Proportional-Integral Field Oriented Control of Induction Motor with Fuzzy Logic Gains adaptation

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Abstract: This paper presents the indirect field vector control of induction motor (IM) which is controlled by an adaptive Proportional-Integral (PI) speed controller. This solution is proposed to handle the induction motor rotor resistance variation problem, which degrades the performance of the speed control. To solve this problem, an adaptive PI controller is designed with gains adaptation based on fuzzy logic in order to improve the performances of electric drive systems towards the parametric variations. The control algorithm is emphasized by simulation tests. Analysis of the obtained results shows the characteristic robustness to disturbances of the load torque and to rotor resistance variation compared to the classical PI control and adaptive control using Model Reference Adaptive System MRAS rotor resistance observer.

Key–Words: Induction motor, Adaptive control, Fuzzy logic, PI gains adaptation, Vector control.

1 Introduction

The first control applications of asynchronous machines were limited only at steady state. These applications were based on the scalar command, also known as the (V/f) control [1]. This technique is characterized by its simplicity and relatively small cost of implementation. Nevertheless, it can not guarantee a high performance due in fact to the existence of an intrinsic coupling between the torque and flux. To overcome the drawbacks of the scalar control, more other sophisticated control techniques have been developed, namely, the direct torque control (DTC: Direct Torque Control) and flux oriented vector control (FOC Field Oriented Control) ([2],[3]). In the literature, there are different vector control strategies that differ essentially by the choice of the (d, q) axes orientation. The most common is the rotor flux oriented vector control. Recently, several studies have been devoted to development of non-linear control techniques to drive the induction motor. These techniques include: control based on the technique of input-output linearization [4], sliding mode control ([5],[6]), backstepping control ([7]-[10]). The major drawback of these control techniques is their sensitivity to parametric variations, in particularly, the rotor resistance (Rr) which can change with the temperature[11]. Indeed, a mismatch of the rotor resistance affects significantly the open loop slip estimator and degrades the performance of the speed control([4],[12]). To solve this problem, many research have been focused toward the adaptive control in order to improve the robustness of the control scheme towards the parametric variations with the use of different type of observers. Among them, the adaptive control of IM using a Model Reference Adaptive Systems (MRAS) observer, which consists in comparing the output of both estimators, but in ([11],[13]), the authors claims that this method doesn't guarantee a high performance of speed control. The sliding mode observer presented in [14] shows that the main drawback of this solution is the appearance of the chattering phenomenon, due to the high switching frequency control signals. The works presented by ([12],[15],[16],[17]), which concerns the backstepping and the luenberger observers respectively, show that the induction motor can suffer from instability problems at low speed, if the estimation error of the rotor resistance is greater than or equal to 10%.

In recent years, the number and variety of applications of fuzzy logic have increased significantly especially for uncertain nonlinear systems ([18],[19]). Moreover, the work presented by [20] propose a new design method for the PI-fuzzy controllers which illustrates the potential of **I**terative **F**eedback **T**uning

(**IFT**) employed in connection with fuzzy control in complex plants. To solve optimization problems for Takagi-Sugeno fuzzy controller, the authors in [21] propose a new design of this type of controller using swarm intelligence optimization algorithms.Recently, some results on type-2 fuzzy logic systems have been reported which is applied to design a novel reliable static output-feedback controller for discrete-time interval type-2 fuzzy-model-based systems with mixed $\mathcal{H}_2/\mathcal{H}_\infty$ performance.

The main purpose of this paper is to design an adaptive control scheme for induction motor that allow high performance using the fuzzy logic. The idea is to design an adaptive PI speed controller which can ensure a good tracking of the reference speed even in the presence of rotor resistance variation. The adaptive mechanism of the PI gains is ensured using a fuzzy logic controller for each gain (k_p and k_i). The control law developed in this paper does not propose the use of any observer mentioned above so as not increase the complexity of the control scheme, and guarantee a good rotor flux orientation even in the case of rotor resistance variation.

This paper is organized as follows: in Section 2, the mathematical model of the induction motor is presented. In the next Section, we briefly review the Vector Control Strategy of induction motor. The procedure design proposed to handle the induction motor rotor resistance effect based on fuzzy logic is described in Section 4. Simulation results are presented in Section 5, and compared with classical PI control and other recent works. Finally, in Section 6 some comments and conclusion are given.

2 Induction Motor Modelling

Vector control of induction motor is based on Park transformation involving the electrical frequencies of stator and rotor respectively ω_s and ω_r. In this case, the dynamic model of the induction motor according the d-q axis can be expressed in a synchronous rotating reference frame as follows [5]:

$$\begin{aligned}
\tfrac{d}{dt}i_{sd} &= -\lambda i_{sd} + \omega_s i_{sq} + k\beta_r\phi_{rd} + k\omega_r\phi_{rq} + \mu v_{sd} \\
\tfrac{d}{dt}i_{sq} &= -\omega_s i_{sd} - \lambda i_{sq} - k\omega_r\phi_{rd} + k\beta_r\phi_{rq} + \mu v_{sq} \\
\tfrac{d}{dt}\phi_{rd} &= M\beta_r i_{sd} - \beta_r\phi_{rd} + \omega_{sl}\phi_{rq} \\
\tfrac{d}{dt}\phi_{rd} &= M\beta_r i_{sq} - \omega_{sl}\phi_{rd} - \beta_r\phi_{rq}
\end{aligned} \tag{1}$$

where

v_{sd}, v_{sq} : d and q components of stator voltages;
i_{sd}, i_{sq} : d and q components of stator currents;
ϕ_{rd}, ϕ_{rq} : d and q rotor flux components;
L_s, L_r : Stator and rotor inductances;
R_s, R_r : Stator and rotor resistances;
M, σ : Mutual inductance and total linkage coefficient;
ω_r, ω_s : Rotor and rotating frame angular velocity;
$\omega_{sl} = \omega_s - \omega_r$: Slip angular frequency.

and the constants are defined as follows:

$$\lambda = \mu R_{sr},\ \mu = \frac{1}{\sigma L_s},\ R_{sr} = R_s + \frac{M^2}{L_r^2}R_r,\ k = \mu\Gamma$$

$$\sigma = 1 - \frac{M^2}{L_r L_s},\ \Gamma = \frac{M}{L_r},\ \beta_r = \frac{R_r}{L_r}.$$

3 Vector Control Strategy of Induction Motor

The difficulty for controlling an induction motor resides in the fact that there is a complex coupling between the input, output and internal machine variables such as flux, torque, speed or position. In 1971 Blaschke proposed a new control theory, which called oriented flux vector control that can bring the IM to the current DC machine with separate excitation [3]. This control theory imposes that $\phi_{rd} = \phi_r$ and $\phi_{rq} = 0$, in order to ensure that the flux and torque will be controlled respectively by the stator currents (i_{sd}) and (i_{sq}). The Field Oriented Control (FOC) strategy can then achieves the decoupling between flux and torque dynamics, but the performance of the FOC depends heavily on the knowledge of the real motor parameters. Unfortunately, those parameters may change widely with the temperature, the current amplitude and the inverter frequency. In particularly, the rotor resistance is the most critical changing parameter ([12],[13],[22]). In fact, the nonlinear mathematical dynamic model of induction motor described by equation (1) can be rewritten by the following equations:

$$\begin{aligned}
\tfrac{d}{dt}i_{sd} &= -\lambda i_{sd} + \omega_s i_{sq} + k\beta_r\phi_r + \mu v_{sd} \\
\tfrac{d}{dt}i_{sq} &= -\omega_s i_{sd} - \lambda i_{sq} - k\omega_r\phi_r + \mu v_{sq} \\
\tfrac{d}{dt}\phi_r &= M\beta_r i_{sd} - \beta_r\phi_{rd} \\
\tfrac{d}{dt}\phi_{rq} &= M\beta_r i_{sq} - \omega_{sl}\phi_r = 0 \\
J\tfrac{d}{dt}\omega_r &= (C_e - C_r) - \tfrac{f}{J}\omega_r
\end{aligned} \tag{2}$$

The electromagnetic torque and the slip frequency are given by the following equations:

$$C_e = \frac{3}{2}\frac{n_p M}{L_r}(\phi_{rd} i_{sq}) \tag{3}$$

$$\omega_{sl} = \frac{M R_r}{L_r \phi_r} i_{sq} \tag{4}$$

Equation (2) show the non-linearity of the induction motor which can be solved by adding the compensations terms as illustrated in Figure 1.

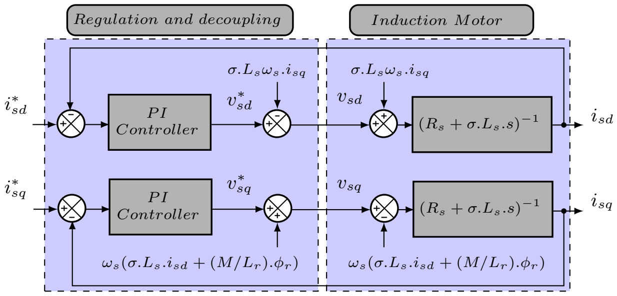

Figure 1: Block diagram of the conventional PI current controller with compensation terms

The PI speed controller determines the reference torque to maintain the same speed. So to calculate the parameters of the controller, it must be assumed that the dynamics of the stator currents is not involved in the dynamics of the speed control loop because the mechanical constant time is considerably greater than the electric constant time.
The speed control loop using a PI corrector is given by the following block diagram:

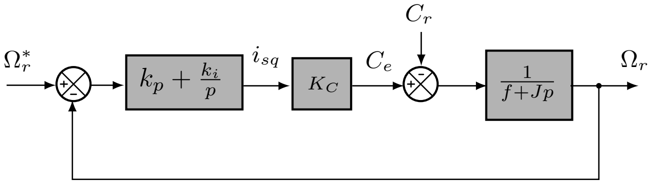

Figure 2: Block diagram of the speed control loop using a PI controller

where
$K_C = \frac{3 n_p M}{2 L_r}\phi_r$: electromagnetic torque constant.

The correction gains of the PI controller are determining using pole placement method to fix the closed-loop system dynamics. The transfer function of the closed loop system represented by Figure 2 without load torque is:

$$H_\Omega = \frac{(k_p p + k_i) K_C}{J p^2 + (k_p K_C + f) p + k_i K_C} \tag{5}$$

The transfer function H_Ω can be identified to a second-order system and gains of this controller can be calculated as follows:

$$k_p = \frac{2\xi k_i}{\omega_n} - \frac{f}{K_C} \tag{6}$$

$$H_\Omega = \frac{J\omega_n^2}{K_C} \tag{7}$$

where
ξ is the damping ratio and ω_n the natural frequency.
The speed response time T_{rs} can be expressed in terms of the natural frequency if the damping coefficient is equal to 1. In this case, the may in calculating the values of speed corrector gains from the following relationship [13]:

$$\omega_n T_{rs} = 4.8 \tag{8}$$

4 Fuzzy Logic Control Based on PI Gains Adaptation

In order to design a robust control law that takes into account the effect of the the rotor resistance variation, and not to increase the complexity of the control scheme with the use of an observer, this section was devoted to the proposal of an adaptive PI controller structure whose parameters are adjusted by fuzzy logic. The fuzzy system generates the parameters of the PI controller k_p and k_i depending on the error between the reference and the system response as shown in Figure 3 to ensure high performance of the developed control law with compensation of the R_r variation effect.

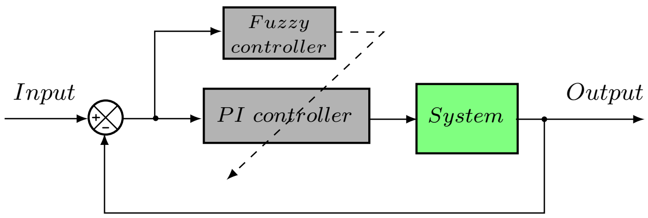

Figure 3: Block diagram of the fuzzy logic gains adaptation of the PI controller

The proposed controller use two fuzzy systems: the first generates the k_p gain and the second generates k_i

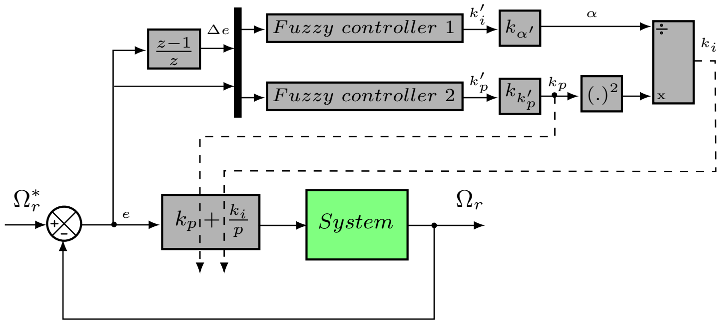

Figure 4: Block diagram of the speed control loop using a fuzzy adaptive PI controller

via another auxiliary parameter α. The fuzzy adaptation system of the PI controller is shown in Figure 4. As indicated in Figure 4, the PI parameters are determined from two fuzzy inferences whose outputs are auxiliary parameters k'_p, k'_i and inputs are the error between the real and reference speed (e), and its derivative (Δe).

The output of the two fuzzy controllers are standardized in intervals between zero and 1. The parameters k_p and k_i are determined using the following equations:

$$k_p = k_{k'_p} k'_p \tag{9}$$

$$k_i = \frac{k_p^2}{\alpha} \tag{10}$$

The fuzzy inference engine uses the fuzzy **IF THEN** rules to perform a mapping from the input vector to the output. The i^{th} fuzzy rule is written as follows:

IF e is Ai and Δe is Bi **THEN** k'_p is Ci and k'_i is Di

where
Ai; Bi; Ci and Di are the fuzzy sets.

The universe of discourse is common to all fuzzy inputs variables (e, Δe) and is divided into seven fuzzy sets (NB, NM, NS, Z, PS, PM, and PB) with triangular membership functions as shown in Figure 5. The establishment of rules defining the output results from operating expertise.

For the output variable of the fuzzy logic controller that generates k'_p, two membership functions are associated as shown in Figure 6. The membership functions for the output that generates k'_i are represented in Figure 7

For our application, we used the basic rules given in Tables 1 and 2, which stems from expertise and are

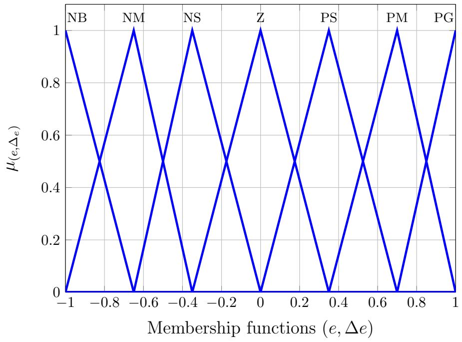

Figure 5: Degree of input membership for e and Δe

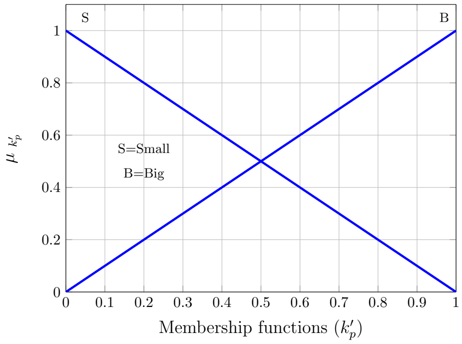

Figure 6: Degree of output membership for k'_p

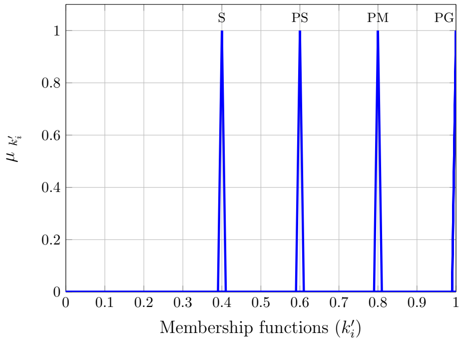

Figure 7: Degree of output membership for k'_i

based on the operating principle of the bang-bang[1] that offers very good results [22]. The latter is organized in the form of a decision tables. The rules defining the output of each fuzzy controller are given by the following tables:

Table 1: Fuzzy control rules for k'_p

$\triangle e$	e						
	NB	NM	NS	Z	PS	PM	PB
NB	B	B	B	B	S	S	B
NM	B	B	B	B	S	B	B
NS	B	B	B	B	B	B	B
Z	B	B	B	B	B	B	B
PS	B	B	S	B	B	B	B
PM	B	B	S	B	B	B	B
PB	B	S	S	B	B	B	B

Table 2: Fuzzy control rules for k'_i

$\triangle e$	e						
	NB	NM	NS	Z	PS	PM	PB
NB	S	S	S	S	S	S	S
NM	PS	PS	S	S	S	PS	PS
NS	PM	PS	PS	S	PS	PS	PM
Z	PG	PM	PS	PS	PS	PM	PG
PS	PM	PS	PS	S	PS	PS	PG
PM	PS	PS	S	S	S	PS	PS
PB	S	S	S	S	S	S	S

5 Simulation Results and Discussion

The effectiveness of the proposed PI field oriented control of induction motor with gains adaptation has been verified by simulations. The rotor field oriented control scheme is illustrated in Figure 8. The simulation results have been obtained by implementing the control scheme illustrated by Figure 9 under the Matlab- Simulink environment with 50μs sampling period.The motor parameters values of the set-up are given in Table 3. The reference value of the rotor flux along the d-axis has been fixed to 1 Wb. Three tests were performed: The first one for the classical PI speed control. A step reference speed was applied at t=1s and is equal to 157 rad/s. The load torque is applied at t=3s. At t=5s, undergone a disturbance on the rotor resistance which has been increased by 50% from its rated value. The second test for the adaptive control, which the classical PI controller was replaced by the proposed adaptive PI fuzzy logic controller using the same speed profile and the same operating conditions. The final test is for an adaptive control using an MRAS rotor resistance observer.

Table 3: Motor parameters values

Symbol		Quantity	UM
R_s	Stator resistance	2.3	$[\Omega]$
R_r	Rotor resistance	1.83	$[\Omega]$
L_s	Stator inductance	261	$[mH]$
L_r	Rotor inductance	261	$[mH]$
M	Mutual inductance	245	$[mH]$
σ	Leakage factor	0.134	-
J	Moment of inertia	0.22	$[Kgm^2]$
f	Friction coefficient	0.001	-
V_n	Rated voltage	380	$[V]$
I_n	Rated current	10.4	$[A]$
P_n	Rated power	3	$[kW]$
n_p	Number of pole pairs	2	-

Figures 10-12 show the simulations results for the classical PI without gains adaptation. Figure 10 shows that the rotor speed decrease by almost 10 rad/s from its rated value, and the rotor speed error illustrated by figure 11 show that this error exceeds 7% when the rotor resistance undergone a variation.
Figure 12 shows the effect of sudden change on the shape of direct and quadratic flux, when a 50% increase of the rotor resistance is introduced, without PI gains adaptation. Just at the moment of variation, the orientation of the fluxes is lost, which deteriorate the controllers performances.

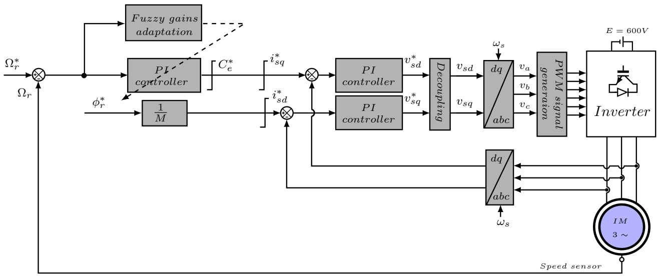

Figure 8: Block diagram of vector control with an adaptive fuzzy logic gains adaptation of the PI speed controller

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[1] Control method used to initially bring the system close to the desired operating point, then change the polarity of the control variable to avoid overshoot.

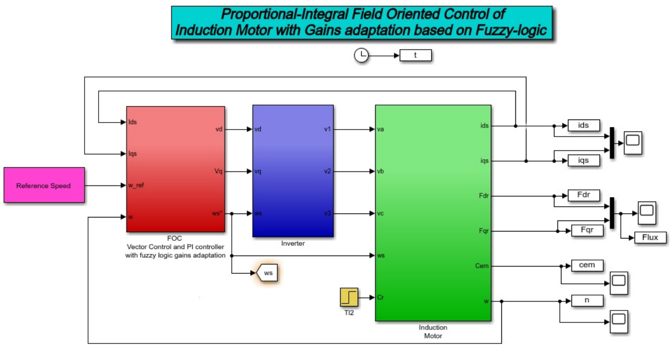

Figure 9: Block diagram of vector control developed under the Matlab- Simulink environment

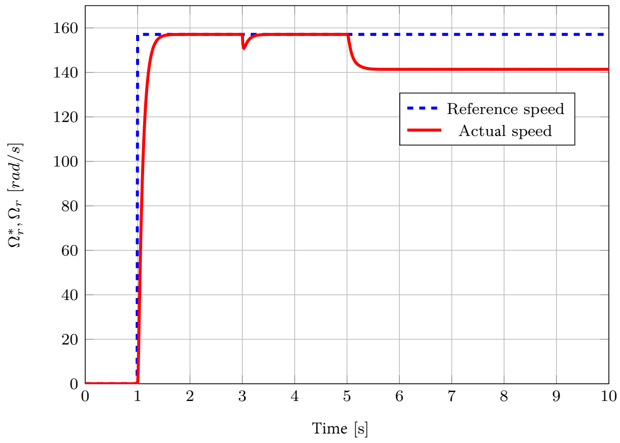

Figure 10: Rotor speed (without PI gains adaptation)

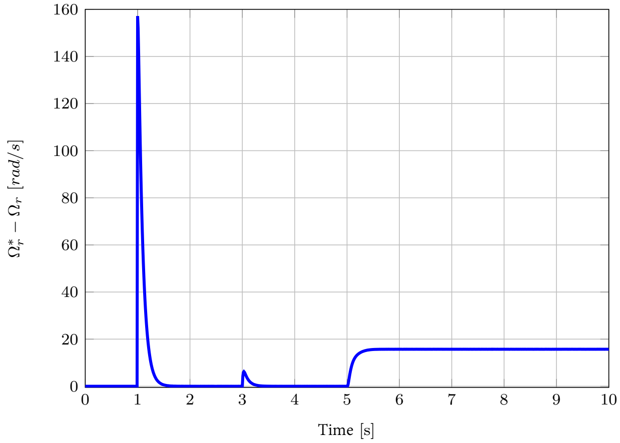

Figure 11: Rotor speed error (without PI gains adaptation)

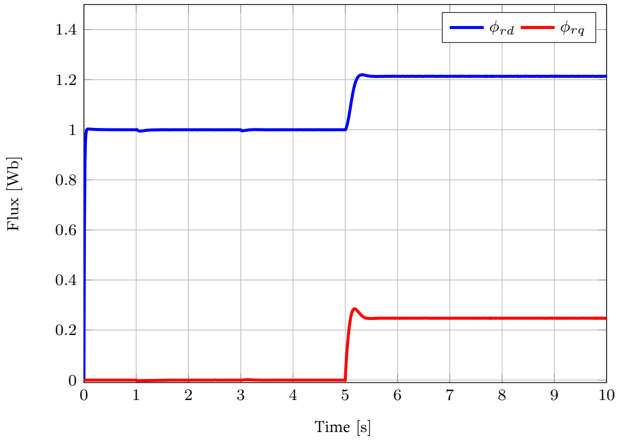

Figure 12: Rotor flux (without PI gains adaptation)

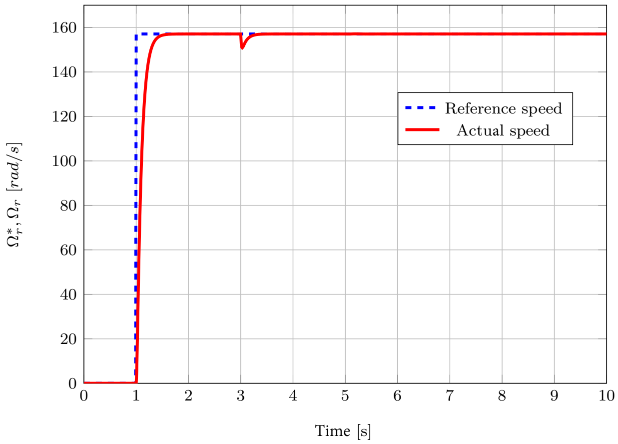

Figure 13: Rotor speed (with PI gains adaptation)

Figures 13-15 show the performance of the adaptive control with fuzzy logic gains adaptation of the PI speed controller. The obtained result demonstrates that even if an increase the rotor resistance is introduced at t = 5s, the proposed adaptive control still gives a good orientation of the rotor flux and a good speed tracking, with a speed error which doesn't exceed 1% of the rated value. However, the adaptive vector control based on MRAS rotor resistance observer does not guarantee a good tracking of the rotor speed as shown in Figure 13. In this case, when the rotor resistance

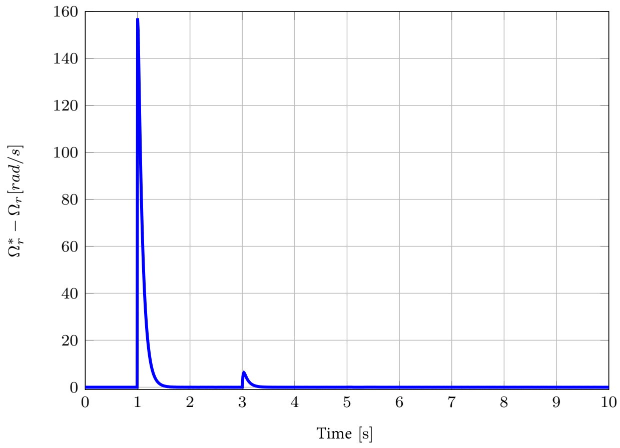

Figure 14: Rotor speed error (with PI gains adaptation))

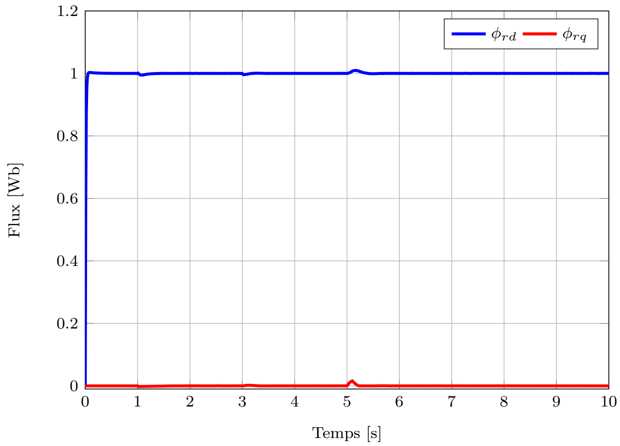

Figure 15: Rotor flux (with PI gains adaptation)

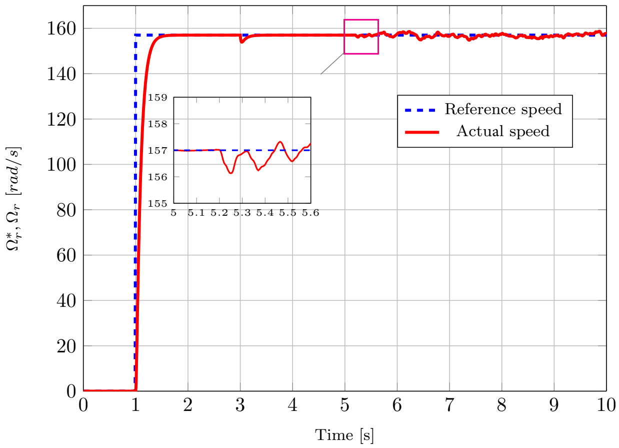

Figure 16: Rotor flux (with PI gains adaptation)

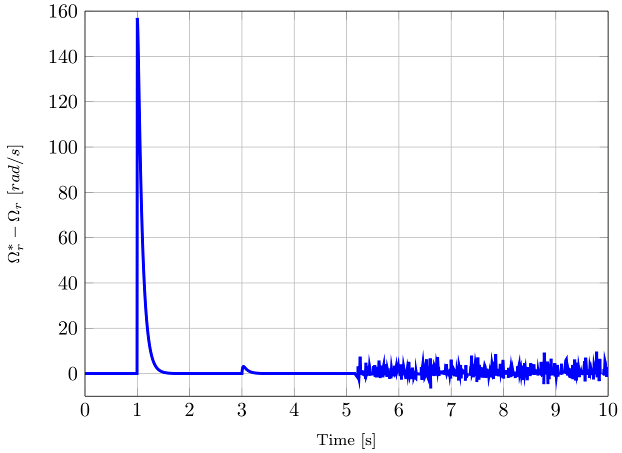

Figure 17: Rotor flux (with PI gains adaptation)

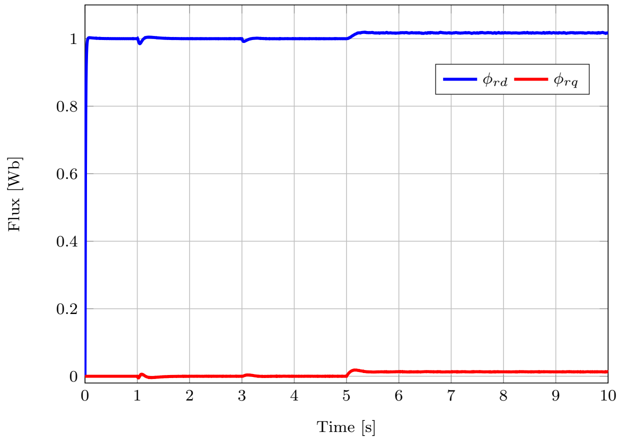

Figure 18: Rotor flux (with PI gains adaptation)

undergoes a variation, the rotor speed decrease by almost 2 rad/s from its rated value with the appearance of ripples as shown in Figures 16-17. Figure 18 shows that using an MRAS rotor resistance observer does not guarantee a good fluxes orientation.

Table 4 shows the quantitative performances comparison produced by the proposed adaptive control scheme, the classical PI control and the adaptive control using an MRAS rotor resistance observer. The results illustrate globally the superiority of the proposed solution compared to the MRAS method. The results obtained demonstrate also that the proposed PI field oriented control of induction motor with gains adaptation based on fuzzy logic has a powerful approach to allow high performance control. Consequently, from the simulation results, the better control performance can be obtained using the PI control with gains adaptation based on fuzzy logic, which shows the effectiveness the proposed scheme in terms of load disturbances rejection, speed reference tracking in transients and stand-still operation and rotor flux orientation.

Table 4: Performance indices: $\Omega_r^*; \phi_r^*$: References values, $\Omega_r; \phi_{rd}$: Actuals values , E: Error, IAE: Integral Absolute Error, $ITAE$: Integral Time multiplied Absolute Error, ISE: Integral Square Error

Control Method	E	IAE	$ITAE$	ISE
Classical PI control	$\Omega_r^* - \Omega_r$	148	862.9	3684
	$\phi_r^* - \phi_{rd}$	1.068	8.025	0.2293
Adaptive MRAS control	$\Omega_r^* - \Omega_r$	25.5	90.35	1403
	$\phi_r^* - \phi_{rd}$	0.11	0.65	0.001
Proposed control based on fuzzy logic	$\Omega_r^* - \Omega_r$	16.08	18.38	373
	$\phi_r^* - \phi_{rd}$	0.004	0.01	$1.95e^{-05}$

6 Conclusions

The PI control with gains adaptation based on fuzzy logic technique is developed in this paper. The proposed method is an alternative to handle the induction motor rotor resistance variation problem. These technique use an adaptive mechanism of the PI gains which is ensured using a fuzzy logic controller for each gain (k_p and k_i). The proposed control scheme can guarantee a high performance compared to the classical PI control and the adaptive control using an MRAS rotor resistance observer. Simulation tests confirm the theoretical concepts and show that this type of adaptive control can overcomes the rotor resistance variation. The simulation results showed that the proposed control scheme can guarantee a good performance of the fact that the speed error exceeds 1% of the rated value.

References:

[1] P. Parida, A sliding mode controller for induction motor drives, *Ph.D. Thesis, National Institute of Technology*, 2009.

[2] K. Hasse, On the dynamics of speed control of a static AC drive with squirrel cage induction machine Dissertation, *Tech. Hochschule Darmstradt*, 1969.

[3] F. Blaschke, The principle of field orientation as applied to the new transvector closed loop control system for rotating field machines, *In Siemens Rev 34*, 1951, pp. 217–220.

[4] F. Alonge, M. Cirrincione, M. Pucci and A. Sferlazza, Input output feedback linearizing control of linear induction motor taking into consideration the end-effects, Part II : Simulation and experimental results, *Control Engineering Practice, Elsevier* 36, 2015, pp. 142-150.

[5] H. A. Shah and A. T Patel, Controller design via sliding mode control approach of induction motor a survey, *In 2014 Fourth International Conference on Advanced Computing Communication Technologies (ACCT), India*, 2014, pp. 541546.

[6] M. Arab and J. Soltani, A current-based output feedback sliding mode control for seed sensorless induction machine drive using adaptive sliding mode flux observer, *International Journal of Engineering Transactions A: Basics* 19(1), 2006, pp. 2134.

[7] C. Ben Regaya, A. Zaafouri and A. Chaari, Loss-minimizing with backstepping technique control for induction motors and on line adaptation of the stator and rotor resistance, *Middle East Journal of Scientific Research* 15(2), 2013, pp. 389397.

[8] R. Yazdanpanah and J. Soltani, Robust backstepping control of induction motor drives using articial neural networks aand sliding mode flux observers, *International Journal of Engineering Transactions A: Basics* 20(3), 2007, pp. 221232.

[9] C. Ben Regaya, F. Farhani, A. Zaafouri and A. Chaari, An adaptive sliding-mode speed observer for induction motor under backstepping control, *Innovative Computing, Information and Control (ICIC Express Letters)* 11(4), 2017, pp. 763771.

[10] F. Farhani, C. Ben Regaya, A. Zaafouri and A. Chaari, Real time PI-backstepping induction machine drive with efficiency optimization, *ISA Transactions* 70, 2017, pp. 348356.

[11] C. Ben Regaya, F. Farhani, A. Zaafouri and A. Chaari, High-performance control of im using mras-fuzzy logic observer, *International Journal of Tomography and Simulation* 30(2), 2017, pp. 40-51.

[12] C. Ben Regaya, F. Farhani, A. Zaafouri and A. Chaari, A novel adaptive control method for induction motor based on backstepping approach using dspace ds 1104 control board, *Mechanical Systems and Signal Processing* 100, 2018, pp. 466-481.

[13] M. Gayathri, S. Himavathi and R. Sankaran, Comparison of rotor flux and reactive power based mras rotor resistance estimators for vector controlled induction motor drive, *International Conference on Advances in Engineering, Science and Management (ICAESM), India*, 2012, pp. 183189.

[14] C. Ben Regaya, A. Zaafouri and A. Chaari, A new sliding mode speed observer of electric motor drive based on fuzzy-logic, *Acta Polytechnica Hungarica* 11(3), pp. 219232.

[15] A. Zaafouri, C. Ben Regaya, H. Ben Azza and A. Chaari, Dsp-based adaptive backstepping using the tracking errors for high-performance sensorless speed control of induction motor drive, *ISA Transactions* 60, pp. 333347.

[16] C. Ben Regaya, F. Farhani, A. Zaafouri and A. Chaari, Comparison between two methods for adjusting the rotor resistance, *International Review on Modelling and Simulations* 5(2), 2012, pp. 938944.

[17] K. Negadi, A. Mansouri and R. Kourek, R. 2012, Hardware implementation of vector control of induction motor drive without speed encoder using an adaptive luenberger based mras observer, *Mechanical Systems and Signal Processing* 20, 2012, pp. 99114.

[18] H. K. Lam, F. H. F. Leung and P. K. S. Tam, P. K. S. 2000. Stable and robust fuzzy control for uncertain nonlinear systems, *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans* 30(6), 2000, pp. 825840.

[19] R. E. Precup, M. L. Tomescu and E. M. Petriu, E. M. 2010, Fuzzy logic-based stabilization of a magnetic ball suspension system, *International Journal of Artificial Intelligence* 5(10), 2010, pp. 56 66.

[20] S. Preitl and R. E. Precup, Iterative feedback tuning in fuzzy control systems. Theory and applications, *Acta Polytechnica Hungarica* 3(3), 2006, pp. 8196.

[21] S. Vrkalovic, T. A. Teban and I. D. Borlea, Stable takagi-sugeno fuzzy control designed by optimization, *International Journal of Artificial Intelligence* 15(2), 2017, pp. 1729.

[22] C. Ben Regaya, A. Zaafouri and A. Chaari, Electric drive control with rotor resistance and rotor speed observers based on fuzzy logic, *Mathematical Problems in Engineering*, 2014, pp. 1-9.