variable n (characterising the inverter switching state). The i_{th} rule R_i can be written as:

R_i : if $\Delta\varphi$, is Ai, $\Delta\Gamma$ is B_i and θ_s is C_i then n is N_i

Those rules are established using literature and our experience with the help of an intensive simulation stage computing the sensitivity factors defined in [10]. The inference method used in this paper is Mamdani's procedure based on min-max decision [10]. The membership functions of variables A, B, C and N are given by μ_A, μ_B, μ_C and μ_N respectively. The weighting factor α_i for i_{th} rule can be written as [13]:

$$\alpha_i = \min(\mu_{A_i}(\varepsilon_\varphi), \mu_{B_i}(\varepsilon_\Gamma), \mu_{C_i}(\varepsilon_{\theta s})) \ , \qquad (12)$$

By fuzzy reasoning, Mamdani's minimum procedure [10] gives :

$$\mu'_{Ni}(n) = \min(\alpha_i, \mu_{NI}(n)) \ , \qquad (13)$$

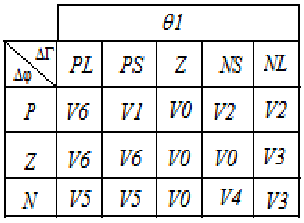
The membership function μ_N of the output n is point given by:

$$\mu_N(n) = \max_{i=1}^{i=180}(\alpha_i, \mu'_{NI}(n)) \ , \qquad (14)$$

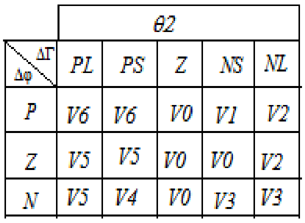
In this case, the outputs are crisp; the maximum criterion is used for defuzzifizcation [10]. By this method, the fuzzy of output which has the maximum possibility distribution, is used as control output.

$$\mu_{Nout}(n) = \max_{i=1}^{7}(\mu_{Nout}(n)), \qquad (15)$$

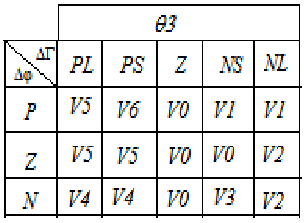
According to the all rules and Mamdani's organ, and all the variable membership function, a fuzzy control have 180 table can gain, as shown table I [13], the fuzzy control table be queried in real time, deposited the table into memory of microcomputer.



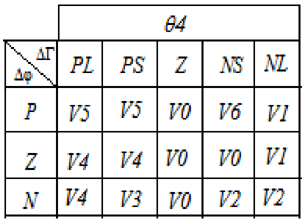
	θ1				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V6	V1	V0	V2	V2
Z	V6	V6	V0	V0	V3
N	V5	V5	V0	V4	V3



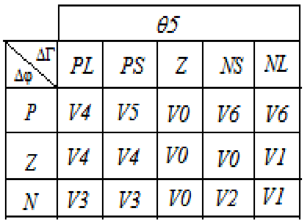
	θ2				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V6	V6	V0	V1	V2
Z	V5	V5	V0	V0	V2
N	V5	V4	V0	V3	V3



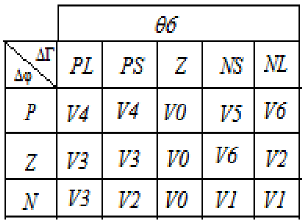
	θ3				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V5	V6	V0	V1	V1
Z	V5	V5	V0	V0	V2
N	V4	V4	V0	V3	V2



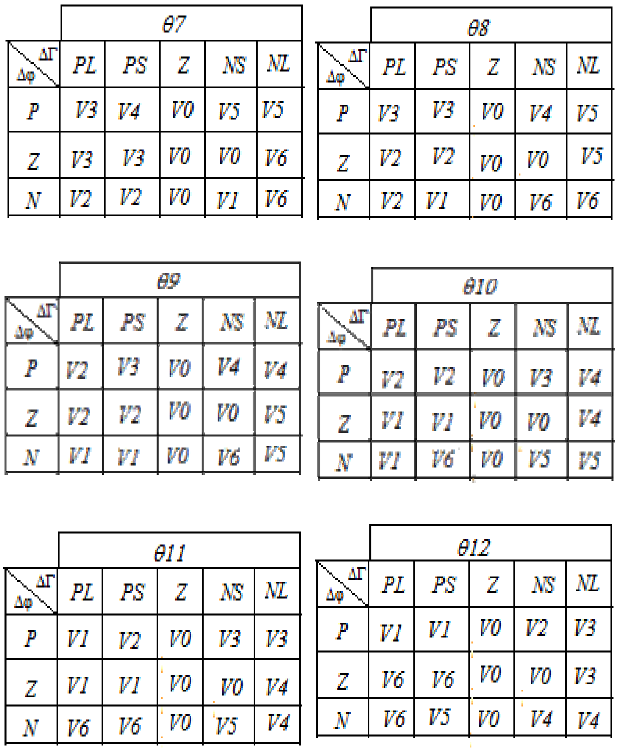
	θ4				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V5	V5	V0	V6	V1
Z	V4	V4	V0	V0	V1
N	V4	V3	V0	V2	V2



	θ5				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V4	V5	V0	V6	V6
Z	V4	V4	V0	V0	V1
N	V3	V3	V0	V2	V1



	θ6				
ΔΓ Δφ	PL	PS	Z	NS	NL
P	V4	V4	V0	V5	V6
Z	V3	V3	V0	V6	V2
N	V3	V2	V0	V1	V1



	$\theta 7$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V3	V4	V0	V5	V5
Z	V3	V3	V0	V0	V6
N	V2	V2	V0	V1	V6

	$\theta 8$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V3	V3	V0	V4	V5
Z	V2	V2	V0	V0	V5
N	V2	V1	V0	V6	V6

	$\theta 9$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V2	V3	V0	V4	V4
Z	V2	V2	V0	V0	V5
N	V1	V1	V0	V6	V5

	$\theta 10$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V2	V2	V0	V3	V4
Z	V1	V1	V0	V0	V4
N	V1	V6	V0	V5	V5

	$\theta 11$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V1	V2	V0	V3	V3
Z	V1	V1	V0	V0	V4
N	V6	V6	V0	V5	V4

	$\theta 12$				
$\Delta\Gamma$ $\Delta\varphi$	PL	PS	Z	NS	NL
P	V1	V1	V0	V2	V3
Z	V6	V6	V0	V0	V3
N	V6	V5	V0	V4	V4

Table II: fuzzy logic rules

5. Interpretation Results

To verify the technique proposed in this paper, digital simulations based on Matlab/Simulink. have been implemented. The induction machine used for the simulations has the following parameters: $P_N = 3KW$, $U_N = 230V$, $f_N = 60Hz$, $R_s = 2.89\Omega$, $R_r = 2.39\Omega$, $P = 2$, $L_s = L_r = 0.225H$, $L_m = 0.214H$, $J = 0.0005kgm2$.

The Sampling period of the system is 50µs. To compare with conventional DTC and FLDTC for IM are simulated. In two cases, the dynamic responses of torque, speed, flux, and stator current for the starting process with [5→7→3] Nm load torque applied at 0.3s are shown in Figure from 9 to 12 respectively.

The simulation results show that flux and torque responses are very good dynamic torque response for two DTC methods, but the response of the torque conventional DTC presented of the ripple, what shows that there is a static error between the couple and the couple of reference what show by the Figure 11a. By FLDTC technique shown Figure 11b, the ripple of torque in steady state is reduced remarkably compared with conventional DTC, the torque changes through big oscillation and the torque ripple is bigger in conventional DTC shown Figure 11a, Figure 12b shows it's FFT. Both the waveforms, in the time and frequency domains, show that the harmonic content of the torque response is highly reduced by employing the fuzzy logic technique.

Is the speed transient waveform when the command speed step changes from 0 to 68 [rad/s]. The short response time is achieved from 0 to stable value based on the FDTC shown Figure 13b, however, the speed is slow and the speed has big ripple in conventional DTC shown Figure 13a, for an abrupt change in command torque. It can be seen Figure 14.b that the stator flux trajectory of the FLDTC is more approximately circle than it of the conventional DTC Figure 14a. Figure 15.(a)-(b) Shows that the magnitude of stator flux of the FLDTC is established more quickly than that of the conventional DTC, the steady state current result are presented in Figure 16.(a)-(b) in the two control methods. compared with large distorted by the conventional DC, the steady state current can be approximately be sine wave including low high frequency component.

6. Conclusion

In this paper, authors present a kind of fuzzy torque control system for induction motor based on fuzzy control technique. On the basis of analysing diagram of voltage vector, authors acquired whole fuzzy control rule set. The simulation results suggest that FLDTC of induction machine can achieve precise control of the stator flux and torque. Compared to conventional DTC, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved.

The main improvements shown are:

- Reduction of torque and current ripples.
- No flux droppings caused by sector changes circular trajectory.
- Fast torque response.
- Zero-steady-state torque and flux.

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8. Biographies

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Hocine Benalla : was born in Algeria in 1957. He received the D.E.A. and Doctor engineer degree in power electronics from the National Polytechnic Institute of Toulouse, France, in 1981 , and. 1984, respectively. In 1995, he received the Ph.D. degrees in electrical engineering from University of Jussieu -Paris 6, France. He is currently an Assistant Professor at University of Constantine Algeria. His current research interests include electric machines, ac drives and active filter.

Meziane Salima : in 2000 received the Engineer degree from the university of Montouri Constantine. Algeria. In 2003 received the M.S. degrees in electrical engineering, Option electrical machine. Associate teacher in Oum El Bouaghi University from October to 2003. In 2004 inscription in doctor's degree, permanent teacher from October 2004 in Souk ahras University, member for laboratory Of Electrical engineering university of Montouri Constantine. Algeria.

9. Simulation Results

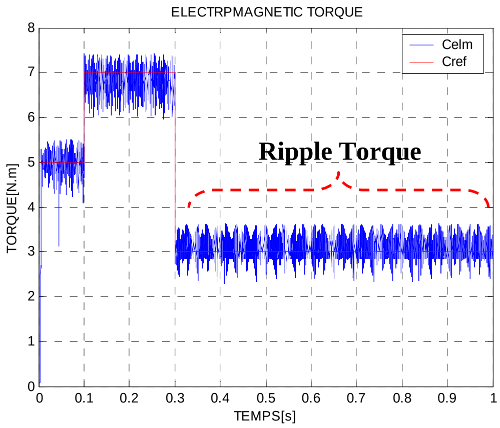

Figure 11a. Electromagnetic Torque Response

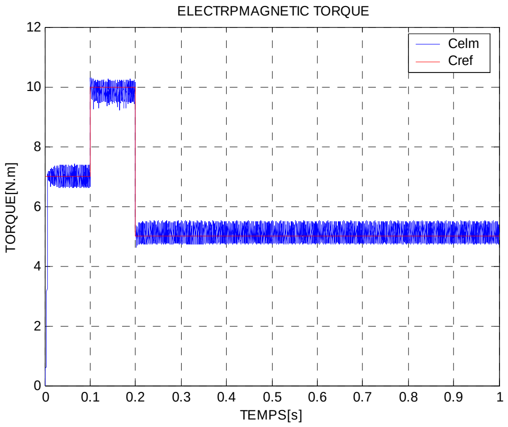

Figure 11b. Electromagnetic Torque Response

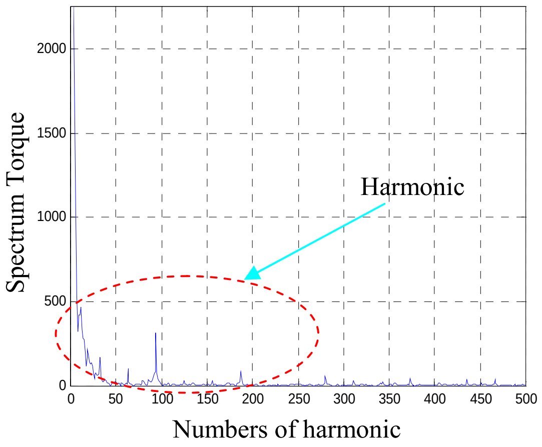

Fig.12a. Frequency spectrum of the torque response

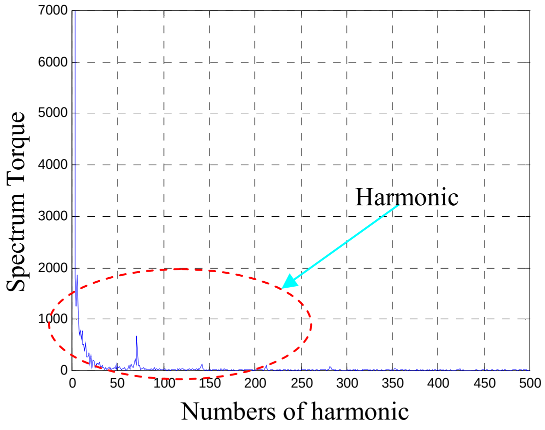

Fig.12b. Frequency spectrum of the torque response

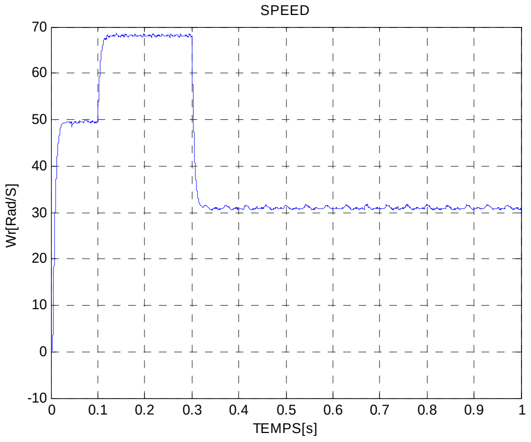

Figure 13a. Speed response

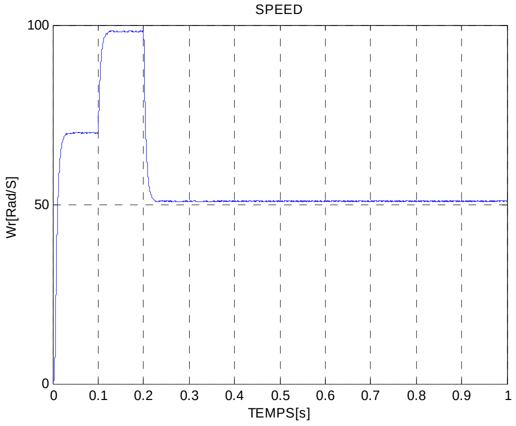

Figure 13b. Speed response

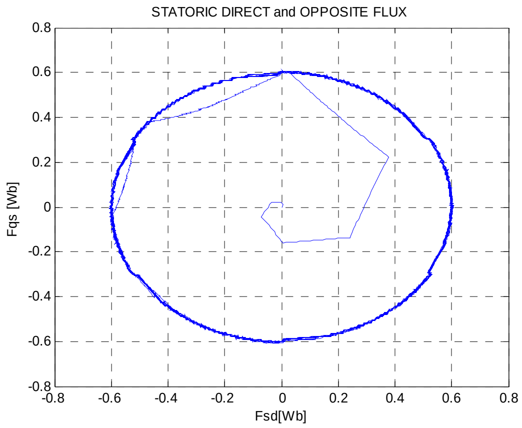

Figure 14a . The stator flux circle

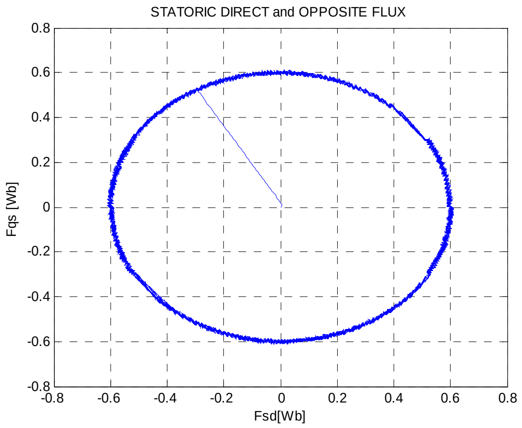

Figure 14b. The stator flux circle

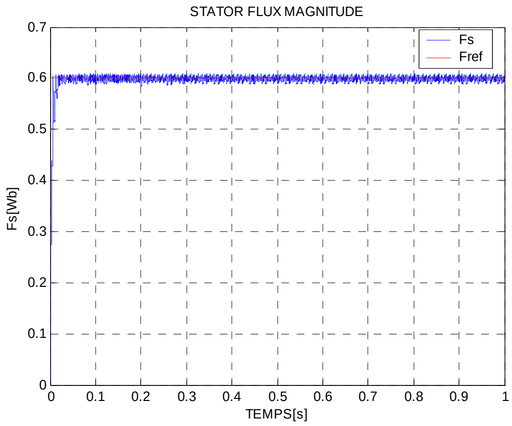

Figure 15a. The stator flux magnitude

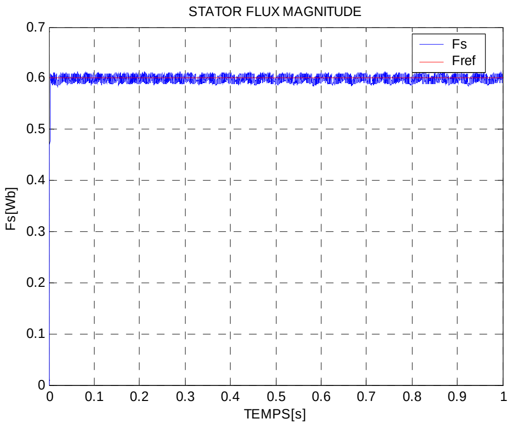

Figure 15a. The stator flux magnitude

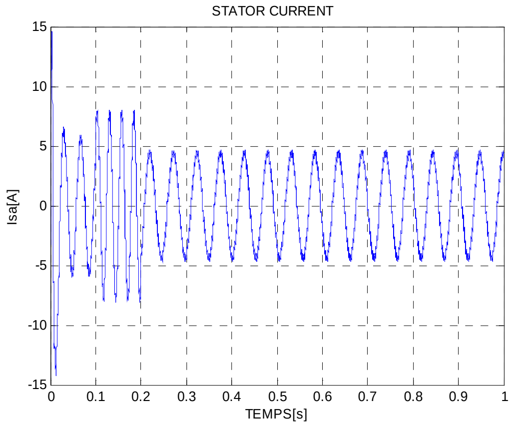

Figure 16a. The stator current

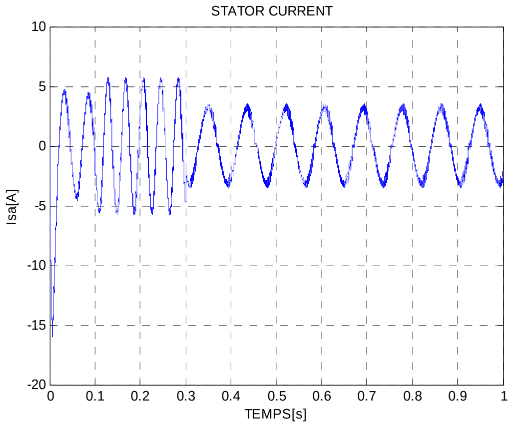

Figure 16b. The stator current

Conventional DTC

Fuzzy Logic DTC