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DESIGN OF ROBUST CONTROL USING FUZZY LOGIC CONTROLLER FOR DOUBLY-FED INDUCTION MOTOR DRIVES

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This paper presents a fuzzy logic controller destined to the doubly-fed induction motor (DFIM) speed controlling. It solves the problems associated with the conventional IP (Integral Proportional) controller. This fuzzy logic controller is based on the decoupling control to enhance robustness under different operating conditions such as load torque and in the presence of parameters variation.

The simulation results for various scenarios show the high performances of the proposed control in terms of piloting effectiveness, precision, rapidity and stability for the high powers DFIM operating at variable speeds.

Keywords: Fuzzy logic controller, IP controller, DFIM, Decoupling Control

1. Introduction

The doubly fed induction motor (DFIM) with wounded rotor have become increasingly used in industry compared to 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, the presence of brushes and the use of converters. However, it has come back to the forefront because of the progression of vector control and the accessibility to its rotor [3].

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 [13], [14], [15], [16]. Among the control techniques currently applied to asynchronous 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 industry. It is widely used

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for its simplicity and low cost and it occupies a large part in industrial applications where variable speeds 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.

The vector control presents the evolution of the scalar control. 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. Indeed, they require Park transformations, evaluation of trigonometric functions, integrations, regulations, which could not be done purely analog [1]. 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 performed by 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 [2]. Based on conventional controllers (proportional, integral and derivative control), 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. The latter adapts better to these requirements and is also less sensitive and robust.

In this work, we will focus on solving robustness problems by using the fuzzy logic technique that is part of artificial intelligence. The Fuzzy Logic tool was introduced in 1965 by Lotfi Zadeh. It is a mathematical tool for dealing with uncertainty [6]. Since the first successful application of fuzzy sets in control systems fuzzy logic control (FLC) has attracted the attention of many researches in engineering [5],[7],[8]. Unlike the other controllers, the FLC design uses practice qualitative knowledge which is provided generally by an experienced operator [8]. It is suitable for systems with uncertain or complex dynamics. Generally, a fuzzy control algorithm consists of a set of decision rules. Thus, it can be considered a nonmathematical algorithm in contrast to conventional control algorithms. 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. The simulation results of both of the IP controller and the new fuzzy logic controller are shown in section 6. Finally, the conclusions are presented in section 7.

2. Mathematic models of DFIM

The structure of DFIM is very complex. Therefore, in order to develop a model, it is necessary to consider the following simplifying assumptions. The machine is considered symmetrical with constant air gap; the magnetic circuit is not saturated, and it is perfectly laminated, with the result that the iron losses and hysteresis are negligible and only the windings are driven by currents; the magneto-motive force (mmf) created in one phase of stator and rotor are sinusoidal distributions along the gap [4].

$$\begin{aligned} V_{ds} &= R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \omega_a \phi_{qs}; \\ V_{qs} &= R_s i_{qs} + \frac{d\phi_{qs}}{dt} - \omega_a \phi_{ds}; \\ V_{os} &= R_s i_{os} + \frac{d\phi_{os}}{dt}. \end{aligned} \tag{1}$$

Where the angular velocity of the axis system (d, q) is: $\omega_a = \frac{d\theta_s}{dt}$

For the rotor, we have:

$$\begin{aligned} V_{dr} &= R_r i_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_a - \omega_r)\phi_{qr}; \\ V_{qr} &= R_r i_{qr} + \frac{d\phi_{qr}}{dt} - (\omega_a - \omega_r)\phi_{dr}; \\ V_{or} &= R_r i_{or} + \frac{d\phi_{or}}{dt}. \end{aligned} \tag{2}$$

To study the transient phenomena (start, brake and load variation), the equation (3) of motion must be added to the precedent system of equations.

$$J\frac{d\Omega_r}{dt} + f_r \Omega_r = C_{em} - C_r, \tag{3}$$

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

$$C_{em} = \frac{3pM}{2L_r}\left(\phi_{dr} i_{qs} - \phi_{qr} i_{ds}\right), \tag{4}$$

3. Structure of the 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 stator flux space vector as shown in the figure 1 [12].

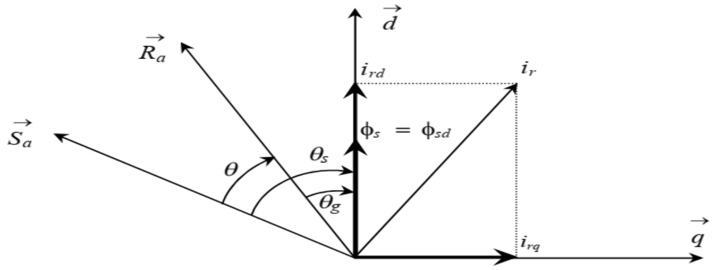

Fig. 1 Illustration of the orientation stator flux.

Then, after the d-axis is aligned with the stator flux vector, we get:

$$\phi_{sd} = \phi_s, \quad \phi_{sq} = 0;$$
$$i_{sq} = -\frac{M}{L_s} i_{rq}, \quad i_{sd} = 0; \tag{5}$$
$$i_{rd} = \frac{\phi_s^*}{M}.$$

Thus, by taking into account these new conditions and substituting equations (5) in equations (2), the dynamic model of an induction machine became:

$$\begin{aligned} V_{rd} &= R_r . i_{rd} + \sigma . L_r \frac{di_{rd}}{dt} + \frac{M}{L_s} V_{sd} - (\omega_s - \omega)\sigma . L_r . i_{rq}; \\ V_{rq} &= \left(R_r + \frac{M^2}{L_s T_s} \right) i_{rq} + \sigma . L_r \frac{di_{rq}}{d} + \frac{M}{L_s} V_{sq} - \frac{M}{L_s} \omega \phi_{sd} + (\omega_s - \omega)\sigma . L_r . i_{rd}. \end{aligned} \tag{6}$$

It can be seen that the voltage equations (6) include two 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 [11].

Two intermediate variables of decoupling can be defined as follows:

$$\begin{aligned} V_{rd1} &= V_{rd} + E_d - \frac{M}{L_s} V_{sd}; \\ V_{rq1} &= V_{rq} + E_q - \frac{M}{L_s} V_{sq}. \end{aligned} \tag{7}$$

With:

$$E_d = \sigma.L_r(\omega_s - \omega)i_{rq};$$
$$E_q = \frac{M}{L_s}\omega\phi_{sd} - \sigma.L_r(\omega_s - \omega)i_{rd}. \tag{8}$$

The principle diagram of direct vector control (CVD) with stator flux oriented on the dq axis is shown in the figure 2. This scheme can be applied either in the case of conventional regulation or in the case of FLC.

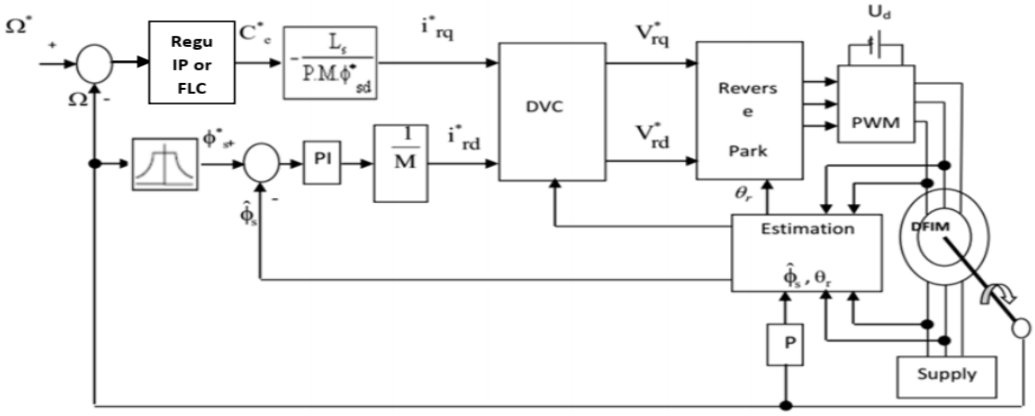

Fig.2. DFIM oriented stator flow directional vector control.

4. Speed control via IP controller

The Integral Proportional (IP) controller has been applied for the control of induction machine speed. The speed control loop with the use of an IP type regulator is shown in the Fig. 3. It is used for the adjustment of the mechanical variable.

Integral proportional controller is advance form of proportional integral (PI) controller. In this controller the integral part is in feed-forward path and proportional part is in feedback path as shown in the Fig. 3 [9]. The IP controller is essentially different from the PI controller by the fact that there is no zero in the transfer function of the closed loop [10]. In general, the presence of a zero in a system transfer function has to limit the influence of the nearest pole since the zero practically compensates the pole closest to the origin of the complex plane. The transfer function of the closed loop is given by:

$$\frac{\Omega(s)}{\Omega^*(s)} = \frac{1}{1 + \frac{K_{p\Omega} + f}{K_{p\Omega}K_{i\Omega}}s + \frac{J}{K_{p\Omega}K_{i\Omega}}s^2}, \tag{9}$$

$K_{p\Omega}$ and $K_{i\Omega}$ denote the proportional and the integral gains of the IP speed controller respectively.

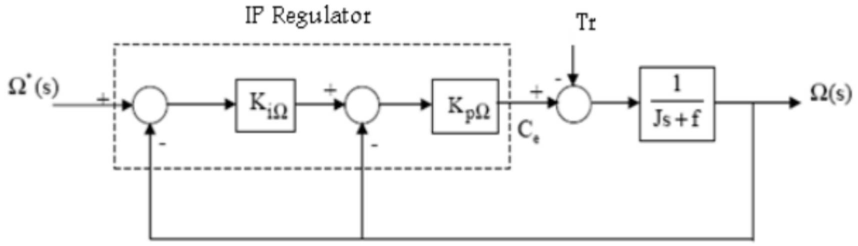

Fig. 3 Speed regulator with IP controller

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 ω_n, the proportional and the integral gains can be represented by equation 10.

$$K_{p\Omega} = 2J\xi\omega_n - f;$$
$$K_{i\Omega} = \frac{J\omega_n^2}{K_{p\Omega}}. \tag{10}$$

5. Fuzzy P.I. Controller

Let us consider the internal schema of the fuzzy regulator in Fig. 4.

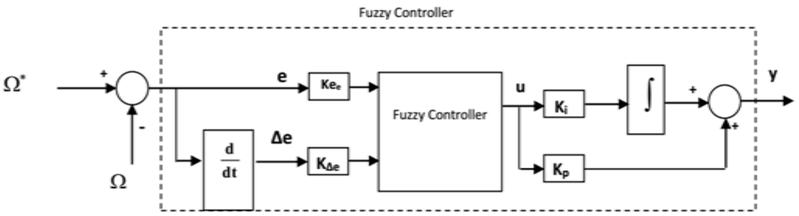

Fig. 4 Internal structure of the blur-PI speed controller

The action of the Controller may be written in the form:

$$u = K_e \cdot e + K_{\Delta e} \cdot \Delta e, \tag{11}$$

The fuzzy-PI output is:

$$y = K_p \cdot u + \int K_i \cdot u, \tag{12}$$

Where: Ke is the gain of the speed error, KΔe is the gain of the variation of the speed error, Kp is the proportional factor, Ki is the integral factor, 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:

$$e(k) = \Omega^*(k) - \Omega(k), \tag{13}$$

Ω^* : Reference speed

The variation of the error Δe can be approached by:

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

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;
- 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.

Fig. 5 shows the different memberships functions of the inputs and the output u. The fuzzy rules allow 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 1

Inference matrix of fuzzy rules

Δe e	NG	NM	NP	Z	PP	PM	PG
NG	NG	NG	NG	NM	NP	NTP	Z
NM	NG	NG	NM	NP	NTP	Z	PTP
NP	NG	NM	NP	NTP	Z	PTP	PP
Z	NM	NP	NTP	Z	PTP	PP	PM
PP	NP	NTP	Z	PTP	PP	PM	PG
PM	NTP	Z	PTP	PP	PM	PG	PG
PG	Z	PTP	PP	PM	PG	PG	PG

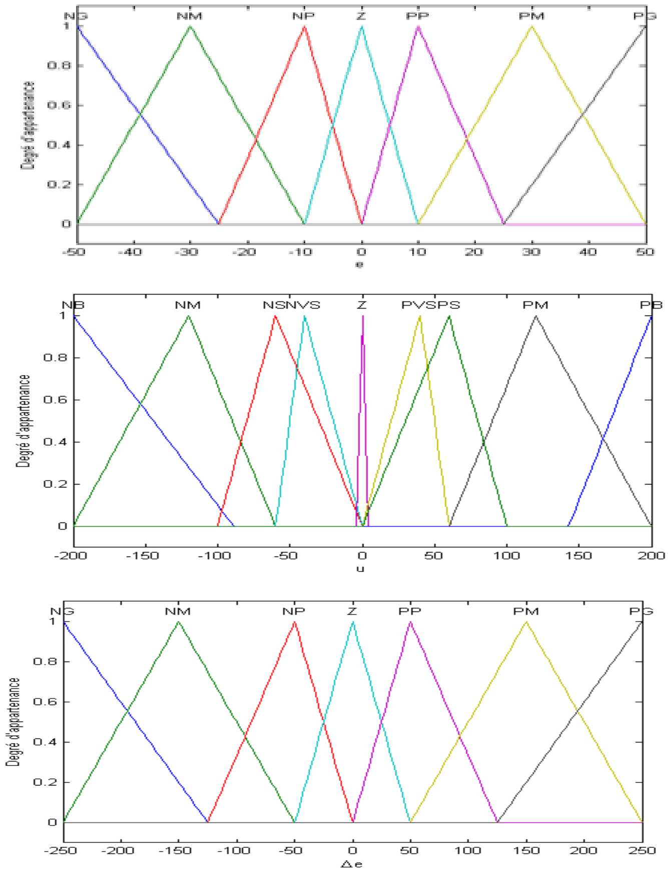

Fig. 5 Functions for membership of inputs (e, Δe) and Output (u)

The two-input fuzzy controller is represented by its characteristic surface (Fig. 6)

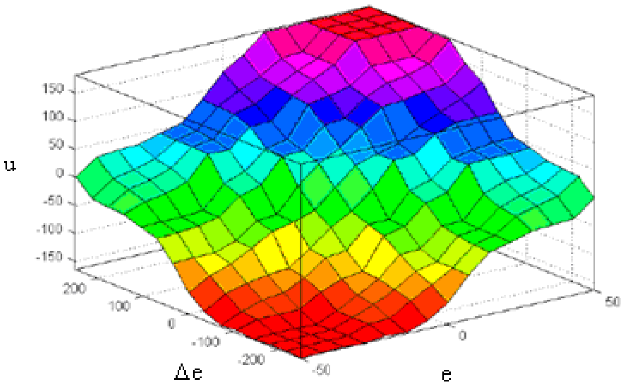

Fig. 6 Characteristic surface of a fuzzy controller

6. Simulation 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 is directly connected to the power network (220/380V, 50Hz) and the rotor is powered through an electronic inverter. The latter is driven by a direct vector controller (DVC) using pulse width modulation PWM and stator flux orientation strategy. Several simulations have been done using the MATLAB/Simulink software in order to validate the theoretical results.

In order to test the robustness of the regulation, two tests are carried out. Firstly a change in the speed set point from (157rd/s) to (-157 rd/s) with a cyclic change of different load torque levels was applied to the DFIM by time. Secondly the rotor resistance is increased up to 50% of its nominal value. The results of this simulation are shown in Fig. 7, Fig. 8 and Fig. 9.

The speed, the electromagnetic torque and the flux components are represented respectively by Figs. 7, 8 and 9. All of them contain zooms on moments of constraint changes. We note that the fuzzy logic controller-based drive system can handle the sudden change in load torque without undershoot, overshoot and a negligible steady state error. However, IP controller presents a steady state error, undershoots and overshoots. Thus, the IP regulator is not perfectly robust with respect to the variation of the load.

It can be seen that the variation in the rotor resistance does not cause any undesirable effect on all the dynamic responses of the fuzzy controller. However, IP controller has a disturbance during the variation in the rotor resistance. Therefore, this shows the robustness of the fuzzy controller in the face of the variation of the rotor resistance.

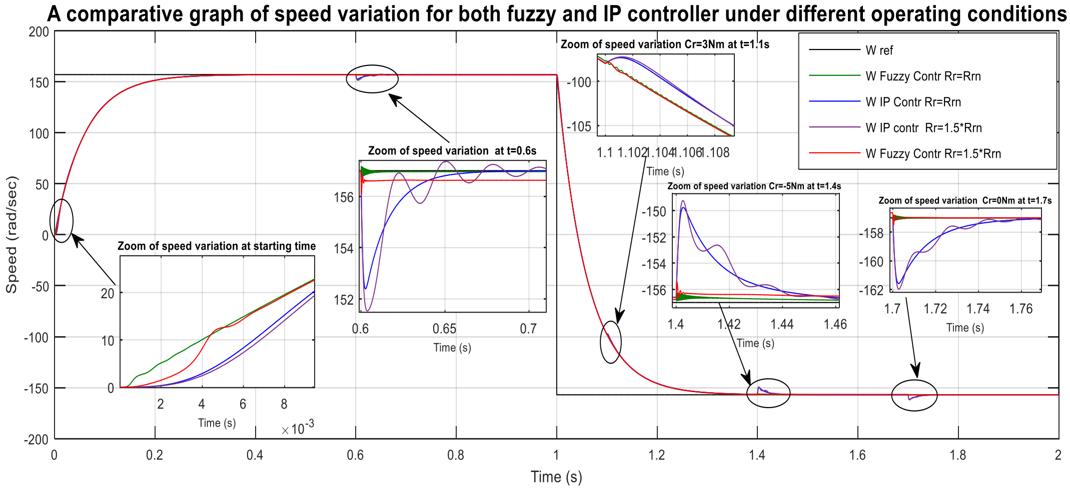

Fig. 7. Simulation results of speed variation

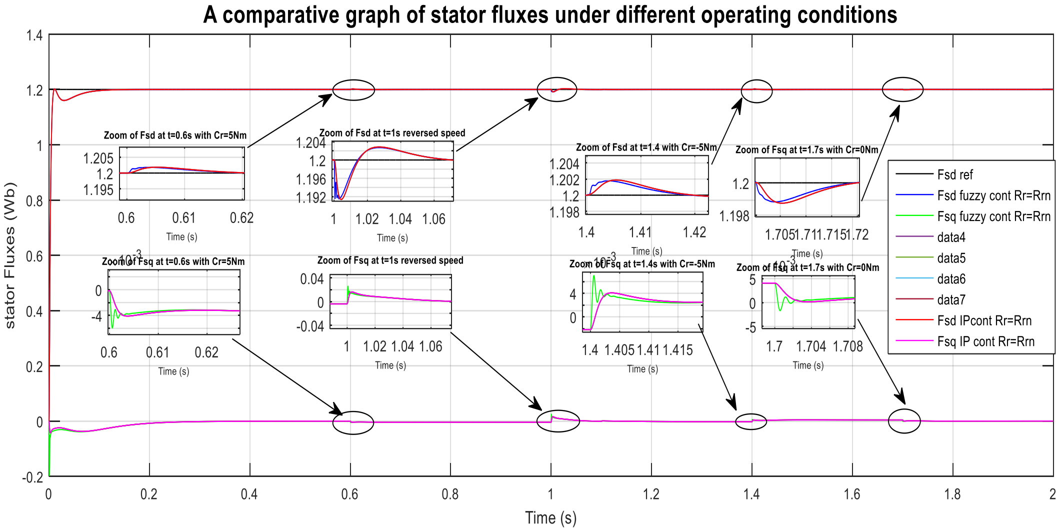

Fig.8. Simulation results of stator flux

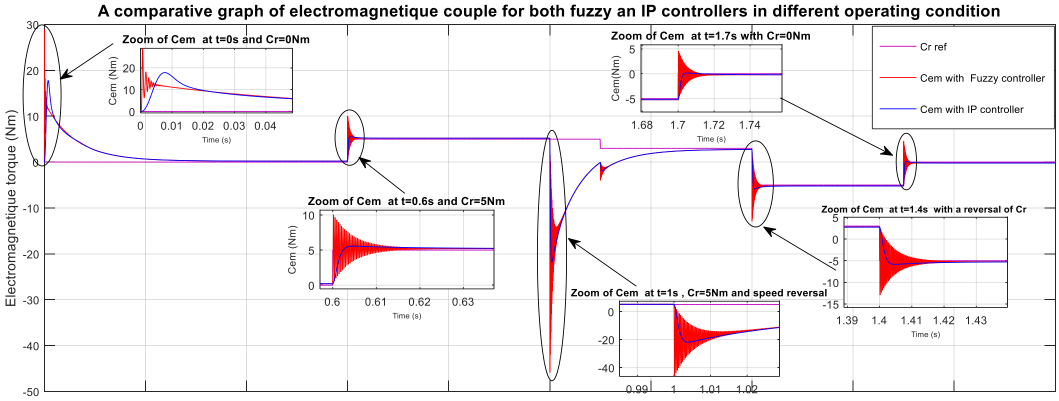

Fig.9. Simulation results of electromagnetic torque

Moreover, the electromagnetic torque (Fig.9) and the flux (Fig. 8), show that the decoupling between the torque and the flux is maintained under different conditions. Thus, the proposed controller has been found superior to the IP controller.

There are, in fact, many different measures which can be used to compare the quality of controlled responses. The three commonly used measures are Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE). A quantitative comparison between the proposed fuzzy logic and the IP technique in load variation are shown in the table 2 using the three measures.

The measure indexes are defined as:

$$
\begin{aligned}
ISE &= \int_0^T e_\Omega^2 dt; \\
IAE &= \int_0^T \left|e_\Omega\right| dt; \\
ITAE &= \int_0^T t\left|e_\Omega\right| dt.
\end{aligned}
\tag{15}
$$

Where eΩ is the tracking error for speed of DFIM.

Table 2

Performance error indexes obtained by Simulink

Controller	Error indexes		
	IAE	ISE	ITAE
Fuzzy	0.0348	0.0015	0.0697
IP	0.5265	1.4960	1.0530

7. Conclusion

In this paper, we have proposed a fuzzy logic controller for the speed control of doubly-fed induction motor (DFIM) with a direct stator flux orientation control. The effectiveness of the proposed controller has been tested in comparison with conventional IP controller under different operating conditions. According to table 2, it is clearly shown that the proposed fuzzy controller has the smallest IAE, ISE and ITAE performance indexes with respect to IP controller. The fuzzy regulator proves robustness against rotor resistance variation and insensitivity to load torque disturbance as well as faster dynamics with negligible steady state error at all dynamic operating conditions. As the result, the proposed fuzzy logic controller (FLC) has very satisfactory tracking performance than those tuned by the IP controller.

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