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Speed control of doubly star induction motor (DSIM) using direct field oriented control (DFOC) based on fuzzy logic controller (FLC)

Lallouani Hellali*, Saad Belhamdi

Electrical Engineering Laboratory, University of Mohamed Boudiaf- Msila, Algeria

Corresponding Author Email: alouani28@live.fr

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ABSTRACT

The aim for this paper is a proportional and integral (PI) controller and fuzzy logic (FLC) controller devoted to improve the performance of Direct field orient control (DFOC) strategy of doubly star induction motor (DSIM) fed by two inverters. In addition, the paper describes a model of doubly star induction motor in d-q reference frame theory and its computer simulation in MATLAB/SIMULINK®, fed by Pulse Width Modulation (PWM) inverter to be studied. The performance of the Direct Field orientated control with a PI and FLC is tested under different speed command and load disturbances. And also show a better robustness beside the parametric variations of the motor.

1. INTRODUCTION

Nowadays, many industry segments need doubly star induction motors are one of widely used motor. 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 higher than the one usually used in three-phase AC machine drives. This machine has been used required in many applications, such as pumps, fans, compressors, rolling mills, cement mills, mine hoists [1].

In recent years, the multiphase machines, five-phase and six-phase induction are the most considered in the literature. The present study is focused on the doubly star Induction motor. This type of machine is composed by two three-phase windings shifted by 30 degrees and a standard simple squirrel-cage rotor [2].

In order to ensure an effective control of DSIM, several methods have been proposed [3]. An alternative solution is the use of Direct Rotor-Field-Oriented Control (DFOC) is modern technique for high-performance control of PWM inverter fed DSIM. To achieve a variable speed operation a power electronics inverter can be used. The Direct field oriented control theory is the base of a special control method for doubly star induction motor drives. With this theory doubly star induction motors can be controlled like a separately excited dc motor. This method enables the control of field and torque of the DSIM independently (decoupling) by manipulating the corresponding field oriented quantities [4-5, 11, 14].

In the aim to improve the performance of the electrical drives based on traditional DFOC, fuzzy logic direct oriented control attracts more and more the attention of many scientists the configuration and design of the fuzzy Logic Controller for the direct field oriented based control of DSIM. The proposed fuzzy logic controller has been successfully simulated on a simulink model with the help of fuzzy logic toolbox. The performance of the FLC compared with the conventional PI controller. The proposed FLC is insensitive to torque and speed command variation changes and changes in parameter variations.

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 Field Oriented control by a fuzzy logic controller; the designed direct field oriented models are introduced and explained, In order to improve the static and dynamic control performance of the DSIM in section 3. Section 4 shows simulation results for a comparison between the performances of FLC speed controller of direct field oriented control DSIM with those obtained from conventional PI controller under various conditions operation (resistant torque, reference speed and parameter variations). The section 5 concludes this paper.

2. MACHINE MODELING

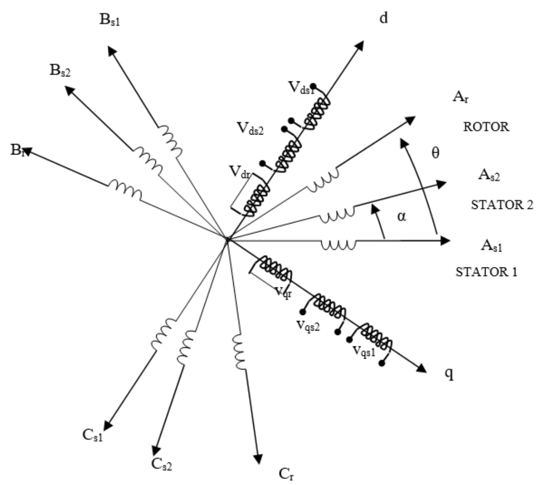


Figure 1. Doubly stator winding representation

The doubly stator induction machine represented by two stators windings: A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2} which are displaced by $\alpha=\pi/6$ electrical angle .and the rotor windings (A_r, B_r, C_r) are sinusoidal distributed and have axes that are displaced apart by $2\pi/3$ [6].

The usual assumptions are adopted [7]:

Motor windings are sinusoidal distributed, and the saturation of magnetic circuit is neglected, and the two stars have same parameters, and the flux path is linear.

The windings of the DSIM are shown in Figure. 1

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

$$[V_{s1,abc}] = [R_{s1}][i_{s1,abc}] + \frac{d}{dt}[\Phi_{s1,abc}][V_{s2,abc}] = [R_{s2}][i_{s2,abc}] + \frac{d}{dt}[\Phi_{s2,abc}]0 = [R_r][i_{r,abc}] + \frac{d}{dt}[\Phi_{r,abc}] \qquad (1)$$

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 d- and q-axes should be presented in state space frame [9]:

$$\dot{X} = AX + BU$$

With, $X = [\Phi_{s1d}\Phi_{s2d} \quad \Phi_{s1q} \quad \Phi_{s2q} \quad \Phi_{rd} \quad \Phi_{rq}]^T$

$U = [V_{s1d}V_{s2d} \quad V_{s1q} \quad V_{s2q} \quad 0 \quad 0]^T$

$I = [i_{s1d}i_{s2d} \quad i_{s1q} \quad i_{s2q} \quad i_{rd} \quad i_{rq}]^T$

where:

$V_{s1,dq}$, $V_{s2,dq}$: Stator voltages dq components.

$i_{s1,dq}$, $i_{s2,dq}$, $i_{r,dq}$: Stator and Rotor currents dq components.

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

$$A = \begin{bmatrix} -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & \omega s & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} & 0 \\ \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \omega s & \frac{R_{s2}L_a}{L_{s2}L_r} & 0 \\ -\omega s & 0 & -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} \\ 0 & -\omega s & \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} \\ \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_{s2}L_r} & 0 & 0 & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) & \omega_{gl} \\ 0 & 0 & \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_{s2}L_r} & -\omega_{gl} & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) \end{bmatrix}$$

$$[A] = [A_{11}] + [A_{12}]\omega_s + [A_{13}]\omega_{gl}$$

$$[A_{12}] = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad [A_{13}] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}$$

$$A_{11} = \begin{bmatrix} -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} & 0 \\ \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} & 0 \\ 0 & 0 & -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} \\ 0 \quad 0 & 0 & \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} \\ \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_{s2}L_r} & 0 & 0 & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) & 0 \\ 0 & 0 & \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_{s2}L_r} & 0 & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) \end{bmatrix}$$

The relation flux (Φ_{s1d},Φ_{s2d} , Φ_{s1q},Φ_{s2q},Φ_{rd}, andΦ_{rq}) and current (i_{s1d},i_{s2d} , i_{s1q},i_{s2q},i_{rd} andi_{rq}) are [9].

$$X = [H]I \qquad (2)$$

$$[H]=\begin{bmatrix} L_{s1}+L_m & L_m & 0 & 0 & L_m & 0 \\ L_m & L_{s2}+L_m & 0 & 0 & L_m & 0 \\ 0 & 0 & L_{s1}+L_m & L_m & 0 & L_m \\ 0 & 0 & L_m & L_{s2}+L_m & 0 & L_m \\ L_m & L_m & 0 & 0 & L_r+L_m & 0 \\ 0 & 0 & L_m & L_m & 0 & L_r+L_m \end{bmatrix}$$

where:

Lm: 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.

Where definitions are given in (3), (4). The electromagnetic torque and the mechanical equations can be written as:

$$C_{em}=p\frac{L_m}{L_m+L_r}\left(\Phi_{rd}(i_{s1q}+i_{s2q})-\Phi_{rq}(i_{s1d}+i_{s2d})\right) \quad (3)$$

$$J\frac{d\Omega}{dt}=C_{em}-C_r-K_f\Omega \quad (4)$$

3. FIELD ORIENTED CONTROL

The field oriented control technique relies on decoupling the machine torque and flux control [5]. We can obtain the DC machine like performance in holding a fixed and orthogonal orientation between the fields and armature fields in an AC machine by orienting the stator current with respect to rotor flux so as to attain independently controlled flux and torque.

There are essentially two general methods of vector control.

3.1 Indirect Field Oriented Control (IFOC)

In this method the angle is obtained by using rotor position measurement and machine parameter's estimation [10].

3.2 Direct Field Oriented Control (DFOC)

In direct FOC the rotor angle or control vector is obtained by the terminal voltages and currents directly by using flux estimators [12,18].

By applying this principle of field oriented control($\Phi_{rd}=\Phi_r^*$ to equations (1) (2) and (3), the final expression of the component references of slip speed ω_{sr} and the electromagnetic torque can be expressed as:

$$\omega_{sr}^*=\frac{R_rL_m}{(L_m+L_r)\Phi_r^*}(i_{s1q}+i_{s2q}) \quad (5)$$

$$C_{em}^*=\left(\frac{p\,L_m\Phi_r^*}{L_m+L_r}\right)(i_{s1q}+i_{s2q}) \quad (6)$$

The relation voltage references (V_{s1d}^*,V_{s1q}^*,$V_{s2d}^*$and V_{s2q}^*) and currents stator components are:

$$\begin{cases} V_{s1d}^*=R_{s1}i_{s1d}+L_{s1}\frac{d}{dt}i_{s1d}-\omega_s^*(L_{s1}i_{s1d}+T_r\omega_{sr}^*\Phi_r^*) \\ V_{s2d}^*=R_{s2}i_{s2d}+L_{s2}\frac{d}{dt}i_{s2d}-\omega_s^*(L_{s2}i_{s2d}+T_r\omega_{sr}^*\Phi_r^*) \\ V_{s1q}^*=R_{s1}i_{s1q}+L_{s1}\frac{d}{dt}i_{s1q}+\omega_s^*(L_{s1}i_{s1d}+\Phi_r^*) \\ V_{s2q}^*=R_{s2}i_{s2q}+L_{s2}\frac{d}{dt}i_{s2q}+\omega_s^*(L_{s2}i_{s2q}+\Phi_r^*) \end{cases} \quad (7)$$

where $T_r=\frac{L_r}{R_r}$

This expression of the torque clearly shows the dependence between the quadrature stator currents and the reference flux, because of this, a necessary to decouple torque and flux control of this machine by introducing new variables:

$$\begin{cases} V_{s1d}=R_{s1}i_{s1d}+L_{s1}\frac{d}{dt}i_{s1d} \\ V_{s2d}=R_{s2}i_{s2d}+L_{s2}\frac{d}{dt}i_{s2d} \\ V_{s1q}=R_{s1}i_{s1q}+L_{s1}\frac{d}{dt}i_{s1q} \\ V_{s2q}=R_{s2}i_{s2q}+L_{s2}\frac{d}{dt}i_{s2q} \end{cases} \quad (8)$$

The equation system (8) shows that stator voltages (V_{s1d}, V_{s2d}, V_{s1q}, V_{s2q}) are directly related to stator currents (i_{s1d}, i_{s2d}, i_{s1q}, i_{s2q}). To compensate for the error introduced during decoupling, the reference stator voltages (V_{s1d}^*, V_{s2d}^*, V_{s1q}^*, V_{s2q}^*) are given by [13,17]:

$$\begin{cases} V_{s1d}^*=V_{s1d}-V_{s1dc} \\ V_{s2d}^*=V_{s2d}-V_{s2dc} \\ V_{s1q}^*=V_{s1q}+V_{s1qc} \\ V_{s2q}^*=V_{s2q}+V_{s2qc} \end{cases} \quad (9)$$

With

$$\begin{cases} V_{s1dc}=\omega_s^*(L_{s1}i_{s1d}+T_r\omega_{sr1}^*\Phi_r^*) \\ V_{s2dc}=\omega_s^*(L_{s2}i_{s2d}+T_r\omega_{sr}^*\Phi_r^*) \\ V_{s1qc}=\omega_s^*(L_{s1}i_{s1d}+\Phi_r^*) \\ V_{s2qc}=\omega_s^*(L_{s2}i_{s2q}+\Phi_r^*) \end{cases} \quad (10)$$

For a perfect decoupling, we add stator currents regulation loops (i_{s1d}, i_{s2d}, i_{s1q}, i_{s2q}).and we obtain at their output stator voltages (V_{s1d}, V_{s2d}, V_{s1q}, V_{s2q}). The goal of the regulation is to assure a best robustness to intern or extern perturbations. In this work, proportional integral and fuzzy regulators have been used.

3.2.1. Rotor Flux Estimation

In direct vector control method, it is necessary to estimate the rotor flux components Φ_{rd} and Φ_{rq} the components of rotor flux can be estimated by:

$$\frac{d}{\mathrm{dt}}\Phi_{\mathrm{rdest}} = \left(\frac{R_r L_m}{L_m+L}\right)(i_{\mathrm{s1d}} + i_{\mathrm{s2d}}) + \omega_{\mathrm{sr}}{}^{*}\Phi_{\mathrm{rqest}} - \frac{R_r L_m}{L_m+L}\Phi_{\mathrm{rdest}} \quad \frac{d}{\mathrm{dt}}\Phi_{\mathrm{rqest}} = \left(\frac{R_r L_m}{L_m+L}\right)(i_{\mathrm{s1q}} + i_{\mathrm{s2q}}) - \omega_{\mathrm{sr}}{}^{*}\Phi_{\mathrm{rdest}} - \frac{R_r L_m}{L_m+L}\Phi_{\mathrm{rqest}} \tag{11}$$

The rotor flux amplitude is given by:

$$|\Phi_{\mathrm{rest}}| = \sqrt{\Phi_{\mathrm{rdest}}{}^{2} + \Phi_{\mathrm{rqest}}{}^{2}} \tag{12}$$

3.2.2. Principe of a fuzzy controller

The control by fuzzy logic permits to obtain a law of drive, often very effective, without having a precise model of the process, from a linguistic description of the behavior of the system. Its approach is different the one of the automatic classic, in the sense that it does not treat mathematical relations well defined, but it exploits the knowledge of an expert. These are expressed by means of conduct rules based on a symbolic vocabulary and manipulate inferences with several rules using the fuzzy operators AND, OR, THEN, applied to linguistic variables. [15].

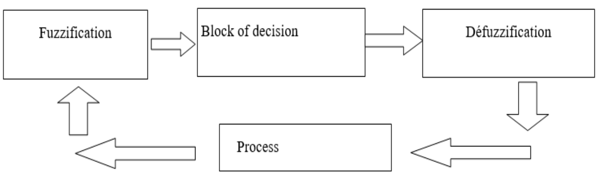


Figure 2. Structure interns of a system Fuzzy

Wo inputs of speed fuzzy controller are chosen, the speed error (e) and its variation Δe:

$$e = \omega_r{}^{*} - \omega_r \tag{13}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{14}$$

Figure 3 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).

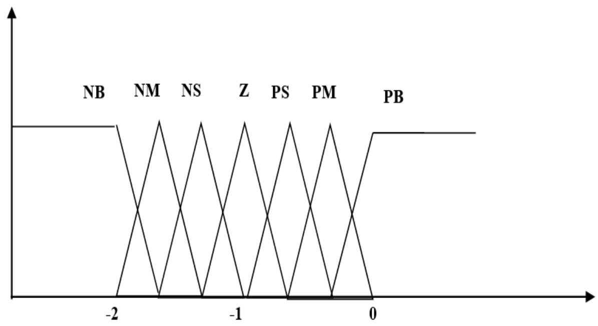


Figure 3. Fuzzification with seven memberships

Table 1 shows one of possible control rules based on seven membership functions [16].

Table 1. The fuzzy control rule bases

e / *Δe*	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 of the fuzzy logic for the DFOC approach of the DSIM is shown in figure 4.

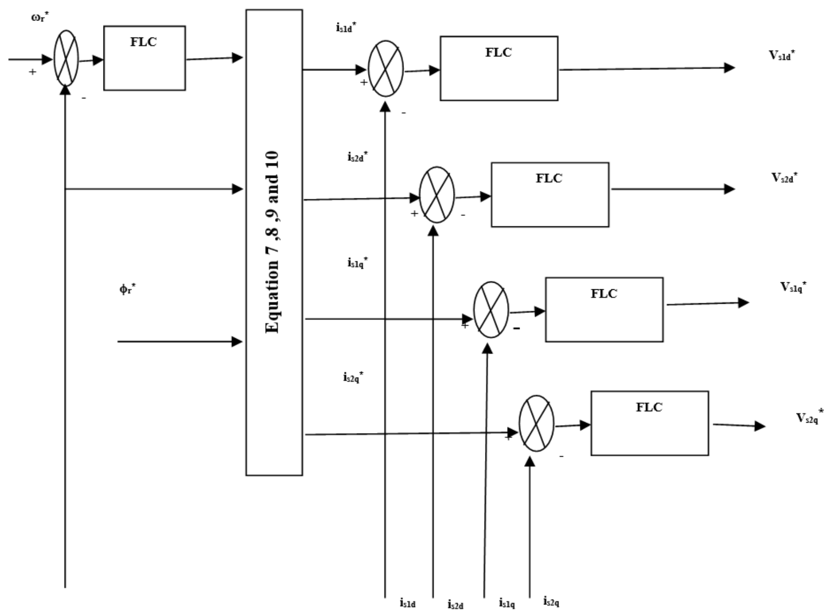


Figure 4. Block diagram of the fuzzy logic PI controller for DFOC approach of the DSIM

The general structure of the doubly stator induction motor with direct field oriented control using a two inverter in each star is represented by figure 5.

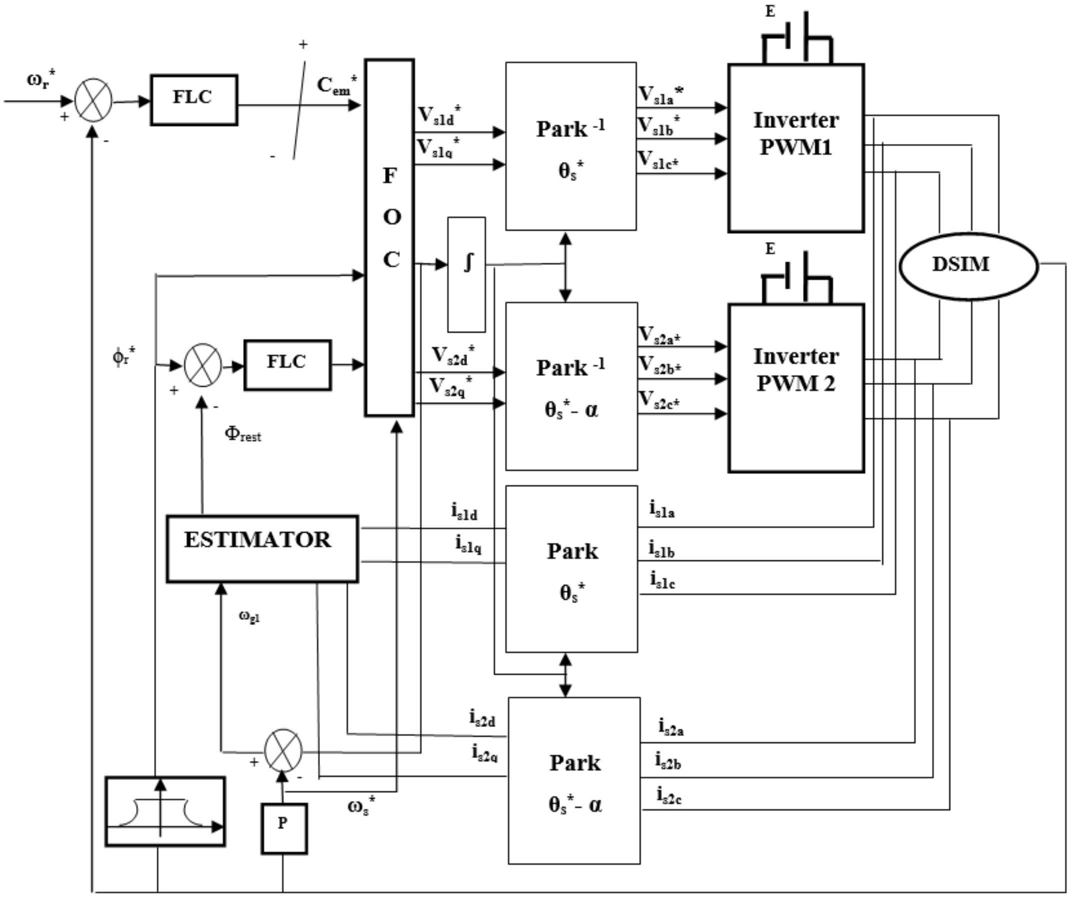
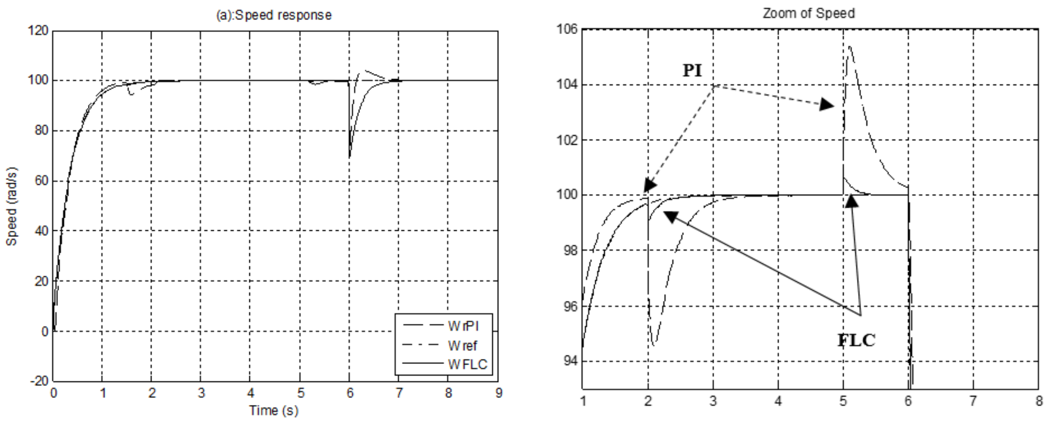


Figure 5. Structure of speed ordering for the DSIM

4. RESULTS AND DISCUSSION

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

In first test the Torque variation with the sign of resistant torque (C_r = 10N.m) during the interval]2-5] sec, and the DSIM runs with speed values (100rad/s during] 0-6] sec, 30rad/s during] 6-9] sec).



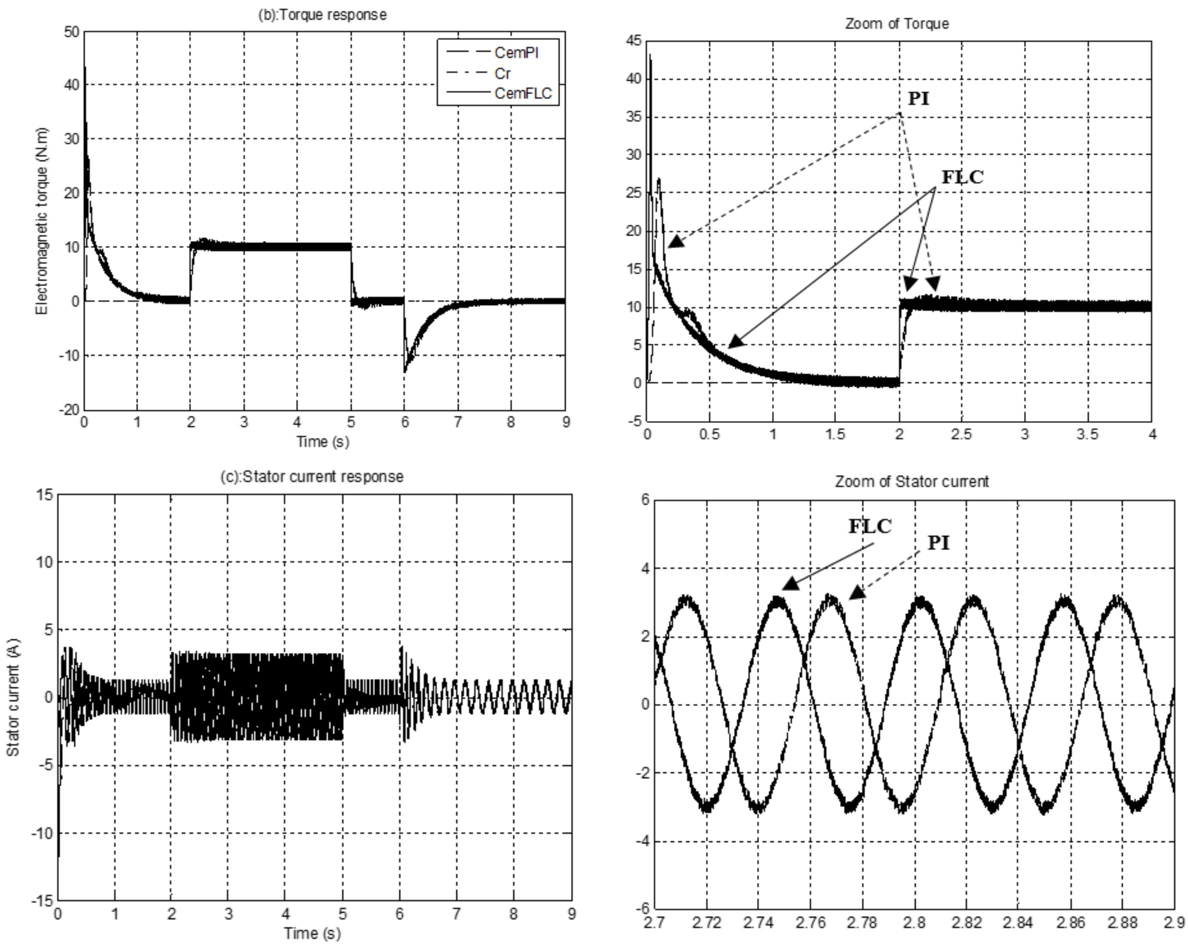


Figure 6. Speed, torque and current stator characteristic of an (DFOC) with PI and FLC

Controllers, at changes in load torque and speed.

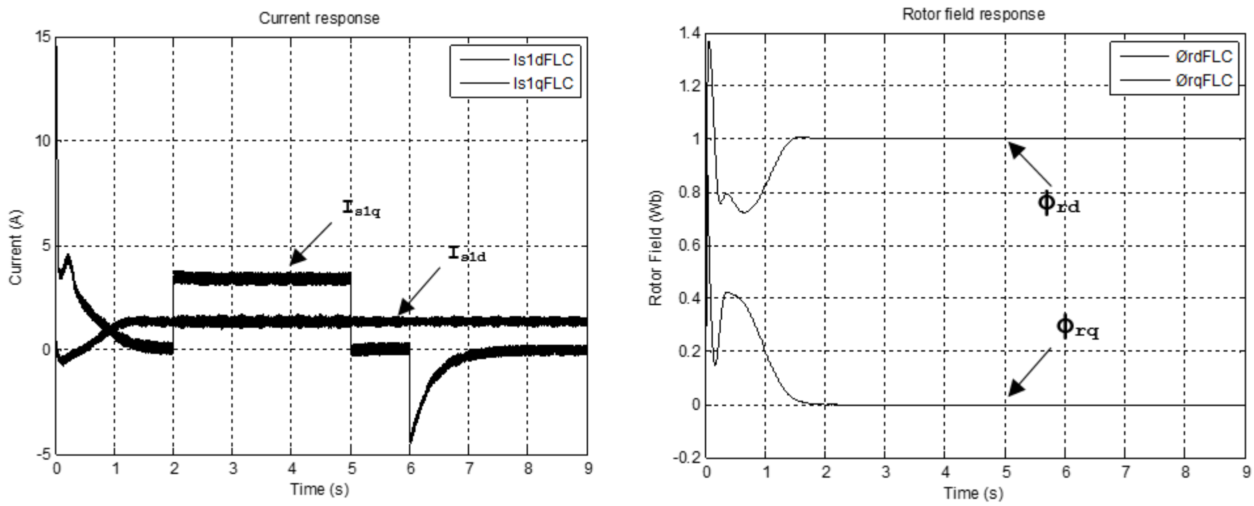


Figure 7. Decoupling and rotor field orientation

The next tests sets the parameters variations of DSIM with the two controllers (PI and FLC), the Rotor resistance changed (R_{r1}=1.5*R_r) at during] 2-5] sec, and the Moment of inertia varied (J_1=1.5*J) at during] 6-9] sec.

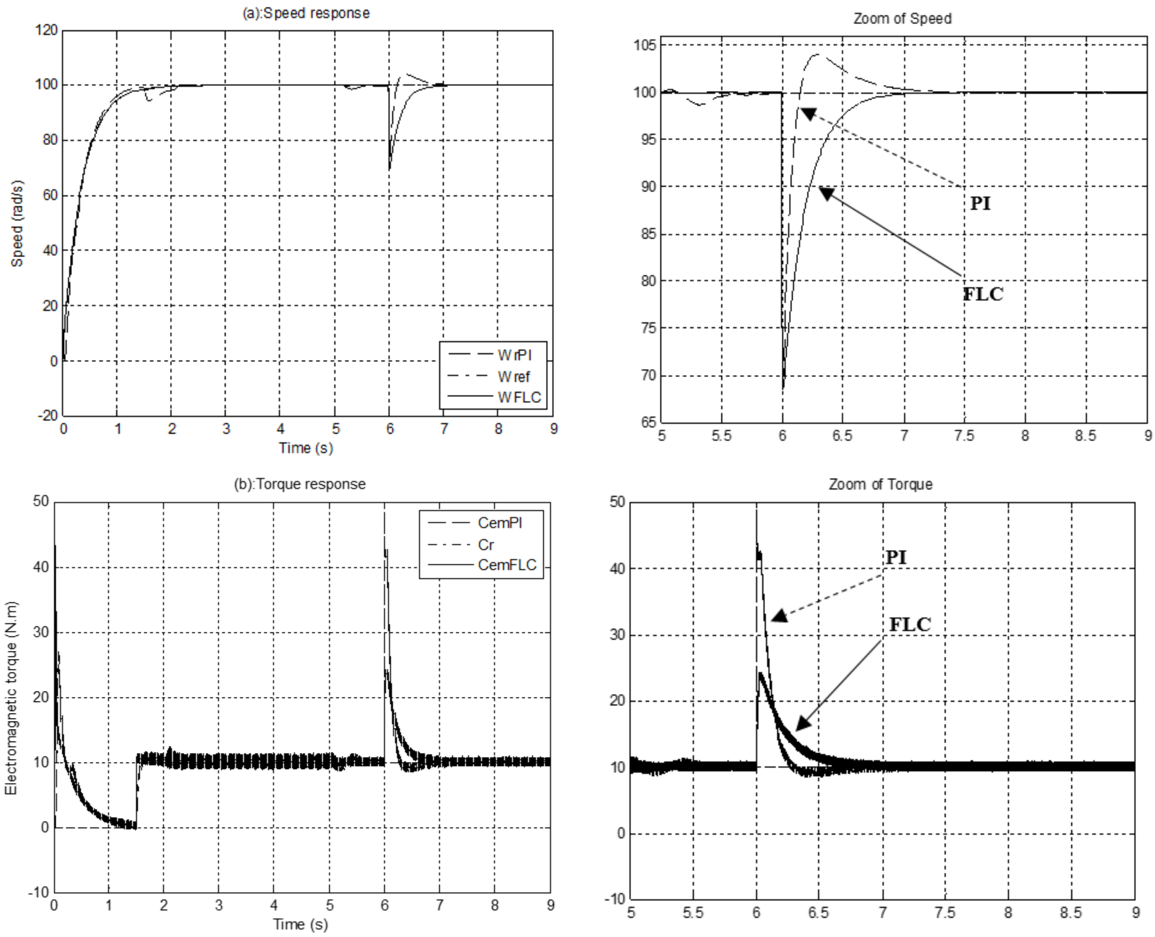


Figure 8. Speed and torque characteristic of an (DFOC) with PI and FLC controllers, at parametric variations (rotor resistance (R_{r1}=1.5*R_r), moment of inertia (J_1=1.5*J)).

Figure 6 shows that responses for DFOC 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 (44 N.m) and falls down to be close zero value because the motor running with no load. At during [2-5] sec we changed the value of load torque to C_r=10N.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.6 (b).and the change in command speed is realized as following: ([0-6] sec ω_r^*=100rad/s) and (]6-9] sec ω_r^*=30rad/s). The rotor speed obtained by the FLC track very quickly the desired reference speed than the one obtained with PI, Figure.6 (a). This test has for object the study of controller behaviors in pursuit and in regulation.

It is clear from Figure 7 the decoupling control of torque and rotor flux can be achieved in terms of d-axis and q-axis magnetizing current, respectively. The direct rotor field (Φrd) follows the reference value (1Wb) and the quadrature component (Φrq) is null. Thus, the orientation is assured, Figure 7(b).

Figure.8 shows the second test concerns a presents the behavior of FLC and PI speed control when the parameter variations (rotor resistance, moment of inertia), the change in the Rotor resistance (Rotor resistance (R_{r1})) is realized as follows: ([2-5] sec R_{r1}=1.5*R_r), and the moment of inertia is varied (moment of inertia (J_1)) at during (] 6-9] sec J_1=1.5*J). Influence of the parameter variations on the electromagnetic torque and speed response is shown in Figure.8 (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-DFOC by a PI and a FLC is presented in all figures.

In the present study, an integral squared error *(ISE*), integral absolute error (*IAE*) and integral time-weighted absolute error (*ITAE*) 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 [19-20]:

$$ISE = \int_0^T e^2(t)\,dt \quad (15)$$

$$IAE = \int_0^T |e(t)|\,dt \quad (16)$$

$$ITAE = \int_0^T t|e(t)|\,dt \quad (17)$$

Table 2. Quantitative comparison between the proposed FLC and PI controllers

Controllers Index		PI	FLC
ISE	Speed	39.38	0.6798
	Flux	0.1987	0.1971
IAE	Speed	10.5	0.6189
	Flux	0.4251	0.4117
ITAE	Speed	34.21	1.762
	Flux	0.2381	0.2142

For quantitative comparison between two methods, *ISE, IAE* and *ITAE* are used as the criterion. Table.2 shows the *ISE,* *IAE* and *ITAE* values of the simulation results using the PI controller and the proposed FLC Controller (Test1). Actually these performances index are obtained at the end of the simulation time (t=9 sec) with a sampling period h=1*e-5.

This comparison shows clearly that the FLC gives good performances and it's more robust than PI.

5. CONCLUSION

In this study, the performances of speed FLC and PI controllers for direct field oriented 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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NOMENCLATURE

DSIM	Doubly Star Induction Motor
FOC	Field Oriented Control
IFOC	Indirect Field Oriented Control
DFOC	Direct Field Oriented Control
PI	Proportional and Integral
FLC	Fuzzy Logic Controller
Ω_r	The rotor angular speed
C_{em}	Electromagnetic torque
K_f	Friction coefficient
J	Moment of inertia
C_r	Load torque

θ_s	Angle between stator and rotor flux
P	Number of pole pairs
ω_{sr}^*	Slip speed reference

APPENDIX

Table 3. DSIM parameters (Radhwane S. et al 2012)

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	0.0625Nms^2/rad
Friction coefficient	0.001Nms/rad