

FUZZY ADAPTIVE CONTROLLER BASED ON THE LYAPUNOV THEORY FOR CONTROL OF THE DUAL STAR INDUCTION MACHINE

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Abstract: In this paper a design of the fuzzy adaptive control(FAC) based on the lyapunov stability theory for improving the dynamic response of the double star induction machine (DSIM) is presented, the fuzzy adaptive control scheme gives fast dynamic response with no overshoot, it has an important feature of being highly robust, insensitive to plant parameters variations, the design procedure is established to control the speed of the machine,the simulation results show that the controller in enhancing the robustness of control systems with high accuracy.

Key words: Dual Star Induction Machine, Indirect Field Oriented Control, Lyapunov Stability Theory, Fuzzy Adaptive Control, Key parameters variation, Robustness.

1. Introduction

The dual star winding induction machine with the squirrel cage rotor was recently shown to give permission in adjustable speed drives and in electric power generation in various application [1],[7],[12] ,The main difficulty in the asynchronous machine control resides in fact is that complex coupling exists between machine input variables, output variables and machine internal variables as the field, torque or speed, the space vector control assures that the torque has made similar as the one of a DC machine [5], the past few years have witnessed a rapid growth in the number and variety of applications of fuzzy logic, ranging from consumer products, industrial process control [11].

This paper presents the speed control methodology using the indirect rotor flux orientation and the fuzzy-PI approach base on the Lyapunov theory. A fuzzy adaptive control based on the Lyapunov's stability theory for control the dual star induction machine schema is an approach to systematically determine the gains (k_e, k_{dce}), while guaranteeing the stability of the control. [19], also the proposed regulator have been successfully used for many numbers of non linear and complex processes, hybrids controllers are robust

and their performances are insensible to parameter variations contrary to conventional regulators.

Recently several researchers make efforts to improve the robustness and performances of the hybrid control by using Lyapunov stability theory [19],[25].

2. Machine model

A schematic of the stator and rotor windings for a dual three-phase induction machine is given in [1] and Fig.1. The stator six phases are divided into two wye-connected three phase sets labelled $A_{s1} B_{s1} C_{s1}$ and $A_{s2} B_{s2} C_{s2}$ whose magnetic axes are displaced by $\alpha = 30^\circ$ electrical angle , the windings of each three phase set are uniformly distributed and have axes that are displaced 120° apart ,The three phase rotor windings A_r, B_r, C_r are also sinusoidal distributed and have axes that are displaced apart by 120° , [1],[4],[5] .

The following assumptions have been made in deriving the dual-stator induction machine model:

- Machine windings are sinusoidally distributed ;
- The two stars have same parameters;
- Flux path is linear;
- The magnetic saturation and the mutual leakage are neglected .

The Park model of DSIM presents below in the references frame at the rotating field (d, q) [5],[13]

The expressions for stator and rotor flux are:

$$\begin{cases} \varphi_{ds1} = L_{s1}i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs1} = L_{s1}i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{ds2} = L_{s2}i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs2} = L_{s2}i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{dr} = L_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qr} = L_r i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \quad (1)$$

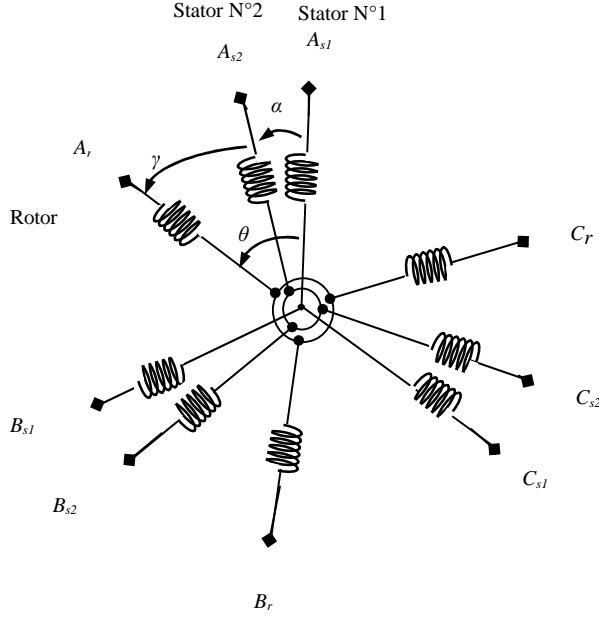


Fig.1. Schematic of the dual star induction machine .

The expressions for stator and rotor voltages are:

$$\begin{cases} v_{ds1} = R_{s1}i_{ds1} + \frac{d}{dt}\phi_{ds1} - \omega_s\phi_{qs1} \\ v_{qs1} = R_{s1}i_{qs1} + \frac{d}{dt}\phi_{qs1} + \omega_s\phi_{ds1} \\ v_{ds2} = R_{s2}i_{ds2} + \frac{d}{dt}\phi_{ds2} - \omega_s\phi_{qs2} \\ v_{qs2} = R_{s2}i_{qs2} + \frac{d}{dt}\phi_{qs2} + \omega_s\phi_{ds2} \\ v_{dr} = R_r i_{dr} + \frac{d}{dt}\phi_{dr} - (\omega_s - \omega_r)\phi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d}{dt}\phi_{qr} + (\omega_s - \omega_r)\phi_{dr} \end{cases} \quad (2)$$

2.1. Mechanical Equation

The mechanical equation is given by [5], [7], [18].

$$\frac{J}{P} \frac{d\omega_r}{dt} = C_e - C_r - \frac{f_r}{P} \omega_r \quad (3)$$

Expression of the electromagnetic torque

$$C_e = P \frac{L_m}{L_m + L_r} [\phi_{dr}(i_{qs1} + i_{qs2}) - \phi_{qr}(i_{ds1} + i_{ds2})] \quad (4)$$

$$\text{With: } \frac{3L_m}{2} = L_{ms} = L_{mr} = L_{sr}$$

In the induction machines, rotor winding has a short-circuited hence.

$$v_{dr} = 0, \quad v_{qr} = 0 \quad (5)$$

3. Field oriented control

The main objective of the vector control of induction

motor is as in DC machines, to independently control the torque and flux [17], we propose to study the IFOC of the DSIM, the control strategy is used to maintain the quadrature component of the flux null $\phi_{qr} = 0$, and

the direct flux equals to the reference $\phi_{dr} = \phi_r^*$ Fig.3. [2], [9].

The final formula of the electromagnetic torque is:

$$C_{ref} = P \frac{L_m}{L_m + L_r} \phi_r^* (i_{qs1}^* + i_{qs2}^*) \quad (6)$$

The slip angular frequency is:

$$\omega_{gl}^* = \frac{R_r L_m}{L_m + L_r} \frac{(i_{qs1}^* + i_{qs2}^*)}{\phi_r^*} \quad (7)$$

Expression of the direct currents:

$$i_{ds1}^* + i_{ds2}^* = \frac{\phi_r^*}{L_m} \quad (8)$$

4. Fuzzy control

The Fuzzy control using linguistic information possesses several advantages such as robustness; model free, non-mathematical decision, the analyses complex [6], [10],[24] .

4.1. Fuzzification

The most common controller has two inputs: error and the derivative of the error with respect to a defined reference signal, and one output, which is usually the command, [26].

The error is given:

$$e(t) = \omega_{ref} - \omega_r(t) \quad (9)$$

$$e(t) = k_e e_n(t) \quad (10)$$

The derivative of the error:

$$\frac{de(t)}{dt} = k_{de} \frac{de_n(t)}{dt} \quad (11)$$

4.2. Fuzzy inference engine

The fuzzy rule consists of the antecedent-consequent pair is expressed by IF-THEN rules codified in a lookup table.1. The input-output mapping is an inference mechanism based on Zadeh logic .

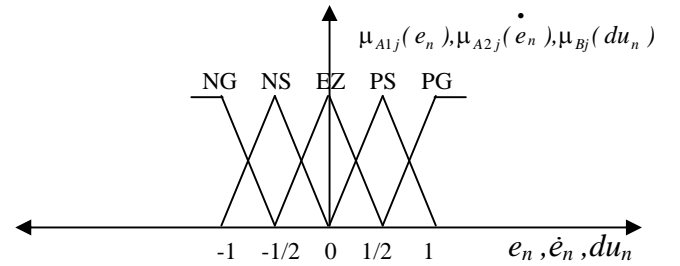


Fig.2. Membership functions of inputs (e_n and \dot{e}_n), and output du_n .

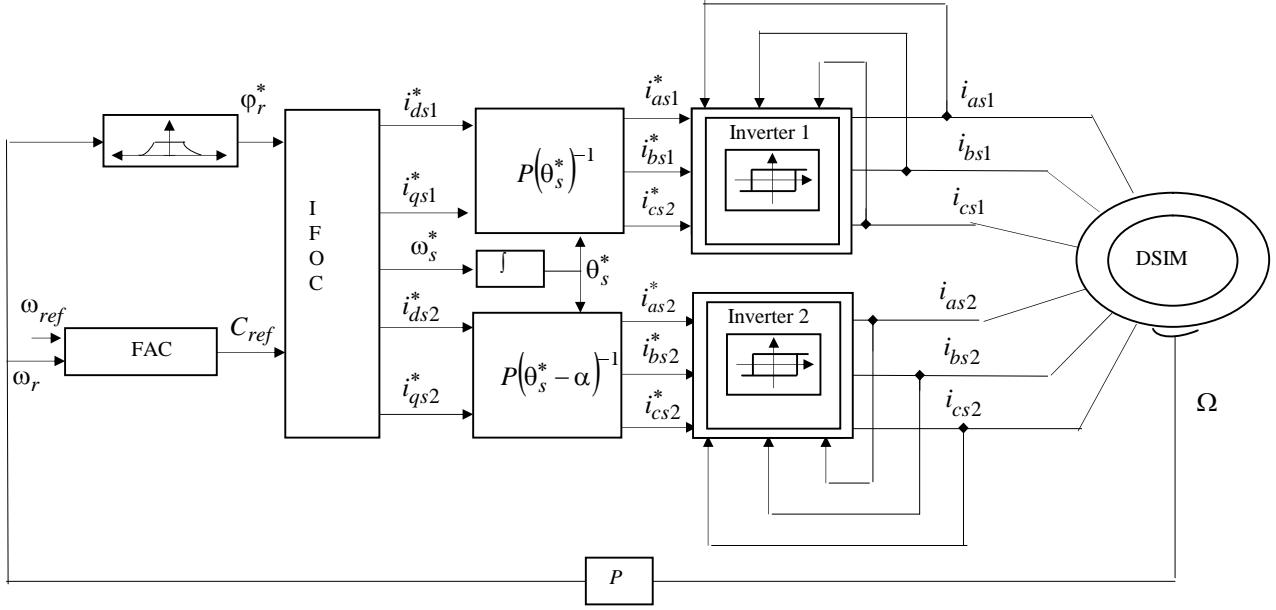


Fig .3. Speed Control of DSIM by using the fuzzy adaptive control based on the Lyapunov theory.

4.3. Fuzzy control rules

The fuzzy inference mechanism contains twenty-five rules for one output. However, The resulting fuzzy inference rules for the one output variable $du_n(t)$ are as follows:

Table .1 The fuzzy inference mechanism $du_n(t)$.

		\dot{e}_n					
e_n		NG	NS	ZE	PS	PG	
	NG	NG	NG	NS	NS	EZ	
	NS	NG	NS	NS	EZ	PS	
	ZE	NS	NS	EZ	PS	PS	
	PS	NS	EZ	PS	PS	PG	
	PG	EZ	PS	PS	PG	PG	

4.4. Defuzzification

The centre of area defuzzification can calculate the crisp value of the output du_n as [8]

$$du_n(t) = \frac{\sum_{j=1}^{25} \mu_{A_{1j}}(e_n(t)) \mu_{A_{2j}}(\dot{e}_n(t)) C_j S_j}{\sum_{j=1}^{25} \mu_{A_{1j}}(e_n(t)) \mu_{A_{2j}}(\dot{e}_n(t)) S_j} \quad (12)$$

C_j, S_j are real value parameters representing the centre and surface of the membership function $\mu_{B_j}(du_n(t))$.

4.5. The Fuzzy-PI Control

It has been shown [20] that the analytical structure of the simplest possible fuzzy controller is a nonlinear PI controller with variable gains. To describe and analyze this fuzzy controller [21], [3], [23], we will use the notations as follows

$$C_{ref}(t) = C_{ref}(t-1) + k_{dce} du_n(t). \quad (13)$$

Where k_{dce} is the gain defuzzification associated to the control C_{ref} with k_{dce}, k_e are the gains inputs normalized (Fuzzification).

5. Adaptive control

Traditionally the design of a fuzzy logic controller is depending on the explicit description often the gains of fuzzy-PI control undetermined with analytic method. The adaptive control system can be represented by fig.4. It is composed of two parts: a FLC containing unknown gains k_e and k_{dce} , an adaptation mechanism for updating the adjustable gains in FAC [15], [16],[6]. [22], the mechanical equation of the motor represented by a differential equation as:

$$\frac{d\omega_r(t)}{dt} = -a_p \omega_r(t) + b_p C_{ref}(t) - d_p C_r \quad (14)$$

Where ω_r is the rotor electrical angular speed C_{ref} is signal of the control with a_p and b_p are constants motor parameters.

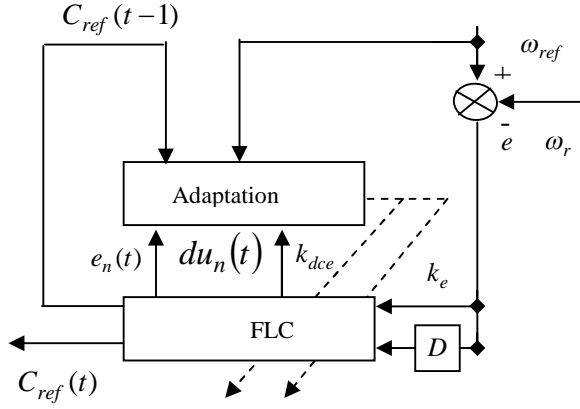


Fig.4. The block diagram of the FAC.

5.1. Choice of control law

As a first step in the adaptive control design, let us choose this law:

$$C_{ref}(t) = C_{ref}(t-1) + k_{dce} du_n(t) \quad (15)$$

The closed-loop dynamics are:

$$\begin{aligned} \dot{\omega}_r(t) = & -a_p \omega_r(t) + b_p C_{ref}(t-1) + \\ & b_p k_{dce} du_n(t) - d_p C_r \end{aligned} \quad (16)$$

In our adaptive control problem since k_{dce} and k_e are unknown, the control input will achieve these objectives adaptively, the adaptation law will continuously search for the right gains based on the Lyapunov theory so as to make ω_r tend to ω_{ref} asymptotically.

5.2. Choice of adaptation law by using the Lyapunov stability theory:

Let us now choose the adaptation law for the gains k_{dce} and k_e by using Lyapunov method, We consider candidate function:

$$V = \frac{1}{2} \left(e^2 + \frac{1}{\gamma_1} k_e^2 + \frac{1}{\gamma_2} k_{dce}^2 \right). \quad (17)$$

The derivative of the candidate function:

$$\dot{V} = e \frac{de}{dt} + \frac{1}{\gamma_1} k_e \frac{dk_e}{dt} + \frac{1}{\gamma_2} k_{dce} \frac{dk_{dce}}{dt} \quad (18)$$

We can obtain:

$$\begin{aligned} \dot{V} = & e(a_p \omega_r(t) - b_p C_{ref}(t-1) - b_p k_{dce} du_n(t) \\ & + d_p C_r) + \frac{1}{\gamma_1} k_e \frac{dk_e}{dt} + \frac{1}{\gamma_2} k_{dce} \frac{dk_{dce}}{dt} \end{aligned} \quad (19)$$

By Using (10) to eliminate the error (e) in equation (19), after that we will have:

$$\begin{aligned} \dot{V} = & -a_p k_e^2 e_n^2 + \frac{k_e}{\gamma_1} (\gamma_1 e_n A + \frac{dk_e}{dt}) \\ & - \frac{k_{dce}}{\gamma_2} (\gamma_2 b_p k_e e_n du_n(t) - \frac{dk_{dce}}{dt}) \end{aligned} \quad (20)$$

Where : $A = (a_p \omega_{ref} - b_p C_{ref}(t-1))$.

If the gains are updated as

$$\begin{cases} k_e = -\int \gamma_1 e_n |A| dt \\ k_{dce} = \int \gamma_2 b_p k_e e_n du_n(t) dt \end{cases} \quad (21)$$

Where γ_2 and γ_1 are constants positive.

We get

$$\frac{dV}{dt} = -a_p K_e^2 e_n^2 \quad (22)$$

5.3. Tracking convergence analysis

In last conditions the proposed control schema is an approach to systematically determine the gains k_{dce} and k_e of the fuzzy-PI logic, while guaranteeing the stability of the control and DSIM.

The Lyapunov stability approach inspired by fuzzy logic controller suggests the necessity to include the adaptation of the gains of k_{dce} and k_e in order to improve its robustness, for the nominal plant, it appears that a design method of fuzzy adaptive controller with Lyapunov stability theory has better performances than simple fuzzy-PI logic.

6. Results and discussions

Fig.5. illustrates the performances of control, we have simulated the starting mode of the motor without load, and the application of the load ($C_r=21N.m$) at the instance $t=0.5$ s and its elimination at $t=1$ s. After that we are applying the load ($C_r=-14N.m$) at the instance $t=1$ s and its elimination at $t=1.5$ s. Moreover, the inversion of value of the load ($C_r=14N.m$) at the instance $t=1.5$ s and its elimination at $t=3$ s.

The parameters variation in tests can be interpret in practice by the bad functioning conditions as overheating and variation of the inertia.

Fig.6. shows the tests of robustness realized with the FAC control in the case of variation of speed step of -100 (rd/s) at $t=1$ s. In addition we minimization the speed 10 (rd/s) at the instance $t=2.5$ s.

1)-Fig.7. Shows variation of $J_r=1.5*J_n$ on rotor inertia.

2)-Fig.8. Shows variation of $R_r=1.5*R_m$ on rotor resistance.

Fig.9. we have simulated the system with a different new technique of control considered and compared to FLC-PI, the control presents the best performances, to achieve tracking of the desired trajectory and to reject disturbances, the decoupling of flux has maintained in

permanent mode. The tests show that an increase of the resistance and the inertia in steady state mode does not have any effects on the performances of the technique used. Consequently, the performances of speed control are approximately like the nominal case.

7. Conclusion

A speed control scheme of a dual stator induction machine with the fuzzy adaptive control has been proposed. The principles of Lyapunov stability theory have been applied to the fuzzy PI control design such that the determine gains k_e and k_{dce} are depending on the stability of control. Classic fuzzy logic design methods are then used for the design of the fuzzy-PI controller.

Traditionally the design of a fuzzy logic controller is dependent on the explicit description often the gains of fuzzy-PI control undetermined with analytic method.

In FAC control schema is an approach to systematically determine the gains fuzzy-PI, while guaranteeing the stability of the control.

The effectiveness of the control scheme was validated with simulation results; the different simulations results obtained show the high robustness of the controller in presences of the parameters variations as the rotor resistance, the inertia and the load, reference speed. The control of the speed gives fast response with no overshoot, the decoupling of the flux; stability and convergence to equilibrium point are verified. The hybrid regulators has a very interesting dynamic performances compared with the fuzzy PI controller.

Nomenclature

$v_{ds1}, v_{qs1}, v_{ds2}, v_{qs2}$: First and second stator voltages in stationary frame (d, q) .

$i_{ds1}, i_{qs1}, i_{ds2}, i_{qs2}$: First and second stator currents in stationary frame (d, q) .

$\varphi_{ds1}, \varphi_{qs1}, \varphi_{ds2}, \varphi_{qs2}$: First and second stator flux in stationary frame (d, q) .

$\varphi_{dr}, \varphi_{qr}$: Rotor flux in stationary frame (d, q) .

R_{s1}, R_{s2}, R_r : Stator and rotor resistances.

L_{s1}, L_{s2}, L_r : Stator and rotor inductances.

L_{sr} : Stator-Rotor inductances.

L_m :Cyclic mutual Stator-Rotor inductances.

ω_s, ω_r : Synchronous and electrical rotor speed.

p : Numbers of pole pairs.

J : Moment of inertia.

f_r : Damping coefficient.

C_e, C_r :Electromagnetic and load torque

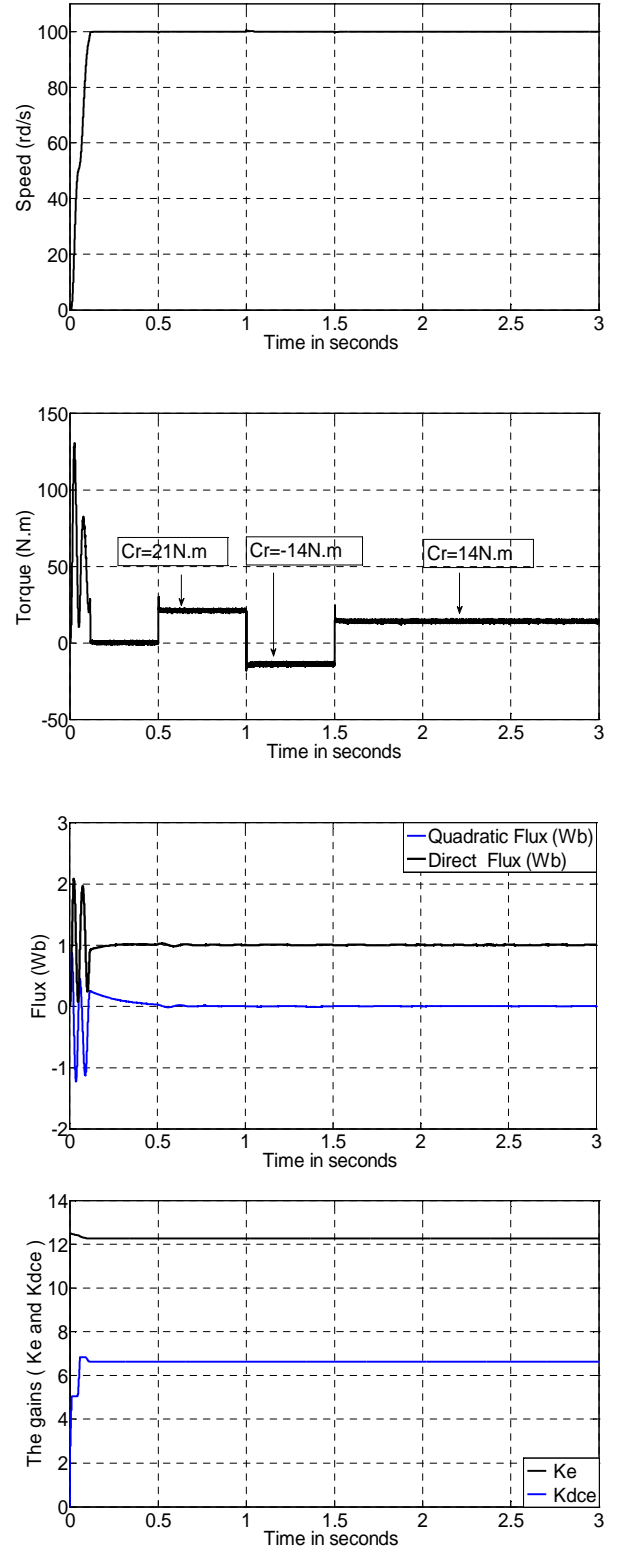


Fig.5. Test of robustness for different values of the load when DSIM is operated at 100 (rd/s), 1) 21 N.m is applied at 0.5 (s), 2) -14 N.m is applied at $t=1$ (s), 3) 14N.m is applied at $t=1.5$ (s).

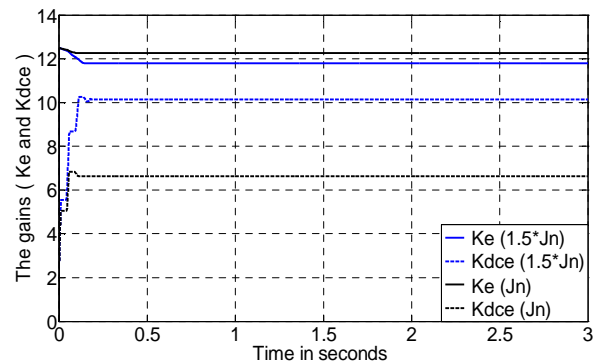
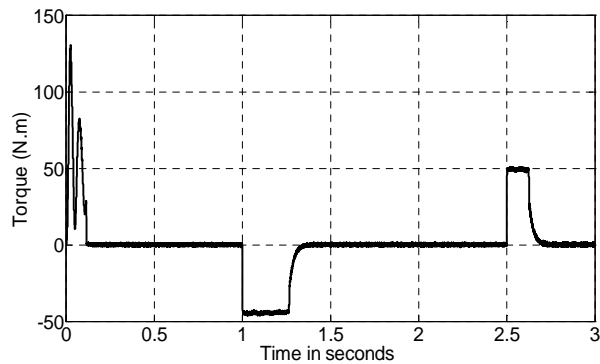
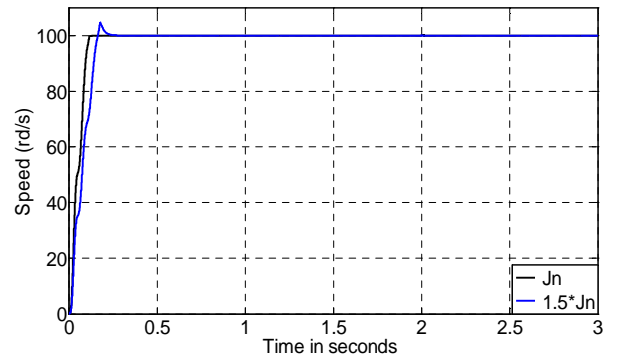
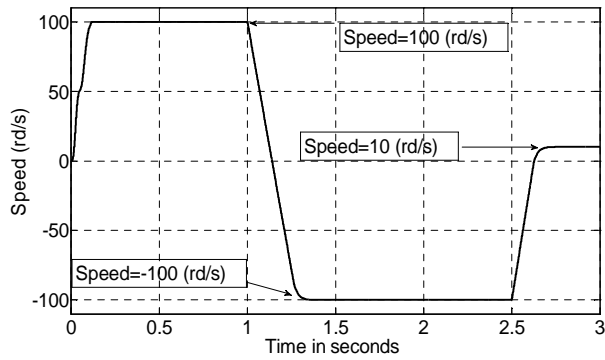


Fig.7. Simulated results test of robustness for different values of the inertia.

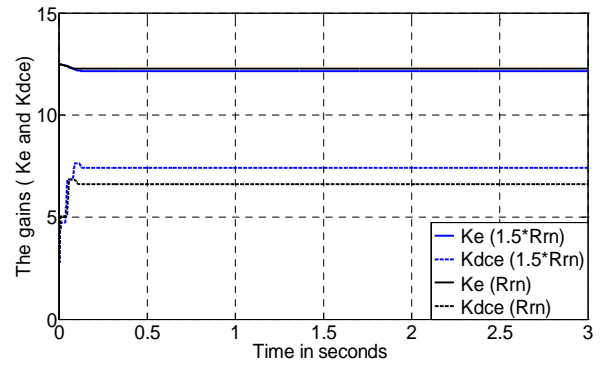
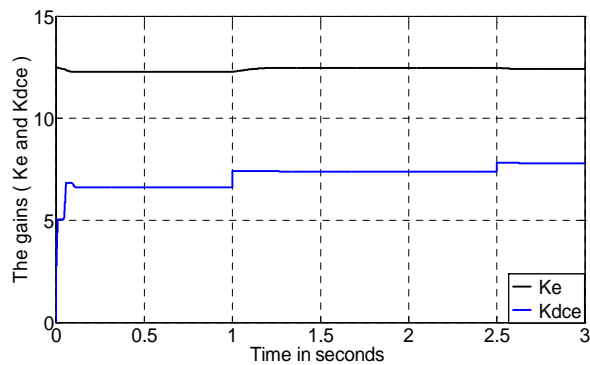
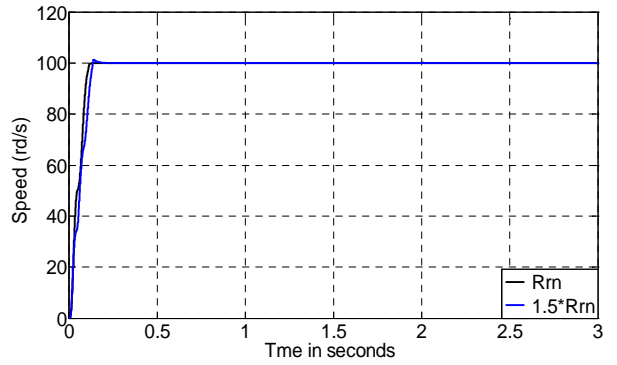
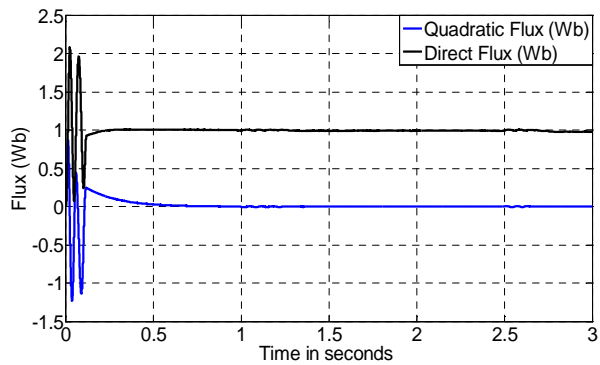


Fig.6. Test of robustness for different values of the speed
1) 100 (rd/s) is applied at 0 (s), 2) -100 (rd/s) is applied at $t=1$ (s), 3) 10 (rd/s) is applied at $t=2.5$ (s).

Fig.8. Simulated results test of robustness for different values of the rotor resistance.

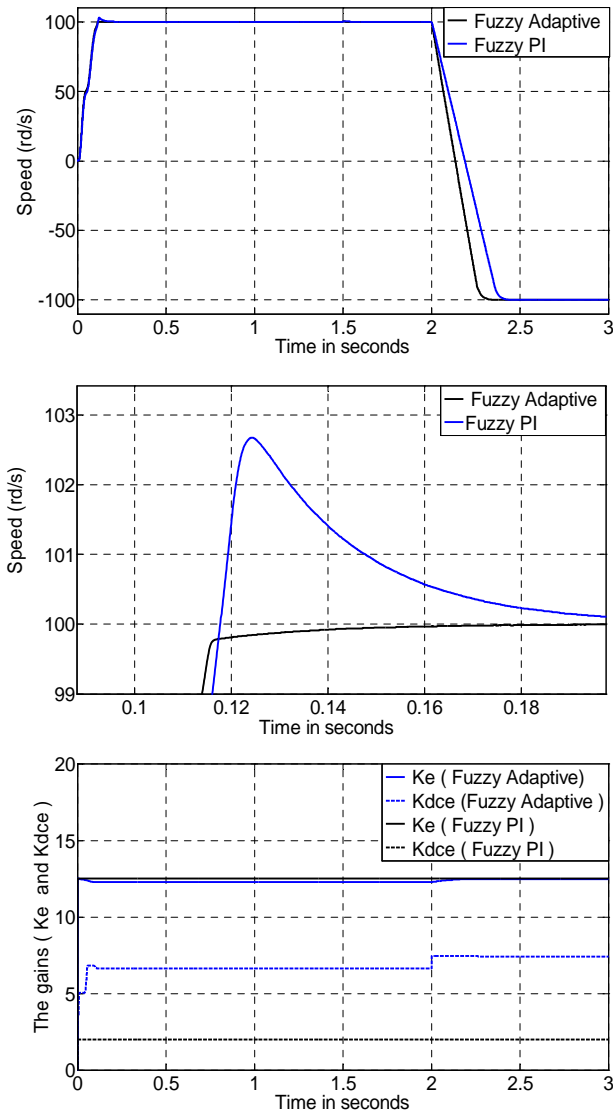


Fig.9. Simulated results test of robustness the Fuzzy Adaptive Control and Fuzzy-PI.

Appendix

A: machine parameters:

Rated voltage 220/380, nominal current 6.5A, $\alpha=30^\circ$, power 4.5 (Kw), frequency 50 (Hz), $R_{s1}=R_{s2}=3.72 (\Omega)$, $p=1$, $R_r=2.12 (\Omega)$, $L_m=0.3672 (H)$, $L_{s1}=L_{s2}=0.022 (H)$, $L_r=0.006 (H)$, $J=0.0625 (Kg.m^2)$, $f_r=0.001 (N.m.s/rd)$.

B: parameters of the control:

$$a_p=f_r/J, b_p=p/J, d_p=J/p, K_{de}=19, \phi_r^*=1 (Wb).$$

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