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INFLUENCE OF FUZZY ADAPTED SCALING FACTORS ON THE PERFORMANCE OF A FUZZY LOGIC CONTROLLER BASED ON AN INDIRECT VECTOR CONTROL FOR INDUCTION MOTOR DRIVE

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This work investigates a simple design of the scaling factors fuzzy tuning procedure of a fuzzy logic controller (FLC) for speed regulation of an indirect field-oriented induction motor (IM). A simple but powerful fuzzy adaptation of the FLC three scaling factors is proposed. This adaptation does not require the knowledge of the system model. The influence of different combinations of the FLC scaling factors fuzzy self-tuning on the performance control is investigated and illustrated by some simulation results at different dynamic operating conditions such as sudden change in command speed, step change in load torque and some key parameters deviation. The suggested controller can be applied to a large class of robotics and other mechanical systems.

K e y w o r d s: FLC, fuzzy self-tuning of the scaling factors, speed regulation, field oriented IM, key parameters variation, robustness

NOMENCLATURE

dq	Synchronously rotating reference frame.
i_{sd}, i_{sq}	dq stator current components.
ψ_{rd}, ψ_{rq}	dq rotor flux components.
ψ_r	Rotor flux amplitude.
M	Mutual inductance.
L_s, L_r, R_s, R_r	Stator/rotor self-inductance/resistance.
J, k_f	Rotor inertia, friction coefficient.
σ	Stator leakage coefficient.
σ_r	Reverse of the rotor time constant.
T_l	Load torque.
T_{em}	Electromagnetic torque.
Ω_r	Rotor angular speed.
P, p	Number of pole pairs, time-derivative.

1 INTRODUCTION

The fuzzy logic controller is one of the useful control schemes used for plants having difficulties in deriving mathematical models or having performance limitations with conventional linear control schemes [1]. However, in spite of high dynamic response and best disturbance rejection [1, 2], the major drawback is that such fuzzy controllers are optimized for a correct action only around a fixed steady-state condition. The question at hand is how we can modify the control action when the operating conditions change and/or the plant model is time-varying [3, 4]. Hence the controller needs to be retuned to achieve good performance and robustness.

The FLC contains a set of parameters that can be altered on-line in order to improve its performance and robustness. These include the scaling factors for each controller variable, the membership function of the linguistic variable, and the rules [4–7]. The present paper investigates the different combinations of the scaling factors fuzzy adaptation to fine-tune the FLC.

Based on the above point, a simple but powerful fuzzy adaptation mechanism which updates on-line one or more of the three scaling factors of the FLC allowing obtaining a better control resolution is presented. Moreover the influence of the self-tuning of all the combinations of the three scaling factors on the speed control performance, even under severe variation of some key parameters of the induction motor is investigated.

The main objective of this investigation is to find a suitable fuzzy adjustment of the FLC scaling factors to improve the effectiveness of the drive which allows achieving the following proprieties: robustness around the operating rated conditions and invariant dynamic performance in presence of some key parameters variation of the induction motor such as rotor resistance and inertia in particular.

The outline of this paper is as follows: in Section 2, we briefly present a review of the induction motor model, and the indirect field-orientation theory applied to the rotor flux. Section 3 deals with the classical fuzzy logic controller with fuzzy adaptive scaling factors. The fuzzy self-tuning procedure of the scaling factors is investigated in Section 4. Then the influence of the scaling factors fuzzy

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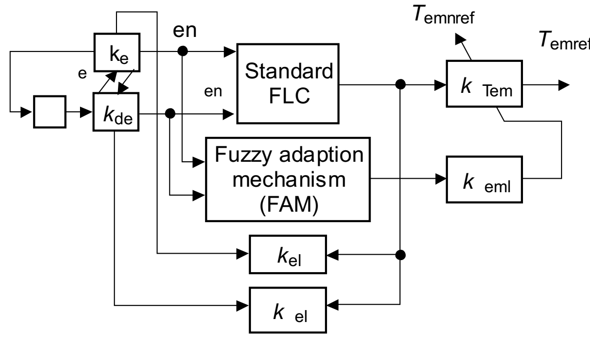

Fig. 1. Scheme structure of the suggested FLC with fuzzy adapted gains.

Table 1. The scaling factors fuzzy self-tuning rules

en / Δen	**NS**	**Z**	**PS**
NB	NB	NB	NB
NM	NM	NM	NM
NS	NS	NVS	Z
Z	NVS	Z	PS
PS	Z	PS	PS
PM	PM	PM	PM
PB	PB	PB	PB

self-tuning on the speed control performance is demonstrated by some simulation results in Section 5. Finally some concluding remarks end the paper.

2 INDUCTION MOTOR MODEL

A standard two-axis model of the induction machine in a rotating reference frame is expressed in the state-space as follows [8, 9]:

$$\dot{x} = Ax + Bv_s \tag{1}$$

where: $x = \begin{bmatrix} i_s^\top & \psi_r^\top \end{bmatrix}^\top$, $i_s = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^\top$, $\psi_r = \begin{bmatrix} \psi_{rd} & \psi_{rq} \end{bmatrix}^\top$, $v_s = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^\top$.

The system matrices are given by:

$$A = \begin{bmatrix} \frac{-1}{\sigma L_s}\big(R_s + \frac{M^2}{L_r}\sigma_r\big) & \omega_s & \frac{M}{\sigma L_s L_r}\sigma_r & \frac{PM\Omega_r}{\sigma L_s L_r} \\ -\omega_s & \frac{-1}{\sigma L_s}\big(R_s + \frac{M^2}{L_r}\sigma_r\big) & -\frac{PM\Omega_r}{\sigma L_s L_r} & \frac{M}{\sigma L_s L_r}\sigma_r \\ M\sigma_r & 0 & -\sigma_r & (\omega_s - P\Omega_r) \\ 0 & M\sigma_r & -(\omega_s - P\Omega_r) & -\sigma_r \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^\top$$

where $\sigma = 1 - \frac{M^2}{L_s L_r}$ and $\sigma_r = \frac{R_r}{L_r}$.

The mechanical modelling part of the system is given by:

$$J\frac{\mathrm{d}\Omega_r}{\mathrm{d}t} = T_{em} - T_l - k_f\Omega_r \tag{2}$$

with:

$$T_{em} = \frac{3}{2}P\frac{M}{L_r}(\psi_{rd}i_{sq} - \psi_{rq}i_{sd}) \tag{3}$$

According to the field orientation theory [9], the machine currents are decomposed into i_{sd} and i_{sq} components, which are respectively, flux and torque components. The key feature of this technique is to keep namely $\psi_{rq} = 0$ and $\psi_{rd} = \psi_r$.

Hence, the flux and the electromagnetic torque are decoupled from each other, and can be separately controlled as desired. Then the drive behaviour can be adequately described by a simplified model expressed by the following equations [9]:

$$\begin{aligned} i_{sq} &= \frac{2L_r}{3PM}\frac{T_{em}}{\psi_r}, \\ \omega_{sl} &= M\sigma_r\frac{i_{sq}}{\psi_r}, \\ i_{sd} &= \frac{p\psi_r + \sigma_r\psi_r}{M\sigma_r}. \end{aligned} \tag{4}$$

3 DESIGN OF A FLC WITH FUZZY ADAPTED SCALING FACTORS FOR IM SPEED CONTROL

A. Design of a FLC for Induction Motor Speed Control

The structure of a standard FLC can be seen as a traditional PI controller, where the speed error e and its variation Δe are considered as input linguistic variables and the electromagnetic reference torque change ΔT_{em} is considered as the output linguistic variable [10, 11] (see Fig. 1).

For convenience, the inputs and the output of the FLC were scaled with three different coefficients k_e, $k_{\Delta e}$ and (see also Fig. 1). These scaling factors can be constant or variable, and play an important role for the FLC design in order to achieve a good behaviour in both transient and steady state.

Seven membership functions with overlap, of triangular shape and equal width, are used for each input variable, so that a 49 rule base is created. The sum-product inference algorithm is selected to complete the fuzzy procedure, and the FLC output is obtained by the gravity centre defuzzification method [12].

The robustness tests of the classical FLC were performed in reference [3]. From these tests, it can be concluded that the classical FLC works properly near to rated plant conditions, in terms of high dynamic response and best disturbance rejection, but the speed behaviour falls dramatically when some parameters variation of the IM occurs (see Fig. 3). Hence an adaptation form of the controller parameters is proposed to improve the speed control robustness and dynamic performance in a wide range of changing conditions.

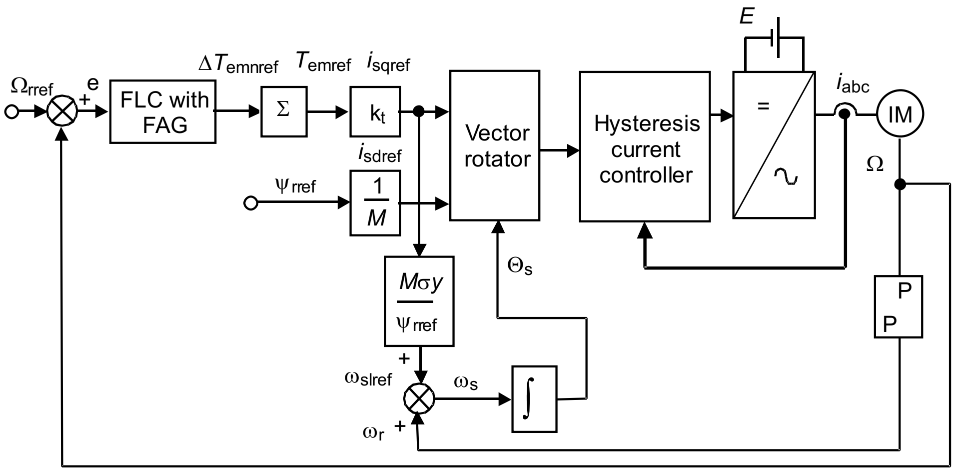

Fig. 2. The FLC with fuzzy adapted gains based on an indirect field oriented IM drive.

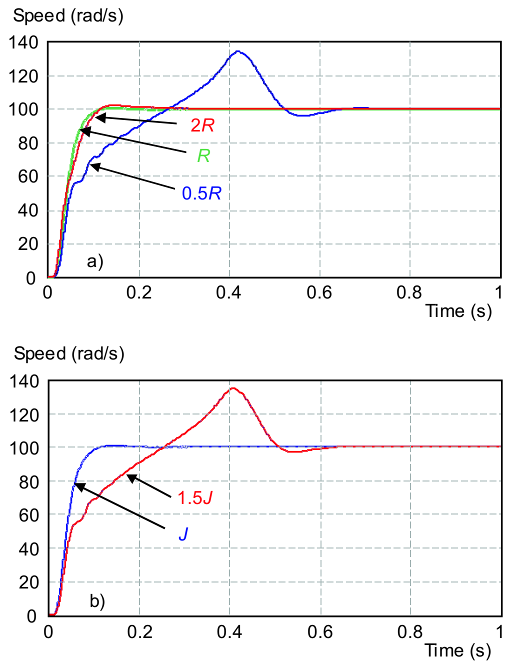

Fig. 3. Simulation results of a speed regulation using a FLC based on a field-oriented induction motor without fuzzy adaptation, considering some key parameters variation: a) $\Delta R_r = -50\,\%$, $+100\,\%$, b) $\Delta J = +50\,\%$.

B. Fuzzy Adaptive Scaling Factors procedure

The proposed FLC with fuzzy adapted gains (FAG) is composed of two parts (see Fig. 1): A standard FLC, and a fuzzy adaptation mechanism (FAM).

The main goal of the scaling factors fuzzy self-tuning is to achieve a lower overshoot and to reduce the settling time of the speed dynamic response even in presence of some key parameters variation.

The basic idea of the fuzzy adaptation mechanism is to build an inference rules table for the scaling factors on-line adaptation, from a lot of robustness tests applied to a speed standard FLC of a field-oriented induction motor, against some key parameters variation (R_r, and J in particular). The following is the built inference rules table used to update on or more of the FLC three scaling factors.

The qualitative influence of the three scaling factors variations on the robustness tests against some key parameters variation of the IM, was used to built this inference rules matrix.

Depending on the choice of the updated scaling factors, the suggested adaptation acts on the corresponding gains in this manner:

$$
\begin{aligned}
k_e(k+1) &= k_e(k) - k_{e1}(k) f\big(e_n(k), \Delta e_n(k)\big)\,,\\
k_{\Delta e}(k+1) &= k_{\Delta e}(k) + k_{\Delta e1}(k) f\big(e_n(k), \Delta e_n(k)\big)\,,\\
k_{\Delta Tem}(k+1) &= k_{\Delta Tem}(k) + k_{\Delta Tem1}(k) f\big(e_n(k), \Delta e_n(k)\big)
\end{aligned} \tag{5}
$$

where k_{e1}, $k_{\Delta e1}$, and $k_{\Delta Tem1}$ are the adaptation fixed gains, and k is a sampling instance (the sampling period is of 0.1 ms in the simulation calculations). The *product-sum* inference mechanism is used to form the fuzzy output of the adaptation mechanism which is the union of the outputs resulting from each rule (the corresponding membership function weighted by the rule strength). Then the crisp value output of the adaptation action f based on Table 1, is calculated from the fuzzy inference output function, using the gravity centre defuzzification method. The main idea of this method is that the larger the firing strength of a rule, the more this rule contributes to the global fuzzy controller output. The feasibility of the proposed algorithm is theoretically verified on a board based on a TMS320C31, 32-bit floating point DSP driven by a 10 MHz clock.

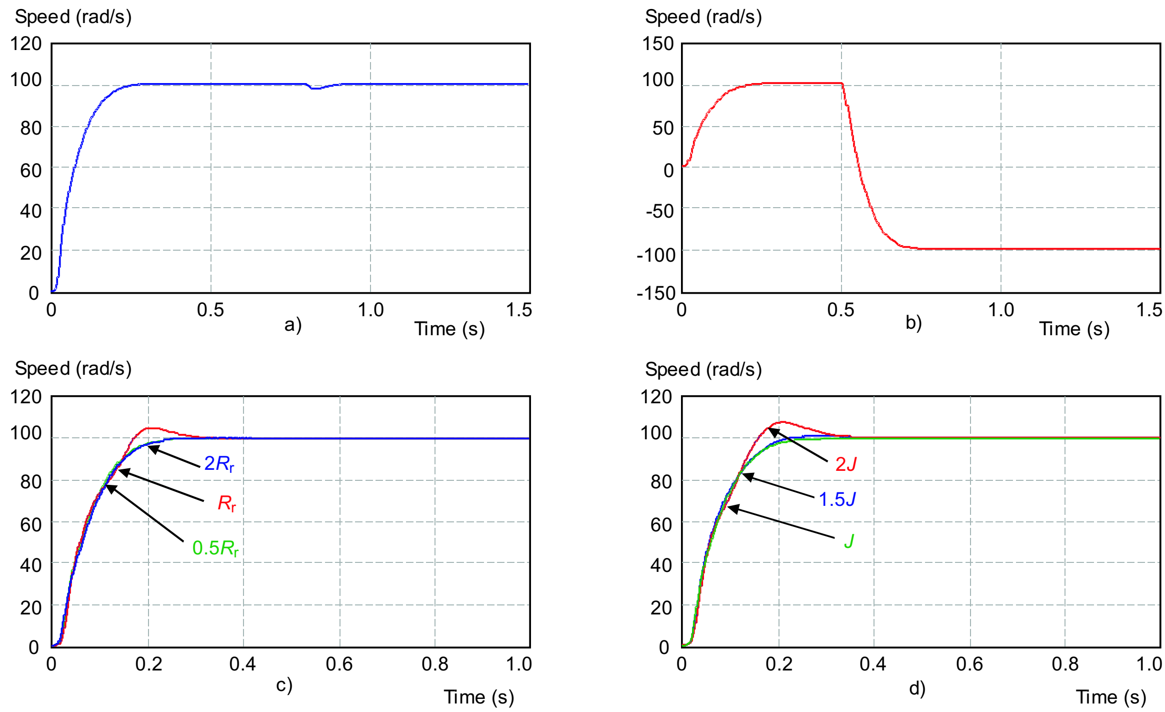

Fig. 4. Simulation results of a speed regulation using a FLC with a fuzzy tuned $k_{\Delta e}$ based on a field-oriented control of an IM. Speed transient from 0 to 100 rad/s: a) followed by applying a rated load torque $T_l = 5$ Nm at $t = 0.8$ s; b) followed by speed reversion from 100 rad/s to -100 rad/s at $t = 0.5$ s. Considering some key parameters variation: c) $\Delta R_r = -50\,\%$, $+100\,\%$, d) $\Delta J = +50\,\%$, $+100\,\%$.

Table 2. Induction motor parameters [13]

Pole pairs	2
Rated power	0.75 KW (at 50 Hz)
Rated voltage	220/380 V
Rated current	3.6/2.1 A
Rated torque	5 Nm
R_s	0 Ω
R_r	6.3 Ω
L_s	0.6560 H
L_r	0.6530 H
M	0.613 H
J	$0.02\,\mathrm{Kg}\cdot\mathrm{m}^2$
k_f	$0\,\mathrm{Nm}\cdot\mathrm{s/rad}$

Table 3. FLC with FAG parameters

Initial gains values		Adaptation gains values	
k_e	1600	k_{e1}	1.6
$k_{\Delta e}$	0.909	$k_{\Delta e1}$	0.089
$k_{\Delta Tem}$	0.96	$k_{\Delta Tem1}$	0.02

4 DIFFERENT COMBINATIONS OF THE SCALING FACTORS FUZZY SELF–TUNING

Based on the tuning procedure described above, the influence of the fuzzy self-tuning scaling factors, on the speed control performance could be reasoned as below:

Firstly, a fuzzy separate adjustment of the three scaling factors is investigated. Secondly, different combinations of two scaling factors fuzzy self-tuning are considered. Lastly the influence of the three scaling factors fuzzy adaptation on the speed control performance is investigated.

In order to demonstrate and compare the viability of these suggested fuzzy adaptation combinations, several simulation tests of the block diagram shown in Fig. 2 were performed for a variety of operating conditions. The data parameters of the test motor are reported in Table 2.

A. Fuzzy Self-tuning of one of the FLC three scaling factors

The updating of each of the three FLC scaling factors by the suggested fuzzy adaptation, allows acquiring a stable performance around a fixed steady-state conditions.

In order to analyze the robustness of the FLC with fuzzy adapted gains against some key parameters variation, some simulation tests under conditions of decreasing and increasing of induction motor rotor resistance and inertia, are tested.

It is worth noting that the fuzzy adaptation of the gains k_e and $k_{\Delta Tem}$ remains unable to compensate parametric variation. But, the fuzzy tuning of the scaling factor $k_{\Delta e}$ can improve greatly the control performance, in fact, the speed is established with a small overshoot, and converges quickly to its reference (see Fig. 4c).

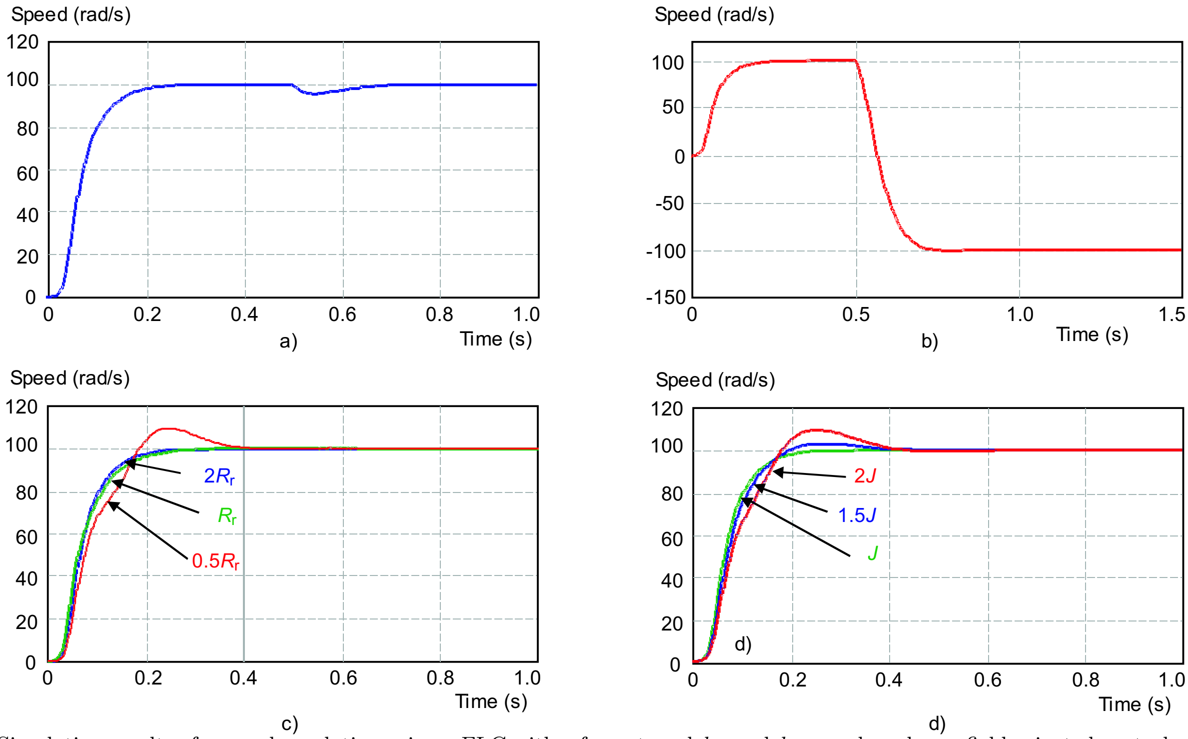

Fig. 5. Simulation results of a speed regulation using a FLC with a fuzzy tuned k_e and $k_{\Delta Tem}$ based on a field-oriented control of an IM. Speed transient from 0 to 100 rad/s: a) followed by applying a rated load torque $T_l = 5$ Nm at $t = 0.8$ s; b) followed by speed reversion from 100 rad/s to -100 rad/s at $t = 0.5$ s. Considering some key parameters variation: c) $\Delta R_t = -50\,\%$, $+100\,\%$; d) $\Delta J = +50\,\%$, $+100\,\%$.

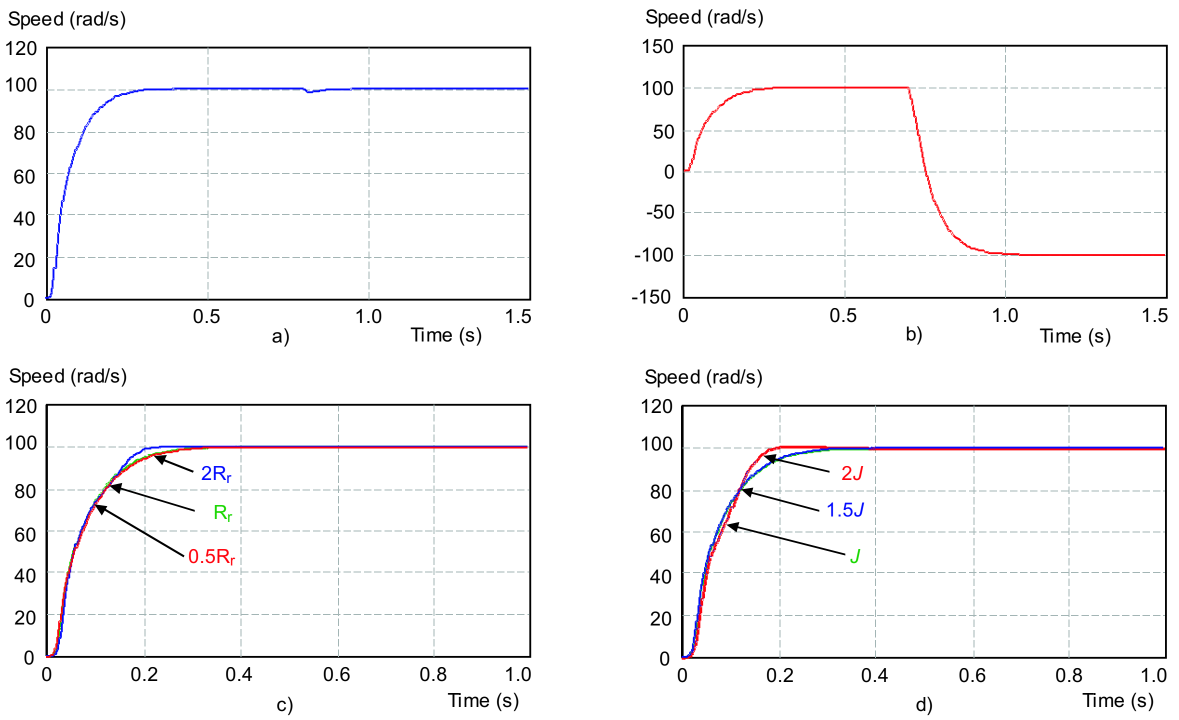

Fig. 6. Simulation results of speed regulation using FLC with fuzzy tuned $k_{\Delta e}$ and $k_{\Delta Tem}$ based on a field-oriented control of an IM. Speed transient from 0 to 100 rad/s: a) followed by applying a rated load torque $T_l = 5$ Nm at $t = 0.8$ s; b) followed by speed reversion from 100 rad/s to -100 rad/s at $t = 0.7$ s. Considering some key parameters variation: c) $\Delta R_t = -50\,\%$, $+100\,\%$; d) $\Delta J = +50\,\%$, $+100\,\%$.

B. Fuzzy Self-tuning of the FLC two scaling factors k_e and $k_{\Delta e}$

This combination yields to a better control response at rated and variable operating conditions, for more details see reference [3].

C. Fuzzy Self-tuning of the FLC two scaling factors k_e and $k_{\Delta Tem}$

From simulation results shown in Figs. 5a and 5b, one can note especially the fast speed response in particu-

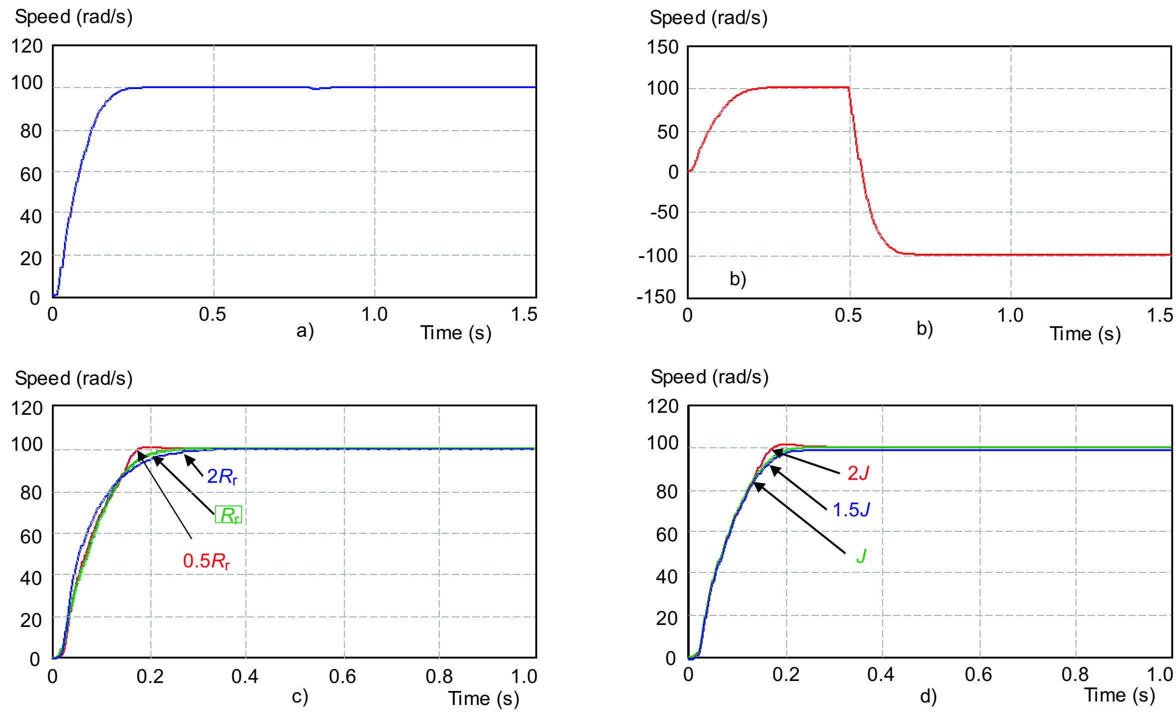

Fig. 7. Simulation results of speed regulation using FLC with fuzzy tuned k_e, $k_{\Delta e}$ and $k_{\Delta Tem}$ based on a field-oriented control of an IM. Speed transient from 0 to 100 rad/s:a) followed by applying a rated load torque $T_l = 5$ Nm at $t = 0.8$ s; b) followed by speed reversion from 100 rad/s to -100 rad/s at $t = 0.5$ s. Considering some key parameters variation: c) $\Delta R_t = -50\,\%$, $+100\,\%$; d) $\Delta J = +50\,\%$, $+100\,\%$.

lar. The robustness test shows that the speed dynamic response is obtained with a maximum overshoot of 7 % (see Fig. 5c).

D. Fuzzy Self-tuning of the FLC two scaling factors $k_{\Delta e}$ and $k_{\Delta Tem}$

Good results are obtained under both transient and steady state conditions (see Figs. 6a and 6b).

From simulation results under severe operating conditions variations shown in Fig. 6c, it is easily seen that the speed response is well improved; in fact the overshoots are more reduced.

E. Fuzzy Self-tuning of the FLC three scaling factors

From the speed behaviour shown in Figs. 7a and 7b, one can notice that a quick and a stable response is obtained at rated operating conditions.

As it is understood from the robustness tests of Fig. 7c, the control performance in this case is more improved then the previous combinations; in fact the speed response is achieved without dip and with a shorter recovery time.

5 CONCLUSION

In this paper, the investigation of the influence of a fuzzy adapted gains applied to a speed FLC of a field-oriented induction motor is fully explained. From this study, it can be concluded: that a simple fuzzy adaptation mechanism can improve greatly the robustness of the drive speed regulation.

To achieve a lower overshoot, a reduced settling time and to improve the control performance under load disturbance and operating conditions changing, different combinations of the FLC three scaling factors fuzzy adaptation FLC are proposed. It is shown from the simulation results, that the robustness of the drive is ameliorated in a wide range of changing conditions especially in the case of the fuzzy tuning of the three scaling factors. This controller can be applied to a large class of robotic systems.

References

[1] HSU, Y. C.—CHEN, G.—LI, H. X. : A Fuzzy Adaptive Variable Structure Controller with Applications to Robot Manipulators, IEEE Trans. Syst., Man. & Cybern. **31** No. 3, June 2001.

[2] IBRAHIM, Z.—LEVI, E. : A Comparative Analysis of Fuzzy Logic and PI Speed Control in High Performance AC Drives Using Experimental Approach, in Conf. Rec. IEEE-IAS, Annu. Meeting, Rome, Italy, October 2000.

[3] KOUZI, K.—MOKRANI, L.—NAIT-SAID, M. S. : A New Design of Fuzzy Logic Controller With Fuzzy Adapted Gains Based on Indirect Vector Control for Induction Motor Drive, in Conf. Rec. IEEE-SSST, Annu. Meeting, West Virginia, USA, pp. 362–366, March. 2003.

[4] MOKRANI, L.—ABDESSEMED, R. : A Fuzzy Self-Tuning PI Controller for Speed Control of Induction Motor Drive, in Conf. Rec. IEEE-CCA, Annu. Meeting, Vol. 2, pp. 785–790, Istanbul, Turkey, June 2003.

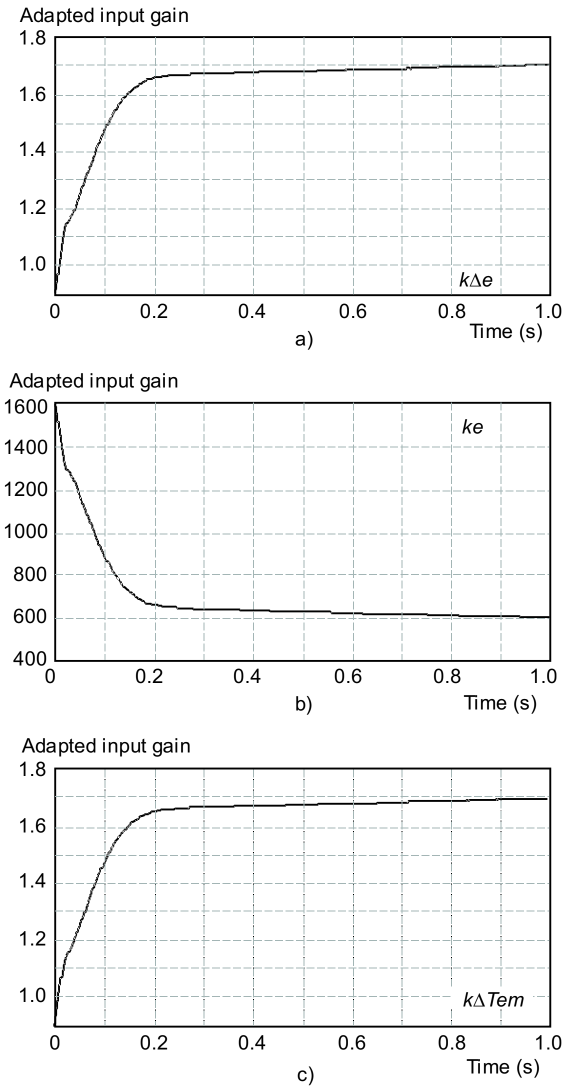

Fig. 8. Evolution of the three scaling factors of the FLC at nominal conditions starting (no load).

[5] HAYACHI, K.—SHIRANITA, K.: Improvement of Conventional Method of PI Fuzzy Control, in Proc. IEICE-Trans, Fundamental, Vol. E 80-A, No. 6, June 2001,.

[6] ROMERAL, L.—LAQUET, J.—ALDABAS, E.—ARIAS, A.: A Simple Fuzzy Adaptive Speed Controller, in Conf. Rec. IEEE-IAS, Annu. Meeting, Rome, Italy, October 2000.

[7] BALESTRINO, A.—LANDI, A.—SANI, L.: CUK Converter Global via Fuzzy Logic and Scaling Factors, IEEE Trans, Ind. Applicat., Vol. 38, No 2, Mars./Apr. 2002,.

[8] GRELLET, G.—CLERC, G.: Actionneurs èlectriques: Principes/Modèle/Commande, Edition Eyrolles, 1999.

[9] VAS, P.: Vector Control of AC Machines, Clarendon Press Oxford, U.K., 1990.

[10] UDDIN, M. N.—RADWAN, T. S.—RAHMAN, M. A.: Performances of Novel Fuzzy Logic Based Indirect Vector Control for Induction Motor Drive, in Conf. Rec. IEEE-IAS, Annu. Meeting, Rome, Italy, October. 2000.

[11] CHOW, B. J.—WAK, S. W.—KIM, B. K.: Design and Stability Analysis of Single-Input Fuzzy Logic Controller, IEEE Trans, On System, Man, and Bernetics-Part B: Cybernetics, 303–309, Vol. 30, No. 2, April 2000,.

[12] SHI, Y.—SEN, P. C.: A New Defuzzification Method for Fuzzy Control of Power Converters, in Conf. Rec. IEEE-IAS, Annu. Meeting, Rome, Italy, October 2000.

[13] LEVI, E.: A Unified Approach to Main Flux Saturation Modeling D–Q Axis Models of Induction Machine, IEEE Trans, On Energy Conversion, Vol. 10, No. 3, December 1995,.

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