Comparative study between IP and Fuzzy-PI Controller in a speed control for doubly fed induction motor

Abderazak SAIDI, Farid NACERI

Abstract—This paper presents a comparison between a fuzzy logic controller and a conventional IP controller used for speed control with a direct stator flux orientation control of a doubly fed induction motor. The effectiveness of the proposed control strategy is evaluated under different operating conditions such as of reference speed and for load torque step changes at nominal parameters and in the presence of parameter variation. Simulation results show that the fuzzy logic controller is more robust than a conventional IP controller against parameter variation and uncertainty, and is less sensitive to external load torque disturbance with a fast dynamic response.

Keywords—conventional IP controller, direct stator flux orientation control, doubly fed induction motor, fuzzy logic controller, Fuzzy PI controller.

I. Introduction

THE asynchronous machine with double feed (DFIM) is very popular since it profit from certain advantages compared to all the other types at variable speed, sound use in the chains of electromechanical conversion as an aero generator or engine knew a spectacular growth during last years. Indeed, it converter of energy used in order to rectify-undulate the alternating currents of the rotor has a fractional nominal output nominal of that of the generator, which reduces its cost by report/ratio with concurrent topologies[1].

The DFIM has some distinct advantages compared to the conventional squirrel-cage machine. The DFIM can be fed and controlled stator or rotor by various possible combinations. Indeed, the input–commands are done by means of four precise degrees of control freedom relatively to the squirrel cage induction machine where its control appears quite simpler. The flux orientation strategy can transform the non linear and coupled DFIM-mathematical model to a linear model conducting to one attractive solution as well as under generating or motoring operations [2], [3].

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But the DFIM control is based on a stationary model which is submissive to many constraints, such as parameters uncertainties, (temperature, saturation .....), that might divert the system from its optimal functioning. That is why the regulation should be concerned with the control's robustness and performance [4, 5].

The fuzzy logic controller is widely used in many control applications. The advantages of using fuzzy logic controller are that the fuzzy logic controller can extract the control strategy from experts.Also,the linguistic control rules of fuzzy controller are fit for human’s thought.However,a primary drawback of the fuzzy logic controller is that the linguistic control rules are hard to generate. It also requires Knowledge and experience of human experts.

The typical PI controller is used most which can satisfy the control requirement under normal operation conditions [10]. However, system performance will fall down when severe disturbance happens, such as voltage dip or swell, parameters variations and so on. In recent years, fuzzy control has been widely applied to power electronics system including speed control of AC drives, feedback control of converters, online and off-line diagnosis, parameter estimation, and so on [11].

In this paper, fuzzy logic control is applied to control the DFIG, a Mamdani type fuzzy logic controller (FLC) is applied to replace the conventional PI controller in the indirect vector control for speed, power and currents control loops. To show the superiority of this method, a comparative study is conducted between the FLC and the traditional PI controller in a fault operating mode and simulation results are presented.

II. DFIM Dynamic Model

The dynamic model of the DFIM in a (d-q) synchronous rotating frame is given by the following voltages equations:

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + \dfrac{d\overline{\phi}_s}{dt} + j\omega_s \overline{\phi}_s \\ \overline{V}_r = R_r \overline{I}_r + \dfrac{d\overline{\phi}_r}{dt} + j\omega_r \overline{\phi}_r \end{cases} \quad (1)$$

Expressions of the fluxes are given by:

$$\begin{cases} \bar{\phi}_s = L_s \bar{I}_s + M_{sr} \bar{I}_r \\ \bar{\phi}_r = L_r \bar{I}_r + M_{sr} \bar{I}_s \end{cases} \quad (2)$$

From (1) and (2) the all currents state model is written as follows:

$$\begin{cases} \frac{d\bar{I}_s}{dt} = -\frac{R_s}{\sigma L_s}\bar{I}_s + \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{I}_r + \frac{l}{\sigma L_s}\bar{V}_s - \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{V}_r \\ \frac{d\bar{I}_r}{dt} = -\frac{R_r}{\sigma L_r}\bar{I}_r + \frac{M_{sr}R_s}{\sigma L_s L_r}\bar{I}_s + \frac{l}{\sigma L_r}\bar{V}_r - \frac{M_{sr}R_r}{\sigma L_s L_r}\bar{V}_s \end{cases} \quad (3)$$

The mechanical equation is expressed by (4):

$$\frac{J}{P}\frac{d\omega}{dt} = T_{em} - \frac{f\omega}{P} - T_r \quad (4)$$

With : $\omega = p.\Omega$

And the electromagnetic torque is given by:

$$T_{em} = pM_{sr} I_m(\bar{I}_s \bar{I}_r^*) \quad (5)$$

So, the equation for the speed variation becomes:

$$\frac{J}{P}\frac{d\omega}{dt} = pM_{sr} I_m(\bar{I}_s \bar{I}_r^*) - \frac{f\omega}{P} - T \quad (6)$$

With :

$$T_r = \frac{L_r}{R_r}, T_s = \frac{L_S}{R_s}$$

III. DIRECT STATOR FLUX ORIENTATION CONTROL

In this section, the DFIM model can be described by the following state equations in the synchronous reference frame whose axis d is aligned with the stator flux vector [6], [7]:

$$\Phi_{sd} = \Phi_s ; \frac{d\Phi_{sq}}{dt} = \Phi_{sq} = 0$$

$$i_{rd} = \frac{\Phi_s^*}{M} \quad (7)$$

$$i_{rq} = -\frac{L_s}{PM\Phi_s^*} C_e^* \quad (8)$$

$$\frac{d\theta_s}{dt} = w_s = \left(\frac{R_s \cdot M}{L_s} i_{rq} + V_{sq} \right) / \Phi_s^* \quad (9)$$

$$V_{rd} = \left(R_r + \frac{M^2}{L_s T_s} \right) i_{rd} + \sigma L_r \frac{di_{rd}}{dt} + \frac{M}{L_s} V_{sd} - \frac{M}{L_s T_s} \Phi_{sd} - \sigma L_r (w_s - w) i_{rq} \quad (10)$$

Substituting the equation (7) in equation (10),we

obtain:

$$V_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} + \frac{M}{L_s} V_{sd} - \sigma L_r (w_s - w) i_{rq} \quad (11)$$

$$V_{rq} = \left(R_r + \frac{M^2}{L_s T_s} \right) i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \frac{M}{L_s} V_{sq} - \frac{M}{L_s} w \Phi_{sd} - \sigma L_r (w_s - w) i_{rd} \quad (12)$$

IV. STATOR FLUX ESTIMATOR

flux vector is necessary. In a DFIM motor mode, as stator and rotor current are measurable, the For the DSFOC of DFIM, accurate knowledge of the magnitude and position of the stator .

stator flux can be estimated (calculate). The flux estimator can be obtained by the following equations [8]:

$$\Phi_{sd} = L_s i_{sd} + M i_{rd} \quad (13)$$

$$\Phi_{sq} = L_s i_{sq} + M i_{rq} \quad (14)$$

The position stator flux is calculated by the following equations:

$$\theta_r = \theta_s + \theta$$

In which:

$$\theta_s = \int w_s dt, \theta = \int w dt, w = P\Omega \quad (15)$$

V. FUZZY LOGIC CONTROLLER

The structure of a complete fuzzy control system is composed from the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification. Figure 1 shows the structure of a fuzzy logic controller. The fuzzification module converts the crisp values of the control inputs into fuzzy values. A fuzzy variable has values, which are defined by linguistic variables (fuzzy sets or subsets) such as low, medium, high, slow… where each is defined by gradually varying membership function. In fuzzy set terminology, all the possible values that a variable can assume are named universe of discourse, and fuzzy sets (characterized by membership function) cover whole universe of discourse. The shape fuzzy sets can be triangular, trapezoidal, etc [9].

A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of a designer and researcher. The data base and the rules form the knowledge base which is used to obtain the inference relation R. The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristics; it contains a collection of fuzzy conditional statements expressed as a set of IF-THEN rules, such as:R(i) : If x1 is F1 and x2 is F2 . . . and xn is Fn THEN Y is G(i), i = 1, . . . ,M

Where: (x1, x2, . . . , xn) is the input variables vector, Y is the control variable, M is the number of rules, n is the number fuzzy variables, (F1, F2, . . .Fn) are the fuzzy sets.

For the given rule base of a control system, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (the output fuzzy variable) [9].

The composition operation is the method by which such a control output can be generated using the rule base. Several composition methods, such as max-min or sup-min and max-dot have been proposed in the literature. The mathematical procedure of converting fuzzy values into crisp values is known as 'defuzzification'. A number of defuzzification methods have been suggested. The choice of defuzzification methods usually depends on the application and the available processing power.

This operation can be performed by several methods of which center of gravity (or centroid) and height methods are common [9].

A. Fuzzy - PI Controller

The fuzzy controller is basically an input/ output static non-linear mapping, the controller action can be written in the form [10]:

$$u = k_e .e + k_{ce} .c_e \quad (16)$$

The Fuzzy-PI output is:

$$y = k_p .u + \int k_i .u \quad (17)$$

Where: ke is the gain of the speed error, kce is the gain of the change of speed error, kp is the proportional factor; i k is the integral factor, e is the speed error, ce is the change of speed error, u is the fuzzy output.

The Fuzzy-PI controller in a vector-control of DFIM is used as presented in Figure 2.

B. Knowledge Base Proposed

Figure 3 and 4 shows respectively the triangle-shaped membership functions of error (e) and change of error (ce). The fuzzy sets are designated by the labels: NB (negative big), NM(negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium),PB (positive big), NVS (negative very small) and PVS (positive very small).

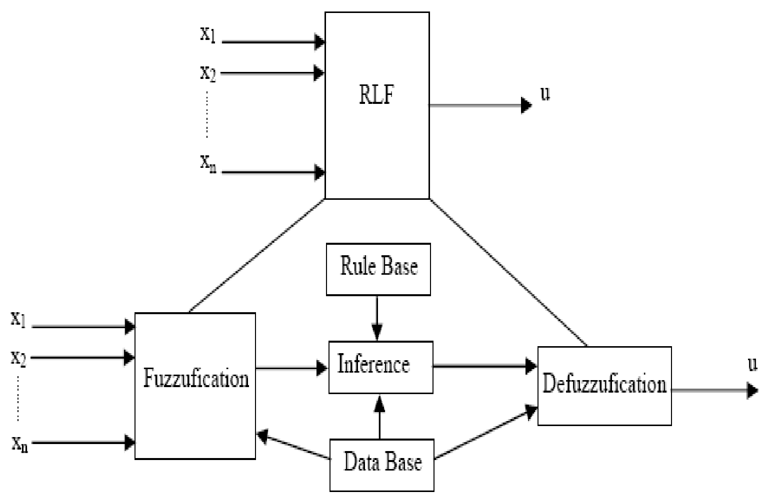


Fig1. The structure of a fuzzy logic controller

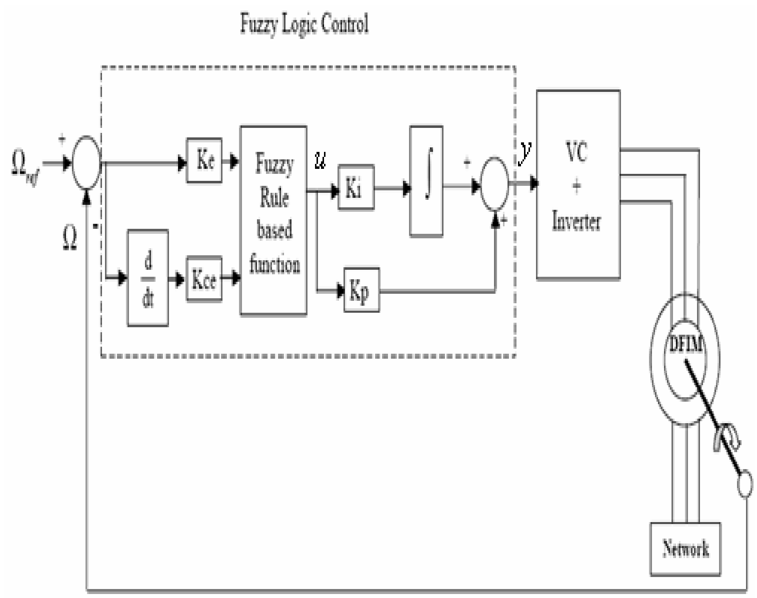


Fig2. Block diagram of vector-control of DFIM using Fuzzy-PI controller

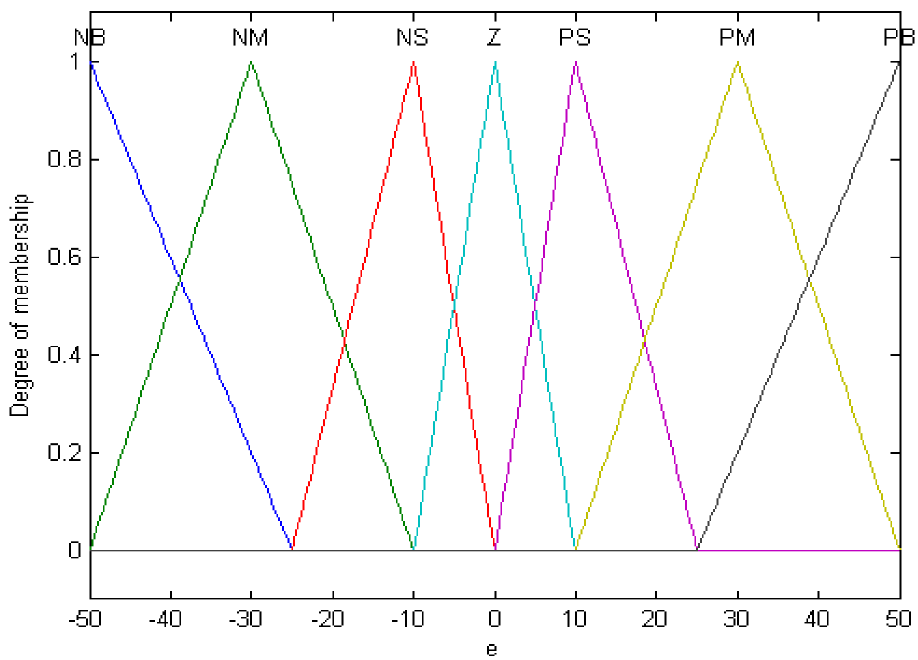


Fig3. Membership functions for input e

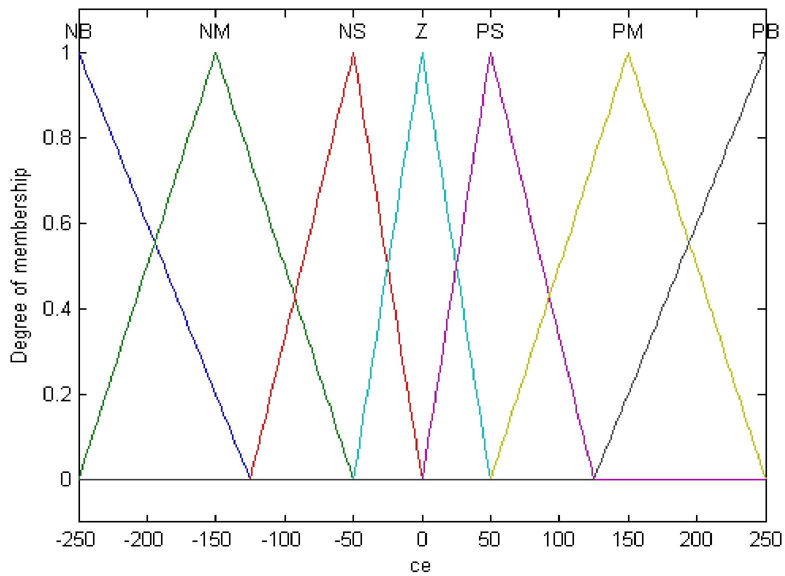


Fig4. Membership functions for input ce

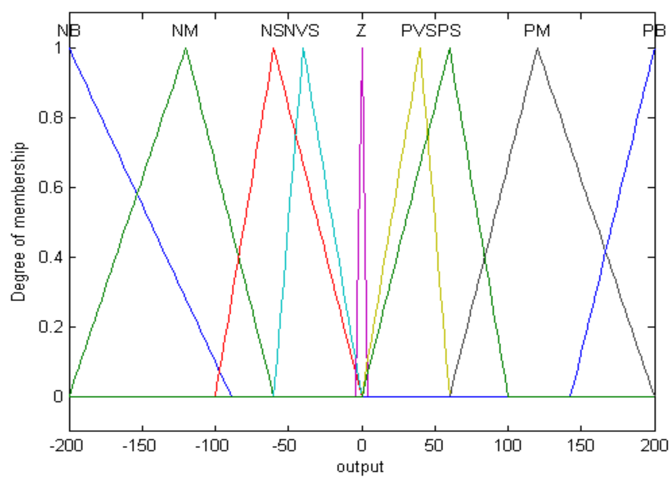


Fig5. Membership functions for output

TABLE1.
LINGUISTIC RULE TABLE.

ce \ e	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

Figure 5 shows the proposed membership functions for output variable.

In this paper, the triangular membership function, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are most frequently used in many literatures [9]. The inference strategy used in this system is the Mamdani algorithm.

All the membership functions (MFs) are asymmetrical because near the origin (steady state), the signals require more precision. Seven MFs are chosen for e and ce signals and nine for output. All the MFs are symmetrical for positive and negative values of the variables. Thus, maximum 7x7 = 49 rules can be formed as tabulated in Table I.

VI. Results and Discussion

The DFIM used in this work is a 0.8 kW, whose nominal parameters are reported in appendix.

The Fuzzy-PI controller in a DSFOC drive system as presented in Figure 2.

The Figure 6 presents the block diagram of fuzzy logic control of the DFIM using MATLAB/SIMULINK.As shown in this figure, the speed loop uses a fuzzy logic controller (Fuzzy-PI) and the stator flux is controlled by PI controller. The block “command system by PI controller” is the vector control, which to produce the quadrature-axis rotor current reference which controls the motor torque. The motor flux is controlled by direct-axis rotor current reference. Block “Park inversion” is used to convert voltage reference V rd and V rq into voltage reference V a , V b and V c for introduce in “PMW inverter”. Motor torque, rotor current, flux and speed signals are available at the output of the “Model of DFIM”.

A. *Load Variation*

In the first test, a cyclic change of different load torque levels are subjected to the motor at certain times and as followings:

Time = [0 0.8 0.8 1.1 1.1 1.4 1.4 1.7 1.7];

Torque = [0 0 5 5 3 3 -3 -3 0];

The responses of speed, torque, stator flux and rotor current are shown in Figure 7.

The Fuzzy-PI regulator shows the good performances to achieve tracking of the desired trajectory.

At these changes of loads, the Fuzzy-PI regulator rejects 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 7). The decoupling of torque-flux is maintained in permanent mode. We can see the control is robust from the point of view load variation.

In order to compare the performance of Fuzzy-PI regulator with another regulator in the same test, the Figure 8 shows the simulated results comparison of traditional IP (Integral Proportional) and Fuzzy-PI regulators of speed control of DFIM under load variation.

The Fuzzy PI controller based drive system can handle the sudden 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 Fuzzy PI controller. Thus the proposed controller has been found superior to the conventional IP controller.

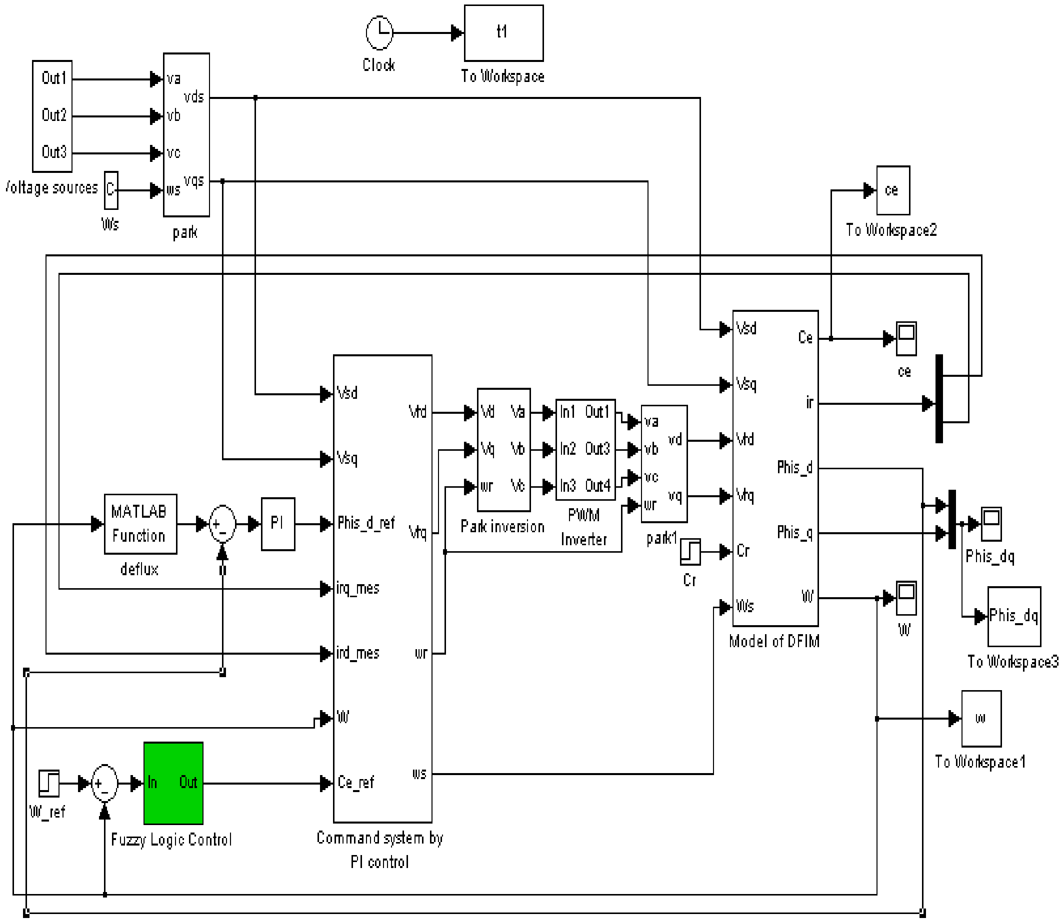
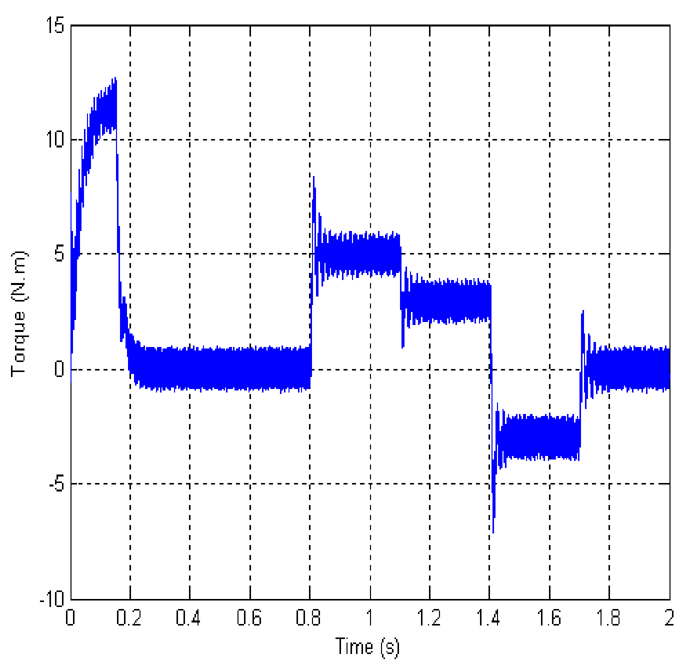
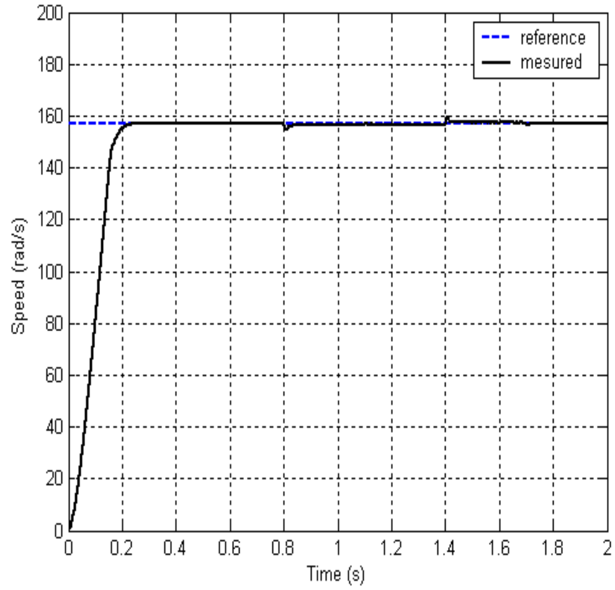


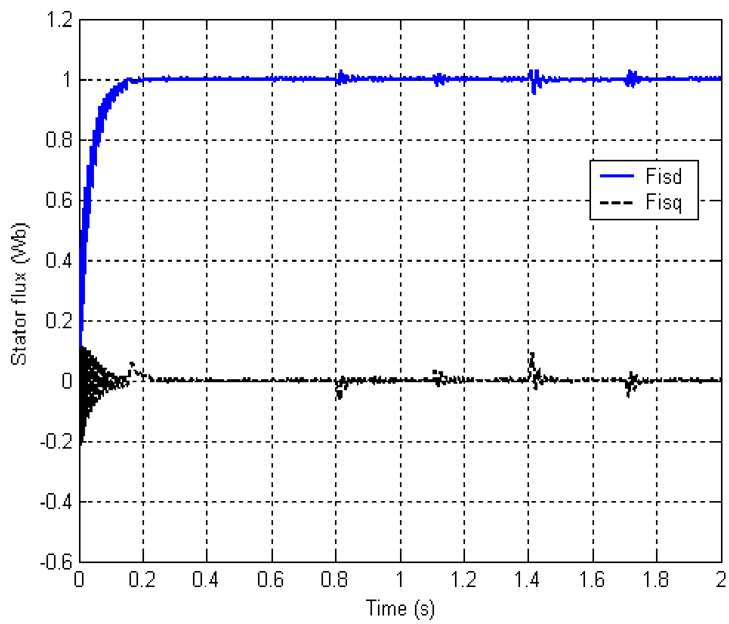
Fig6. Block diagram of fuzzy logic control of the DFIM using MATLAB/SIMULINK



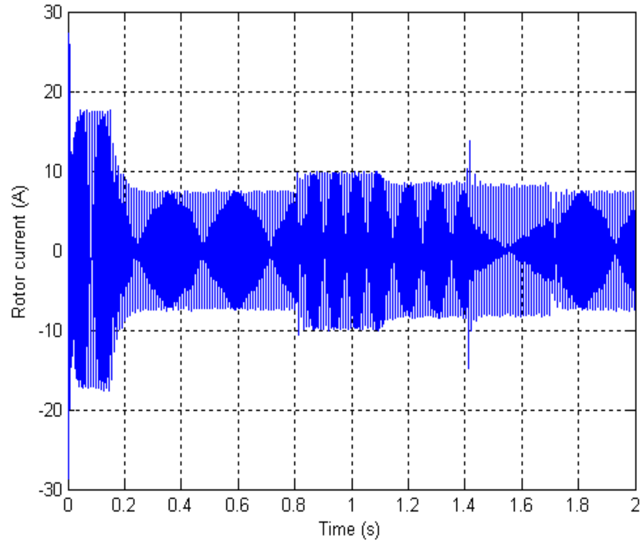
(a)


reference
mesured
Speed (rad/s)
Time (s)
200
180
160
140
120
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

(b)

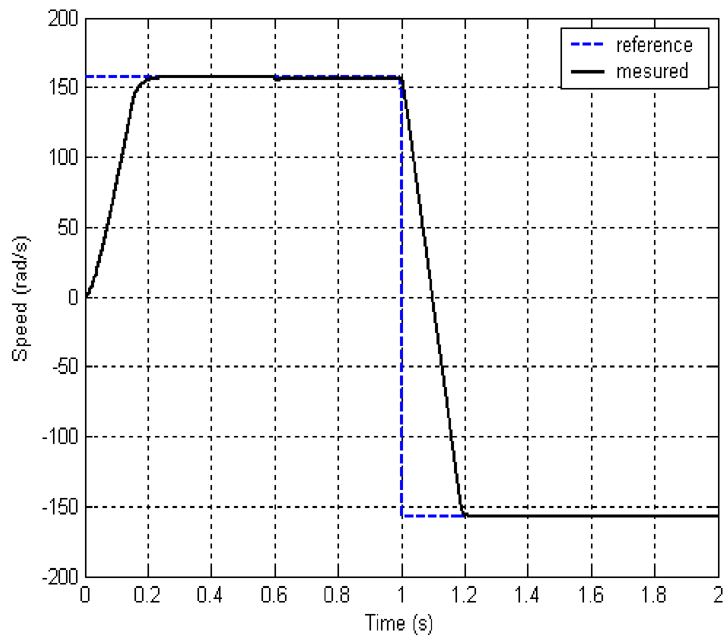

Fisd
Fisq
Stator flux (Wb)
Time (s)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

(c)

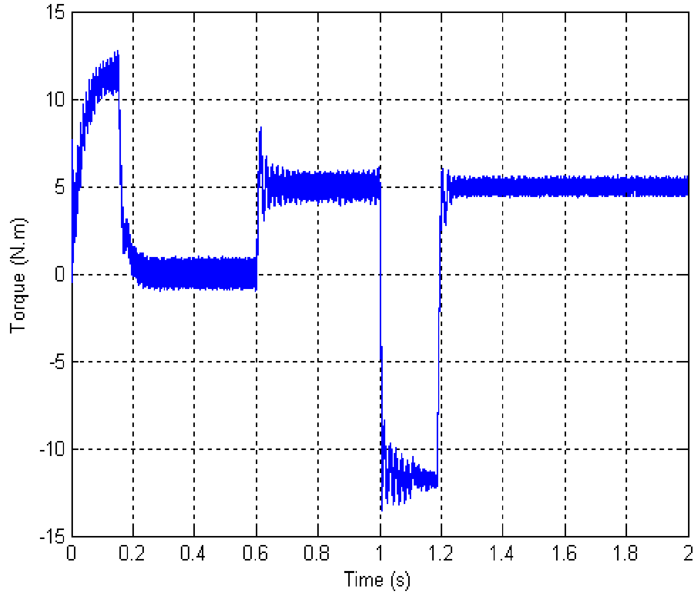


(d)

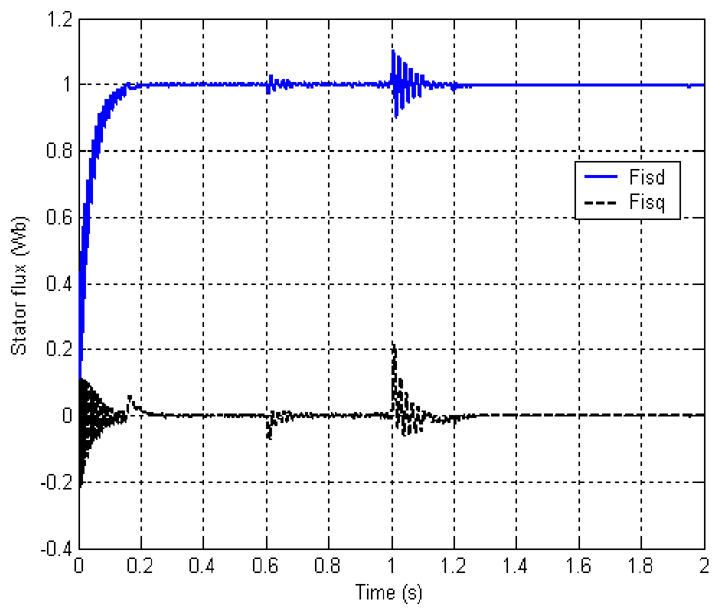
Fig. 7. Results of speed (a), torque (b), stator flux (c), and rotor (d)Rotor current under load variation



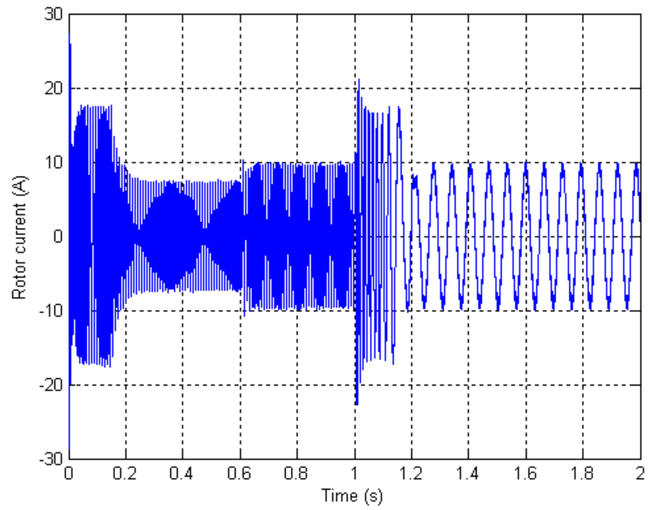
(a)


15
10
5
0
-5
-10
-15
Torque (N.m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (s)

(b)


1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Stator flux (Wb)
Fisd
Fisq
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (s)

(c)



(d)

Fig 8. Results of speed (a), torque (b), stator flux (c), and rotor current (d) under reversal speed

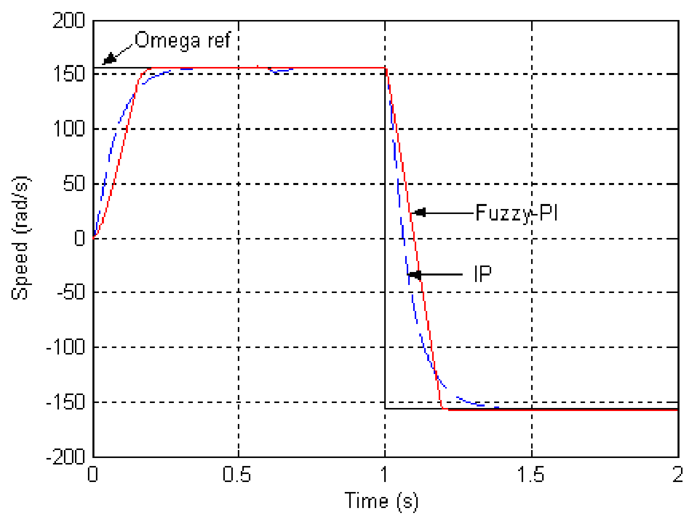
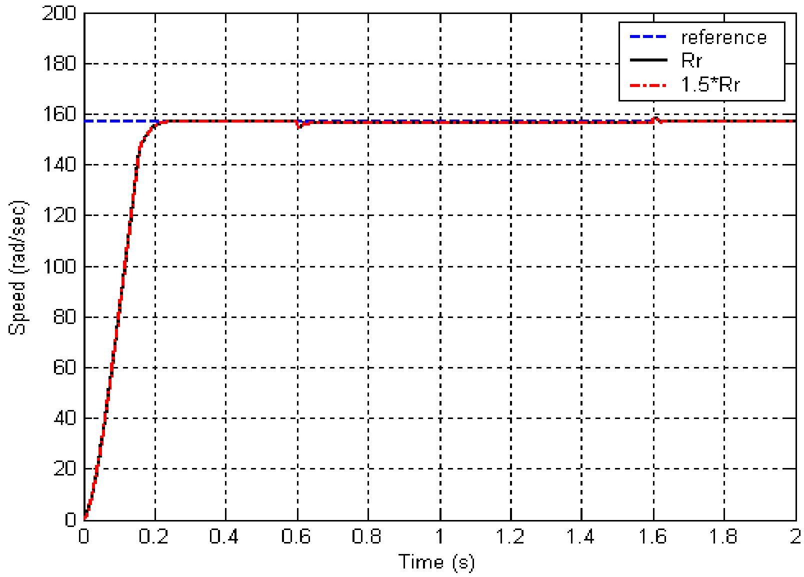
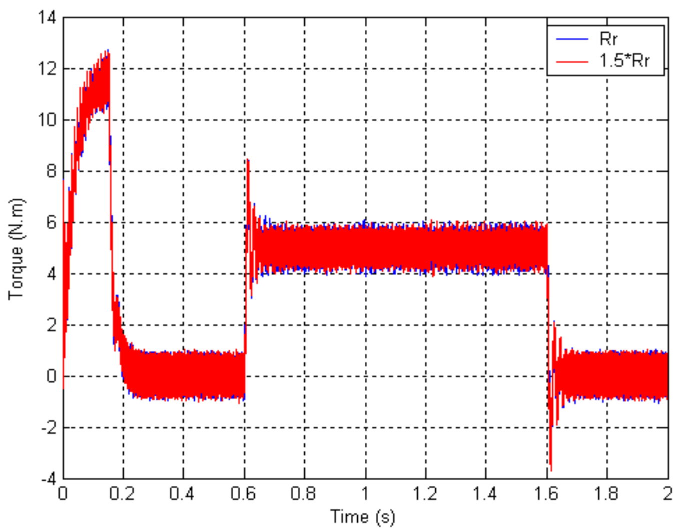


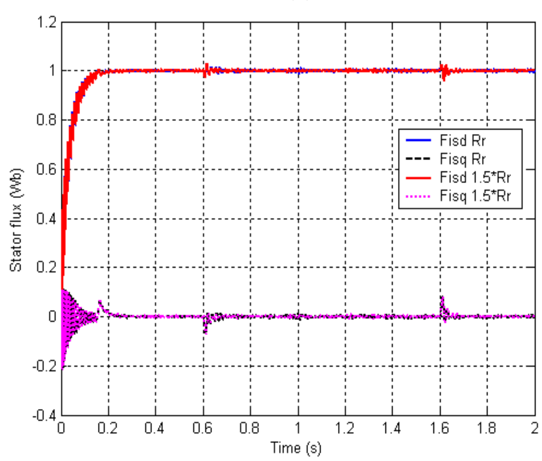
Fig 9. Simulated results comparison of IP and Fuzzy-PI regulators of speed control of DFIM under reversal speed



(a)



(b)



(c)

Fig 10. Test of robustness result for rotor speed (a), torque (b), and stator flue(c) for different values of rotor resistance: nominal case and +50%

A. *Speed Reversal of Rated Value*

In the second test, speed reversal of (157, -157 rad/s), with a load of 5N.m applied at t = 0.6 s.

Figure 9 presents the responses of speed, torque, stator flux and rotor current versus time under speed reference reversal. The speed follows its reference value without overshooting.

Figure 10 shows the result under the steady state and the transient condition i.e. step change in load torque at t=0.6 s and speed reversal stage at t=1s for the Fuzzy PI controller and conventional IP controller from which it can be see that the speed reached the rated value in very short period for the Fuzzy PI controller.

A. *Robust Control for Different Values of Rotor Resistance*

In order to verifier the robustness of Fuzzy-PI regulator under motor parameters variations, we have simulated the system with different values of the parameter considered and compared to nominal value (real value), one case is considered:

The rotor resistance variations (increase at 50 % of nominal value rotor resistance). Figure 10 shows the responses speed, torque and stator flux in the test of robustness for different values of rotor resistance.

The results indicate that the Fuzzy-PI regulator is insensitive to the rotor resistance change, which results in the no influence on the torque and stator flux. For the robustness of control, an increase of the resistance does not have any effect on the performances of the proposed controller.

The fuzzy control gives to our controller a great place towards the control of the system with unknown parameters.

VII. Conclusions

In this paper, we have proposed a fuzzy logic controller for the speed control of doubly fed induction motor with a direct stator flux orientation control. The effectiveness of the proposed controller has been tested on DFIM in comparison with conventional IP controller under different operating conditions.

The fuzzy PI 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. Simulation results have shown correct stator flux oriented control behaviour and speed tracking performances.

Appendix

i_{rd} , i_{rq}: Rotor current components,
φ_{sd}, φ_{sq}: Stator flux components,
V_{sd}, V_{sq}: Stator voltage components,
V_{rd}, V_{rq}: Rotor voltage components.
R_s, R_r: Stator and rotor resistances,
L_s, L_s: Stator and rotor inductances,
M: Mutual inductance,
σ: Leakage factor,
P: Number of pole pairs,
C_e: The electromagnetic torque,
C r : The load torque,
J: The moment of inertia,
Ω : Mechanical speed,
ω_s ,ω: The stator pulsation,
f : The friction coefficient,
T_s, T_r : Statoric and rotoric time-constant.
θ_s : The electrical stator position,
θ: The electrical rotor position.

Rated Data of the simulated doubly fed induction motor:
Rated values: 0.8 KW; 220/380 V-50 Hz; 3.8/2.2 A, 1420 rpm.
Rated parameters:
$R_s = 11.98\ \Omega$
$R_r = 0.904\ \Omega$
$L_s = 0.414$ H
$L_r = 0.0556$ H
M= 0.126 H
P = 2.0
Mechanical constants:
$J = 0.01\ Kg.m^2$
f = 0.00 I.S.

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