

Direct Torque Control of Doubly Star Induction Motor Using Fuzzy Logic Speed Controller

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ABSTRACT

This paper presents the simulation of the control of doubly star induction motor using Direct Torque Control (DTC) based on Proportional and Integral controller (PI) and Fuzzy Logic Controller (FLC). In addition, the work describes a model of doubly star induction motor in α - β reference frame theory and its computer simulation in MATLAB/SIMULINK®. The structure of the DTC has several advantages such as the short sampling time required by the TC schemes makes them suited to a very fast flux and torque controlled drives as well as the simplicity of the control algorithm. The general-purpose induction drives in very wide range using DTC because it is the excellent solution. The performances of the DTC with a PI controller and FLC are tested under different speeds command values and load torque.

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1. INTRODUCTION

Doubly star induction machines are one of widely used in many industry segments, due to their advantages in power segmentation, reliability and minimized torque pulsations. Such segmented structures are very attractive for high-power applications, since they allow the use of lower rating power electronic devices at a switching frequency superior than the one frequently utilized in three-phase AC machine drives. This machine have been used in various applications, such as; compressors, cement mills, pumps, rolling mills, fans and mine hoists [1].

The aim of our work is based on the utilization of a simple model of the DSIM, this machine has several advantages such as [2] reliability, robustness and meets the best behavior criteria than the simple induction machine, because it reduces the electromagnetic torque ripples and improves the power factor.

The technique of DTC introduced in 1985 by TAKAHASHI [3, 4] uses a promising strategy due to its usefulness and implementation simplicity. Many studies have allowed a rigorous modeling of this approach [4, 5] Direct Torque Control is a control technique in AC drive systems to get high performance torque control. A Fuzzy Controller is coming to ameliorate (DTC) performance and reduce considerably torque and flux ripples. Fuzzy Logic direct torque control attracts the attention of many researchers the configuration of the fuzzy Logic Controller for the direct torque control. The proposed FLC has been successfully simulated on a simulink model with the help of fuzzy logic toolbox. The performance of the FLC will be compared with the conventional PI controller as well as the testing the use of PI and FLC in case of torque and speed command changes and parametric variations.

So far several types of control are used for the control of such kinds of motors, and to the best of our knowledge; this is the first attempt for a comparative study between PI and fuzzy speed controller of doubly star induction motor using direct torque control.

This paper is structured as follows: In Section 2 the model of the DSIM is presented, a suitable transformation matrix is used to develop a simple dynamic model. We will describe the direct torque control by a fuzzy logic controller; the designed direct torque control models are introduced and explained, in order to improve the static and dynamic control performances of the DSIM in section 3. Section 4 shows simulation results for a comparison between the performances of PI and FLC speed controller of direct torque control of DSIM under various conditions operation (load torque, reference speed, parameter variations). The section 5 concludes this paper.

2. MACHINE MODELING

The doubly star induction machine represented by two stators windings: A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2} which are displaced by $\alpha = \frac{\pi}{6}$ electrical angle .and the rotor windings (A_r, B_r, C_r) are sinusoidal distributed

and have axes that are displaced apart by $\frac{2\pi}{3}$ [6].

The customary assumptions are adopted [7]:

1. Motor windings are sinusoidal distributed.
2. The saturation of magnetic circuit is neglected.
3. The two stars have same parameters.
4. The flux path is linear.

The windings of the DSIM are shown in Figure 1.

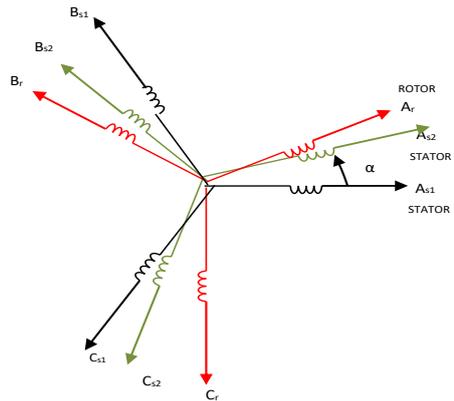


Figure 1. Doubly stator winding representation

The voltage equations for stator and rotor circuits for model of the DSIM motor have the following matrix form [8]:

$$\begin{aligned} \begin{bmatrix} V_{s1,abc} \end{bmatrix} &= \begin{bmatrix} R_{s1} \end{bmatrix} \begin{bmatrix} i_{s1,abc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{s1,abc} \end{bmatrix} \\ \begin{bmatrix} V_{s2,abc} \end{bmatrix} &= \begin{bmatrix} R_{s2} \end{bmatrix} \begin{bmatrix} i_{s2,abc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{s2,abc} \end{bmatrix} \\ 0 &= \begin{bmatrix} R_r \end{bmatrix} \begin{bmatrix} i_{r,abc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{r,abc} \end{bmatrix} \end{aligned} \quad (1)$$

With:

$V_{s1,abc}, V_{s2,abc}$: Stator voltages.

$i_{s1,abc}, i_{s2,abc}, i_{r,abc}$: Stator and rotor currents.

$\Phi_{s1,abc}$, $\Phi_{s2,abc}$, $\Phi_{r,abc}$: Stator and rotor flux.

$[R_{s1}]$, $[R_{s2}]$, $[R_r]$: Resistance matrices stator and rotor .

In order to ensure the control, the DSIM model expressed in terms of α - and β -axes should be presented by [9]:

$$\left\{ \begin{array}{l} V_{s1\alpha} = R_{s1}i_{s1\alpha} + L_{s1} \frac{d}{dt} \Phi_{s1\alpha} \\ V_{s2\alpha} = R_{s2}i_{s2\alpha} + L_{s2} \frac{d}{dt} \Phi_{s2\alpha} \\ V_{s1\beta} = R_{s1}i_{s1\beta} + L_{s1} \frac{d}{dt} \Phi_{s1\beta} \\ V_{s2\beta} = R_{s2}i_{s1\beta} + L_{s2} \frac{d}{dt} \Phi_{s1\beta} \\ 0 = R_r i_{r\alpha} + L_r \frac{d}{dt} \Phi_{r\alpha} \\ 0 = R_r i_{r\beta} + L_r \frac{d}{dt} \Phi_{r\beta} \end{array} \right. \quad (2)$$

Where:

$V_{s1,\alpha\beta}$, $V_{s2,\alpha\beta}$: Stator voltages $\alpha\beta$ components.

$i_{s1,\alpha\beta}$, $i_{s2,\alpha\beta}$, $i_{r,\alpha\beta}$: Stator and Rotor currents $\alpha\beta$ components.

$\Phi_{s1,\alpha\beta}$, $\Phi_{s2,\alpha\beta}$, $\Phi_{r,\alpha\beta}$: Stator and Rotor flux $\alpha\beta$ components.

The relation flux ($\Phi_{s1\alpha}$, $\Phi_{s2\alpha}$, $\Phi_{s1\beta}$, $\Phi_{s2\beta}$, $\Phi_{r\alpha}$, and $\Phi_{r\beta}$) and current ($i_{s1\alpha}$, $i_{s2\alpha}$, $i_{s1\beta}$, $i_{s2\beta}$, $i_{r\alpha}$ and $i_{r\beta}$) are [19]:

$$\left\{ \begin{array}{l} \Phi_{s1\alpha} = L_{s1}i_{s1\alpha} + L_m(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}) \\ \Phi_{s1\beta} = L_{s1}i_{s1\beta} + L_m(i_{s1\beta} + i_{s2\beta} + i_{r\beta}) \\ \Phi_{s2\alpha} = L_{s2}i_{s2\alpha} + L_m(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}) \\ \Phi_{s2\beta} = L_{s2}i_{s1\beta} + L_m(i_{s1\beta} + i_{s2\beta} + i_{r\beta}) \\ \Phi_{r\alpha} = L_r i_{r\alpha} + L_m(i_{s1\alpha} + i_{s2\alpha} + i_{r\alpha}) \\ \Phi_{r\beta} = L_r i_{r\beta} + L_m(i_{s1\beta} + i_{s2\beta} + i_{r\beta}) \end{array} \right. \quad (3)$$

Where:

L_m : Cyclic mutual inductance between stator 1, stator 2 and rotor.

$L_{s1,s2,r}$: the inductance of a stator 1, stator 2 and rotor respectively.

$L_{s1}+L_m$, $L_{s2}+L_m$, L_r+L_m : the total inductance of a stator 1, stator 2 and rotor respectively.

The electromagnetic torque and the mechanical equations can be written as:

$$C_{em} = p \frac{L_m}{L_m + L_r} (\Phi_{rd}(i_{s1\beta} + i_{s2\beta}) - \Phi_{rq}(i_{s1\alpha} + i_{s2\alpha})) \quad (4)$$

$$J \frac{d\Omega}{dt} = C_{em} - C_r - K_f \Omega \quad (5)$$

3. DIRECT TORQUE CONTROL STRATEGY

The fundamental idea of a direct torque control is based on the switching tables with hysteresis of torque and stator flux. Using this method, for the minimization of the commutations of the inverter switches, on the torque/stator flux decoupling, on the control of the PWM generator, DTC requires precise knowledge of the amplitude and angular position of the controlled flux with respect to the stationary stator axis in addition to the angular velocity for the torque control purpose [8, 13]. We don't require the rotor position in order to choose the voltage vector. This particularity defines the DTC as an adapted control technique of AC machines [10-12].

The principle of DTC operation can also be explained by analyzing the stator voltage equation in the stator flux reference frame [14]:

$$\Phi_{s1\alpha} = \int_0^{T_e} (V_{s1\alpha} - R_{s1}i_{s1\alpha})dt + \Phi_{s0} \quad (6)$$

$$\Phi_{s1\beta} = \int_0^{T_e} (V_{s1\beta} - R_{s1}i_{s1\beta})dt + \Phi_{s0} \quad (7)$$

$$\Phi_{s2\alpha} = \int_0^{T_e} (V_{s2\alpha} - R_{s1}i_{s2\alpha})dt + \Phi_{s0} \quad (8)$$

$$\Phi_{s2\beta} = \int_0^{T_e} (V_{s2\beta} - R_{s1}i_{s2\beta})dt + \Phi_{s0} \quad (9)$$

During the switching interval $[0-T_e]$, $V_s \gg R_s i_s$ we can express :

$$\Phi_s(t) = \Phi_{s0} + V_s T_e \quad (10)$$

3.1. Vectors flux control

By neglecting the stator resistances, (10) implies that the ends of the stator flux vectors will move in the direction of the applied voltage vectors as shown in Figure 2.

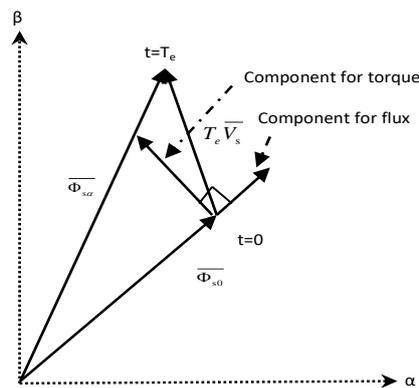


Figure 2. Stator flux vector deviation.

For instance, vectors are selected to increase and decrease the amplitude of flux vectors and their angular position as:

if $\bar{V}_{(i+1)}$ is selected then $\bar{\Phi}_s$ increase and θ_s increase;

if $\bar{V}_{(i-1)}$ is selected then $\bar{\Phi}_s$ increase and θ_s decrease;

if $\bar{V}_{(i+2)}$ is selected then $\bar{\Phi}_s$ decrease and θ_s increase;

if $\bar{V}_{(i-2)}$ is selected then $\bar{\Phi}_s$ decrease and θ_s decrease.

The selected voltage vector will be applied to the DSIM at the end of the sample time, as are shown in (10)

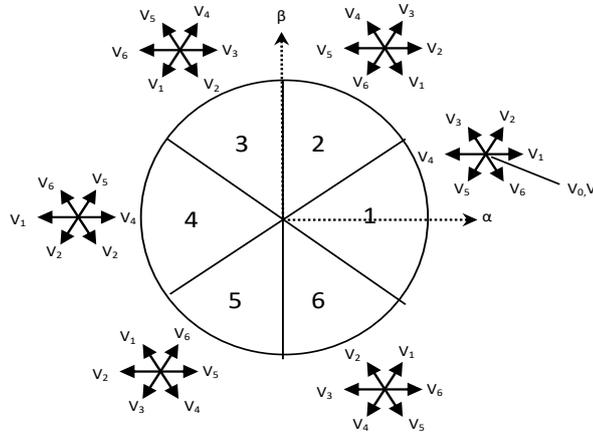


Figure 3. Voltage vector selection

3.2. Stator flux estimation

The magnitude of stator flux, which can be estimated as following:

$$\bar{\Phi}_s = \int_0^T (V_s - R_s i_s) dt \quad (11)$$

The stator flux linkage phasors are given by:

$$|\Phi_{s1}| = \sqrt{\Phi_{s1\alpha}^2 + \Phi_{s1\beta}^2} \quad (12)$$

$$|\Phi_{s2}| = \sqrt{\Phi_{s2\alpha}^2 + \Phi_{s2\beta}^2} \quad (13)$$

The stator flux linkage phasors positions are:

$$\theta_{s1} = \arctg\left(\frac{\Phi_{s1\beta}}{\Phi_{s1\alpha}}\right) \quad (14)$$

$$\theta_{s2} = \arctg\left(\frac{\Phi_{s2\beta}}{\Phi_{s2\alpha}}\right) \quad (15)$$

The electromagnetic torque expressions are given by [14]:

$$C_{em1} = p(\Phi_{s1\alpha} i_{s1\beta} - \Phi_{s1\beta} i_{s1\alpha}) \quad (16)$$

$$C_{em2} = p(\Phi_{s2\alpha} i_{s2\beta} - \Phi_{s2\beta} i_{s2\alpha}) \quad (17)$$

$$C_{em} = C_{em1} + C_{em2}$$

$$C_{em} = P((\Phi_{s1\alpha}i_{s1\beta} - \Phi_{s1\beta}i_{s1\alpha}) + (\Phi_{s2\alpha}i_{s2\beta} - \Phi_{s2\beta}i_{s2\alpha})) \tag{18}$$

3.3. Flux and torque corrector

The reference values of flux (Φ_s) and torque (C_{em}) are compared to their actual values and the resultant errors are fed into a two level hysteresis comparator for the flux and three level hysteresis comparator for the torque, who allows controlling the motor in the two directions of rotation, shown in Figure 4.

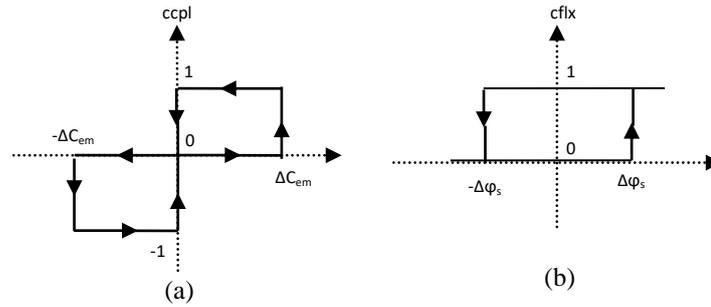


Figure 4. Hysteresis comparator, (a): three level hysteresis comparator for the torque, (b): two level hysteresis comparator for the flux

3.4. Elaboration of the switching table

The switching table allows to select the appropriate inverter switching state according to the state of hysteresis comparators of flux (cflx1 and cflx2) and torque (ccpl) and the sector where is the stator vector flux (Φ_s) in the plan (α, β), in order to maintain the magnitude of stator flux and electromagnetic torque inside the hysteresis bands. The above consideration allows construction of the switching table as presented in Table 1.

Table 1. Switching table with zero voltage vectors

Sectors		1	2	3	4	5	6
cflx=1	ccpl=1	V_2	V_3	V_4	V_5	V_6	V_1
	ccpl=0	V_7	V_0	V_7	V_0	V_7	V_0
	ccpl=-1	V_6	V_1	V_2	V_3	V_4	V_5
cflx=0	ccpl=1	V_3	V_4	V_5	V_6	V_1	V_2
	ccpl=0	V_0	V_7	V_0	V_7	V_0	V_7
	ccpl=-1	V_5	V_6	V_1	V_2	V_3	V_4

3.5. Principe of a fuzzy controller

The control by fuzzy logic permits to get a law of drive, often very effective, without having a precise model of the process, from a linguistic description of the performance of the system. Its strategy is different the one of the automatic classic [15, 16]. The fuzzy logic controller is a set of linguistic control rules associated by the dual concepts of fuzzy implication and the compositional rule of inference. The FLC provides an algorithm which can transfer the linguistic control approach based on expert knowledge into an automatic control strategy [20].

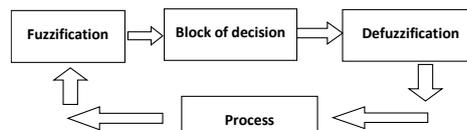


Figure 5. Structure interns of a system Fuzzy

Figure 6 in which the linguistic variables are represented by NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). Table 2 shows one of possible control rules based on seven membership functions [17].

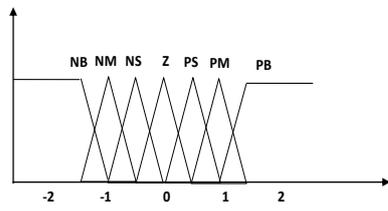


Figure 6. Fuzzification with seven memberships

Table 2. The fuzzy control rule bases

de ^e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The block diagram for the direct torque control applied to the doubly star induction machine shown in Figure 7.

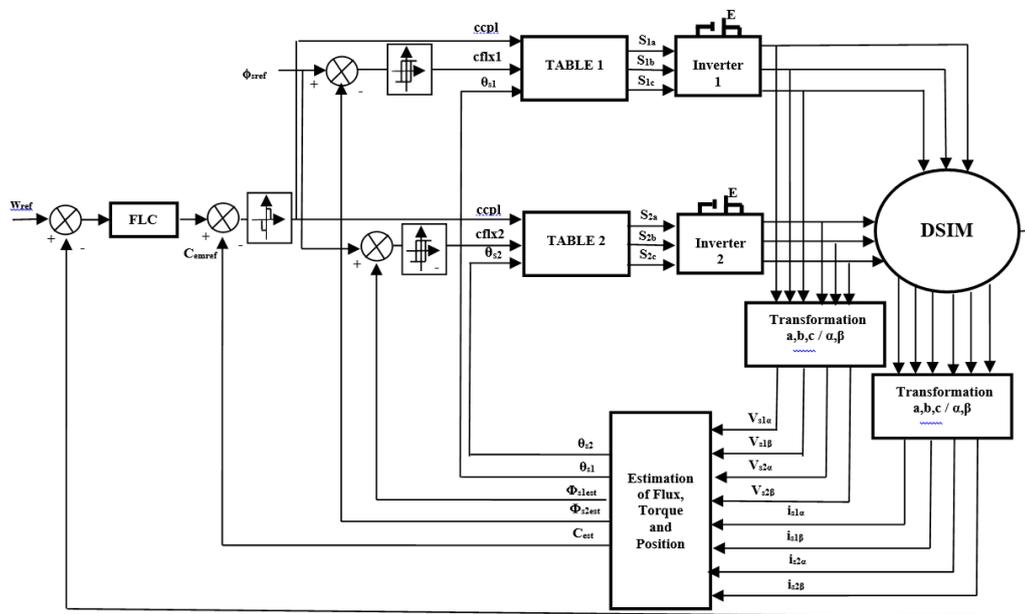


Figure 7. DTC applied to doubly star induction machine (DTC-DSIM)

4. RESULTS AND DISCUSSION

The simulation is done using MATLAB and results are presented here, the motor used in the simulation study is a 4.5 Kw cage rotor, 220 V, 50 Hz. The parameters of the DSIM are summarized in Appendix. The simulation work is passed on three tests of Robustness studies:

4.1. Torque variation

In primary test the Torque variation with the sign of resistant torque ($C_r = 10 \text{ N.m}$) for the period of the interval] 2-3.5] s, and the DSIM runs with speed values (100 rad/s).

Figure 8 shows that responses for DTC of DSIM using the proposed PI and FLC, We note that when the motor starts, the speed reaches its reference speed (100 rad/s), the mechanical torque increases to reach the peak value (35 N.m) with PI and (37 N.m) with FLC and falls down to be close zero value because the motor running with no load. At during] 2-3.5] s we changed the value of load torque to $C_r=10\text{N.m}$, the motor output torque will increase to cover this load. The harmonics magnitude of electromagnetic torque produced by the FLC is inferior than produced by PI. Figure 8 (d), (e), where flux trajectory of PI and FLC controllers is shown from the zero to its rated value, Almost circular flux trajectory with equal amplitudes in both α and β axes.

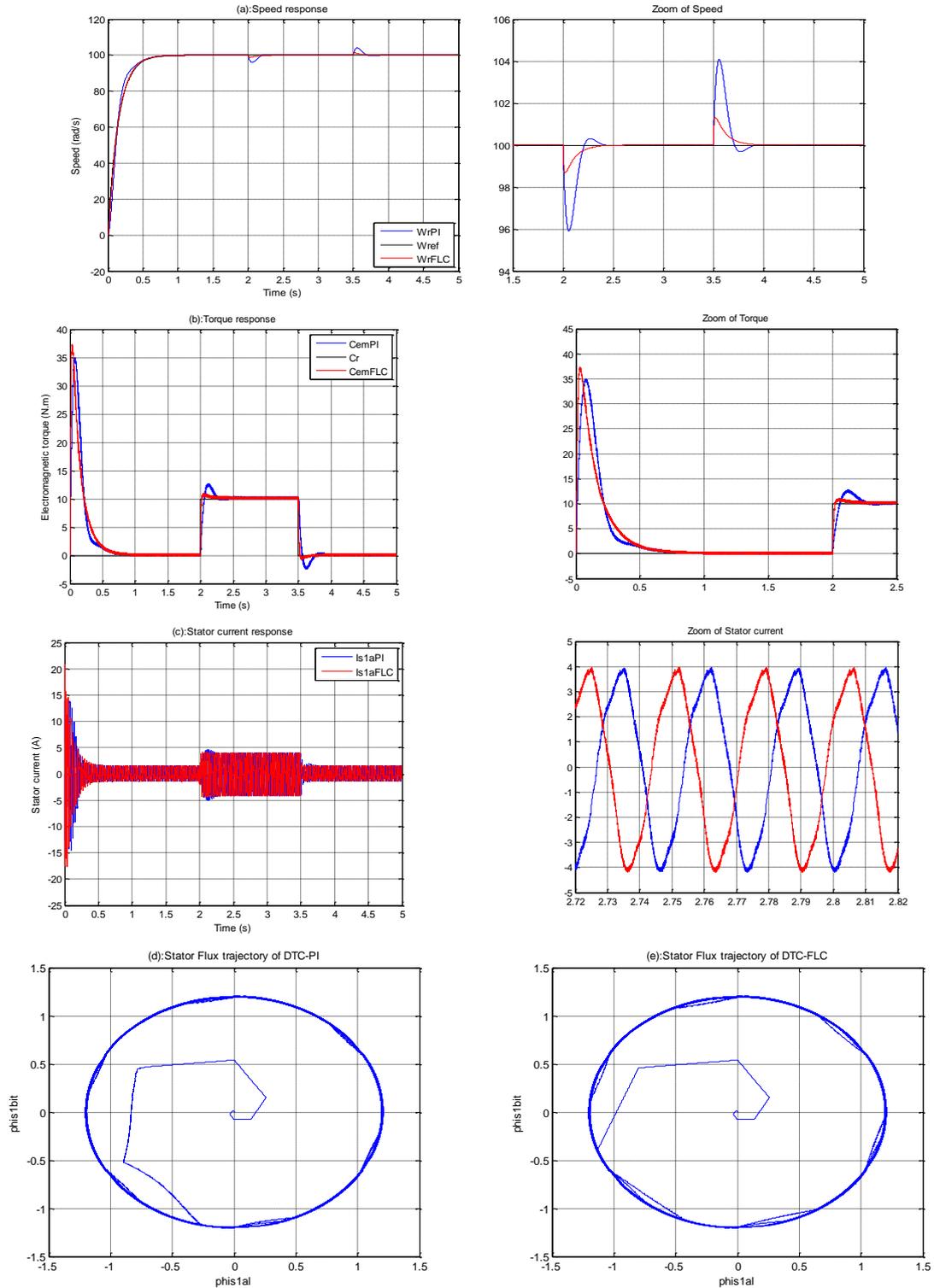


Figure 8. DTC of DSIM with load torque (10N.m) between] 2 -3.5] s

4.2. Speed variation

In next test the Torque is applied at $t = 2s$ ($C_r = 10N.m$), and the DSIM runs with speed variation values (100rad/s during] 0-3] s, 50rad/s for the duration of] 3-5] s).

Figure 9 shows the change in command speed is realized as following: ([0-3] s $w_{ref}=100rad/s$) and ([] 3-5] s $w_{ref} =30rad/s$). The rotor speed obtained by the FLC track very quickly the desired reference speed

than the one obtained with PI, Figure 9 (a). This test has for object the study of controller behaviors in pursuit and in regulation.

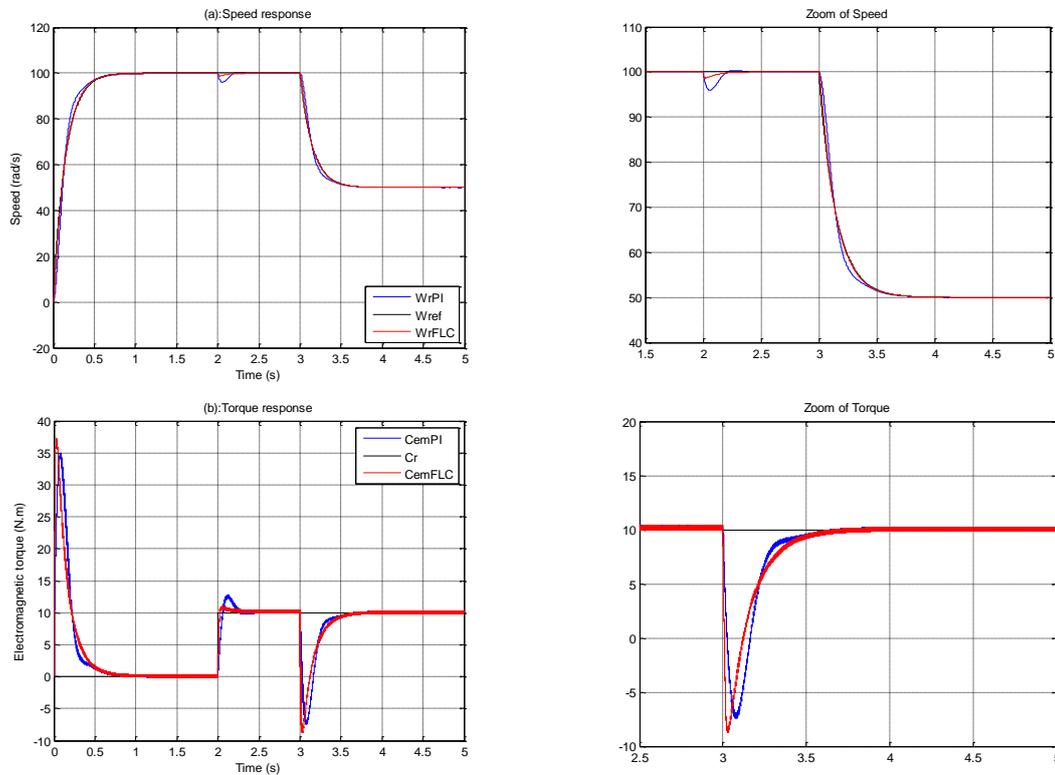


Figure 9. Speed, torque characteristic of an (DTC) with PI and FLC Controllers, at changes in Speed

4.3. Robust control for star resistance variation

In order to confirmed the robustness for parameters variations we carried out a test for a variation of 50% in the value of star resistance ($1.5 \cdot R_{S1}$ and $1.5 \cdot R_{S2}$) for the period of the interval] 3-5] s .The speed is fixed at 100 rad/s and a resistant torque of 10N.m is applied at $t = 2$ s.

Figure 10 shows the final test concerns a presents the behavior of FLC and PI speed control when the parameter variations (star resistance), the change in the star resistance is realized as follows: ([3-5] s $1.5 \cdot R_{S1}$ and $1.5 \cdot R_{S2}$), Influence of the parameter variations on the electromagnetic torque and speed response is shown in Figure 10 (a), (b).

The PI and a FLC controller is tuned at rated conditions in order to make a fair comparison between the speed control of the DSIM-DTC by a PI and a FLC is presented in all Figures.

In the present study are utilized to judge the performance of the controllers. ISE, IAE and ITAE criterion is widely adopted to evaluate the dynamic performance of the control system.

The index *ISE*, *IAE* and *ITAE* is expressed as follows [18]:

$$ISE = \int_0^T e^2(t) dt \quad (19)$$

$$IAE = \int_0^T |e(t)| dt \quad (20)$$

$$ITAE = \int_0^T t|e(t)|dt \quad (21)$$

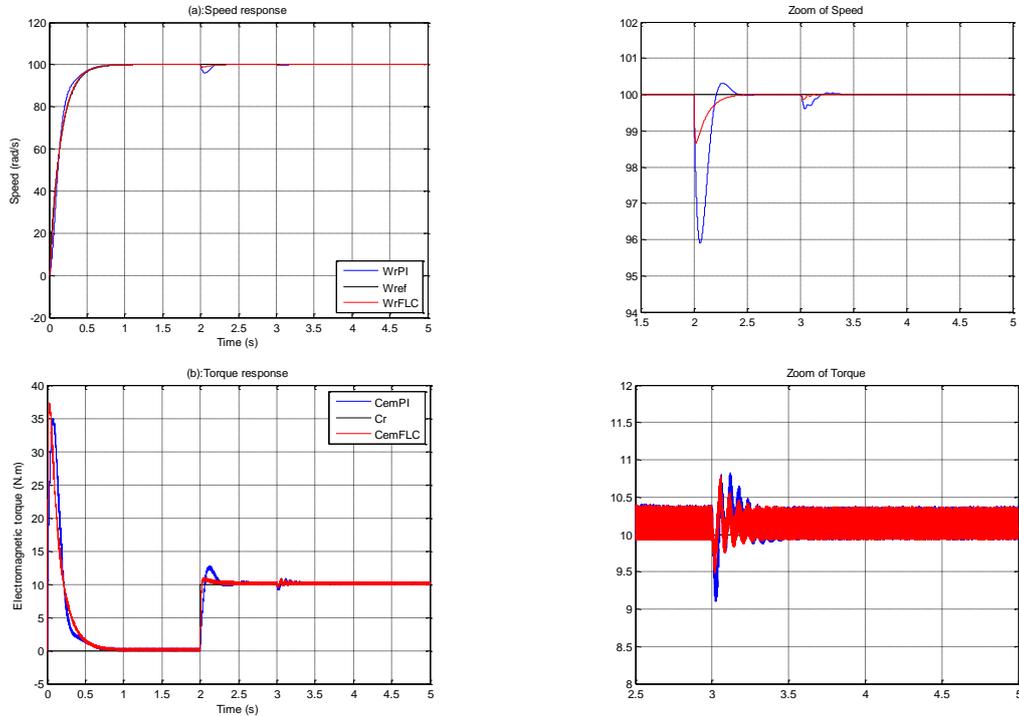


Figure 10. Speed and torque characteristic of an (DTC) with PI and FLC controllers, at parametric variations (star resistance $1.5 \cdot R_{S1}$ and $1.5 \cdot R_{S2}$).

ISE: integral squared error, *IAE*: integral absolute error, *ITAE*: integral time-weighted absolute error.

For quantitative comparison between two methods, *ISE*, *IAE* and *ITAE* are used as the criterion. Table 3 shows the *ISE*, *IAE* and *ITAE* values of the simulation results of direct torque control using the PI controller and the proposed FLC Controller (DTC-PI, DTC-FLC in Test1). Actually these performances index are obtained at the end of the simulation time ($t=5$ sec) with a sampling period $h=1 \cdot e^{-5}$. This comparison shows clearly that the FLC gives good performances and it's more robust than PI.

Table 3. Quantitative comparison between the proposed FLC and PI controllers

Index	Controllers		
		PI	FLC
ISE	Speed	19.37	2.552
	Flux	0.00343	0.002256
IAE	Speed	3.333	1.072
	Flux	0.01864	0.01452
ITAE	Speed	3.376	1.153
	Flux	0.02749	0.0269

5. CONCLUSION

In this study, the performances of speed FLC and PI controllers for direct Torque control of DSIM are presented, has been described. The system was analyzed and designed. The performances were studied extensively by simulation to validate the theoretical concept. To avoid the complexity of the FLC and the decrease of its precision. The robustness tests show too that the FLC is more robust than the PI controller with the speed and torque and parameter variations. The FLC is a useful tool for replacing the PI in all applications (high power variable-speed multi-phase induction machine drives) requiring a good performance and a great robustness and reach high quality in control of non linear systems.

The simulation study indicates clearly the superior performance of FLC, the comparison done in this work shows that the limits of this type of PI controller can have negative effects on the performance of the DSIM.

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Hellali Lallouani was born in Bordj Bou Arréridj, Algeria on January 12, 1987. He received the Engineer degree from the University of M'sila, Algeria in 2010 and the M.S degrees in Electrical engineering option electrical industrial from the University of Batna. Algeria in 2016. He is the member of the Research Laboratory Electromagnetic Induction of M'sila Algeria. His main research interests are control system to drive Machines and fault detection in Electric Drives.



Belhamdi Saad was born in M'sila, Algeria in 1976, in 2002 received the Engineer degree from the University of Biskra, Algeria, and in 2005 received the M.S degrees in Electrical engineering option electrical industrial, In 2014 received the PhD, permanent teacher from December 2008 in M'sila University. His main research interests include electrical drives modeling simulation and control He is the member of the Research Laboratory Electromagnetic Induction of M'sila Algeria.

APPENDIX

Table 4. DSIM parameters [8]

DSIM Mechanical Power	4.5 kW
Nominal voltage	220 V
Frequency	50 Hz
Pole pair number	1
Stators 1,2 resistances	3.72 Ω
Rotor resistance	2.12 Ω
Stators 1,2 self inductances	0.022 H
Rotor inductance	0.006 H
Mutual inductance	0.3672 H
Moment of inertia	0.0625 Nms ² /rad
Friction coefficient	0.001 Nms/rad

List of abbreviations and symbols:

Designation	Abbreviations
Doubly Star Induction Motor	DSIM
Direct Torque Control	DTC
Proportional and Integral	PI
Fuzzy Logic Controller	FLC
Voltage Source Inverter	VSI
the rotor angular speed	Ω_r
Electromagnetic torque	C_{em}
Friction coefficient	K_f
Moment of inertia	J
Load torque	C_r
Angle between stator and rotor flux	θ_s
Number of pole pairs	p