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Implementation of a Fuzzy Logic System to Tune a PI Controller Applied to an Induction Motor

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***Abstract*—The simplicity of traditional regulators makes them popular and the most used solution in the nowadays industry. However, they suffer from some limitations and cannot deal with nonlinear dynamics and system parameters variation. In the literature, several strategies of adaptation are developed to alleviate these limitations. In this paper, we propose a combination of two strategies for PI parameters supervision and adaptation. We apply the obtained structure to the control of induction machine speed. Simulation and experimental results of the proposed schema show good performances as compared to two strategies.**

***Index Terms*—Induction motor, fuzzy control, hybrid control, field orientation, supervisor**

I. INTRODUCTION

Classical controllers (PI, PID) are widely used in industry while more advanced techniques of control, such as adaptive controllers are less used in industry. This is due to the fact that:

1. Classical controllers are simpler to implement and their algorithms are easier.
2. Parameter tuning of classical controllers is not a hard task for manipulators.

In spite of the fact that these controllers present an attractive solution for many industrial applications, they have some limitations. Indeed, optimal tuning of parameters, sometimes, leads to unacceptable results in practice. Ziegler - Nichols method, for example, may provoke a high oscillatory transitory state, which explains that 50% of controllers in industry are used in open loop and in manual mode because operators are unsatisfied with the obtained performance of this method [1]. Furthermore, in the case of important variations of the system parameters, classical controllers cannot self-adapt optimally. Self-adaptation capability and robustness of this class of controllers are limited [2]. This can explain the fact that the obtained performances are unsatisfactory without being optimal and that additional tuning may be necessary [3]. The main cases where classical controllers become under optimal can be explained by:

1. Presence of large non-linear dynamics in the system makes the classical controller incapable to compensate for these important non linearity.
2. Important variation of noise in the regulation loop, for example: sensors noise [4, 5].
3. Operating domain (point) variation which makes necessary the controller gain re-adaptation [1].

Hence, improving the classical controller aptitude to the optimal control of perturbed systems with a fine-tuning of the controller parameters is the question key. Fuzzy logic provides mainly a facility of coding and using fuzzy and linguistic information. Furthermore, incorporation of desire of manipulator in the control action is more difficult with conventional techniques [6]. The fuzzy formalism is very close to the human reality of the perception of the world and the process of human reasoning. Thus, the fuzzy linguistic formalism is clearer to operators than the mathematical approaches, fuzzy data and fuzzy rules are easily understandable [7].

So, it is very interesting to explore it is potential for adaptation and supervision of conventional controllers. Combination of classical PI regulator and fuzzy supervisor makes it possible to increase the precision of the mathematical algorithm in the classical controllers with flexibility and simplicity of the fuzzy linguistic formalism.

Several works in the literature study the adaptation and the supervision of conventional controller parameters. In this context, we can mention for example the strategies developed by R. Babuska et al, S. Tzafestas et al, and J. Litt.

Analyzing these strategies, we can identify two types of procedures concerning the supervision of classical controllers:

1. Supervisor inputs are the output error and its variation, and the gain adaptation is to correct the regulation laws.
2. Supervisor inputs are the achieved performance by the closed-loop system during a transitory state, measuring the regulation quality during a certain time interval to decide a change in the control law in order to achieve better performance at the next interval.

These strategies are based on adjusting the parameters of classical controllers separately and simultaneously. In this work, we propose a new strategy for supervising classical controllers. Our strategy is based on the combination of the two above-mentioned methods. The first one proposed by R. Babuska makes improvements during the transitory state and the second one proposed by J.Litt provides improvement of steady state. To benefit of these two strategies, a fuzzy supervisor selects the most advantageous cases during the system functioning. This control strategy is applied for the speed control of the induction machine.

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II. INDUCTION MACHINE MODELLING

$$\frac{dX}{dt} = AX + BU \tag{1}$$

$$A=\begin{bmatrix} -(\frac{1}{T_s\sigma}+\frac{1}{T_r}.\frac{1-\sigma}{\sigma}) & 0 & \frac{1-\sigma}{\sigma}.\frac{1}{L_mT_r} & \frac{1-\sigma}{\sigma}.\frac{1}{L_m}w_r \\ 0 & -(\frac{1}{T_s\sigma}+\frac{1}{T_r}.\frac{1-\sigma}{\sigma}) & -\frac{1-\sigma}{\sigma}.\frac{1}{L_m}w_r & \frac{1-\sigma}{\sigma}.\frac{1}{L_mT_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & -w_r \\ 0 & \frac{L_m}{T_r} & w_r & -\frac{1}{T_r} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \ X = \begin{bmatrix} i_{ds} \\ i_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} \text{ and } U = \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$$

With:

$\sigma = 1 - \frac{L_m^{\ 2}}{L_s.L_r}$: Blondel coefficient

T_s, T_r: Time constants of stator and rotor respectively;
σ: coupling coefficient;
L_s, L_r: Cyclic inductances of stator and rotor respectively;
L_m: Mutual inductance.

III. CONTROL STRUCTURE

We consider that the controlled variable is the inverter current. To obtain the control laws, it is necessary to define the dynamical model machine if we suppose that the machine is supplied by current, and by the application of Park transformation in a field rotation frame, the phases currents, *Ids* and *Iqs* are known [1,7,8] the model (1) is reduced to two equations; the equation of field (2) and the equation of motion (3), thus:

$$X = \begin{bmatrix}\varphi_{dr} & \varphi_{qr}\end{bmatrix}^T \tag{2}$$

$$\frac{dX}{dt} = \begin{bmatrix} \frac{-1}{T_r} & w_{sl} \\ -w_{sl} & \frac{-1}{T_r} \end{bmatrix} X - \frac{L_m}{T_r}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}$$

$$w_{sl} = w_s - w_r \tag{3}$$

$$Te = \frac{3}{2}\frac{pL_m}{L_r}\left(\varphi_{dr}.i_{qs} - \varphi_{qr}.i_{ds}\right)$$

$$j.\frac{dw_r}{dt} = p.(Te - \frac{ff}{p}.w_r - Tch)$$

In order to obtain the decoupling between the two control variables, we have to apply the principle of flux orientation φqr=0, the equations of the machine (2) and (3) can be written as follows:

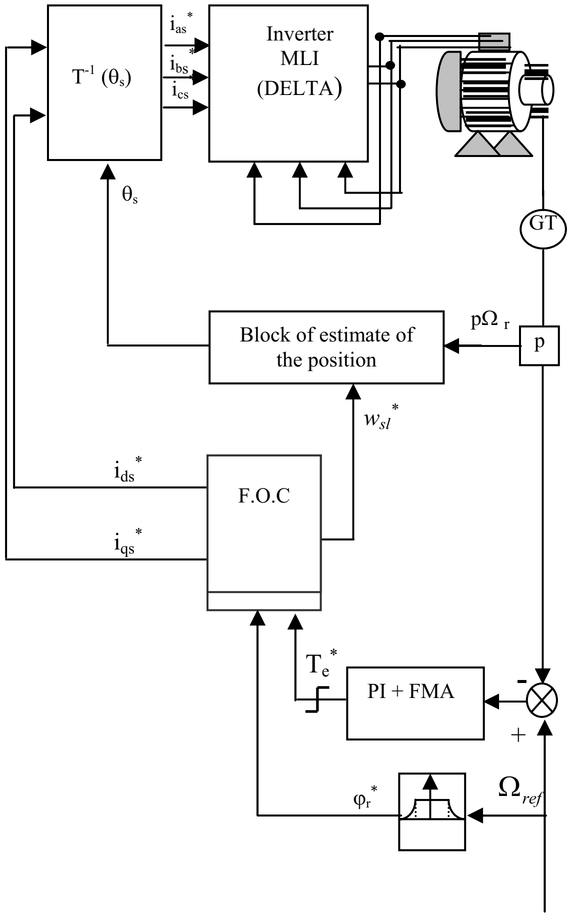

Figure 1. Speed regulation by the field orientation.

$$T_r\frac{d\varphi_r}{dt} + \varphi_r = L_m.i_{ds} \tag{4}$$

$$w_{sl} = \frac{L_m}{T_r}.\frac{i_{qs}}{\varphi_r} = w_s - p.\Omega_r$$

$$T_e = \frac{3}{2}p\frac{L_m}{L_r}\varphi_r i_{qs}$$

$$j\frac{d\Omega_r}{dt} + ff\Omega_r = T_e - T_c \tag{5}$$

Where $T_r = \frac{L_r}{r_r}$: rotor time constant.

If we consider the torque T_e^* and the flux φ_r^* as references of control, and we inverse the equation system (4) and (5), we obtain the following control equations [9]:

$$i_{qs}^{\ *} = \left(\frac{2}{3}\frac{L_r}{p.L_m}\right).\left(\frac{Te^*}{\varphi_{r^*}}\right)$$

$$i_{ds}^{\ *} = \left(\frac{1+s.T_r}{L_m}\right)\varphi_r^{\ *}$$

$$\omega_{sl}^{\ *} = \left(\frac{L_m}{T_r}\right).\left(\frac{i_{qs}^{\ *}}{\varphi_r^{\ *}}\right) \tag{6}$$

where T_e^* , φ_r^*, $i_{qs}{}^*$, $i_{ds}{}^*$, $\omega_{sl}{}^*$ the reference size

From these equations, we obtain the general structure of the F.O.C block (Field Orientation Control). Figure 1 shows the simplified diagram block of indirect space control with oriented rotor field based on the equations (1). i_{ds} and i_{qs} present the control of the rotor field and the torque. The image of the torque is generated by the speed controller; a controller with an integral-proportional action combined with supervisor (PI+FAM) [8, 10]. In Fig. 1, the estimation's block of the position is used to control the orientation of the field, and the block T^{-1} (θ_s) presents the Parck reverse transformation.

IV. SUPERVISOR STRATEGY

The combination of the two strategies R. Babuska and J. litt are based on the error and its variation, the system performances respectively. In order to use the two strategies advantages, we use the first in transient state and the second in steady state. R. Babuska and al propose two bases of fuzzy rules to generate the weights to be applied to each regulator gains P,I [11]. The used heuristic laws are:

Increase K_p if the system response is far from the reference to increase the convergence speed and decrease Ki if the system response is near from the reference to anticipate the overshoot.

This strategy of improving the control law in transitory state helps us to obtain better responses than using only the PI or fuzzy regulator alone [11].

Performance such as response time, overshoot, oscillation period and steady state are the elements of the strategy proposed by J. litt. His method suggests the following heuristic:

K_i decrease so overshoot decrease also, K_p decrease overshoot decrease [1].

So, it is very interesting to combine the two strategies in order to have a very fast response with acceptable performance.

V. COMBINATION OF STRATEGIES

The adjustment of regulator parameters is performed according to the error of the system output and its variation; parameters of the regulator are set initially online.

During the transient state and online operation, one fuzzy matrix is used to adjust the two parameters according to expression 9. At the end of transient state, two other fuzzy matrices are used to adjust the parameters of the controllers according to expression 10 and to optimize the characteristics of the response time. Figure 2 shows the decomposition of the phase plan as discussed below:

1. Far from the reference, transient state (zone1)
2. Around the reference, convergence phase (zone2)
3. Around the reference, divergence phase (zone3)
4. Divergence and instability (zone4),

Now, it is possible to make rules according to the following suggestions:

- For zone 1: decrease response time of regulator;

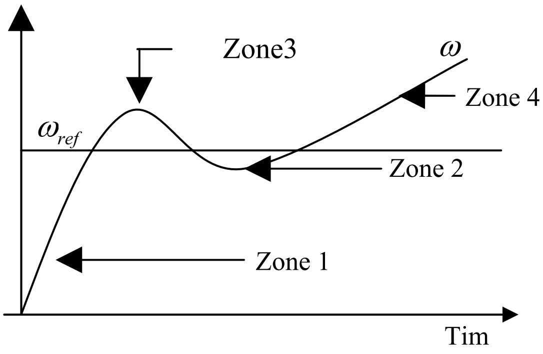

Figure 2. Time domain illustration of phase zones.

- For zone 2: minimize the overshoot;
- For zone 3: minimize steady state error to eliminate oscillation;
- For zone 4: stabilize the response and ensure an adequate tracking.

VI. GENERAL STRUCTURE OF THE COMBINATION

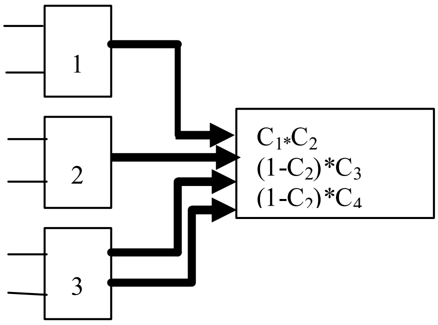

Figure 3. Structure of the combination.

The figure 3 represents the general structure combination combined by three fuzzy mechanisms each one is formed by:

A. Fuzzfication

To obtain C1, C2, C3 and C4, we must normalize the three block inputs. The inputs (e and Δe) are normalized in the interval [-1 1] which used also for the blocks outputs C1, C3 and C4. Interval [0 1] is used in normalization of output of the block that calculates the weighting factor (C2). Relationship that links normalized data with the normal one, is given by:

TABLE 1 RULES USED TO DETERMINE C3 AND C4

Δe e	NB	NM	NS	EZ	PS	PM	PB
NB	B	B	B	B	B	B	B
	B	B	B	B	B	B	B
NM	B	S	S	S	S	S	B
	S	B	B	B	B	B	S
NS	B	B	S	S	S	B	B
	S	S	B	B	B	S	S
EZ	B	B	B	S	B	B	B
	S	S	S	B	S	S	S
PS	B	B	S	S	S	B	B
	S	S	B	B	B	S	S
PM	B	S	S	S	S	S	B
	S	B	B	B	B	B	S
PB	B	S	B	B	B	B	B
	S	B	B	B	B	B	B

$$e_{normalisé} = \frac{e}{e_{\max}}$$

$$\Delta e_{normalisé} = \frac{\Delta e}{e_{\max}} \qquad (7)$$

Then the normalized values are converted into fuzzy values. After that, for each obtained fuzzy singletons, an intersection is made with the fuzzy set in the universe of discourses of e and Δe to determine the degree of membership of each input.

To achieve this step, it is necessary to define the number, shape and distribution of fuzzy set on the universe of discourse.

The choices of the membership functions and their justifications are outlined below.

Based on experimental evaluation, seven fuzzy sets have been fixed: NB (negative big), NM (negative medium), NS (negative small), ZE (approximately zero) PS (small positive), and PM positive medium), PB (positive large).

The shape of these membership functions are chosen to be triangular to simplify the processing. Figure 4 illustrate these functions [12].

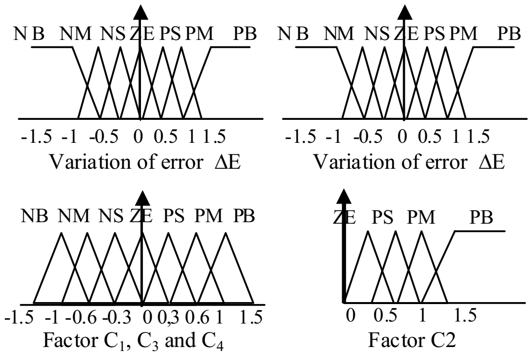

Figure 4. Membership function.

TABLE 2 RULES USED TO DETERMINE C3 AND C4

Δe e	NB	NM	NS	EZ	PS	PM	PB
NB	B	B	B	B	B	B	B
	B	B	B	B	B	B	B
NM	B	S	S	S	S	S	B
	S	B	B	B	B	B	S
NS	B	B	S	S	S	B	B
	S	S	B	B	B	S	S
EZ	B	B	B	S	B	B	B
	S	S	S	B	S	S	S
PS	B	B	S	S	S	B	B
	S	S	B	B	B	S	S
PM	B	S	S	S	S	S	B
	S	B	B	B	B	B	S
PB	B	S	B	B	B	B	B
	S	B	B	B	B	B	B

Once the membership degree is determined, an inference is carried out in line, in order to obtain accurate results. Knowledge reflecting the actions of each block is grouped into tables of type Macvilar-Whelan, reproduced on the following tables 1 and 2.

B. *Defuzification*

The output of inference engine transmit the values of variables in each block C1f, C2F, C3F and C4F form as a fuzzy quantity weighted by weights is representing the weight of each rule fired. The de-fuzzifucation mechanism extracts a numeric value appropriate C1, C2, C3 and C4. The used method is the center of gravity given by:

$$c_j = \frac{\sum_i^j (c_{ij}\mu(c_{ij}))}{\sum_i^j \mu(c_{ij})} \qquad (8)$$

I: index of fuzzy sets inferred

J: index of factor j=1, 2, 3

C_{ij}: centre of the fuzzy set inferred

C_J value obtained after the fuzzification stage is normalized to C1, C4 and C3 in the range [-1 1] and for C2 in the interval [0 1].

The last step of calculating the supervisor action is to determine the independent actions done on each gain of the PI regulator given by [12]:

For C_2= 1 in transient state:

$$k_{p'} = k_{p\,\text{int}} + k_1 C_1 C_2$$

$$k_{i'} = k_{i\,\text{int}} - k_2 C_1 C_2 \qquad (9)$$

$k_{p\ \text{int}}$ and $k_{i\ \text{int}}$ are respectively the proportional and integral gains given by Ziegler et Nichols method

k_1, k_2 factors tuned in such way that the simulated model give an optimal response [13, 14].

In steady state with C_2= 0 we have:

$$k_{p'} = (k_{p\max} - k_{p\min})C_3 + k_{\min}$$

$$k_{i'} = (k_{i\max} - k_{i\min})C_4 + k_{i\min} \qquad (10)$$

VII. SIMULATION AND INTERPRETATION

In this part we discuss results obtained in simulation. The used control scheme is given by Fig. 1, excepting that the PI regulator is replaced by the proposed combination.

To validate the proposed method, one meets many problems to obtain parameters of the different blocks of the combination (PI supervised by strategy of R. Babuska, PI supervised by combination proposed, PI supervised by strategy of J. Litt) by trial and error procedure which takes a lot of time. The two parameters of the equation 9 have been adjusted to obtain an optimal response. Consequently, the following formulas have been deduced from simulation.

$$k_1 = \frac{k_{p\,\text{int}\,i}}{12}$$

$$k_2 = \frac{k_{i\,\text{int}\,il}}{2} \qquad (11)$$

In our case a comparative study of the discussed controllers is made both in transient and steady states.

We have analyzed the effect of load variation and of rotation sense inversion under the choice of the reference flux which is equal to 1 Wb, an application of the resistant couple of 10N at t = 1.5s and of rotation sense variation of 100rd/s to -100rd/s.

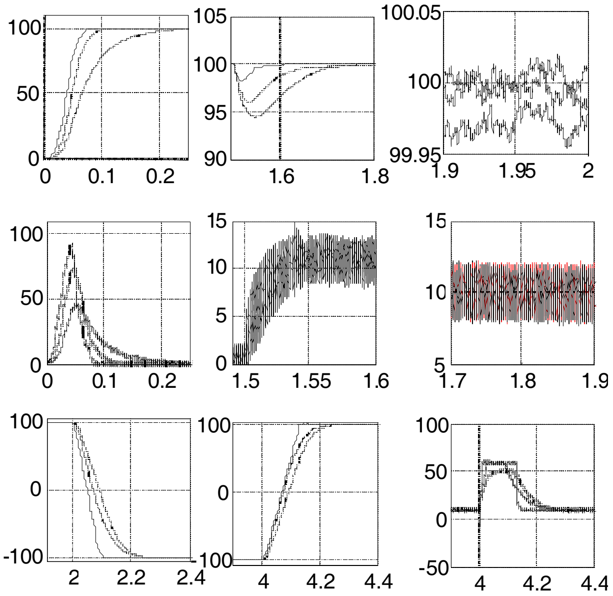

Figure 5. A comparison between the different regulators.

Figure 5 shows that the system response stabilizes to the reference value with fast time response with the case of the proposed combination. In the case of perturbation, we note that the necessary time to eliminate the perturbation effect is smaller with this proposed combination. In the case of rotation sense inversion from -100 rad/s to 100 rad/s, we also note that the static error decreases when using the proposed combination (see table 3).

TABLE 3. A COMPARISON BETWEEN THE DIFFERENT CONTROLLERS PI

	Sup R	Super J	Comb
Δω	4	2	1,6
Δt(s)	0.1	0.05	0,04
tm	0.9	0.07	0.06
e	5 .059	1.236	1.25

Figures 6, 7 and 8 show the variation of the weighting factors and the detection of the functioning zone (transient, permanent); the figure 8 shows also the good choice of factors and the fact that the operating area is well detected, and the Figures 9,10 and shows the perfect coupling.

The figure 5 show a comparison between the different controllers PI, supervised by strategy of R. Babuska, supervised by combination proposed , and supervised by strategy of J. litt); one notes the superiority of the combination in the different areas (transient and permanent).

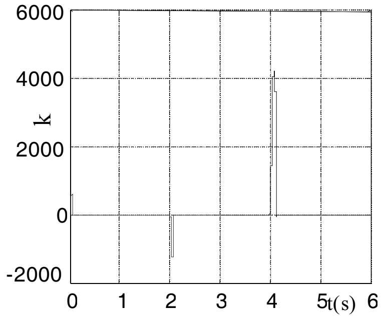

Figure 6. Adaptation of the K_i.

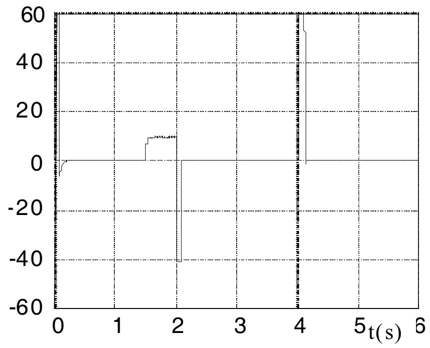

Figure 7. Adaptation of the K_p.

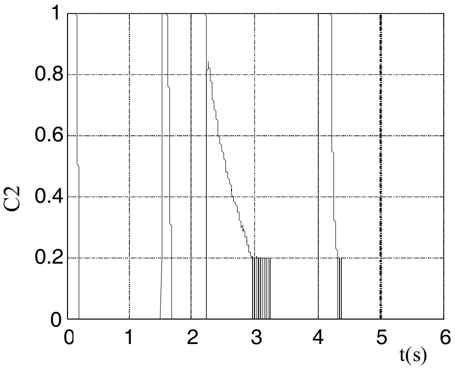

Figure 8. Détection of zones (C_2).

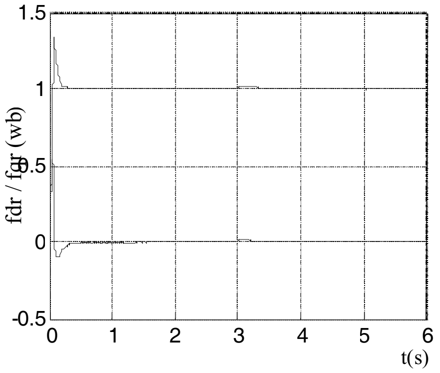

Figure 9. Flux variation.

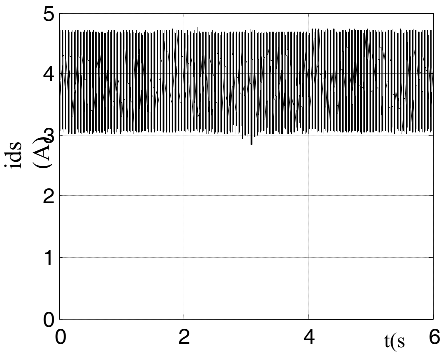

Figure.10. Inverse current.

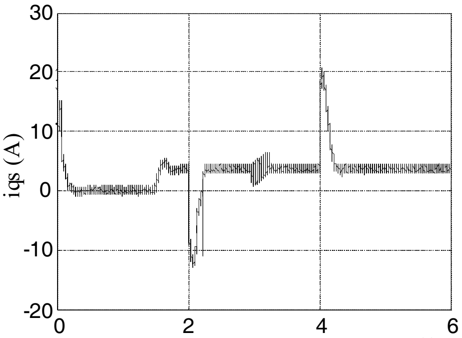

Figure 11. Direct current.

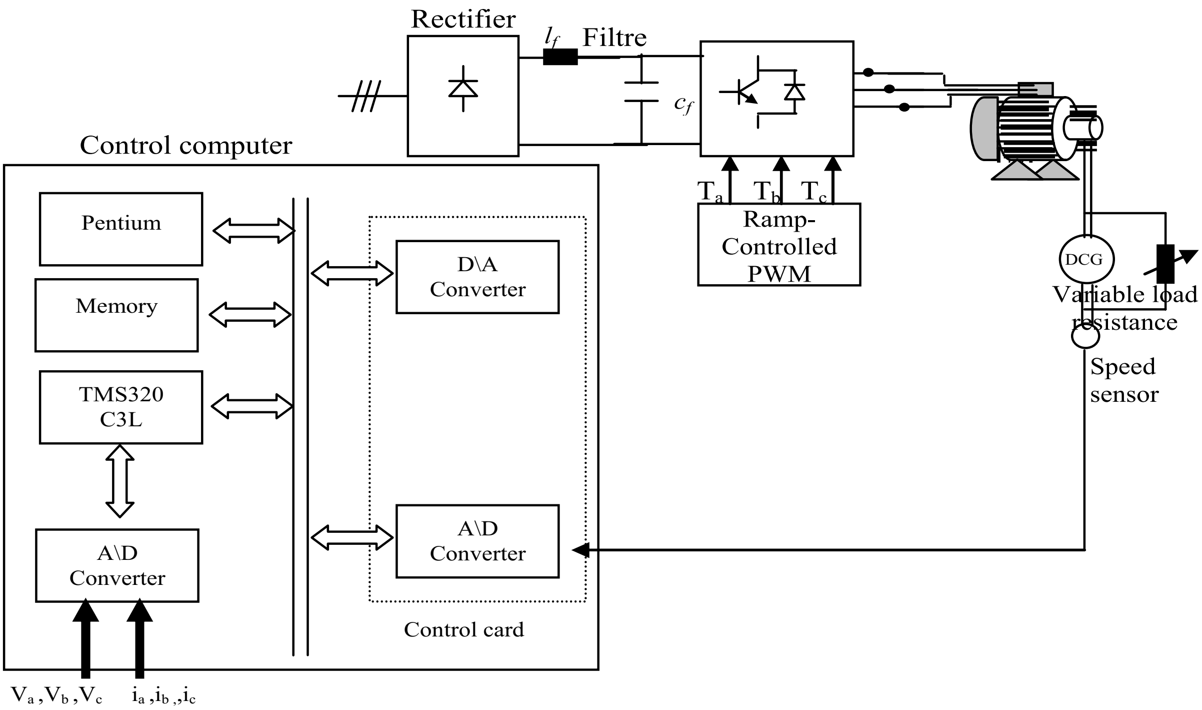

Figure 12. Block diagram of the co-processor control system for the IFOC IM.

VIII. EXPERIMENTAL RESULTS

Experimental results are provided to further demonstration to ensure the effectiveness of the proposed control system. The block diagram of the co-processor control computer for the induction motor is shown in Figure 12 the adaptive FLC-speed controller, indirect field oriented control, and the current regulation are all executed in Pentium III microcomputer via Matlab/Simulink software with Real-Time workshop to deliver the PWM signals to the drive circuit. Motor current feedback signals are obtained using Hall-effect current sensors, and the speed is measured with a tachometer. To reduce the calculation burden of the CPU and to increase the accuracy of the tree-phase current command, an AD2S100 AC vector processor implements the coordinate transformations in the field oriented mechanism. Sampling time is 2×10^{-3} sec, since the actual computation time of the algorithm is about $3\text{x}10^{-3}$ sec. The parameters of the tested induction machine are given in the Appendix A.

The machine is stepped up to 100 rad\sec under no load. And then at 90 sec load torque disturbance approximately equal 10 N.m is applied , followed by inversion (0 rad\sec) of retation sense at 2 sec figure 13 from the experimental results by the combination proposed rejects the load disturbance rapidly with a negligible steady state error.

Figure 9c shows the resulting parameter of the PI controller with fuzzy gain tuning during the control operation.

Furthermore, compared with the experimental results of the PI with fixed parameter control system shown in Figure 9a, the responses are much improved when using the proposed adaptive controller.

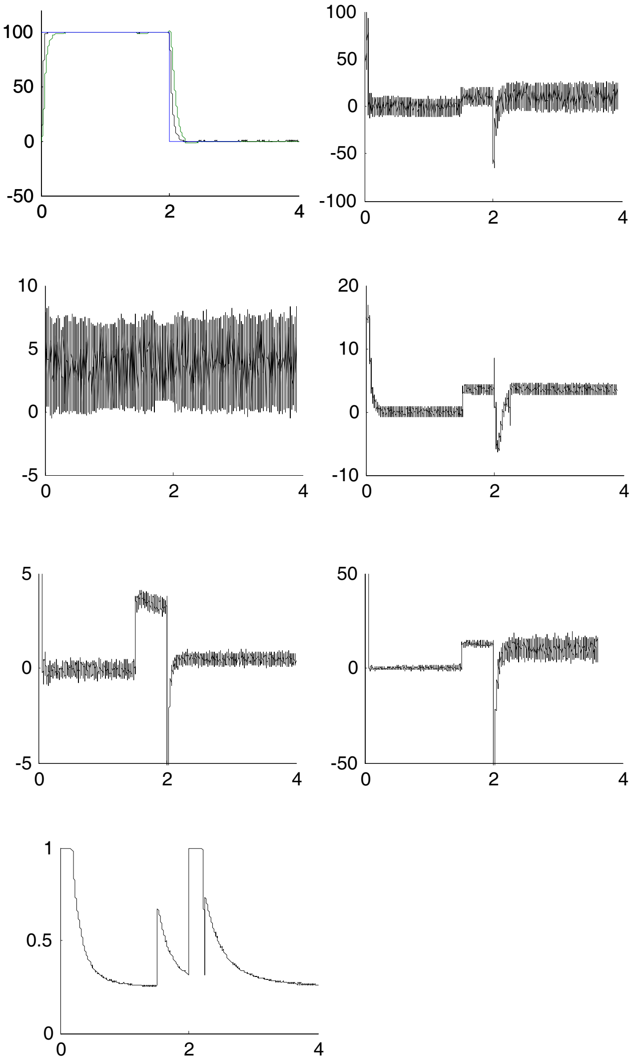

Figure 13. Experimental response of the system to a steed reference from 100 rad\sec to 0.

IX. CONCLUSION

In this study, we showed that the supervisor improves the system response in terms of oscillating behaviour terms, amplitudes of the first overshoot which are minimized globally and the frequency of the oscillations which are reduced.

The fuzzy supervisor improves the results of the PI regulator initialized with Ziegler-Nichols tuning method.

Simulations show that, due to the fuzzy supervisor, the PI regulator performances are improved both in tracking the reference and in stabilizing the system in question.

APPENDIX A

θ_r Position of the rotor rd ; Ω_r Rotor speed rd/s ; φ flux Wb ; ΔE Variation of error ; E Error

I, i_{ds}, i_{qs} Current, direct and inverse current A ; J Moment of inertia Kg.m ; K_i , K_p Adjustment factors of the profits

M A number of fuzzy rules; P A number of pairs of poles; R_r Rotor resistance Ω ; R_s Stator resistance Ω

T_e Electromagnetic couple of exit and reference N.m; T_{fr} Rotor time-constant of escape s; T_r, Rotor time constant s

T_s Stator time constant s; V Tension V; w_s, w_e Stator pulsation rd/s; w_r Rotor pulsation rd/s ; w_{sl} Frequency of slip rd/s

φ, $\varphi_{dr}\varphi_{qr}$ Field, direct rotor field, inverse rotor field web ; θ_r Position of the rotor rd ; Ω_r Rotor speed rd/s; φ flux Wb

ΔE Variation of error; E Error ; I, i_{ds}, i_{qs} Current ,direct and inverse current A ; J Moment of inertia Kg.m

K_i , K_p Adjustment factors of the profits ; M A number of fuzzy rules ; P A number of pairs of poles ;R_r Rotor resistance Ω

R_s Stator resistance Ω ;T_e Electromagnetic couple of exit and reference N.m ;T_{fr} Rotor time-constant of escape s
T_r, Rotor time constant s ;T_s Stator time constant s :V Tension V ; w_s ,w_e Stator pulsation rd/s ; w_r Rotor pulsation rd/s
w_{sl} Frequency of slip rd/s ; φ, $\varphi_{dr}\varphi_{qr}$ Field, direct rotor field , inverse rotor field web

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