Fuzzy Logic Speed Controller for Dual Stator Induction Motor Based On Indirect Vector Control

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Abstract

The purpose of this paper is to improve the dynamic response performance of a double star induction motor (DSIM) based on indirect field oriented control by using the Artificial Intelligence techniques (AI) and more precisely the Fuzzy Logic. Furthermore, this work presents a model of this motor in (dq) reference frame fed by two pulse width modulation (PWM) inverters and their simulation. Firstly, the speed control of the motor is made up with help of classic proportional-integral PI regulator. Then, a fuzzy logic controller (FLC) is adopted in the control loop instead of the traditional PI regulator in order to catch the differences of the dynamic behavior of the machine. Finally, a comparison study between the two controllers is made on MATLAB/SIMULINK, the simulation results show that the intelligent controller achieved an amelioration in terms of settling time, rise time, precision and more stability against parametric and torque load variations. Also, the proposed fuzzy logic controller in this work succeeded to accomplish better results in terms of rise time by comparison to previous studies.

Keywords

Double Star Induction Machine, Proportional Integral Controller, Fuzzy Logic Controller

1. Introduction

The AC motors and more precisely the induction motors, has guaranteed an essential part in the industrial and domestic fields in the last decades and plays a crucial role in it, especially after the quick development of power electronics.

In recent years, there has been a growing trend towards the adoption of multiphase machines, particularly the dual star induction motor (DSIM). This type of machine is essentially an AC induction motor with two stators that are shifted by 30 or 60 electrical degrees. The DSIM finds applications in a wide range of fields, including electric vehicles, naval ship propulsion, industrial machinery and manufacturing. Its many benefits over the conventional three phase induction motor are one of the key factors contributing to its increasing demand in the industry. Firstly, it offers an improved magneto motive force (MMF) waveform, resulting in enhanced performance. Additionally, the DSIM helps reduce rotor current harmonics and allows for a decrease in current per phase without requiring a voltage increase. This motor also minimizes torque ripples and exhibits a higher torque density. However, perhaps the most significant advantage of the DSIM is its high fault tolerant capability. It can withstand the loss of one or even two phases, making it exceptionally reliable in demanding applications [1], [2], [3].

Multiple approaches have been suggested to guarantee an efficient control of this machine. One viable option is employing the famous method of vector orientation to achieve an optimal control of the (PWM) inverters supplied (DSIM) [4]. This method has a simple structure and is widely employed in industrial processes [5].

The (FOC) techniques' primary concepts are drawn from the d-q model of the induction motor, which entails directing the flux with the d-axis and preserving this orientation while the torque is orientated with the q-axis. The two amounts can then be managed independently as a result, and the very coupled and complicated (DSIM) can then be controller as a simple (DC) motor [6].

In general, the (FOC) strategy can be classified to direct and indirect approaches. Both of these types usually use conventional controllers like PID, PD, IP and PI [6] due to their cost-effectiveness and ease of implementation. The main disadvantages of conventional controllers and specifically the proportional integral-derivative (PID) and the proportional-integral (PI) are their sensitivity to variations in system parameters, inadequate rejection of internal perturbations and load changes and the fact that designing these controllers depend on the exact machine model with precise parameters [1].

Therefore, Researchers had tried to employ the Artificial Intelligence techniques in the field of control theory in order to overcome the shortness's of classic PID and PI regulators.

Fuzzy Logic proposed by Lotfi A. Zedeh in 1965 and developed later by several researchers; is one among the

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advanced techniques used in control engineering field for a wide range of applications from stability control of electric vehicles to Self-Tuning Controllers of induction motor drives [7]. Moreover, among all the different advanced regulators, Fuzzy Logic Controller (FLC) is the most simple, robust with less sensitivity for both source and load, also it can save more energy consumed by the induction motor especially during the transitional periods [8].

The designing process of (FLC) composes from three 03 main procedures; the first is fuzzification process that converts the crisp inputs into fuzzy sets. Then it comes the inference engine phase, which applies fuzzy rules base to determine the fuzzy output sets, and finally the defuzzification step, that converts the fuzzy output sets back into crisp output data.

The whole procedure of (FLC) makes the controlling decisions more flexible and human-like manner, it can handle easily the imprecise and uncertain informations witch consequently affects positively on the dynamic response of the system to be controlled (multiphase motor in this case) and overcome the shortages of PI regulators.

This paper is structured into six sections; the second section contain the dynamic model of the dual star induction motor (DSIM), the indirect field oriented control is presented in section three and fuzzy logic control technic is detailed in section four 04. While the simulation results are presented and discussed in section five 05, and finally the 6th section concludes the paper.

2. Induction Machine Modelling

As it name indicates, the dual star induction motor composes from 02 two stators spatially shifted with 30 electrical degrees and share a common magnetic core as shown in figure1 bellow; Also, they are assumed identical in all intern parameters (resistance, inductance, number of phases …) with a sinusoidaly distributed windings and neglected saturation for the magnetic circuit [1], [4], [5].

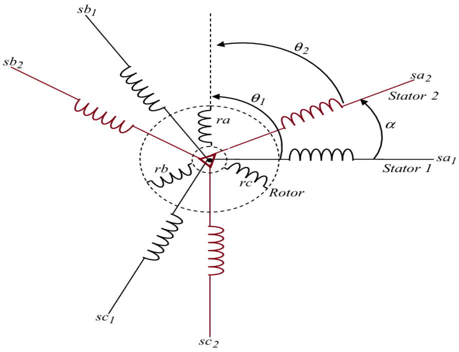

Figure 1: Structure of the DSIM windings.

The system of equations below represents the electric equations for the model of (DSIM) in the (dq) reference frame [9]:

$$\begin{cases} V_{ds1} = R_s.I_{ds1} + \dfrac{d}{dt}\varphi_{ds1} - \omega_s.\varphi_{qs1} \\ V_{ds2} = R_s.I_{ds2} + \dfrac{d}{dt}\varphi_{ds2} - \omega_s.\varphi_{qs2} \\ V_{qs1} = R_s.I_{qs1} + \dfrac{d}{dt}\varphi_{qs1} + \omega_s.\varphi_{ds1} \\ V_{qs2} = R_s.I_{qs2} + \dfrac{d}{dt}\varphi_{qs2} + \omega_s.\varphi_{ds2} \\ V_{dr} = R_r.I_{dr} + \dfrac{d}{dt}\varphi_{dr} - (\omega_s - \omega_r).\varphi_{qr} = 0 \\ V_{qr} = R_r.I_{qr} + \dfrac{d}{dt}\varphi_{qr} + (\omega_s - \omega_r).\varphi_{dr} = 0 \end{cases} \tag{1}$$

Where the stators and rotor flux linkages are expressed by the system of equations bellow in the (dq) reference frame [9]:

$$\begin{cases} \varphi_{ds1} = L_s.I_{ds1} + L_m.(I_{ds1} + I_{ds2} + I_{dr}) \\ \varphi_{ds2} = L_s.I_{ds2} + L_m.(I_{ds1} + I_{ds2} + I_{dr}) \\ \varphi_{qs1} = L_s.I_{qs1} + L_m.(I_{qs1} + I_{qs2} + I_{qr}) \\ \varphi_{qs2} = L_s.I_{qs2} + L_m.(I_{qs1} + I_{qs2} + I_{qr}) \\ \varphi_{dr} = L_r.I_{dr} + L_m.(I_{ds1} + I_{ds2} + I_{dr}) \\ \varphi_{qr} = L_r.I_{qr} + L_m.(I_{qs1} + I_{qs2} + I_{qr}) \end{cases} \tag{2}$$

and electromagnetic torque T_e can be expressed as [9]:

$$T_e = p.\frac{L_m}{L_m + L_r}.[\varphi_{dr}.(I_{qs1}+I_{qs2}) - \varphi_{qr}.(I_{ds1}+I_{ds2})] \tag{3}$$

While the expression that describes the mechanical dynamic behavior is [9]:

$$J.\frac{d\Omega}{dt} = T_e - T_r - f.\Omega \tag{4}$$

Where:

R_s, L_s, R_r and L_r are the resistances and inductances of the stator and rotor respectively, $L_m$is the cyclic mutual inductance between stator 1, stator 2 and rotor.

$V_{ds1,2}$, $V_{qs1,2}$, $I_{ds1,2}$ and $I_{qs1,2}$ are the two 02 stators voltages and currents respectively in the (dq) reference frame; while V_{dr}, V_{qr}, I_{dr} and I_{qr} are rotor voltages and currents.

Also, we have the synchronous reference frame and rotor electrical angular speeds ω_s, ω_r With J the moment of inertia, T_r the load torque, f the coefficient of viscous friction, and Ω the mechanical rotor speed.

3. Field oriented control model

The control approach discussed in this paper enables the tracking of the drive operating point to guarantee the best possible operating conditions. This control strategy is based on indirect vector control orientation which has made conceivable use of motor drives for industrial applications operates under high performance needed [5], [10].

A double star induction motor can be presented by utilizing four 04 quadrature current components (02 for every stator) instead of dual three-phase currents originally fed to the motor. The two currents alimenting each stator are known as direct (id) and quadrature (iq), they are in charge of creating flux and torque separately in motor and each one of those four currents is controlled with its correspondent regulator [10].

The orientation of the synchronously rotating frame (dq) such that the d-axis aligned along the rotor flux vector φ_{dr} and q-axis with φ_{qr} with the last one equal to zero will eventually ensure decoupling between the torque and flux and an AC motor behavior similar to DC motor [6].

When the technique of rotor field orientation applied on the (DSIM) model, we will have the following conditions [11]:

$$\begin{cases} \varphi_{dr} = \varphi_r \\ \varphi_{qr} = 0 \end{cases} \tag{5}$$

And the flux linkages expression will become [11]:

$$\begin{cases} \varphi_{ds1} = \lambda_1.I_{ds1} + L_r.\eta.I_{ds2} + \eta.\varphi^*_{r\,ref} \\ \varphi_{ds2} = \lambda_2.I_{ds2} + L_r.\eta.I_{ds1} + \eta.\varphi^*_{r\,ref} \\ \varphi_{qs1} = \lambda_1.I_{qs1} + L_r.\eta.I_{qs2} \\ \varphi_{qs2} = \lambda_2.I_{qs2} + L_r.\eta.I_{qs1} \end{cases} \tag{6}$$

With: $\eta = \frac{L_m}{L_m+L_r}$ and: $\lambda_{1,2} = L_{s1,2} + \eta.L_r$

The main expression of voltages will be as follow [11]:

$$\begin{cases} V_{ds1(ref)} = R_s.I_{ds1} + L_{s1}.\dfrac{dI_{ds1}}{dt} - \\ \qquad \omega^*_{s\,ref}.(L_s.I_{qs1} + T_r.\varphi^*_{r\,ref}.\omega^*_{gl(ref)}) \\ V_{ds2(ref)} = R_s.I_{ds2} + L_{s2}.\dfrac{dI_{ds2}}{dt} - \\ \qquad \omega^*_{s\,ref}.(L_s.I_{qs2} + T_r.\varphi^*_{r\,ref}.\omega^*_{gl(ref)}) \\ V_{qs1(ref)} = R_s.I_{qs1} + L_{s1}.\dfrac{dI_{qs1}}{dt} + \\ \qquad \omega^*_{s\,ref}.(L_s.I_{ds1} + \varphi^*_{r\,ref}) \\ V_{qs2(ref)} = R_s.I_{qs2} + L_{s2}.\dfrac{dI_{qs2}}{dt} + \\ \qquad \omega^*_{s\,ref}.(L_s.I_{ds2} + \varphi^*_{r\,ref}) \end{cases} \tag{7}$$

With: $T_r = \frac{L_r}{R_r}$ and: $\omega^*_{gl(ref)} = \omega^*_{s\,ref} - \omega_r$

Also, we will have the following expressions of the component references of slip speed and electromagnetic torque [4], [11]:

$$\omega^*_{gl\,ref} = \frac{R_r.L_m}{(L_m + L_r).\varphi^*_{r\,ref}}.(I_{qs1} + I_{qs2}) \tag{8}$$

$$T^*_{e\,ref} = p.\frac{L_m}{L_m + L_r}.\varphi^*_{r\,ref}.(I_{qs1} + I_{qs2}) \tag{9}$$

The system of equations (7) is composed of two terms and it is clearly obvious they are not completely independent from each other and the quadrature stators currents with flux reference still not perfectly free to be controlled [11], [12].

To fix that shortness it is good idea to use the decomposition method to guarantee flux and torque completely decoupling, The system (7) will be decomposed into two parts [11], [12]:

First Part (Linear Part). consists of introducing the linear stators voltages $V_{ds1\,L}$, $V_{ds2\,L}$, $V_{qs1\,L}$ and $V_{qs2\,L}$ which they are directly related to the stators currents I_{ds1}, I_{ds2}, I_{qs1} and I_{qs2} respectively [11], [12].

$$\begin{cases} V_{ds1\,L} = R_s.I_{ds1} + L_s.\dfrac{dI_{ds1}}{dt} \\ V_{ds2\,L} = R_s.I_{ds2} + L_s.\dfrac{dI_{ds2}}{dt} \\ V_{qs1\,L} = R_s.I_{qs1} + L_s.\dfrac{dI_{qs1}}{dt} \\ V_{qs2\,L} = R_s.I_{qs2} + L_s.\dfrac{dI_{qs2}}{dt} \end{cases} \tag{10}$$

Second part (Compensation part). Consists of introducing the compensating stator voltages $V_{ds1\,C}$, $V_{ds2\,C}$, $V_{qs1\,C}$ and $V_{qs2\,C}$ which they are calculated on function of stators currents, synchronism pulsation, slip speed and the reference of rotor flux [11], [12].

$$\begin{cases} V_{ds1\,C} = \omega^*_{s\,ref}.(L_s.I_{qs1} + T_r.\varphi^*_{r\,ref}.\omega^*_{gl\,ref}) \\ V_{ds2\,C} = \omega^*_{s\,ref}.(L_s.I_{qs2} + T_r.\varphi^*_{r\,ref}.\omega^*_{gl\,ref}) \\ V_{qs1\,C} = \omega^*_{s\,ref}.(L_s.I_{ds1} + \varphi^*_{r\,ref}) \\ V_{qs2\,C} = \omega^*_{s\,ref}.(L_s.I_{ds2} + \varphi^*_{r\,ref}) \end{cases} \tag{11}$$

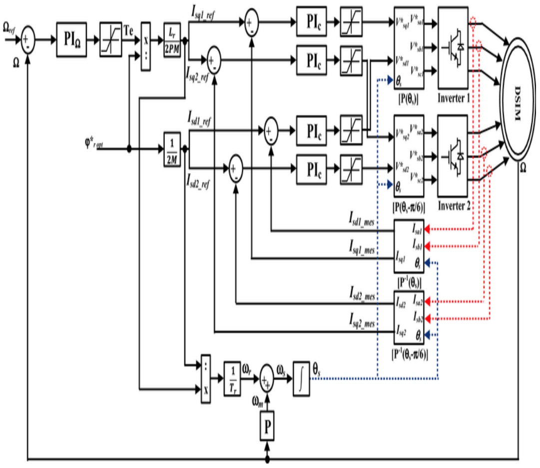

Figure 2: Control scheme of DSIM operating under IRFOC.

In order to get perfect decoupling, a control loops for stators currents are added and the stator voltages are obtained at their outputs [12].

Finally, the block diagram for an indirect field oriented controller of (DSIM) is represented in “Fig. 2” above (in previous page).

3.1. PI Controller

To realize vector control for dual star induction motor, a PI regulator must be implemented to control the stator currents, the flux and the speed. This classic controller is commonly used in industries due to its high performance of electric drives, rapid dynamic response, null steady state error and more importantly its simplicity in implementation [6],[9],[12].

Actually, we must remind out that, regardless how simple and effective the PI regulators are, but picking the wrong or inappropriate PI gains might have an impact on the system variables. Furthermore, even if PI gains were chosen in the most optimal manner possible, the dynamic behavior of the system may still have certain shortcomings (rising time, settling time, overshot, undershot, precision ...) [6].

3.2. PI Speed Controller

Speed controllers plays vital role in IRFOC, because it determines the reference torque needed to maintain the corresponding reference speed.

The dynamic model of speed control for double stator induction motor is represented by “Fig. 3” bellow [6],[9]: The closed buckle’s transfer function for speed control if $T_r = 0$, is as follows [6]:

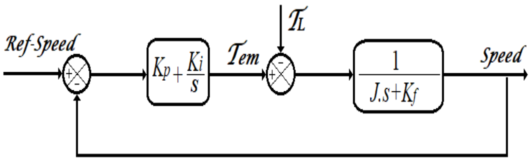

Figure 3: Block diagram of speed control.

$$G(s) = \frac{K_{ps}.S + K_{is}}{J.S^2 + (K_{ps} + f).S + K_{is}} \tag{12}$$

By comparison, of the dominator with respect to that of a system of second order, we find [6]:

$$\begin{cases} K_{is} = J\omega_n^2 \\ K_{ps} = \dfrac{2\xi}{\omega_n}.K_{is} - f \end{cases} \tag{13}$$

4. Speed Control with Fuzzy Logic

Speed control of induction motors is crucial in industrial applications for precise control over rotational speed, leading to increased efficiency and performance.

Advanced AI techniques, including fuzzy logic, machine learning and deep learning algorithms, offer numerous benefits over traditional methods, such as improved efficiency, accurate speed regulation (in terms of: rising time, settling time, overshot elimination and precision in steady-state), enhanced overall performance, fault detection and adaptability plus reducing complex systems. By optimizing energy consumption, ensuring consistent product quality, and adapting to variable load conditions, cost savings, sustainability, and enhanced productivity in industries relying on induction motors for their processes.

4.1. Fuzzy Logic Controller

Fuzzy logic theory is based on the strategy of artificial intelligence that was first proposed and put its theoretical foundations in 1965 by Lotfi Zedeh, it is powerful tool that helps to overcome the shortness’s of classic PI regulators [4], [9].

Fuzzy logic can be used as an excellent controller, it is mostly used for complex nonlinear analyses and nonlinear loads because it does not need a precise mathematical model of the process to generate an effective law of drive, it only requires an expert to choose wisely the fuzzy rules and fuzzy inference system parameters [4], [6], [8]. FLC or Fuzzy Logic Controller is an advanced speed control system that has two inputs and one single output. It is composed generally from three 03 main units [4], [8], [13]:

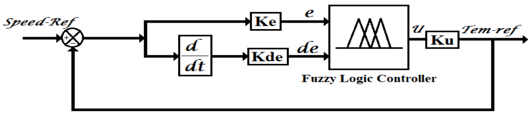

Figure 4: Fuzzy Logic Speed Controller Structure.

The first is fuzzification unit that includes the wise choose by an expert for the membership functions, linguistic variables and universe of discourses. For example, in our study we have decided to use triangular mfs because the subject of control (speed error) varies in range of −X to X and it is preferred in such cases to use symmetric membership function.

The second unit is fuzzy inference system; it contains linguistic fuzzy base rules based on method of Mamdani, the following examples explains the logic behind selecting our fuzzy rules:

Table 1
Fuzzy rules used in the design of the FLC

E ΔE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	Z
NM	NB	NB	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PB	PB
PB	Z	PVS	PS	PM	PB	PB	PB

- If speed error is negative and speed derivative is also negative, then it means that real speed curve is above reference curve. Therefore, we need to decrease the speed in order to lead the speed curve down to its reference.
- If speed error is zero and speed derivative is also zero, then it means that real speed curve is aligned on the reference curve. Therefore, we need to maintain the speed control signal.
- If speed error is positive and speed derivative is also positive, then it means that real speed curve is under reference curve. Therefore, we need to increase the speed in order to lead the speed curve up to its reference.

The third and final process is the defuzzification unit; it generates a control response using the center of gravity rule to generate signals that drives the system.

In addition, to ensure better performance of the controller, it is required to normalize the input variables and de-normalize the output variable by choosing suitable scaling factors. Selection of these scaling factors usually done by using trial and error basis [13].

The first input of this intelligent controller is error (e), which is the difference between the reference speed and the actual speed, while the second is for the derivative of error (de). These two inputs defined by the following equations [6], [9]:

$$\begin{cases} e_\Omega(k) = \Omega_{ref}(k) - \Omega(k) \\ de_\Omega(k) = e_\Omega(k) - e_\Omega(k-1) \end{cases} \tag{14}$$

The figure bellow represents the fuzzy inference system used in fuzzification step for the two inputs, it contains seven 07 triangular membership functions, with universe of discourses limited between [-1 1]. The fuzzy sets designed according to the following labels:

- “N”, “P” refers for negative and positive respectively,
- “B”, “M” and “S” refers for Big, Medium and Small,
- “Z” refers for Zero.

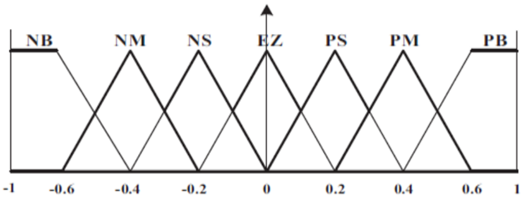

Figure 5: Membership Functions of "e" and "de".

While the output (du) have 09 mfs, with: NVS (Negative Very Small) and PVS (Positive Very Small). The table above illustrates fuzzy rules that defines output of the controller based on its two inputs.

Moreover, the control surface of the output U is shown in “Fig. 6”:

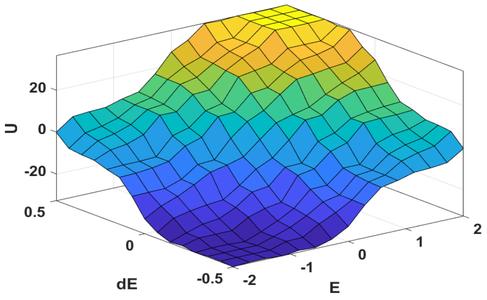

Figure 6: Fuzzy control surface.

5. Simulation Results and Interpretation

In this section, we present the simulation results and comparative analysis of speed controllers for a dual stator induction motor utilizing both Proportional-Integral (PI) and Fuzzy Logic controller (FLC). The simulations were conducted over a time span of 4 seconds for each test scenario to evaluate the controllers' performance under various operating conditions. The primary objective of these tests is to assess and compare the effectiveness of both controllers in regulating the motor's speed, especially in the presence of load torque variations and abrupt changes in rotor reference speed; the key metrics considered for evaluation included the rising time, settling time, overshot and steady-state error. These metrics will provide valuable insights into the controllers' capabilities in achieving accurate and robust speed control.

5.1. Normal Conditions Test:

The first test involved running the motor under normal operating conditions, without any external disturbances or load variations. This scenario serves as the baseline for assessing the controllers' ability to reach the nominal speed and achieve good performances especially in the transitional period.

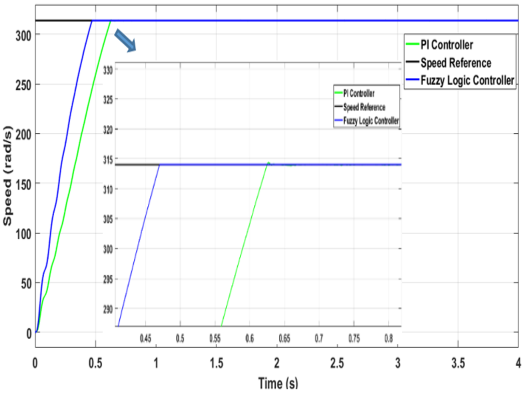

Figure 7: Speed during First Test.

The "fig.7" above represents the dynamic speed response of (DSIM) with both FLC and PI controllers' in function of time. We notice that the speed curve of FLC controller has better rise and settling time compared to the green curve of PI controller; also, we noticed that the last one had a small overshot of 0.12% contrary to the intelligent controller that reached the reference speed without any influencing shortness in term of overshot or undershot (only 0.01%).

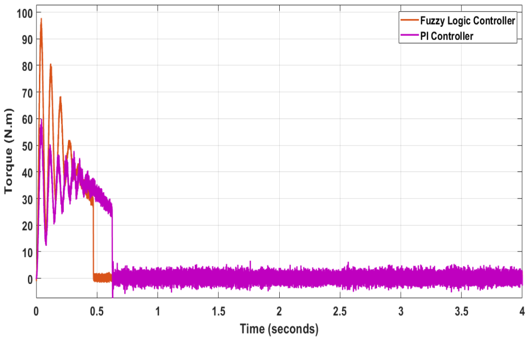

Figure 8: Electromagnetic Torque during First Test.

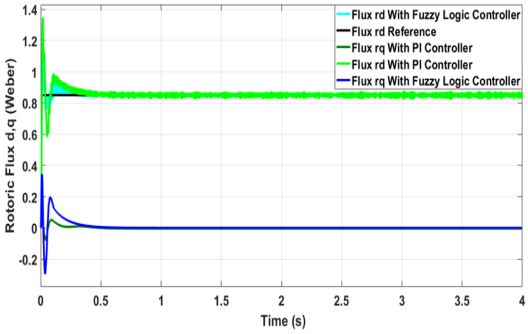

Figure 9: Rotor Flux in (dq) Reference during First Test.

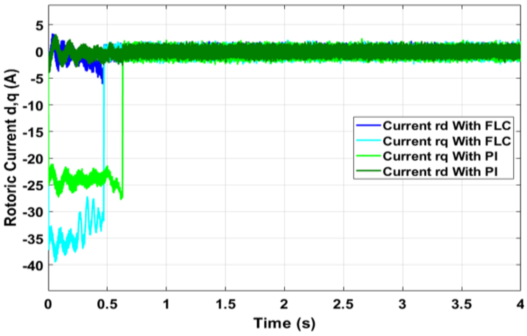

Figure 10: Rotor Currents in (dq) Reference during First Test.

While the figure after, represents the electromagnetic torque in function of time, we notice that the curve of FLC had less amplitude of torque ripples in steady state, which minimizes the electrodynamic effect on the motor.

The third and fourth figure of rotor flux and currents in the (dq) rotating reference frame proves that the main Principe of indirect field oriented control (IFOC) is achieved successfully.

Table 2
Dynamic Performances Results during first Test

	PI	FLC
Overshoot (%)	0.1176	0.0130
Rise Time (s)	0.4868	0.3595
Settling Time (s)	0.6087	0.4556

5.2. Load Torque Variation Test

In the second test, a load torque of 20 (N*m) was applied to the motor beginning at 2s until the whole remaining time. This test aimed to evaluate how well the speed controllers adapt and command the motor's speed in the presence of sudden load charges.

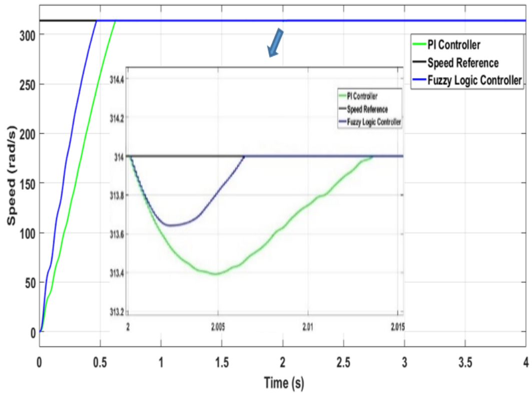

Figure 11: Speed during 2nd Test.

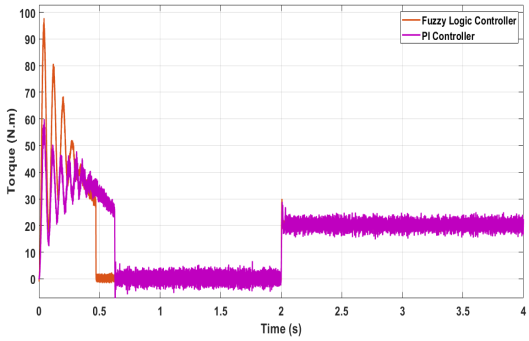

Figure 12: Electromagnetic Torque during 2nd Test.

We notice in “fig.11” that the application of load torque at 2s has resulted in transitory decrease of speed. Both controllers managed to overcome the load torque but the impact in fuzzy logic controller of speed was less remarkable in both amplitude and period of drop (0.35 rad/s and 0.006s compared to 0.6 rad/s and 0.014s in the classic regulator). In addition, the torque ripples in “fig.12” were less intense in the curve of (FLC) and the decoupling Principe remained stable in “fig.13” and “fig.14”.

We conclude from this test that the intelligent controller adapts very well against the sudden load changes.

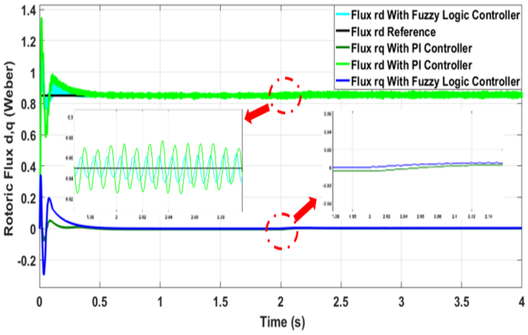

Figure 13: Rotor Flux in (dq) Reference during 2nd Test.

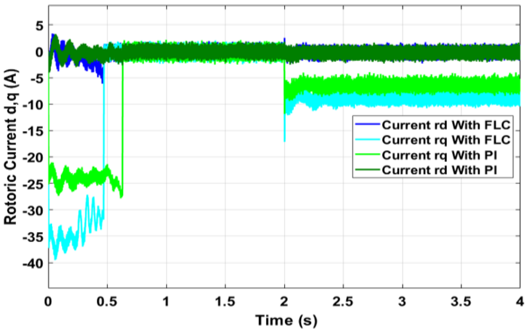

Figure 14: Rotor Currents in (dq) Reference during 2nd Test.

Table 3
Dynamic Performances Results during first Test

	PI	FLC
Speed Drop (rad/s)	0.6	0.35
Period of speed drop (s)	0.014	0.0065

5.3. Test of multiple changes in speed reference Combined with applied load torque

The third test involved a maneuver of sudden and multiple changes in speed reference with simultaneous load torque of 20 (N*m) applied beginning at 1 second, this test examine the controllers' robustness and challenges its ability to respond promptly and maintain speed stability during multiple dynamic changes.

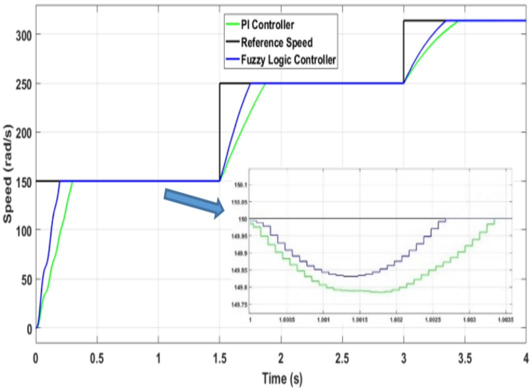

Figure 15: Speed during 3rd Test.

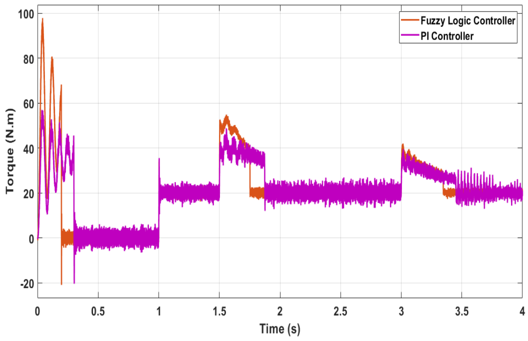

Figure 16: Electromagnetic Torque during 3rd Test.

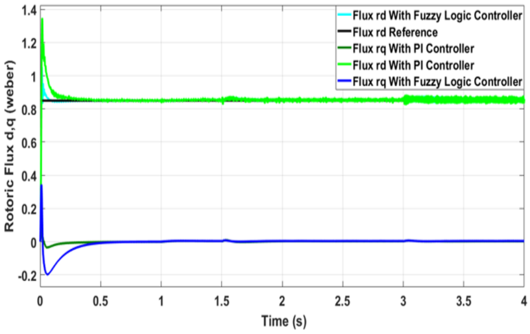

Figure 17: Rotor Flux in (dq) Reference during 3rd Test.

During the third test, we notice that the blue curve of fuzzy logic speed controller was able to reach the speed reference faster in terms of rise and settling time in all cases (150 rad/s 250 rad/s and 314 rad/s), even with presence of load torque, which proves its efficiency. In addition, the electromagnetic torque ripples with (FLC) were less intense which minimizes the electrodynamic effects on the motor and extends its lifespans.

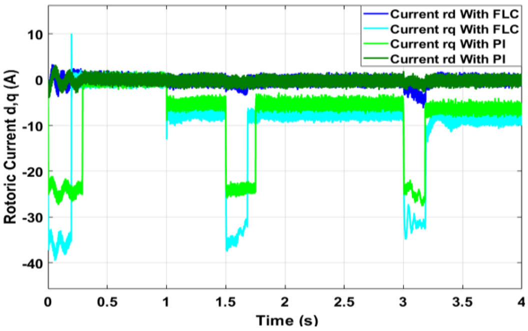

Figure 18: Rotor Currents in (dq) Reference during 3rd Test.

Figure 16 and 17 of rotor fluxes and currents in (dq) reference frame proves that the decoupling Principe of field oriented control (FOC) is realized.

5.4. Test of Inverting rotor direction sense combined with applied load torque

In the fourth test, the machine will face a continuingly external disturbance represented in load torque of 20 N*m beginning at 1s threw the whole left time of simulation, and the rotor direction sense will get inversed exactly at 2s.

This scenario assesse the controllers' performance and robustness in more complex and demanding condition.

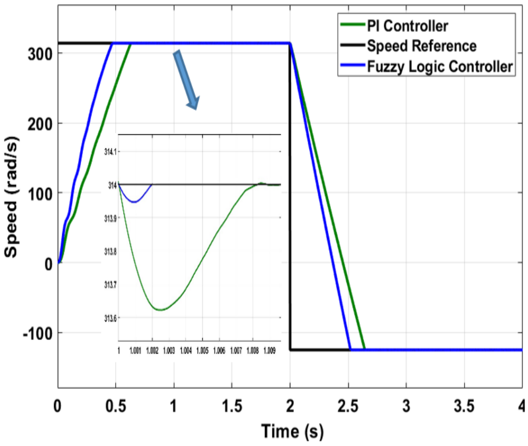

Figure 19: Speed during 4th Test.

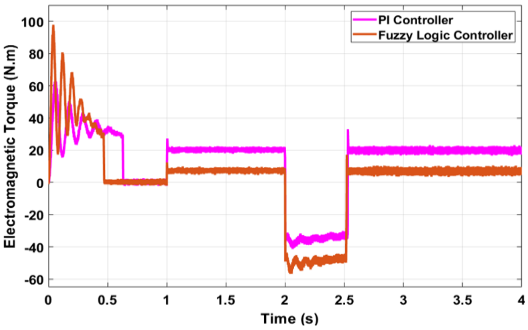

Figure 20: Electromagnetic Torque during 4th Test.

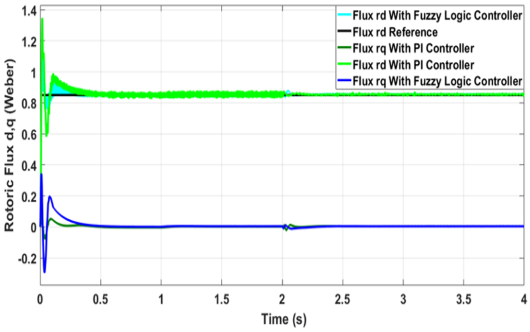

Figure 21: Rotor Flux in (dq) Reference during 4th Test.

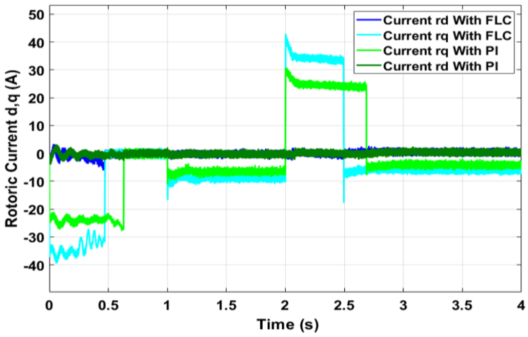

Figure 22: Rotor Currents in (dq) Reference during 4th Test.

We notice in “fig.19” that the advanced controller easily managed to invert the speed rotation sense with good dynamic performance despite the presence of load torque.

Moreover, the rotor flux and currents in (dq) reference frame proves the existence of essential decoupling Principe of field oriented control (FOC).

6. Conclusion

In this paper, we have made a study about speed control for the double stator induction motor (DSIM), firstly the model of motor was presented, then we successfully managed to achieve indirect field oriented control for the machine, this method needs speed controller. This task is usually carried out using a conventional (PI) controller due to it is strong, reliable, and most importantly has reasonable price. However, unfortunately they suffer from many shortness’s especially in the transitional period. Therefore, in order to resolve it we tried to benefit from the artificial intelligence, we implemented the fuzzy logic theory to design a sufficient controller. the experimental tests made with MATLAB/Simulink has proved its efficiency by achieving very good results in terms of rising time, settling time, overshot and precision compared to the classic (PI) regulator.

In addition, the (FLC) proved its robustness and superiority in every assessment where made over the traditional PI controller. These results can still be improved by integrating the advantages of fuzzy logic with artificial neural networks and use the Adaptive neuro-fuzzy inference system (ANFIS) to achieve even better results.

7. Appendices

Table 4
Machine, PI and FLC Parameters

Dual Stator Induction Machine Parameters		
U = 400 V	N = 3000 RPM	P = 5.5 KW
$R_{s1} = 3.72\,\Omega$	$R_{s2} = 3.72\,\Omega$	$R_r = 2.12\,\Omega$
$L_{s1} = 0.022\,H$	$L_{s2} = 0.022\,H$	$L_r = 0.006\,H$
$L_m = 0.3672\,H$	$J = 0.0662\,Kg.m^2$	$f = 0.001$
$\alpha = \frac{\pi}{6}$	$F_s = 50\,Hz$	$p = 1$
PI Speed Controller Parameters		
$K_p = 10$	$K_i = 0.01$	
Fuzzy Logic Speed Controller Parameters		
$K_e = 0.2$	$K_{de} = 0.0005$	$K_u = 10$

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