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Impact of Artificial Intelligence on Enhancing Dynamic Performance of DFIM

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***Abstract*— This paper presents a comparative study between conventional and artificial intelligence (AI) controllers. These controllers are destined to the speed control of doubly fed induction motor (DFIM). The most widely used controller for speed control of induction motor is the proportional integral controller. However, the PI controller has some disadvantages due to the different operating conditions and in the presence of parameters variation. Therefore, one of the frequently discussed applications of artificial intelligence (AI) in control is the replacement of a proportional integral speed controller with a fuzzy logic (FL) or artificial neural network (ANN) speed controller. These speed controller with, FL or ANN are based on the decoupling control to solve the problem associated with PI controller and to enhance robustness under different operating conditions such as load torque and in the presence of variations in the parameters of the machine. To provide a numerical comparison between different controllers, an Error Tracking performance index based on speed error is assigned. Simulation results for different test show the high performance of the proposed Artificial Intelligence controller in terms of, precision and stability for the DFIM operating at variable speeds.**

***Keywords*— DFIM, Decoupling Control , PI, AI, FLC, ANNC**

I. Introduction

The doubly fed induction motor (DFIM) with wounded rotor have become increasingly used in industry compared to direct current (DC) motors and synchronous motors. This type of motor has been neglected by researchers for several years because of its disadvantages, namely its high cost, its volume, and the presence of brushes. However, it has come back to the forefront because of the progression of control techniques and the accessibility to its rotor [1].

The operation of a variable speed motor needs some control techniques in order to obtain a high performance system. These performance criteria are tracking accuracy, control accuracy (rise time, response time, overtaking and permanence), robustness with respect to disturbances (load, moment of inertia) and sensitivity to parameter variation [2]. Among the control techniques currently applied to induction machines, we can find scalar control, vector control, direct torque control and nonlinear control. Indeed, the scalar control is the first that has been introduced in the industrial applications where variable speed are needed. However, this control does not satisfy the most efficient applications. This has opened the way for researchers to search for new control techniques that meet industrial requirements and among these controls is vector control (FOC), which is the evolution of scalar control while maintaining its performance in transient regimes. Its first theoretical developments were made at the beginning of 70's by Blaschke. However, they could not be implanted and used really only with advanced microelectronics. In addition, they require the evaluation of trigonometric functions, integrations, regulations and Park transformations, which could not be done purely analog [3].

In the vector control, the parameters of the machine must be well known in order to become more efficient. This control strategy can provide the same performances as those achieved from a separately excited DC machine. It can be done by

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two basic methods: direct vector control (DVC) and indirect vector control (IVC). These ensures control of the flux and the electromagnetic torque at the same time [4]. Based on the proportional, integral and derivative controllers, vector control is not always able to control the transient speeds and parametric variations of the machine. So this fact has led other researchers to find a new methods of control. These efforts have been rewarded by the introduction of modern control techniques such as artificial intelligence (AI) [7]. Great efforts were made since the early 1950s towards the development of a scientific theory of intelligence and the development of an artificial model of the brain capable to mimic our perception, cognition and behavioral systems [15, 16].

Different techniques of artificial intelligence exist in the literature today, such as genetic algorithms, evolutionary algorithms, fuzzy logic, neural networks and swarm intelligence, which are increasingly applied in the control of induction machines. In our study we have focused on these last three techniques.

In the first design approach the basic fuzzy logic controller (FLC) is proposed. Lotfi Zadeh introduced the fuzzy logic tool in 1965 as a mathematical tool for dealing with uncertainty [3]. Since the first successful application of fuzzy sets in control systems fuzzy logic control has attracted the attention of many researches in engineering [4],[5]. Compared to the other controllers, the FLC design uses practice qualitative knowledge, which is provided generally by an experienced operator [5]. It also is suitable for systems with uncertain or complex dynamics. In general, a fuzzy control algorithm is a set of decision rules. Thus, it can be considered a non-mathematical algorithm in contrast to conventional control algorithms [14].

The second design approach is based on the neural networks to improve the robustness of the classical controller. Due to the theoretical and practical results obtained in the recent years, neural networks have become an increasingly used tool in various fields (industry, banking, services). However, they remain a subject of great interest for researchers who wish to improve the performance of these networks and extend their field of application.

The remainder of this paper is structured as follows: in section 2, the machine model is developed and in section 3, the decoupling control of DFIM is presented. In section 4, speed controllers synthesis are presented. The simulation results of FL, ANN and the PI controller are shown in section 5. Finally, the conclusions are presented in section 6.

II. MATHEMATIC MODELS OF DFIM

The structure of DFIM is very complex. So, in order to develop a model, it is necessary to take in consider these following simplifying assumptions. the used machine is considered symmetrical configurations with constant air gap; the magnetic circuit is not saturated and it is perfectly laminated, the magneto-motive force (mmf) created in one phase of stator and rotor are sinusoidal distributions along the gap, with the result that the iron losses and hysteresis are negligible and only the windings are driven by currents; [6].

The DFIM model is expressed by its dynamic model in the synchronous reference frame which is given by:

$$V_S = R_S I_S + \frac{d\phi_S}{dt} + j\omega s\phi_S \quad (1)$$

$$V_R = R_R i_R + \frac{d\phi_R}{dt} - j\omega_R \phi_R \quad (2)$$

$$\phi_S = L_S I_S + M_{SR} I_R \quad (3)$$

$$\phi_R = L_R I_R + M_{SR} I_R \quad (4)$$

To study the transient phenomena (start, brake and load variation), the equation (5) of motion must be added to the precedent system of equations.

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

III. STRUCTURE OF DECOUPLING CONTROL

The main objective of the vector control of doubly fed induction motors is to control the torque and the flux independently; this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector as shown in the Figure 1 and the general full order dynamic model of DFIM is given by:

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$$V_{Sd}= R_S I_{Sd} + \frac{d\phi_{Sd}}{dt} - \omega_S \phi_{Sq} \quad (6)$$

$$V_{Sq}=R_S I_{Sq} + \frac{d\phi_{Sq}}{dt} + \omega_S \phi_{Sd} \quad (7)$$

$$V_{Rd}=R_R I_{Rd} + \frac{d\phi_{Rd}}{dt} - \omega_R \phi_{Rq} \quad (8)$$

$$V_{Rq}=R_R I_{Rq} + \frac{d\phi_{Rq}}{dt} + \omega_R \phi_{Rd} \quad (9)$$

The electromagnetic torque of a three-phase doubly fed induction machine modeled in the Park reference is given by the following relation:

$$C_{em} = \frac{3pM}{2L_R}\left(\phi_{Rd} I_{Sq} - \phi_{Rq} I_{Sd}\right) \quad (10)$$

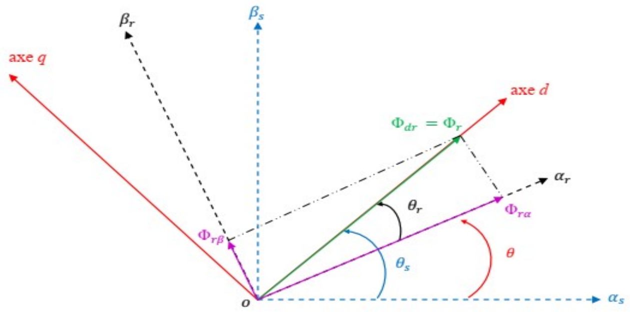

Fig. 1 Rotor field orientation on the d-axis

Then, after the d-axis is aligned with the rotor flux vector as shown in the Figure 1, we get:

$$\phi_R = \phi_{Rd}, \quad \phi_{Rq} = 0;$$
$$I_{Rq} = -\frac{M_{SR}}{L_R} I_{Sq}, \quad I_{Rd} = 0; \quad (11)$$

A. Control of currents and compensation terms

It can be seen that the voltage equations (6), (7), (8) and (9) include terms of coupling between d-axis and q-axis. These terms are considered as disturbances and are cancelled by using a decoupling method that utilizes nonlinear feedback of the coupling voltages [8]. In order to obtain a decoupling between d and q axis I have used a method which was introduced by D. LECOQ [9]. It requires the use of four current correctors; let us define new voltages as:

$$\begin{aligned}
V_{tSd} &= V_{Sd} - \frac{M_{SR}}{L_R} V_{Rd} \\
V_{tSq} &= V_{Sq} - \frac{M_{SR}}{L_R} V_{Rq} \\
V_{tRd} &= V_{Rd} - \frac{M_{SR}}{L_S} V_{Sd} \\
V_{tRq} &= V_{Rq} - \frac{M_{SR}}{L_S} V_{Sq}
\end{aligned} \quad (12)$$

Using equations (3-4),(11) and (12), we can write:

$$\begin{aligned}
V_{tSd} &= R_S I_{Sd} + \sigma L_S \frac{dI_{Sd}}{dt} - R_R \frac{M_{SR}}{L_R} I_{Rd} - \phi_{Sq}\omega_S + \frac{M_{SR}}{L_R}\phi_{Rq}\omega_R \\
V_{tSq} &= R_S I_{Sq} + \sigma L_S \frac{dI_{Sq}}{dt} - R_R \frac{M_{SR}}{L_R} I_{Rq} + \phi_{Sd}\omega_S - \frac{M_{SR}}{L_R}\phi_{Rd}\omega_R \\
V_{tRd} &= R_R I_{Rd} + \sigma L_R \frac{dI_{Rd}}{dt} - R_S \frac{M_{SR}}{L_S} I_{Sd} - \omega_R \phi_{Rq} + \frac{M_{SR}}{L_S}\phi_{Sq}\omega_S \\
V_{tRq} &= R_R I_{Rq} + \sigma L_R \frac{dI_{Rq}}{dt} - R_S \frac{M_{SR}}{L_S} I_{Sq} + \omega_R \phi_{Rd} - \frac{M_{SR}}{L_S}\phi_{Sd}\omega_S
\end{aligned} \quad (13)$$

Thus:

$$\begin{aligned}
V_{tSd} &= V_{tSdc} + V_{tSdc1} = R_S I_{Sd} + \sigma L_S \frac{dI_{Sd}}{dt} + V_{tSdc1} \\
V_{tSq} &= V_{tSqc} + V_{tSqc1} = R_S I_{Sq} + \sigma L_S \frac{dI_{Sq}}{dt} + V_{tSqc1} \\
V_{tRd} &= V_{tRdc} + V_{tRdc1} = R_R I_{Rd} + \sigma L_R \frac{dI_{Rd}}{dt} + V_{tRdc1} \\
V_{tRq} &= V_{tRqc} + V_{tRqc1} = R_R I_{Rq} + \sigma L_R \frac{dI_{Rq}}{dt} + V_{tRqc1}
\end{aligned} \quad (14)$$

Where V_{tsdc1}, V_{tsqc1}, V_{tRdc1} and V_{tRqc1} are considered as compensation terms. This method gives us the same transfer function between the currents and voltages of the same axis as shown by the following equation (15):

$$\begin{aligned}
\frac{I_{Sq}(S)}{V_{tSqc}(S)} &= \frac{I_{Sd}(S)}{V_{tSd}(S)} = \frac{1}{R_S + \sigma L_S.S} \\
\frac{I_{Rq}(S)}{V_{tRqc}(S)} &= \frac{I_{Rd}(S)}{V_{tRd}(S)} = \frac{1}{R_R + \sigma L_R.S}
\end{aligned} \quad (15)$$

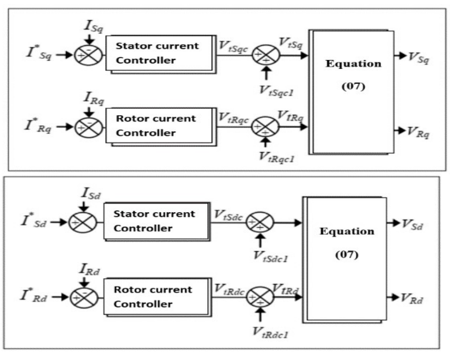

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Fig. 2 Decoupling and regulation of the currents

The current references are given by:

$$\begin{aligned} I_{Sd}^* &= \frac{L_R}{M_{SR}}\phi_{Rd}^* \\ I_{Sq}^* &= \frac{L_R}{P.M_{SR}.\phi_{Rd}^*}C_{em}^* \\ I_{Rd}^* &= 0 \\ I_{Rq}^* &= -\frac{1}{P.\phi_{Rd}^*}C_{em}^* \end{aligned} \quad (16)$$

Thus, Figure 2 shows the control structure of the currents.

IV. SPEED CONTROLLERS SYNTHESIS

A. Speed control via PI controller

The PI controller has been applied for the control of induction machine speed. The speed control loop with PI type regulator is shown in the Figure 3. It is used for the adjustment of the mechanical variable.

Basing on relation (10) and the assumption to work with I_{Rd} equal to zero, the electromagnetic torque can be written as:

$$C_{em} = -p\phi_{Rd} I_{Rq} = K_{em} I_{Rq} \quad (17)$$

Substituting (20) in (5), it results:

$$J\frac{d\Omega}{dt} = K_{em} I_{Rq} - f\Omega - C_r \quad (18)$$

K_{em} is the torque constant.

Therefore, the speed transfer function can be expressed by:

$$\frac{\Omega(s)}{\Omega^*(s)} = \frac{\dfrac{K_m K_p S + K_m K_i}{T_m}}{S^2 + S(\dfrac{1 + K_m K_p}{T_m}) + \dfrac{K_m K_i}{T_m}} \quad (19)$$

With: $K_m = \dfrac{P}{f}$ and $T_m = \dfrac{J}{f}$

K_p and K_i denote the proportional and the integral gains of the PI speed controller respectively.

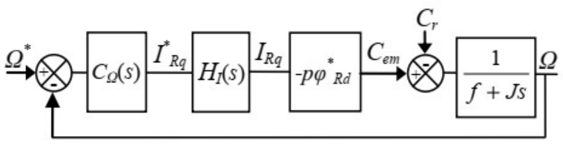

Fig.3 Block diagram of the speed regulator with PI controller

It can be seen that the motor speed is represented by the differential equation of the second order. Since, the choice of the parameters of the regulator is chosen according to the choice of the damping constant (ξ) and the natural pulse wn, the proportional and the integral gains can be represented by equation (20).

$$\begin{aligned} K_p &= \frac{(2\xi\omega_n T_m) - 1}{K_m}; \\ K_i &= \frac{T_m \omega_n^2}{K_m}. \end{aligned} \quad (20)$$

B. Speed control via Fuzzy logic controller

Let us consider the internal schema of the fuzzy regulator in Figure 4 [11].

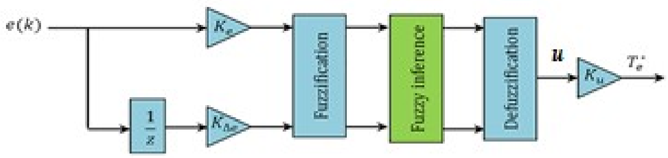

Fig.4 Internal structure of the FLC

The output of defuzzification may be written in the form:

$$u = K_e \cdot e + K_{\Delta e} \cdot \Delta e \,, \quad (21)$$

The fuzzy output is:

$$T_e^* = K_u \cdot u \,, \quad (22)$$

Where: Ke is the gain of the speed error, KΔe is the gain of the variation of the speed error, e is the speed error, Δe is the variation of the speed error and u is the fuzzy output.

The error e is defined by:

$$e(k) = \Omega^*(k) - \Omega(k), \quad (23)$$

Ω^* : Reference speed

The variation of the error Δe can be approached by:

$$\Delta e(k) = e(k) - e(k-1), \quad (24)$$

Given the lack of systematic procedures for choosing the various parameters of the fuzzy controller:

The triangular membership functions are chosen to cover the linguistic variables reference sets;

The Mamdani Max-min method is used to perform fuzzy inference;

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The center of gravity method is selected to de-fuzzily the fuzzy output;

We take, as input of the controller, the error of the speed of rotation $e = \Omega^{*} - \Omega$ of the DFIM and its variation Δe, and as output the variation of the command u.

Figure 5 shows the different memberships functions of the inputs and the output u.

The fuzzy rules are used for the determination of the regulator output variable according to the input variables that are deduced from the inference table. In this case, there are 49 rules. Table.1

TABLE I
INFERENCE MATRIX OF FUZZY RULES

		Δe						
		NG	**NM**	**NP**	**Z**	**PP**	**PM**	**PG**
e	**NG**	NG	NG	NG	NM	NP	NP	Z
	NM	NG	NG	NM	NP	NP	Z	PP
	NP	NG	NM	NP	NP	Z	PP	PP
	Z	NM	NP	NP	Z	PP	PP	PM
	PP	NP	NP	Z	PP	PP	PM	PG
	PM	NP	Z	PP	PP	PM	PG	PG
	PG	Z	PP	PP	PM	PG	PG	PG

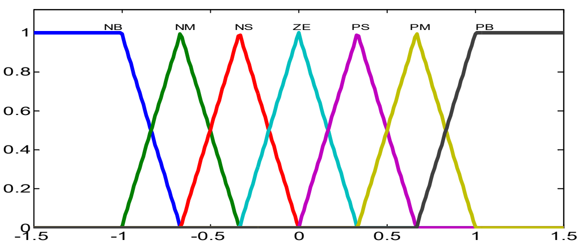

Fig. 5 Functions for membership of inputs (e, Δe) and Output (u)

C. *Speed control via Neural Network controller*

The most useful neural networks in function approximation are Multi Layer Perceptron (MLP) and Radial Basis Function (RBF) networks [12]. In this paper we have choosed the MLP networks that has been successfully applied in the control of dynamic systems [10]. Many algorithms exist for determining the network parameters (the weights and the biases) . Therefor, the most well known are back-propagation and Levenberg-Marquardt algorithms. In our case, we have used Levenberg-Marquardt algorithm that performs the adaptation of weights until the error between target vectors and the output of the ANN is less than an error goal.

1) *The neural network block design :* After simulating the DFIM by using, a PI controller that is synthesized for different operating points Figure 6, the number of data for training and the length of the data are provided. The design of artificial neural network model is created through our program in MATLAB/ SIMULINK and databases (Err1, Cmd1) that are collected from running machine. After training process, we use command gensim of SIMULINK that it automatically generates a SIMULINK file with the neural network block. In the Neural Network panel displays the general structure of ANN that is used in this study. In this network, singl input and singl target have been used. The hidden layer consists of 15 neurons with a non-linear sigmoid transfer function and the output layer consists of one neuron with a linear transfer function [13]. The Algorithms panel shows the details of the algorithms that have been used for the complete training process. For training process the Levenberg - Marquardt algorithm has been used. To analyse the performance, the MSE is used.

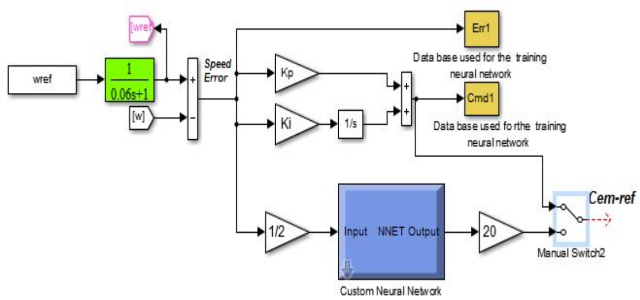

Fig.6 Developed simulation model of speed controller and neural network training

Open also the weight (W) block we will see the blok diagram of the internal structure of hidden layer.

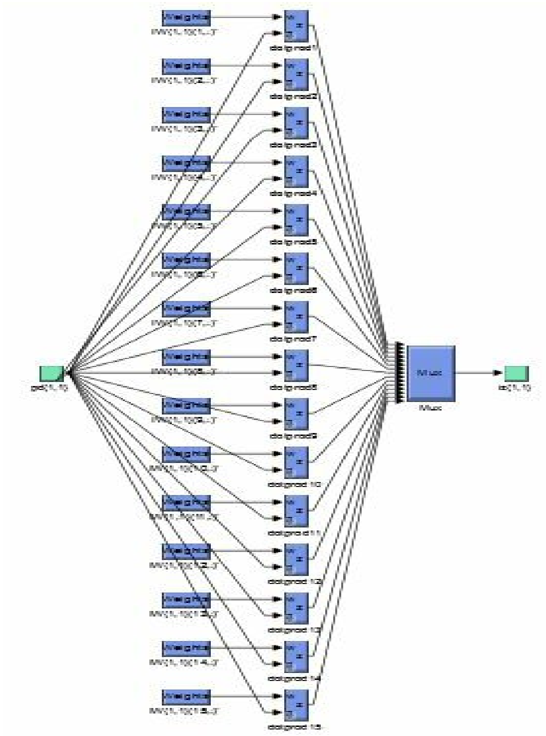

Fig. 7 Blok diagram of the internal structure of hidden layer composed of 15 neurons.

The Plots panel consists of three buttons, which allows the user to get information related to Performance, Training State and Regression. To analyse the performance, the MSE is used as shown in Figures 8. The Plot Interval gives option for the user to view the selected iteration. Figure 8 shows the performance curve of the chosen network with 15 hidden neurons and LM-learning algorithm.

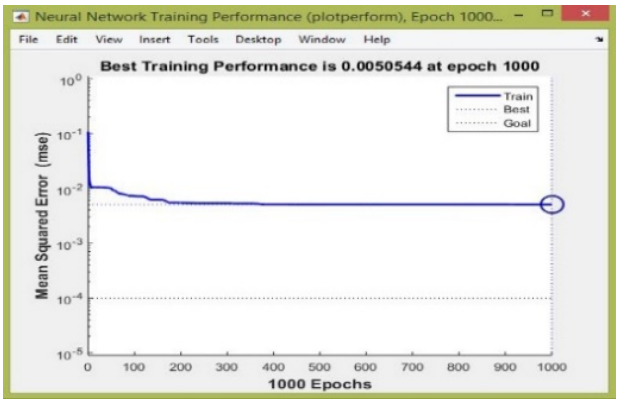

Fig. 8 Performance-plot of the chosen network

The principle diagram of direct vector control (CVD) with rotor flux oriented on the d-q axis is shown in the Figure 9.

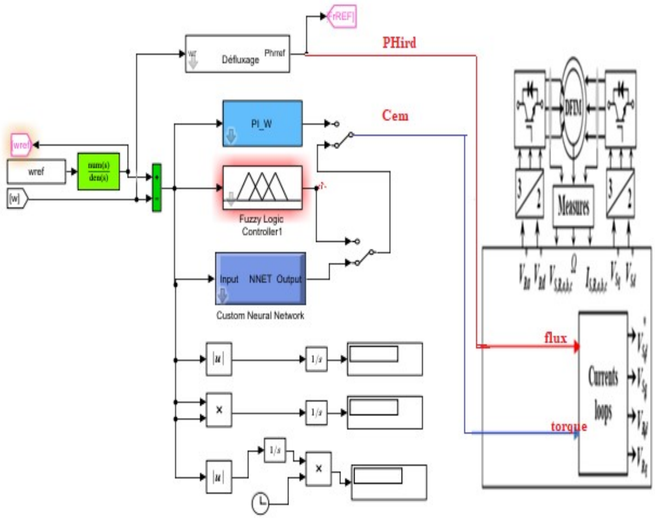

Fig. 9 Block diagram of the proposed control scheme of the DFIM

V. SIMULTION RESULTS

All the simulations of the commands presented in this work are carried out on a two-power supply and a doubly fed induction motor (DFIM). The stator and the rotor are fed through two electronic inverters. These latter are driven by a direct vector controller (DVC) using pulse width modulation (PWM) and rotor flux orientation strategy. Several simulations have been done using the MATLAB/Simulink software in order to validate the theoretical results.

To test the robustness of the regulation, two tests are carried out. Firstly a change in the speed set point from (150rd/s), (-150 rd/s) to (30 rad/s) with a cyclic change of different load torque levels was applied to the DFIM by time. Secondly increasing in the rotor resistance up to 50% of its nominal value. The results of this simulation are shown in Figures 10 ,11, 12 and all of them contain zooms on moments of constraint changes

The speed and the flux components are represented respectively by Figures 10, 11 and 12. We note that the ANN controller based drive system can handle the sudden change in load torque without undershoot, overshoot and without steady state error but with negligible ripples. However The FL controller presents negligible steady state error,

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undershoots and overshoots. The PI controller presents a steady state error, undershoots and overshoots. Thus the PI regulator is not perfectly robust with respect to the variation of the load Figure 10.

It can be seen that the variation in the rotor resistance does not cause any undesirable effect on all the dynamic responses of the FL and the ANN controllers Figure 11. However the PI controller has a disturbance during the variation in the rotor resistance Figure 11. Therefore, this shows the robustness of the ANN and FL controllers in the face of the variation of the rotor resistance.

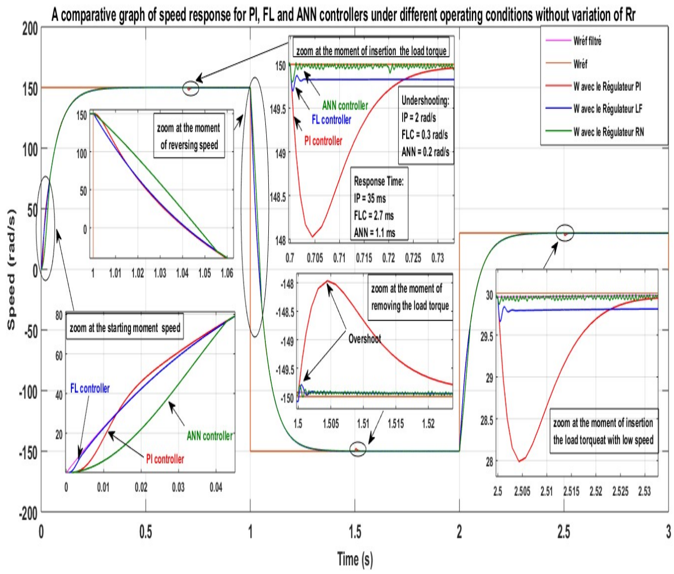

Fig. 10 Simulation results of speed variation

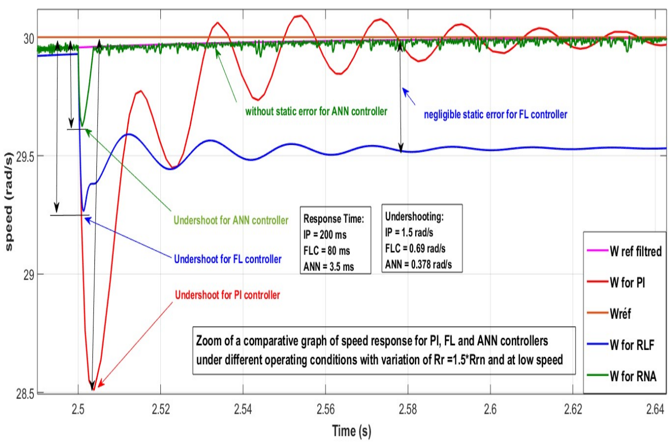

Fig. 11 Simulation results of speed variation with Rr = 1.5*Rrn and at low speed.

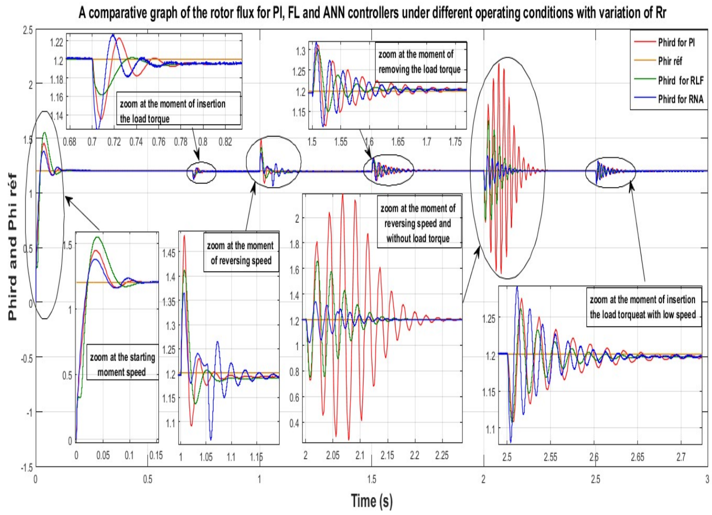

Fig.12 Simulation results of rotor flux

Moreover, the flux Figure 12, show that the decoupling between the torque and the flux is maintained under different operating conditions. Thus the FL and the ANN controllers have been found superior to the PI controller.

There are, in fact, many different measures which can be used to compare the quality of controlled responses and the three commonly used measures are Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE) as shown in Figure 9 . A quantitative comparison between the proposed ANN, FLC and the PI technique in load variation are shown in the table II using the three measures.

The measure indexes are defined as:

$$ISE = \int_0^T e_\Omega^2 dt; \quad IAE = \int_0^T |e_\Omega| dt \quad and \quad ITAE = \int_0^T t|e_\Omega| dt. \tag{25}$$

Where eΩ is the tracking error for speed of DFIM.

TABLE II
COMPARISON OF PERFORMANCE INDEX.

		Controller		
		PI	**FLC**	**ANN**
Error indexes	**IAE**	0.5265	0.0348	0.01591
	ISE	1.4960	0.0015	0.0004809
	ITAE	1.0530	0.0697	0.04774

VI. CONCLUSIONS

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In this paper, the performance study of the modern control techniques based on the artificial intelligence regulator has been carried out under direct vector control for the speed control of doubly fed induction motor (DFIM). The effectiveness of the proposed controllers ANN and FL have been tested in comparison with conventional PI controller under different operating conditions. The results obtained with this ANN and FLC are very interesting compared to the PI controller. According to table 2, it is clearly shown that the proposed ANN and FLC mode controller have the smallest IAE, ISE and ITAE performance indexes with respect to PI controller. The ANN and FL regulators both show great robustness during rotor resistance variation and insensitivity to load torque disturbance, as well as faster dynamics without steady state error when ANN controller is deployed, whereas a negligible steady state error is present when FLC is applied, at all dynamic operating conditions. As the result, the ANN mode controller has very satisfactory tracking performance than those tuned by the FL and IP controller.

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