Fuzzy Logic Speed Controller for Permanent Magnet Synchronous Motor Based on Direct Torque Control

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Abstract **-** Aiming for the integration of Artificial Intelligence techniques (AI) in speed tracking of a direct torque controlled permanent magnet synchronous motor (PMSM) as well as achieving good dynamic parameters response. We have introduced Fuzzy Logic theory in this paper in order to develop a speed controller that is able to maintain the motor's speed at its reference despite the external disturbance and load torques. The validity of the proposed method is verified by carrying out a comparative study to the classic PI regulator with multiple tests performed in MATLAB/Simulink platform, the obtained results proves and demonstrates the efficiency, reliability and robustness of such controller.

Keywords **-** Artificial Intelligence, Direct Torque Control, Fuzzy Logic Controller, Permanent Magnet Synchronous Motor, PI regulator.

I. INTRODUCTION

Machines are electromechanical devices designed to perform various tasks efficiently and are integrated completely in modern society to the point that we almost can't find any field that doesn't involve an electric motor in it. Among these, Permanent Magnet Synchronous Motors (PMSMs) stand out as a crucial component in various industries and applications such as: Automotive Industry, Renewable Energy, Medical Equipment, robotics and precision tasks [1].

PMSMs are electric motors that use permanent magnets to create a magnetic field in the rotor, which interacts and synchronizes with the rotating magnetic field of the stator windings. This synchronization results in efficient and precise control of rotational motion, making (PMSMs) very favorable because it can provide high efficiency, power density, excellent torque control and low maintenance cost, contributing significantly to the advancements in electric propulsion and automation technologies [2].

Several control technics are used currently for motor speed tracking and optimal torque control. Among them all, there is two 02 methods employed the most in industry, the first is field oriented control (FOC) that is based on making the complicated (PMSM) model similar to a simple (DC) machine. However, it suffers from the need for coordinate transformation, plus multiple current regulators with their delicate gains choosing process. The second is direct torque control method (DTC) that has the advantages of simple structure, robustness, sensorless control and low cost [3, 4].

The basics and principles of (DTC) was first introduced by Depenbrock and Takahashi in the middle of 1980s with a very competitive benefits that can achieve a precise, rapid and direct control of motor's torque and speed. However, it's conventional scheme suffer from many drawbacks such as the need of variable switching table frequency, the hysteresis comparators that generates high electromagnetic flux/torque ripples, noise and harmonics in motor currents and more importantly the use of (PI) speed controller that can cause shortness's in the transient period response [5, 6, 7].

The proportional integral (PI) regulator is a common type of feedback control system used for automation adjustment, its role in (DTC)

control loop is to keep motor's speed within specified range, it is robust and has simple structure for implementation. Nevertheless, it can encounter into many limitations. basically because it was designed in first place to control linear systems and if it encounter nonlinear characteristics (like the synchronous motor in our case) or a variation in the controlled object settings, it will result for the (PI) regulator of linear constant parameters to come across problems especially in the transient period (overshot, undershot, rise time, settling time …). Which obliges the researchers to find a more developed and sophisticated controlling unit that can eliminate and overcome those drawbacks [8, 9]. Therefore, the solution resides in the Artificial Intelligence (AI) techniques that possess the adaptability and advanced data analyzing logic to handle a complex task like the nonlinear and strongly flux/torque coupled electric machines.

In this paper, we shall use the fuzzy logic to create and implement an advanced speed controller instead of the traditional (PI) regulator in order to improve the motor's transitional regime parameters.

Fuzzy set theory was first proposed in 1965 by the scientist Lotfi Zadeh. It aims to plant the human knowledge, way of thinking, intuition and making decisions in an advanced controller. and simulate human's intelligence without the need for mathematical model of the controlled object, which leads to better adaptability of its nonlinearity and parameter variation with stronger immunity against interference and noise [10, 11].

Fuzzy logic controller or simply (FLC) is a control unit based on linguistic rules summarized in control laws designed by experts. It consist three main stages; the first is fuzzification process that transforms the crisp input into fuzzy sets (where each input is described by a membership function and linguistic value). Then it comes the inference engine process with a role of assessing fuzzy sets on the base of predefined if-then rules that represents human expertise of taking decisions. The results fuzzy sets assessment will become essential part in the third and final stage, which is a defuzzification process that generates control signal [12, 13].

This paper is organized as follows: the model of permanent magnet synchronous motor is presented in section II with a brief introduction to direct torque control basics in section III, the fuzzy logic controller is detailed in Section IV while the simulation results with their interpretations are presented in section V and Finally Section VI concludes the Paper.

II. PERMANENT MAGNET SYNCHRONOUS MACHINE MODELLING

The mathematical model of the machine stator's current and flux can be described in the synchronously rotating frame (d,q) by the following system of equations [1, 14]:

$$\begin{cases} \frac{dI_d}{dt} = \frac{1}{L_d}.V_d - \frac{R}{L_d}.I_d + \frac{L_q}{L_d}.p.\omega_m.I_q \\ \frac{dI_q}{dt} = \frac{1}{L_q}.V_q - \frac{R}{L_q}.I_q - \frac{L_d}{L_q}.p.\omega_m.I_d \\ \varphi_d = L_d.I_d + \varphi_f \\ \varphi_q = L_q.I_q \end{cases} \quad (1)$$

where R reflects for the stator resistance; L_d, L_q represent inductance values according to d and q axis; I_d, I_q and V_d, V_q are respectively stator currents and voltages; ω_m, p represents the (PMSM) angular rotor speed and number of pole pairs; φ_d, φ_q denotes for stator (d_q) flux while φ_f represent the permanent magnet flux linkage.

The electromagnetic torque T_e is expressed by the equation bellow [4]:

$$T_e = \frac{3}{2}p\left(\varphi_{sd}I_{sq} - \varphi_{sq}I_{sd}\right) \quad (2)$$

The PMSM rotor speed is determined based on the following formula [2]:

$$T_e - T_l - f.\Omega = J.\frac{d\Omega}{dt} \quad (3)$$

Where T_l is the load torque; J represent the total moment of inertia and f is the coefficient of viscous friction.

III. PROPOSED DIRECT TORQUE CONTROL STRATEGY

For induction and synchronous motors in particularly Direct Torque Control (DTC) was first proposed in the middle of the 1980s by

Takahashi and Depenbrock. It is a sophisticated command strategy with an objective of revolutionizing motors control. By offering a technique that is simple in structure, robust against parameters variation and can improve the machine's dynamic performance. Which made it a useful tool in various industrial and automatic applications [11, 15].

The Principle of (DTC) is quite simple as its structure. It has an estimator dedicated for estimating torque, flux and sector angle values based on stator voltages and currents. In addition, there is speed controller that delivers a torque reference, the latter along with the flux reference will get subtracted with their estimated values and become an input for two hysteresis comparators that generates an output logic signal and commands the switching table. Which in turn produces control signals for the inverter interrupters [6, 7].

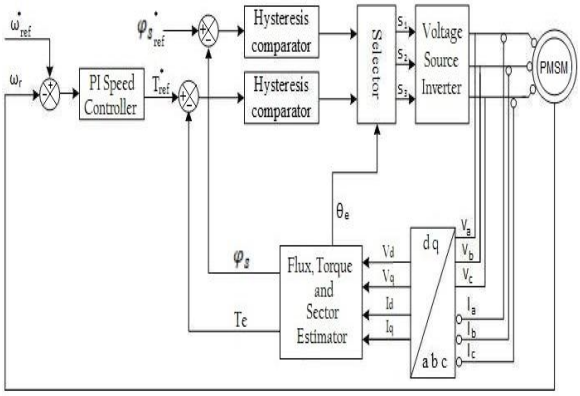


Fig. 1. Synoptic scheme of direct torque control for PMSM

A) Estimation process of stator flux, torque and sector angle

The stator flux linkages components according to (d_q) axis can be estimated based on the following equations [3]:

$$\begin{cases} \varphi_{ds} = \int (V_{ds} - R_s I_{ds}) dt \\ \varphi_{qs} = \int (V_{qs} - R_s I_{qs}) dt \end{cases} \quad (4)$$

While the stator flux amplitude and sector angle are expressed as follows [2]:

$$\begin{cases} |\varphi_s| = \sqrt{\varphi_{ds}^2 + \varphi_{qs}^2} \\ \theta_s = arctg\left(\frac{\varphi_{qs}}{\varphi_{ds}}\right) \end{cases} \quad (5)$$

In addition, electromagnetic torque is estimated through the following equations [7]:

$$T_e = \frac{3}{2} p\left(\varphi_{ds}.i_{qs} - \varphi_{qs}.i_{ds}\right) \quad (6)$$

B) Hysteresis comparators of flux and torque

The two-hysteresis comparator objective is to maintain the motor's magnetic flux and electromagnetic torque within a predefined band. These comparators monitor the actual flux/torque values and compares it to their reference. Based on that comparison they generate control logic signals to select the appropriate voltage vector in order to achieve and maintain the desired reference level by increasing, decreasing or to be kept constant as a third case for the torque [15, 16].

The following figure and equations represent the flux hysteresis comparator and its corresponding output algorithm [16]:

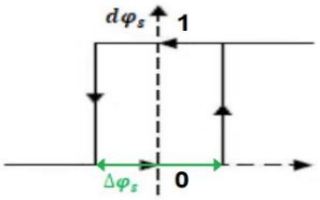


Fig. 2. Flux hysteresis comparator.

$$\begin{cases} d\varphi_s = 1 \; if \; |\varphi_s| \leq \left|\varphi_{s_{ref}}\right| - |\Delta\varphi_s| \\ d\varphi_s = 0 \; if \; |\varphi_s| \geq \left|\varphi_{s_{ref}}\right| + |\Delta\varphi_s| \end{cases} \quad (7)$$

Also, the figure of torque hysteresis comparator and equations of its corresponding output are represented bellow [16]:

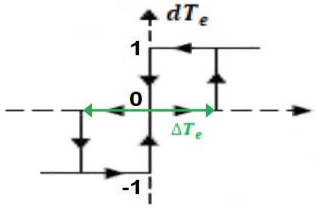


Fig. 3. Torque hysteresis comparator.

$$\begin{cases} dT_e = 1 \; if \; |T_e| \leq \left|T_{e_{ref}}\right| - |\Delta T_e| \\ dT_e = 0 \; if \; |T_e| = \left|T_{e_{ref}}\right| \\ dT_e = -1 \; if \; |T_e| \geq \left|T_{e_{ref}}\right| + |\Delta T_e| \end{cases} \quad (8)$$

C) Switching table (voltage vector selection)

When the hysteresis comparators produce a logic digital output, it goes directly as an input for the switching table, which is basically an algorithm that controls the inverter interrupters [6].

Table 1. Voltage Vector Selection

Flux and torque hysteresis comparators outputs		Sectors					
		1	2	3	4	5	6
$d\varphi_s = 1$	dTe= 1	V2	V3	V4	V5	V6	V1
	dTe= 0	V7	V0	V7	V0	V7	V0
	dTe=-1	V6	V1	V2	V3	V4	V5
$d\varphi_s = 0$	dTe= 1	V3	V4	V5	V6	V1	V2
	dTe= 0	V0	V7	V0	V7	V0	V7
	dTe=-1	V5	V6	V1	V2	V3	V4

D) Voltage source inverter (VSI)

In traditional Direct Torque Controlled synchronous machine, a three phase two level inverter is usually used to provide the (AC) power supply needed for the stator windings. Such vector source inverter (VSI) can provide eight different voltage sequences whereas six of them are active vectors and two are null. The main goal in (DTC) is to find the optimal voltage vector that leads to the minimum cost function and best flux/torque vector [4].

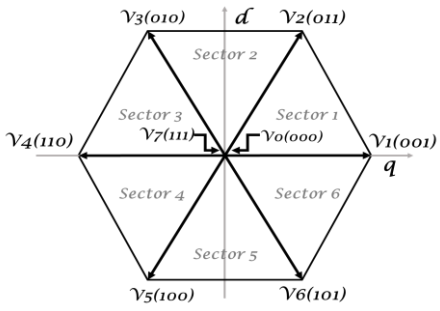


Fig. 4. Space Vector Modulation for DTC.

The voltage vector provided to the supposedly perfect inverter switches is presented by the following equation [7]:

$$V_s = \sqrt{\frac{2}{3}} V_{dc}[S_1 + aS_2 + a^2 S_3] \; with \; a = e^{\frac{2\pi}{3}j} \quad (9)$$

With:

$\boldsymbol{S_1}$, $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$ represent the upper interrupter for each of the three inverter legs, and every one of them can have status of 1 or 0 (on or off). While $\boldsymbol{V_{dc}}$ is the (DC) link voltage.

E) PI speed controller

In order to control the speed of (PMSM) and produce the electromagnetic torque reference needed for loop control, a (PI) regulator is usually used in traditional (DTC) mainly for its simple structure, ease to implement and cost-effective advantage. This controller has one single input, which is the speed error and two gains; the first is proportional Kp that ensures the system stability while the second is integral Ki gain with role of eliminating steady stat error and ensure the precision [7].

However, despite the several advantages it possesses. But we must mention that the system's stability might get affected if the (PI) gains were chosen badly and even if they were selected in the best possible way, but the dynamic response might still suffer from shortness's especially in terms of rise time, settling time, overshot and stability during load torques and parametric variations [4, 7].

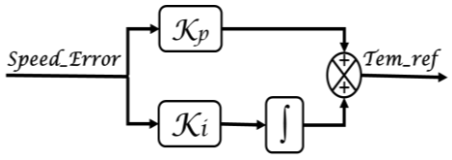


Fig. 5. PI controller structure.

IV. FUZZY LOGIC SPEED CONTROLLER

Fuzzy logic control is an advanced approach for controlling systems, derived from fuzzy set theory of Lotfi Zadeh. Its origin principals are based on putting the human expertise and way of thinking in an algorithmic language that can be

analyzed and processed by computers. For purpose of overcoming the deviations that may produce from the traditional Boolean Logic [9], by improving the motor response during transitional period and adapting quickly to any external change in operating conditions such as, load torque [1]. Also, Fuzzy theory can be used as base for modeling and controlling non-linear complex systems that do not possess a precise mathematical model, but it requires only an effective controlling laws from the expert.

A fuzzy logic controller (FLC) is composed mainly from three blocks. the first is fuzzifier that convert the inputs into fuzzy variables, the second is inference engine that process those variables and based on pre-defined rules made by the expert it produces a fuzzy output, and finally the third block is a Defuzzifier with a purpose of converting the output fuzzy into numerical value [11].

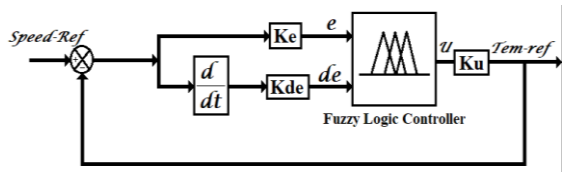


Fig. 6. Synoptic scheme for fuzzy logic controller.

This intelligent controller has two inputs that represent the speed error e_Ω for the first and its derivative de_Ω for the second with one single output that refers to the electromagnetic torque [8].

$$\begin{cases} e_\Omega(k) = \Omega_{ref}(k) - \Omega(k) \\ de_\Omega(k) = e_\Omega(k) - e_\Omega(k-1) \end{cases} \quad (10)$$

We must mention that it very crucial to choose carefully the scaling factors of error (Ke), change in error (Kde), and torque reference (Ku) in the designing process of FLCs in order to guarantee a good convergence speed and sensitivity [12].

The predefined membership function of inputs and output are Mamdani type, each input has 07 triangular mmfs while the output has 09. The fuzzy sets are designed according to the following labels: (PB, PM, PS, Z, NS, NM, NB), with (P, N) refers to positive and negative, (B, M, S) for big, medium and small. The output has the same labels plus extra two 02, which they are: NVS, PVB for negative very small and positive very big.

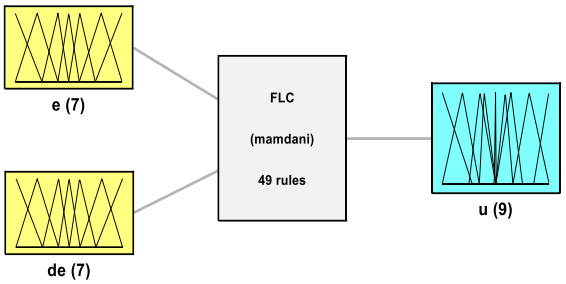


Fig. 7. FLC used for PMSM speed control.

The fuzzy inference system (FIS) used for our controller that contains 49 rules is represented by the table and figure below:

Table 2. Fuzzy Rules.

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

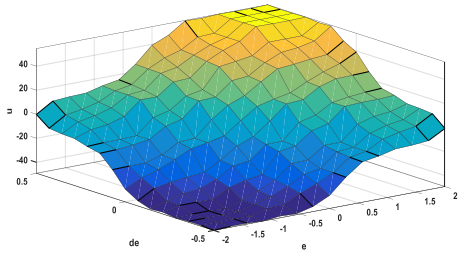


Fig. 8. Fuzzy surface.

V. SIMULATION RESULTS

In order to verify the proposed method, we have used MATLAB/Simulink platform to simulate a direct torque controlled permanent magnet synchronous motor with both traditional (PI) and advanced (FLC) speed controllers under different conditions. For purpose of evaluating their performance and assess witch regulator is more efficient. Especially in front of parametric and external disturbances such as multiple

applied load torques and speed reference variations.

The key metrics considered for evaluation include the rising time, settling time, overshoot, steady-state error and diverse tests designed to push both regulators to their limits. These metrics will provide valuable insights into the controllers' capabilities in achieving accurate and robust speed control.

A) Normal Condition Test

The first test will involve running the machine in normal operating conditions to evaluate controllers' performance in transitional period, it will not face any external or internal disruptions in order to create a baseline for assessment in the afterward tests.

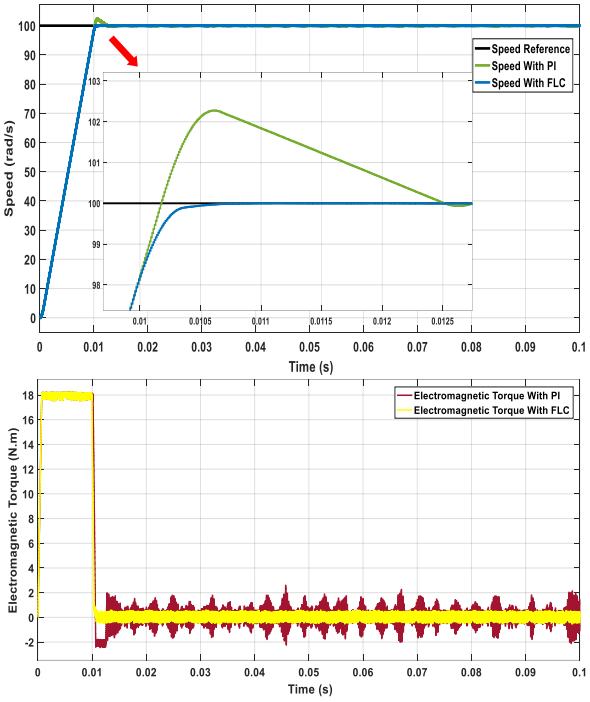


Fig. 9. Motor's speed and torque during normal condition test.

The figures above represent the speed and torque results of first test. We notice in figure -a- which represent speed curves comparison that the blue one of (FLC) controller had realized better performance especially in term of overshot (0.0067 %) compared to speed regulation with classic PI controller (2.2756 %). Also we notice that the intelligent controller achieved better rising and settling time. While in the steady state phase, both controllers had an excellent precision.

Table 3. Comparison between Controllers' Results

	PI	FLC
Overshot (%)	2.2756	0.0067
Rise Time (s)	0.0079	0.0079
Settling Time (s)	0.0125	0.0100

In Figure 9, we notice that the electromagnetic curve of (FLC) had less intensive torque ripples, which minimizes the electrodynamic effect on the motor.

The results of this first test indicates strongly the efficiency and reliability of fuzzy logic controller in both transitional and steady-stat periods.

B) Load Torque Variation Test

The second test is about applying a load torque on the machine after it starts and keeping it applied for the whole time of simulation for purpose of evaluating the controllers' reaction against external disturbances and sudden load changes.

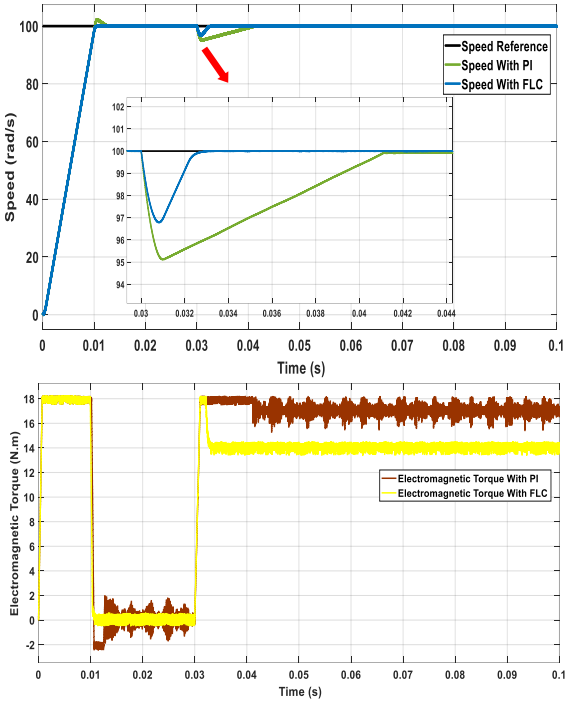


Fig. 10. Motor's Speed and Torque under external disturbances Test.

The figures above represent the results obtained from the second test. In figure -a- during transitional period, the advanced controller was superior as in first test, and after applying a load torque of 20 N.m beginning at 0.03 s and permanently threw the rest of simulation time it has resulted in transitory decrease of speed in both curves. The two controllers managed to overcome the load torque but the impact in FLC of speed was less remarkable in both amplitude and period of drop (3.2 rad/s and 3 ms compared to 4.9 rad/s and 16 ms for classic regulator). Moreover, it was noticed in figure -b- that torque ripples were less intense with FLC regulator.

We conclude from this test that the intelligent controller has the superiority of adaptation against sudden load torques.

C) Inverting rotor direction sense with load torque applied

The third test is about applying a permanent load torque of 20 N*m beginning at 10 ms on the (PMSM), and after a while will get inverting rotor direction sense maneuver. This scenario examines the two controllers' robustness and ability to maintain the stability of system in more complex and demanding conditions.

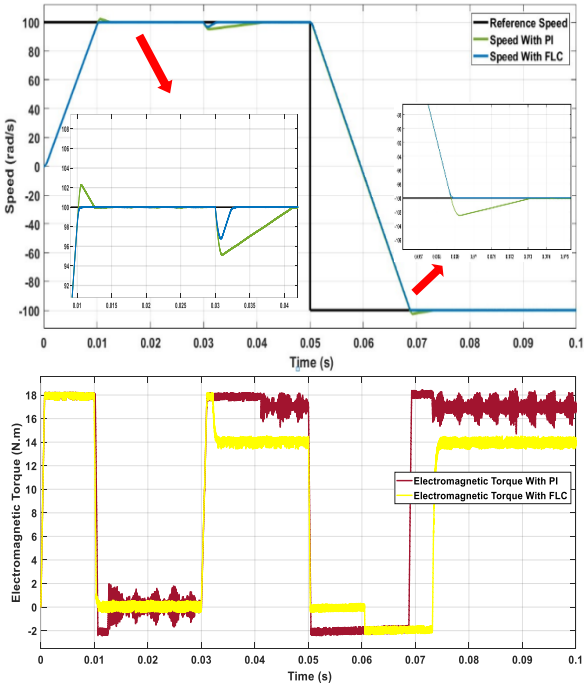


Fig. 11. Motor's Speed and Torque with Rotor Sense Inversion Test

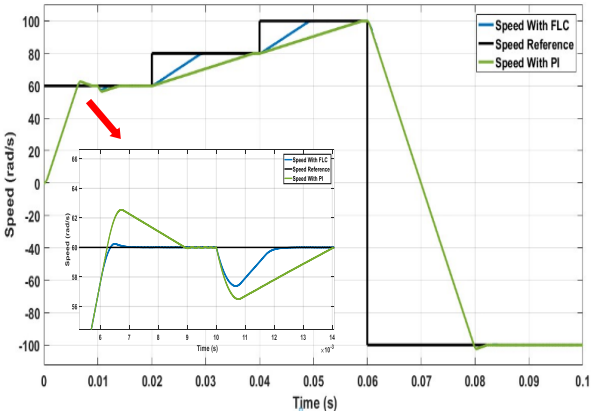
The figures above represent the results obtained from the third test. In figure -a- of speed curves, we notice during the direct sense rotation (first half of experience) that it was identical to the first two tests with FLC achieving better performances. Beginning at 50 ms a sharp sense rotation inversion was made along with load torque applied since 30 ms, both controllers reacted but as usual, an overshot was noticed in green graph of PI regulator while FLC graph managed to change speed from 100 rad/s to -100 rad/s with better settling time and almost null overshot.

We conclude from this test that the fuzzy controller is capable of achieving good performance response after changing rotation sense even at the presence of load torque of 20 N*m which indicates to be powerful, robust and very effective.

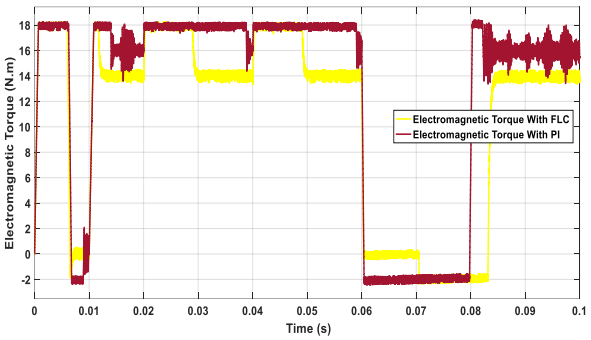
D) Combined sudden change in speed reference, rotation sense inversion and load torque variation test

The fourth test is about expressing the two controllers into a more complex and demanding conditions with multiple challenges applied.

Firstly, the motor will start in reduced speed 60% of nominal speed after that a load torque with be applied permanently and speed will increase to 80% then 100% and finally the motor will go through a sharp inversion of rotation sense.



(a)



(b)

Fig. 12. Motor's Speed and Torque during the 4th Test.

And with the fourth and last test, the Permanent Magnet Synchronous machine with fuzzy logic speed controller had successfully managed to perform all the challenges quality performance, the torque ripples during where less intense and by comparison to PI regulator the whole performance were much superior.

VI. CONCLUSION

In this paper, a comparative study about advanced and conventional speed controllers of permanent magnet synchronous machine where made, the advanced technique has the advantage of adaptability threw the operating process with ability to model and control complex systems which result in amelioration for the dynamic response characteristics. The simulation was made with MATLAB/Simulink and the results were very optimistic for favor of the intelligent controller, which has proved its efficiency by achieving good results in terms of rising time, settling time and especially for the overshot. Also, the (FLC) proved its robustness and superiority in all the tests they were made.

Moreover, these results can still be improved by using other advanced technics like the artificial neural networks, genetic algorithms, metaheuristic methods or the adaptive neural fuzzy inference systems (ANFIS).

APPENDIX

Table 4. Machine, PI and FLC Parameters

Permanent magnet synchronous machine parameters			
Fs = 50 HZ	R_S = 1.4 Ω	L_{ds} = 0.0066 H	L_{qs} = 0.0058 H
P = 3	U = 400 V	Φ = 0.1546 W	J = 0.00176 Kg.m^2
PI Speed controller parameters			
$K_p = 2.2564$		$K_i = 0.0321$	
Fuzzy logic speed controller parameters			
$K_e = 0.759$	$K_{de} = 0.001$	$K_u = 50$	

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