Volume 6, Issue 3
June 2017

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Speed Control of a Doubly Fed Induction Motor Based on Fuzzy Gain-Adaptive IP

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ABSTRACT

This paper presents a comparison between a fuzzy-IP gain adaptive controller and a conventional IP controller used for speed control with a direct stator flux orientation control of a doubly fed induction motor. In particular, the introduction part of the paper presents a Direct Stator Flux Orientation Control (DSFOC), the first part of this paper presents a description of the mathematical model of DFIM, and an adaptive IP controller is proposed for the speed control of DFIM in the presence of the variations parametric, A fuzzy inference system is used to adjust in real-time the controller gains. The obtained results show the efficacy of the proposed method.

Keywords: *doubly fed induction motor, direct stator flux orientation control, fuzzy gain-adaptive IP controller, IP controller.*

1. INTRODUCTION

In recent years, the use of doubly fed induction machine (DFIM) is a best solution for applications where the torque is proportional to the square of the speed; DFIM is an asynchronous wound-rotor machine whose stator and rotor windings are connected to electrical sources [1-2] .

The advantages of DFIM in motor operation for high power applications such as traction, marine propulsion or as a generator in wind systems [3-5], the many benefits of this machine are: reduced manufacturing cost, relatively simple construction, higher speed and do not require ongoing maintenance. For operation at different speeds must be inserted in the machine a converter PWM (Pulse Width Modulation) between the machine and the network. For, whatever the speed of the machine, the voltage is rectified and an inverter connected to the network side is responsible for ensuring consistency between the network frequency and that delivered by the device. The DFIM is essentially nonlinear, due to the coupling between the flux and the electromagnetic torque [6] [7] .

With the field orientation control (FOC) method, induction machine drives are becoming a major candidate in high-performance motion control applications, where servo quality operation is required. Fast transient response is made possible by decoupled torque and flux control. The most widely used control method is perhaps the proportional integral control (PI). It is easy to design and implement, but it has difficulty in dealing with parameter variations, and load disturbances [8]. Recent literature has paid much attention to the potential of Gain Adaptive control in machine drive applications.

A number of methods have been proposed in the literature for nonlinear Adaptive applied to the DFIM. A Speed Sensorless Sliding-Mode Controller for DFIM Drives with Adaptive Backstepping Observer in [9] and Robust Speed Sensorless Control Based on Input-output Feedback Linearization Control Using a Sliding-mode Observer in [10]. Our purpose in this paper is to introduce a Fuzzy Gain-Adaptive IP control for DFIM drive system; Fuzzy logic, whose theoretical bases have been established since the early 1960, allows exploiting the linguistic information describing the dynamic behavior of the system. This information, provided by the human expert, can be expressed as a set of fuzzy rules type of If-Then.

The definition of rules and membership functions to said sets "fuzzy sets" enables designers to better understand the vague and difficult to model processes. One area of application of fuzzy logic that has evolved considerably and continues to attract the interest of many researchers is the modeling and control systems [11-13].

A number of methods have been proposed in the literature for PID gain scheduling [14] a stable gain-scheduling PID controller is developed based on grid point concept for nonlinear systems. Different gain scheduling methods were studied and compared [15], [16] a new PID scheme is proposed in which the controller gains were scheduled by a fuzzy inference scheme. Many method and research works in this domain in [17-20]. The interested readers can find a brief review of different fuzzy PID structures in [21].

The paper is organized as follows: In Section 2 mathematical model of the DFIM is presented. In section 3, we begin with the DFIM oriented model in view of the vector control; next the stator flux ϕ_s is estimated. The Fuzzy Gain-Adaptive IP and design Fuzzy Gain-Adaptive IP of motor speed in section 4, and the simulation results are given in section 5. Finally, we give some conclusion remarks on the control proposed of DFIM using fuzzy logic.

2. DESCRIPTION AND MODELING OF DFIM

The electrical model of the DFIM is expressed in a (d-q) synchronous rotating frame (figure 1).

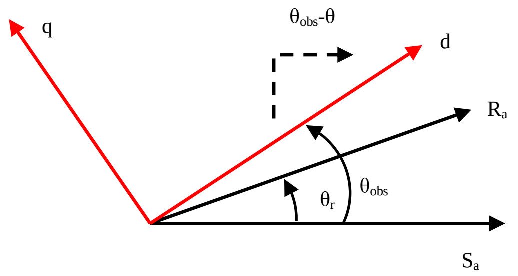

Fig.1 Defining the real axes of DFIM from the reference (d, q)

A. Reference fixed relative to the rotating field (d, q)

For a reference related to the rotating field, was $\omega_s = \omega_r + \omega_m$ in the system of equations is as follows:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{sd} \\ \Phi_{sq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_s \\ \omega_s & 0 \end{bmatrix} \begin{bmatrix} \Phi_{sd} \\ \Phi_{sq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} \quad (2)$$

Expressions of flux are given by

$$\begin{cases} \phi_{sd} = l_s I_{sd} + M I_{rd} \\ \phi_{sq} = l_s I_{sq} + M I_{rq} \\ \phi_{rd} = l_r I_{rd} + M I_{sd} \\ \phi_{rq} = l_r I_{rq} + M I_{sq} \end{cases} \quad (3)$$

Replaces (3) in (1) and (2) we obtained:

$$\begin{cases} V_{sd} = R_s I_{sd} + l_s \frac{dI_{sd}}{dt} + M \frac{dI_{rd}}{dt} - \omega_s l_s I_{sq} - \omega_s M I_{rq} \\ V_{sq} = R_s I_{sq} + l_s \frac{dI_{sq}}{dt} + M \frac{dI_{rq}}{dt} + \omega_s l_s I_{sd} + \omega_s M I_{rd} \\ V_{rd} = R_r I_{rd} + l_r \frac{dI_{rd}}{dt} + M \frac{dI_{sd}}{dt} - \omega l_r I_{rq} - \omega M I_{sq} \\ V_{rq} = R_r I_{rq} + l_r \frac{dI_{rq}}{dt} + M \frac{dI_{sq}}{dt} + \omega l_r I_{rd} + \omega M I_{sd} \end{cases} \quad (4)$$

B. DFIM model in the form of state equation

For the DFIM the control variables are the stator and rotor tensions, [22] with considering:

- An input-output current decoupling is set for all currents;
- The (d-q) frame is oriented with the stator flux;
- Due to the large gap between the mechanical and electrical time constants, the speed can be considered as invariant with respect to the state vector.

Under these conditions, the electrical equations of the machine are described by a time variant state space system as shown in (5)

$$\begin{aligned} \dot{X} &= A.X + B.U \\ Y &= C.X \end{aligned} \quad (5)$$

With X, A, B, U, Y and C represent the state vector, system state evolution matrix, matrix of control, vector of the control system, output vector and output matrix (observation matrix) respectively,
Where

$$X = \begin{bmatrix} i_{sd} & i_{sq} & i_{rd} & i_{rq} \end{bmatrix}^T g \quad (6)$$

$$U = \begin{bmatrix} V_{sd} & V_{sq} & V_{rd} & V_{rq} \end{bmatrix}^T \quad (7)$$

Where i_s, i_r, V_s and V_r denote stator currents, rotor currents, stator terminal voltage and rotor terminal voltage, respectively. The subscripts s and r stand for stator and rotor while subscripts d and q stand for vector component with respect to a fixed stator reference frame [23].
From a matrix representation:

$$\frac{d}{dt} \begin{bmatrix} I_{sd} \\ I_{sq} \\ I_{rd} \\ I_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix}^{-1} . \begin{bmatrix} -R_s & \omega_s L_s & 0 & \omega_s M \\ -\omega_s L_s & -R_s & -\omega_s M & 0 \\ 0 & (\omega_s - \omega) M & -R_s & (\omega_s - \omega) L_r \\ -(\omega_s - \omega) M & 0 & -(\omega_s - \omega) L_r & -R_s \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \\ I_{rd} \\ I_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix}^{-1} \begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} \quad (8)$$

Let:

$$[L] = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_s & 0 \\ 0 & M & 0 & L_s \end{bmatrix} \text{and}$$

$$[Z] = \begin{bmatrix} -R_s & \omega_s L_s & 0 & \omega_s M \\ -\omega_s L_s & -R_s & -\omega_s M & 0 \\ 0 & (\omega_s - \omega) M & -R_s & (\omega_s - \omega) L_r \\ -(\omega_s - \omega) M & 0 & -(\omega_s - \omega) L_r & -R_s \end{bmatrix}$$

Then equation (5) becomes:

$$\frac{dX}{dt} = [L]^{-1} . [Z] . X + [L]^{-1} . U \quad (9)$$

In analogy to equation (9) with equation (5) we find $A = [L]^{-1} . [Z]$ and $B = [L]^{-1}$ [23].

$$A=\begin{bmatrix} -a_1 & a\omega+\omega_s & a_3 & a_5\omega \\ -a\omega-\omega_s & -a_1 & -a_5\omega & a_3 \\ a_4 & -a_6\omega & -a_2 & -\dfrac{\omega}{\sigma}+\omega_s \\ a_6\omega & a_4 & \dfrac{\omega}{\sigma}-\omega_s & -a_2 \end{bmatrix} \tag{10}$$

$$B=\begin{bmatrix} b_1 & 0 & -b_3 & 0 \\ 0 & b_1 & 0 & -b_3 \\ -b_3 & 0 & b_2 & 0 \\ 0 & -b_3 & 0 & b_2 \end{bmatrix} \tag{11}$$

$$C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

Where

$$a=\frac{1-\sigma}{\sigma} \quad a_1=\frac{R_s}{\sigma L_s} \quad a_2=\frac{R_r}{\sigma L_r} \quad a_3=\frac{R_r M}{\sigma L_S L_r} \quad a_4=\frac{R_s M}{\sigma L_s L_r}$$

$$a_5=\frac{M}{\sigma L_s} \quad a_6=\frac{M}{\sigma L_r} \quad b_1=\frac{1}{\sigma L_s} \quad b_2=\frac{1}{\sigma L_r} \quad b_3=\frac{M}{\sigma L_s L_r}$$

$$\sigma=1-\frac{M^2}{L_s L_r}$$

Where ω_s , ω , L , R and M denote stator pulsation, rotor pulsation, inductance, resistance and mutual inductance, respectively. σ is redefined leakage factor [22].

The generated torque of DFIM can be expressed in terms of stator currents and stator flux linkage as:

$$C_e=\frac{PM}{L_S}\left(\phi_{sq}.i_{rd}-\phi_{sd}.i_{rq}\right) \tag{13}$$

Where P , is the number of pole pairs. In addition the mechanical dynamic equation is given by

$$J\frac{d\Omega}{dt}=C_e-C_r-f\Omega \tag{14}$$

Where J and f denote the moment of inertia of the motor and viscous friction coefficient, respectively, C_r is the external load and Ω is the mechanical speed.

3. VECTOR CONTROL BY DIRECT STATOR FLUX ORIENTATION

To simplify the control you need to make a judicious choice reference. To this, we place ourselves in a reference (d, q) related to the rotating field with an orientation of the flux stator, according to the condition of the stator flux orientation [24]

$$\phi_{sd}=\phi_s \text{ and } \phi_{sq}=0 \tag{15}$$

Replaces (15) in (1) and (2) we obtained

$$\begin{cases} V_{sd}=R_s I_{sd} \\ V_{sq}=R_s I_{sq}+\omega_s\phi_{sd} \\ V_{rd}=R_r I_{rd}-\omega\phi_{rq} \\ V_{rq}=R_r I_{rq}+\omega\phi_{rd} \end{cases} \Leftrightarrow \begin{cases} \phi_{sq}=0 \Rightarrow I_{sq}=-\dfrac{M}{L_s}I_{rq} \\ I_{sd}=0 \\ I_{rd}=\dfrac{\phi_s^*}{M} \end{cases} \tag{16}$$

The torque equation becomes

$$C_e=-\frac{PM}{L_S}\phi_s^*.I_{rq} \tag{17}$$

$$I_{rq}=-\frac{L_S}{P.M.\phi_s^*}.C_e^{\ *} \tag{18}$$

Equation (4) was:

$$\frac{d\theta_s}{dt}=\frac{\dfrac{R_s M}{L_s}I_{rq}+V_{sq}}{\phi_s^*} \tag{19}$$

According to the equation (3) of the stator flux, then:

$$\begin{cases} I_{sd}=\dfrac{1}{L_s}(\phi_{sd}-MI_{rd}) \\ I_{sq}=\dfrac{1}{L_s}(\phi_{sq}-MI_{rq}) \end{cases} \tag{20}$$

From the relations (20) and (4)

$$\begin{cases} \dot{\phi}_{sd}=V_{sd}+\dfrac{M}{T_s}I_{rd}-\dfrac{1}{T_s}\phi_{sd} \\ \dot{\phi}_{sq}=V_{sq}+\dfrac{M}{T_s}I_{rq}-\omega_s\phi_{sq} \end{cases} \tag{21}$$

The relationship of the rotor current

$$\begin{cases} \dot{I}_{rd}=-\dfrac{1}{\sigma}(\dfrac{1}{T_r}+\dfrac{M^2}{L_s T_s L_r})I_{rd}-\dfrac{M}{\sigma L_s L_r}V_{sd} \\ \qquad +\dfrac{M}{\sigma L_r L_s T_s}\phi_{sd}+(\omega_s-\omega)I_{rq}+\dfrac{1}{\sigma L_r}V_{rd} \\ \dot{I}_{rq}=-\dfrac{1}{\sigma}(\dfrac{1}{T_r}+\dfrac{M^2}{L_s T_s L_r})I_{rq}-\dfrac{M}{\sigma L_s L_r}V_{sq} \\ \qquad +\dfrac{M}{\sigma L_r L_s}\omega\phi_{sd}-(\omega_s-\omega)I_{rd}+\dfrac{1}{\sigma L_r}V_{rq} \end{cases} \tag{22}$$

The relationship of the mechanical speed

$$\frac{d\Omega}{dt}=\frac{P.M}{J.L_s}(I_{rq}.\phi_{sd})-\frac{C_r}{J}-\frac{f}{J}\Omega \tag{23}$$

Where $T_s=\dfrac{L_s}{R_s}$ and $T_r=\dfrac{L_r}{R_r}$ are stator and rotor time-constant respectively [22].

A. Stator flux estimator

In the direct vector control stator flux oriented DFIM, precise knowledge of the amplitude and the position of the stator flux vector is necessary. Motor mode of DFIM, the stator and rotor currents are measured, the stator flux can be estimated [22].

The flux estimator may be obtained by the following equations

$$\begin{cases}\phi_{sd} = l_s I_{sd} + M I_{rd} \\ \phi_{sq} = l_s I_{sq} + M I_{rq}\end{cases} \tag{24}$$

The position stator flux is calculated by the following equations:

$$\theta_r = \theta_s - \theta \tag{25}$$

In which:

$$\theta_s = \int \omega_s dt \quad , \theta = \int \omega \, dt \tag{26}$$

Where: $\omega = P.\Omega$ and θ_s is the electrical stator position, θ is the electrical rotor position.

4. FUZZY GAIN-ADAPTIVE STRATEGY

The control scheme for DFIM using the vector controller is presented in Figure 2; Conventional IP and PI controllers are is a generic control loop feedback mechanism (controller) widely used in industrial control systems. They are simple and easy to use due to the fact that they do not need any mathematical model of the controlled process or complicated theories. But one of the main drawbacks of these controllers is that there is no certain way for choosing the control parameters which guarantees the good performance.

Although IP controllers are robust against structural changes and uncertainties in the system parameters, their performance may be affected by such changes or may even lead to system instability. Therefore in real world applications these gains need to be fine-tuned to keep the required performance. To overcome this shortcoming, Fuzzy Gain Adaptive IP Controller is used to tune IP gains online where the tracking error and the change of the tracking error are used to determine control parameters.

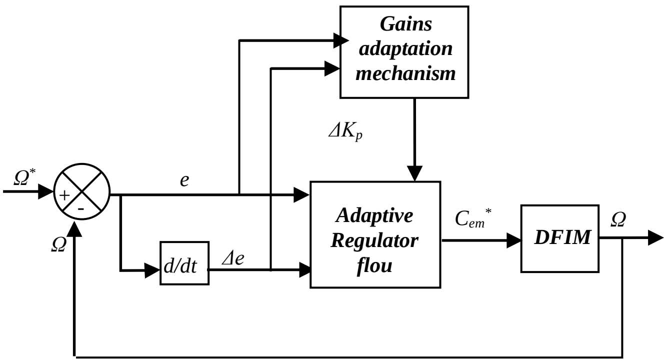

Fig.2 Control scheme for DFIM using the Fuzzy Gain Adaptive IP Controller

A set of linguistic rules in the form of (27) is used in the Fuzzy Gain Adaptive IP Controller structure to determine IP gains:

$$if\ e(k)\ is\ A_i\ and\ \Delta e(k)\ is\ B_i\ then\ K_p\ is\ C_i \tag{27}$$

Where A_i, B_i and C_i are fuzzy sets corresponding to $e(k)$, $\Delta e(k)$ and K_p respectively. 3 sets of 49 rules are used to determine controller gain. The membership functions for input and output variables are defined with triangle and trapezoidal shapes (Figures 3 and 4). All the fuzzy sets for input and output values are normalized for convenience.

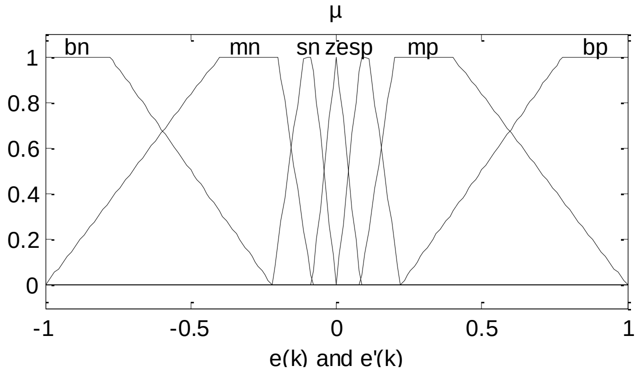

Fig.3 Membership function for $e(k)$ and $\Delta e(k)$ [25]

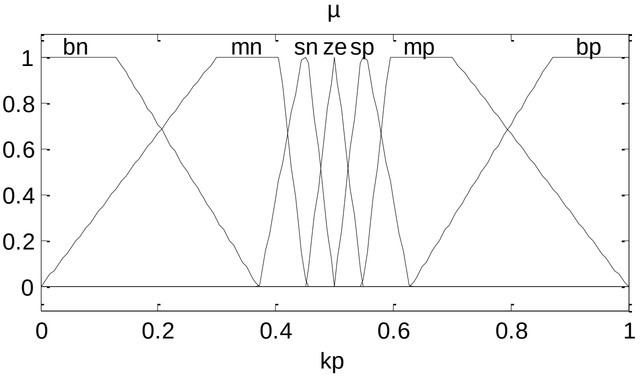

Fig.4 Membership function for gain K_p [25]

Table 1 show the linguist rules used in the Fuzzy Gain Adaptive IP Controller. In these tables, bn, mn, sn, ze, sp, mp, bp represent negative big, negative medium, negative small, zero, positive small, positive medium, and positive big respectively.

Tab.1 Fuzzy tuning rules for K_p [25]

		$\Delta e(k)$						
$e(k)$		NB	NM	NS	ZE	PS	PM	PB
	NB	NB	NB	NB	NM	NS	NVS	ZE
	NM	NB	NB	NM	NS	NVS	ZE	PVS
	NS	NB	NM	NS	NVS	ZE	PVS	PS
	ZE	NM	NS	NVS	ZE	PVS	PS	PM
	PS	NS	NVS	ZE	PVS	PS	PM	PB
	PM	NVS	ZE	PVS	PS	PM	PB	PB
	PB	ZE	PVS	PS	PM	PB	PB	PB

The generated surfaces for the Fuzzy Gain Adaptive IP Controller are shown in Figure 5.

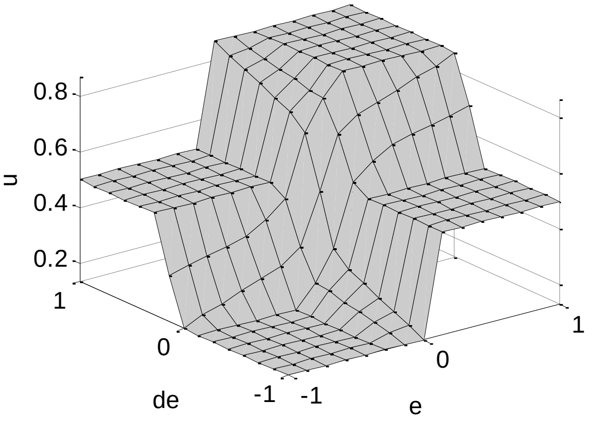

Fig.5 Surface for K_p

5. SIMULATION RESULTS

The IP and Fuzzy Gain-Adaptive IP controllers in a DSFOC of DFIM are used as presented in Fig.1. The DFIM used in this work is a 0.8 KW, whose nominal parameters are reported in the table 2.

Tab.2 Parameters of the DFIM [23]

Definition	Symbol	Value
DFIM Mechanical Power	P_w	4 kW
Stator voltage	U_{sn}	380 V
rotor voltage	U_{rn}	220 V
Nominal current	I_n	3.8/2.2 A
Nominal mechanical speed	Ω_n	1420 rpm
Nominal stator and rotor frequencies	ω_{sn}	50 Hz
Pole pairs number	P	2
Stator resistance	R_s	11.98 Ω
rotor resistance	R_r	0.904 Ω
Stator self inductance	L_s	0.414 H
rotor self inductance	L_r	0.0556 H
mutual inductance	M	0.126 H
Moment of inertia	J	0.01 Kg.m^2
friction coefficient	f	0.00 IS

In the present article the results of two different simulations are reported. In the first simulation, the motor is operated at 157 rad/s and in the second simulation the desired value is chose square type, in the interval time [0Sec, 1Sec] we chose Wref=157 rad/s and in the interval time [1Sec, 2Sec], Wref=50 rad/s. The speed and flux regulation performance of the proposed Fuzzy Gain-Adaptive IP is checked in terms of load torque variations (5 N.m) is suddenly applied at t=0.6s and eliminated at t=1.6s (-5 N.m) and the rotor resistance variations (increase at 100 % of nominal value rotor resistance), while the other parameters, e.g., friction coefficient f , mutual inductance M and stator inductance L_s are held constant for the tow scenario.

A. Step responses of the DFIM

The responses of speed, torque, stator flux and rotor current are shown in Figures 6-9 The Fuzzy Gain Adaptive IP controller shows the good performances to achieve tracking of the desired trajectory. At these changes of loads and resistance, the Fuzzy Gain Adaptive IP controller throw-outs the load disturbance very rapidly with no overshoot and with a negligible static error as can be seen in the response of speed (see Figure 6). The decoupling of torque-flux is maintained in permanent mode. We can see the control is robust from the point of view load variation.

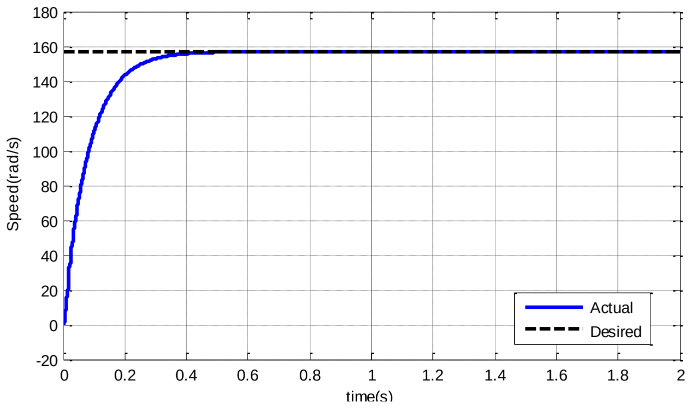

Fig.6 Result of speed

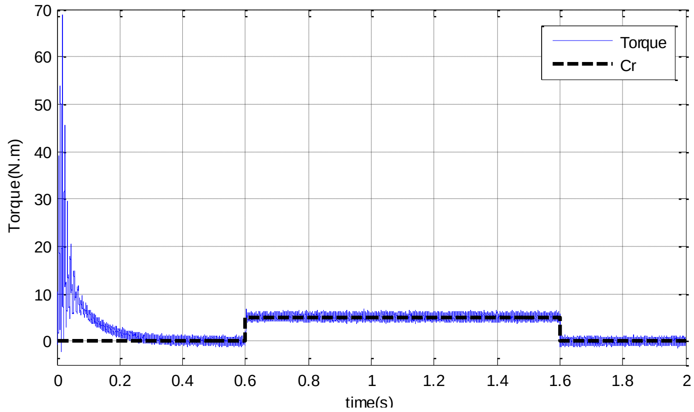

Fig.7Result of Torque

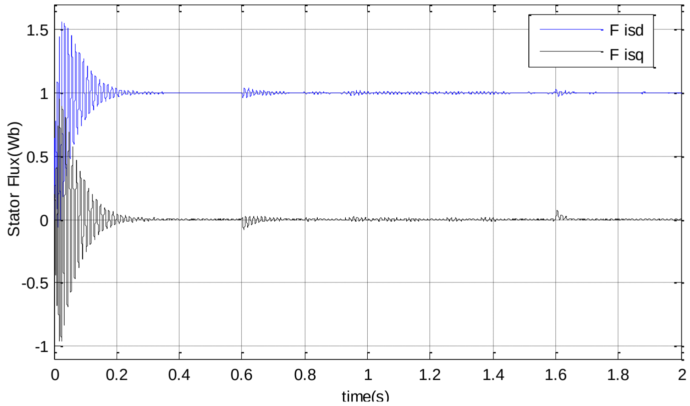

Fig.8 Result of Stator flux

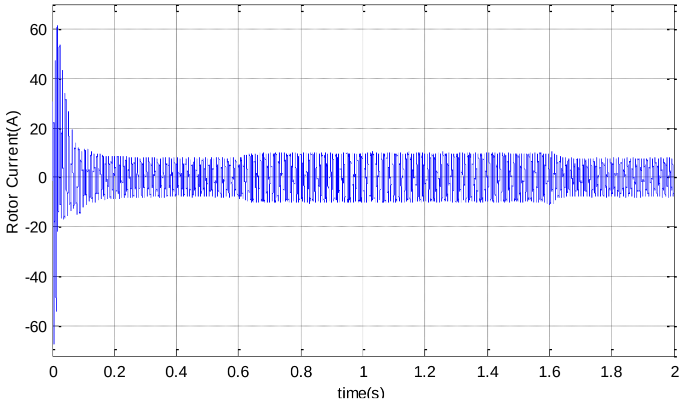

Fig.9 Result of Rotor current

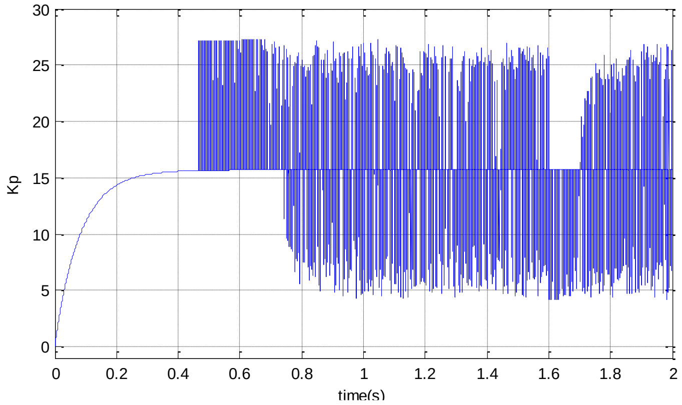

Fig.10 Gain K_p

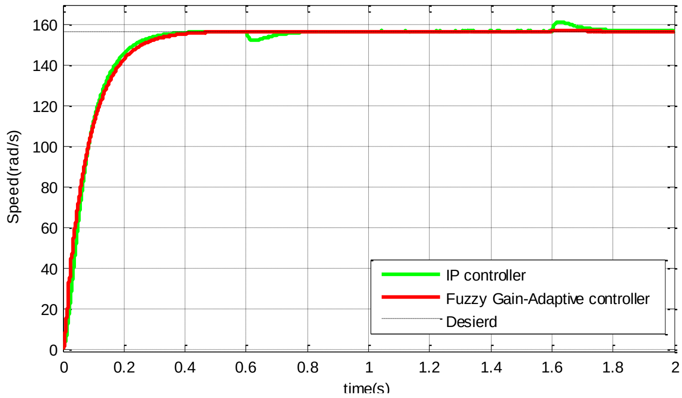

Fig.11 Simulated results comparison of IP and Fuzzy Gain-Adaptive control of speed control of DFIM under load variation.

In order to compare the performance of The Fuzzy Gain Adaptive IP controller with another controller in the similar test, the Figure 11 shows the simulated results comparison of conventional IP (Integral Proportional) and The Fuzzy Gain Adaptive IP controller of speed control below load and resistance variation.

The Fuzzy Gain Adaptive IP controller based drive system can handle the rapid change in load torque without overshoot and undershoot and steady state error, whereas the IP controller has steady state error and the response is not as fast as compared to The Fuzzy Gain Adaptive IP controller. Thus the proposed controller has been found superior to the conventional IP controller.

B. Square responses of the DFIM

The results of using the Fuzzy Gain Adaptive IP controller are shown in figures 12-16:

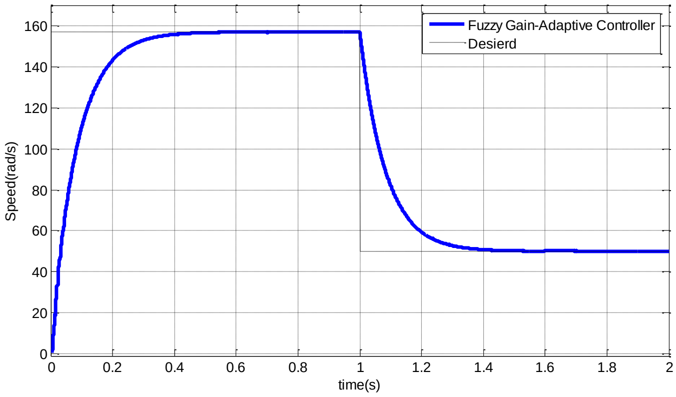

Fig.12 Result of speed

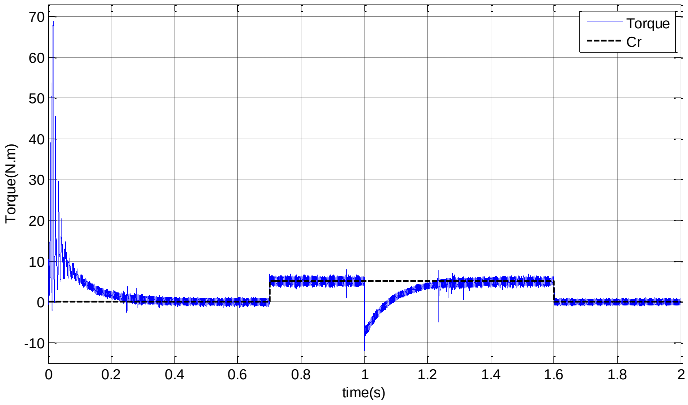

Fig.13 Result of Torque

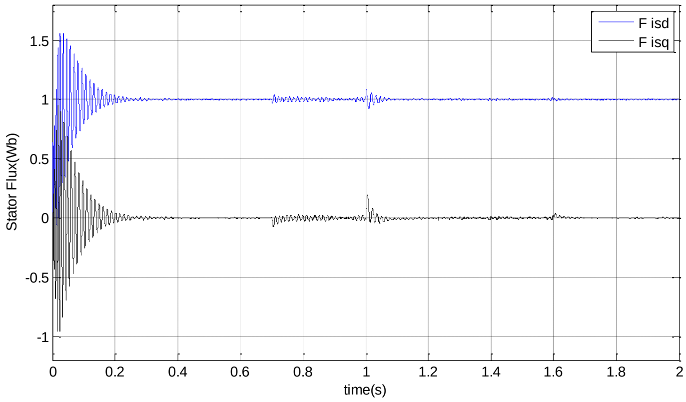

Fig.14 Result of Stator flux

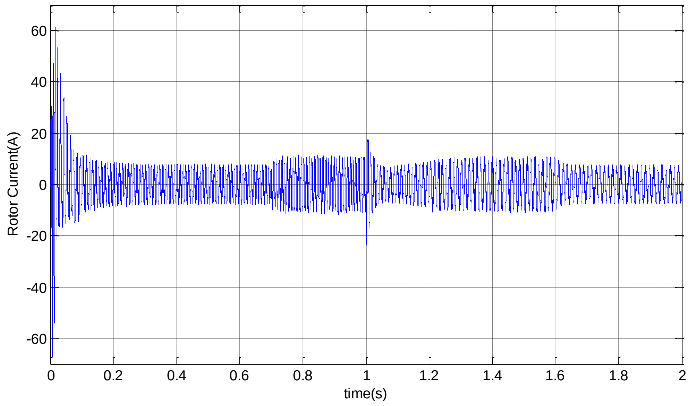

Fig.15 Result of Rotor current

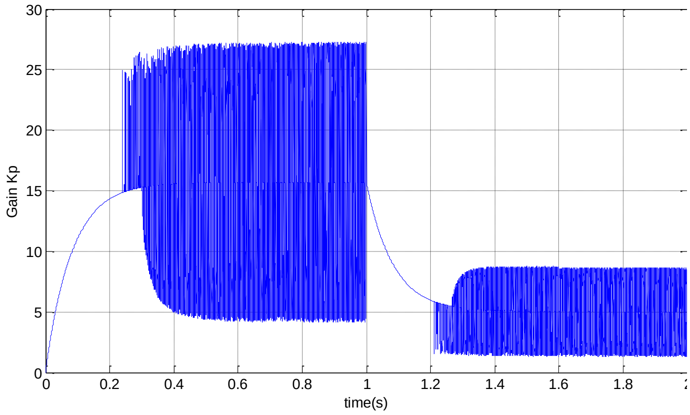

Fig.16 Gain K_p

6. CONCLUSION

In this paper, the speed regulation of DFIM with two controllers, traditional IP and Fuzzy Gain Adaptive IP controller has been designed and simulated. The comparative study shows that the Fuzzy Gain Adaptive IP controller can be improve the performances of speed of the DFIM control. The simulation results have confirmed the efficiency of the Fuzzy Gain Adaptive IP controller for different working conditions. The results show that the Fuzzy Gain Adaptive IP controller has good performance, and it is robust against exterior perturbations.

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