Speed Control of Induction Motor Drives Using Self-Tuning Fuzzy Logic Controller

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Abstract - **In this paper a self-tuning fuzzy logic speed controller is proposed for the high performance drives of induction motor. Here, the output gain of the controller is adjusted on-line by fuzzy rules according to the current trend of the controlled process. Tuning of the output gain has been given the highest priority because of its strong influence on the performance and stability of the system. The ability of the proposed controller is verified in the presence of external load variations using MATLAB simulation with the comparison of conventional PI controller. Simulation results showed the effectiveness and robustness of the proposed approach.**

I. INTRODUCTION

This scheme is based on the fact that irrespective of the nature of the process to be controlled and the control policy to be adopted, a skilled human operator always tries to manipulate the process input, usually by adjusting the controller gain based on the controller process states (generally e and Δe) to get the process optimally controlled [1-2]. The exact manipulation strategy of an operator is quite complex in nature and possibly no mathematical model can replace it accurately [3]-[5].

Standards regulators with fixed parameters may be insufficient in controlling systems, such as the robotic arms, that are subject to large variations of inertia and load during their normal operating cycles. However, more sophisticated controllers are required, such as adaptive regulators, self-tuning regulators, which in presence of variations of plant parameters, are able to modify their features in order to maintain the desired dynamic behavior of the system [6]. Different type of adaptive FLC's (Fuzzy Logic Controller) have been developed and proposed in the last years. In [7] a simple algorithm for modifying triangular input membership functions has been used. Another approach to adaptation described in [8], [9] has involved modification of the whole fuzzy rule base.

In this paper we propose a simple but robust model independent self-tuning scheme, where the controller gain is adjusted continuously with the help of fuzzy rules. Here, our objective is to adapt only the output SF (Scaling Factor) for given input SF's. Tuning of the output SF has been given the highest priority because of its strong influence on the performance and stability of the system [10]. The proposed scheme is applied to the speed control of an IFOC. The simulation results show its effectiveness in case of parameter variation of the system.

II. DYNAMIC MODEL OF THE INDUCTION MACHINE

The model of the squirrel-cage induction machine can be expressed in terms of d- and q-axes quantities resulting in the following equations:

$$\dot{X} = AX + BU \tag{1}$$

where definitions are given in "(2)-(5)," . The electromagnetic torque and the mechanical equations can be written as follows:

$$T_e = \frac{3}{2} pL_m (i_{dr} i_{qs} - i_{qr} i_{ds}) \tag{2}$$

$$J \frac{d\Omega_r}{dt} + f\Omega_r = T_e - T_L \tag{3}$$

where J is the moment of inertia, f the viscous friction coefficient and T_L the load torque. A simulation model of the induction machine has been built using top and bottom equations.

$$A = \begin{bmatrix} -\frac{1}{\sigma T_s} & \omega_e + \frac{1-\sigma}{\sigma}\omega_r & \frac{L_m}{\sigma L_s T_r} & \frac{L_m}{\sigma L_s}\omega_r \\ -\omega_e - \frac{1-\sigma}{\sigma}\omega_r & -\frac{1}{\sigma T_s} & -\frac{L_m}{\sigma L_s}\omega_r & \frac{L_m}{\sigma L_s T_r} \\ \frac{L_m}{\sigma L_r T_s} & -\frac{L_m}{\sigma L_r}\omega_r & -\frac{1}{\sigma T_r} & \omega_e - \frac{1}{\sigma}\omega_r \\ \frac{L_m}{\sigma L_r}\omega_r & \frac{L_m}{\sigma L_r T_s} & -\omega_e + \frac{1}{\sigma}\omega_r & -\frac{1}{\sigma T_r} \end{bmatrix} \tag{4}$$

$$B = \frac{1}{\sigma L_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -\frac{L_m}{L_r} & 0 \\ 0 & -\frac{L_m}{L_r} \end{bmatrix} \quad X = \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}$$

$$U = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \tag{5}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, T_r = \frac{L_r}{R_r}, T_s = \frac{L_s}{R_s} \tag{6}$$

The system, which is presented in "Fig. 1", is an indirect field oriented control (IFOC)-based induction motor drive. It consists mainly of a squirrel- cage induction motor, a voltage-regulated pulse width modulated inverter, fuzzy speed controller and fuzzy rotor resistance estimator. The induction motor is a three phase, Y connected, four pole, 1.5 Kw, 1420tr/mn 220/380V, 50Hz and 6.4/3.7A.

Under field orientation condition, the d-q equations of the motor in the synchronous reference frame are:

$$R_r i_{qr} + \omega_{sl}\psi_{dr} = 0 \tag{7}$$

$$R_r i_{dr} + \frac{d}{dt}\psi_{dr} = 0 \tag{8}$$

$$L_m i_{qs} + L_r i_{qr} = 0 \tag{9}$$

$$L_m i_{ds} + L_r i_{dr} = \psi_{dr} \tag{10}$$

where R_s, R_r L_r,L_s, L_m are motor parameters, i_{dr}, i_{qr}, i_{ds}, $i_{qs,}$ $\psi_{dr,}$ ψ_{ds} are motor currents and fluxes, and ω_{sl} is slip frequency. The equations describing the motor operation in decoupling mode are deduced from" (2)," and "(7)-(10),":

$$\omega_{sl} = \frac{L_m}{\psi_r}\left(\frac{R_r}{L_r}\right) i_{qs} \tag{11}$$

$$T_e = \frac{3}{2} p \frac{L_m}{L_r}\psi_r i_{qs} \tag{12}$$

$$\left(\frac{L_r}{R_r}\right)\frac{d\psi_r}{dt} + \psi_r = L_m i_{ds} \tag{13}$$

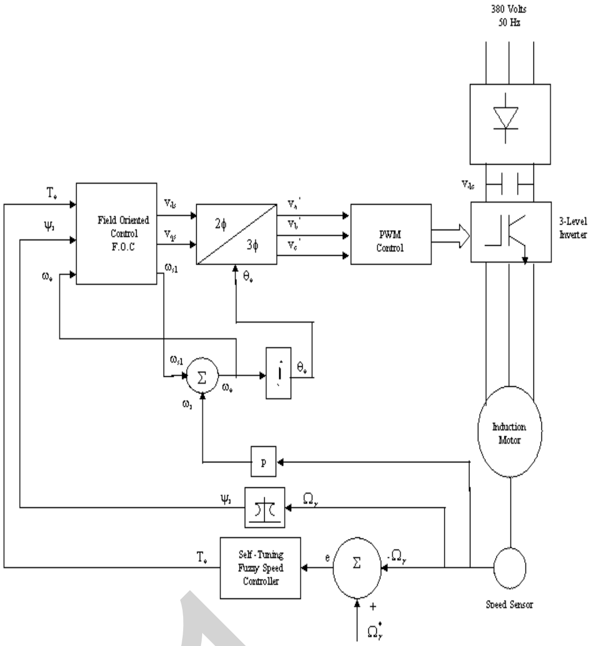


Fig .1. Block diagram of the complete system.

III. THE PROPOSED SELF-TUNING FUZZY CONTROLLER

In literature fuzzy logic algorithms with adaptive characteristics can be found under various names: self-tuning, self-organizing, self-learning, adaptive and expert algorithms or fuzzy logic algorithms with a varying rule base. Our proposed FLC is tuned by modifying the output SF of an existing FLC so we describe it as a self-tuning FLC.

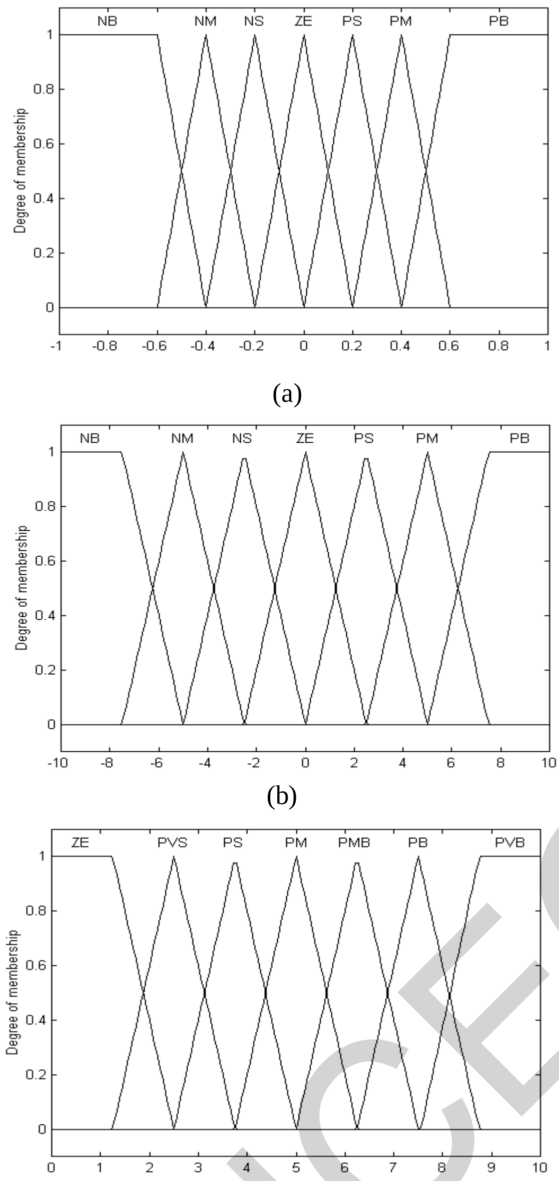
The block diagram of the proposed self-tuning FLC is shown in "Fig. 3". The output SF (gain) of the controller is modified by a self-tuning mechanism, which is shown by the dotted boundary.

In order to design a self-tuning fuzzy logic controller, the following steps must be performed:

1) development of a suitable rule set;
2) selection of input/output variables and their quantization in fuzzy sets;
3) definition of membership functions to be associated to the input/output variables;
4) Selection of the inference method ;
5) Selection of the defuzzification technique.

1. Membership Functions

All membership functions (MF's) for: 1) controller inputs, i.e., error (e) and change of error (Δe) and 2) incremental change in controller output (ΔT^*), are defined on the common interval [-1,1]; [-10,10] respectively, whereas the MF's for the gain updating factor (α) is defined on [0,10]. We use symmetric triangles (except the two MF's at the extreme ends which are trapezoidal) as shown in "Fig. 2". These input membership functions are used to transfer crisp inputs into fuzzy sets.



(a)

(b)

(c)

Fig.2. Membership functions of (a) e and Δe; (b) ΔT^*; (c) gain updating factor (α).

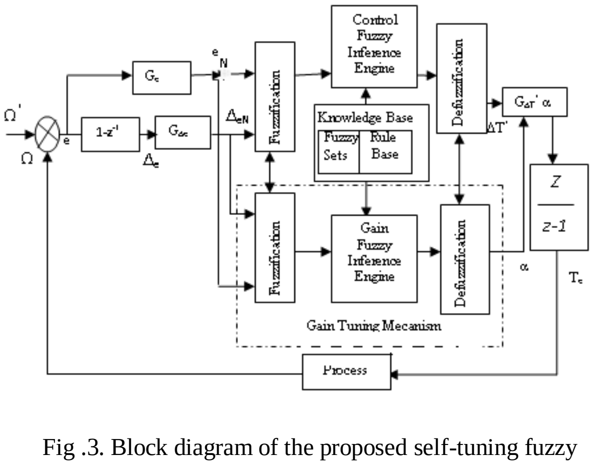


Fig .3. Block diagram of the proposed self-tuning fuzzy speed controller

2. Scaling Factors

The values of the actual inputs e and Δe are mapped onto [-1,1] by the input SF's G_e and $G_{\Delta e}$, respectively. On the other hand, the actual output of the self-tuning FLC is obtained by using the effective SF ($\alpha.G_{\Delta T}^*$) as shown in "Fig. 3". Selection of suitable values for G_e , $G_{\Delta e}$ and $G_{\Delta T}^*$ are made based on the knowledge about the process to be controlled and sometimes through trial and error to achieve the best possible control performance.

We propose to compute α on-line using a model independent fuzzy rule base defined in terms of e and Δ_e. The relationships between the SF's and the input and output variables of the self-tuning FLC are as follows:

$$e_N = G_e.e \tag{14}$$

$$\Delta e_N = G_{\Delta e}.\Delta e \tag{15}$$

$$T^* = \Delta T^*.\ \alpha.G_{\Delta T}^* \tag{16}$$

The value of $G_{\Delta T}^*$ is constant for a particular type of conventional FLC. But the gain of our self-tuning FLC does not remain fixed while the controller is in operation, rather it is modified in each sampling time by the gain updating factor α, depending on the trend of the controlled process output. The reason behind this on-line gain variation is to make the controller respond according to the desired performance specifications.

3. The Rule Bases

The expert experience has been incorporated into a knowledge base with 49 rules (7x7). Then, the inference engine based on the input fuzzy sets, uses appropriate IF-THEN rules in the knowledge base to imply the final output fuzzy sets as shown in the "Fig. 4". where NB, NM, NS, ZE, PVS, PS, PM, PB, PMB, PVB, correspond to Negative Big, Negative Medium, Negative Small, Zero, Positive Very Small, Positive Small, Positive Medium, Positive Big , Positive Medium Big, Positive Very Big, respectively.
Some of the important considerations that have been taken into account for determining the rules are as follow:

1) To make the controller produce a lower overshoot and reduce the settling time (but not at the cost of increased rise time) the controller gain is set at a small value when the error is medium big (it may be + ve or - ve), but e and Δe are of opposite signs. For example, if e is PM and Δe is NS THEN α is PS or if e is NM and Δe is PS THEN α is PS. Now if the error is big but both e and Δe are of the same sign (i.e., the process is now not only far away from the set point but also it is

moving farther away from it), the gain should be made very large to prevent from further worsening the situation. This has been realized by the rules of the form: if e is PB and Δe is PS THEN α is PVB or if e is NB and Δe is NS THEN α is PVB.

2) Depending on the process trend, there should be a wide variation of the gain around the set point (i.e., when e is small) to avoid large overshoot and undershoot. For example, overshoot will be reduced by the rule IF e is ZE and Δe is NM THEN α is PM. This rule indicates that the process has just reached the set point but it is moving away upward from the set point rapidly. Similarly, a large undershoot can be avoided using the rules of the form: IF e is NS and Δe is PS THEN α is ZE. This type of gain variation around the set point will also prevent excessive oscillation and as a result the convergence rate of the process to the set point will be increased.
3) To improve the control performance under load disturbance, the gain should be sufficiently large around the steady-state condition. IF e is PM and Δe is PS THEN α is PVB or IF e is NM and Δe is NS THEN α is PMB. At steady state(i.e.,e≈0 and Δe ≈ 0) controller gain should be very small (e.g., IF e is ZE and Δe is ZE THEN α is ZE) to avoid chattering problem around the set point. It is very important to note that the rule base for for computation of α will always be dependent on the choice of the rule base for the controller. Any significant change in the controller rule base may call for changes in the rule base for α accordingly.

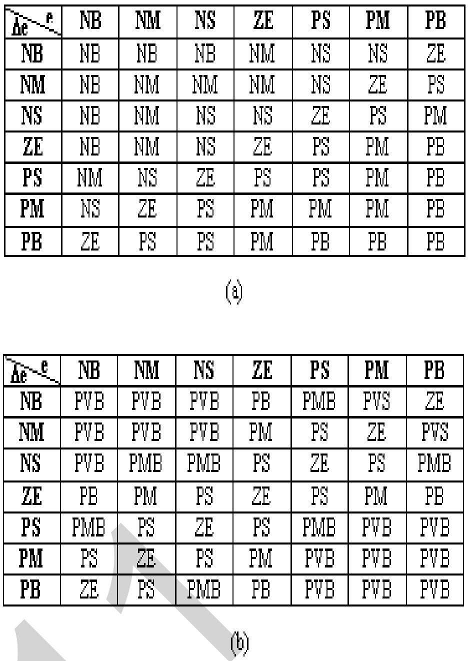
Once all the rules are established, the implied fuzzy set is transformed to a crisp output by the center of gravity defuzzification technique as given by the formula (12), z_i is the numerical output at the ith number of rules and $\mu(z_i)$ corresponds to the value of fuzzy membership function at the ith number of rules. The summation is from one to n, where n is the number of rules that apply for the given fuzzy inputs, [1]-[2].

$$z = \frac{\sum_{i=1}^{n} z_i.\mu(z_i)}{\sum_{i=1}^{n} \mu(z_i)} \qquad (17)$$

The crisp output ΔT^* is multiplied by the gain factor $\alpha.G_{\Delta T}{}^*$ and then integrated to give:

$$T_e(k) = T_e(k-1) + \Delta T^*.\ \alpha.G_{\Delta T}{}^* \qquad (18)$$

This torque component command is used as an input to the F.O.C. block of "Fig. 1".



Δe e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

(a)

Δe e	NB	NM	NS	ZE	PS	PM	PB
NB	PVB	PVB	PVB	PB	PMB	PVS	ZE
NM	PVB	PVB	PVB	PM	PS	ZE	PVS
NS	PVB	PMB	PMB	PS	ZE	PS	PMB
ZE	PB	PM	PS	ZE	PS	PM	PB
PS	PMB	PS	ZE	PS	PMB	PVB	PVB
PM	PS	ZE	PS	PM	PVB	PVB	PVB
PB	ZE	PS	PMB	PB	PVB	PVB	PVB

(b)

NB	:	Negative Big
NM	:	Negative Medium
NS	:	Negative Small
ZE	:	Zero
PVS	:	Positive Very Small
PS	:	Positive Small
PM	:	Positive Medium
PMB	:	Positive Medium Big
PB	:	Positive Big
PVB	:	Positive Very Big

Fig. 4. (a) Fuzzy rules for computation of ΔT^*.
(b) Fuzzy rules for computation of α

IV. RESULTS

In order to verify the validity of the proposed self-tuning fuzzy logic controller, several simulations are carried out using MATLAB and Simulink software. The configuration of the overall control system is shown in "Fig. 1".

Simulations are based on the facts that whether the proposed controller is better and more robust than the PI linear controller or not. For the comparison, simulations of the speed response were performed according to the speed command variation, the load variation, inertia variation, viscous friction variation, rotor resistance variation and speed tracking variation of the induction motor.

Table 1 shows the parameter of the used induction motor for simulation whose general specifications are

1.5 Kw, 1420 rev/mn, 380V, 50 Hz, 4 pole. The sampling time of the controller is 100 μs .

TABLE I.

Induction Motor Parameters Used For Simulation	
Stator resistance	4.85 Ω
Rotor resistance	3.805 Ω
Stator inductance	274mH
Rotor inductance	274mH
Magnetising inductance	258mH
Rotor inertia	0.031 Kg.m^2 0.00114
Viscous friction	Kg.m^2 /s
Rated torque	10 Nm

"Fig. 5,6"show speed response in case of load variation using conventional PI speed controller and proposed self-tuning fuzzy controller respectively. The command speed is 104.7 rad/sec which is increased linearly from zero and the 50% disturbance load of the rated torque ($T_{LN)}$ is applied at 6 sec. Th e proposed controller rejects the load disturbance rapidly with no overshoot with a maximum drop of speed of 0.66 rad/ sec, whereas, the PI controller presents an overshoot and the rejection of the load disturbance is 8.66 rad/sec.

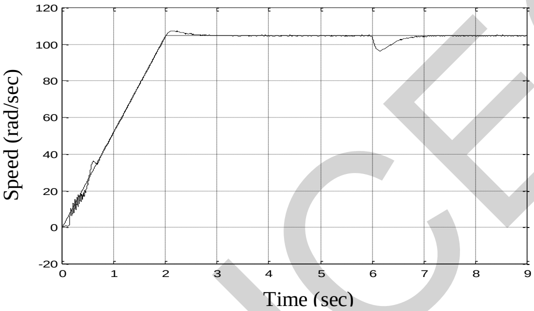


Fig. 5. Speed response using PI controller
(T_L= 0.5 T_{LN})

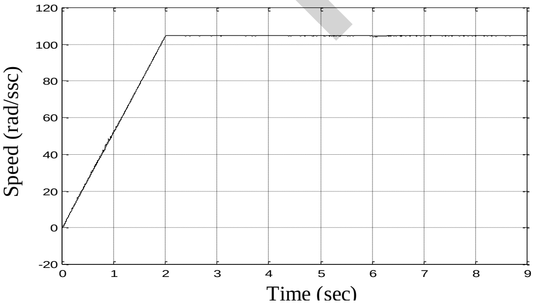


Fig . 6. Speed response using proposed controller
(T_L= 0.5 T_{LN})

"Fig.7,8"show speed response waveforms when applying full load. In all point view such as rejection of load disturbance and speed recovery time, proposed self-tuning fuzzy controller is better than conventional PI controller. "Fig.9,10"show speed response with inertia variation, where the load moment of inertia J_L is changed to four times of the nominal value J_{LN} and full load is applied at 6 sec. We can see that proposed fuzzy self-tuning controller is more robust to the inertia variation.

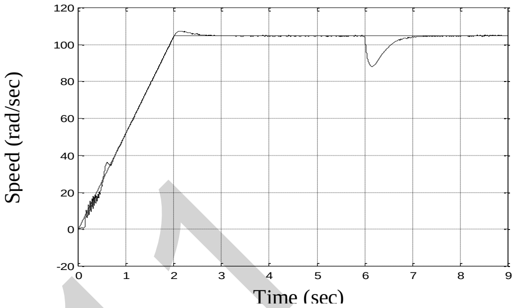


Fig . 7. Speed response using PI controller
(T_L = T_{LN})

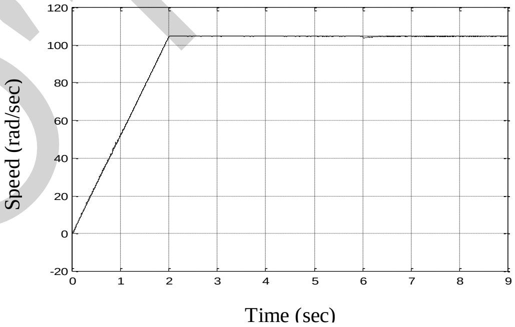


Fig . 8. Speed response using proposed controller
(T_L = T_{LN})

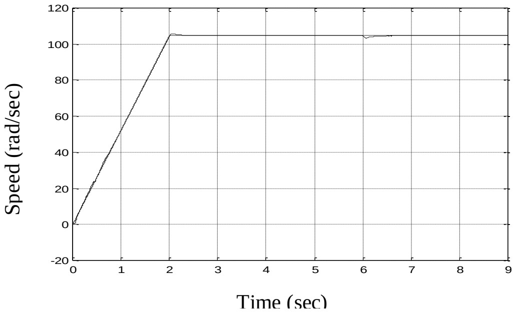


Fig . 9. Speed responce using proposed controller
(J_L = 4 J_{LN})

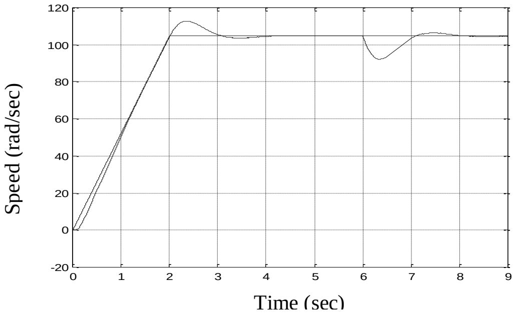


Fig . 10. Speed responce using PI controller
(J_L = 4 J_{LN})

"Fig.11,12"show speed response with viscous friction variation at nominal value and "Fig.13,14"show speed response with viscous variation, where the load viscous friction f_L is changed to ten times of its nominal value f_{LN} and full load is applied at 6 sec. Here again, the performance of proposed controller is much better than the PI controller. One can observe as well that varying the viscous friction from its nominal value to ten times by using the same controller has no effect on the speed response.

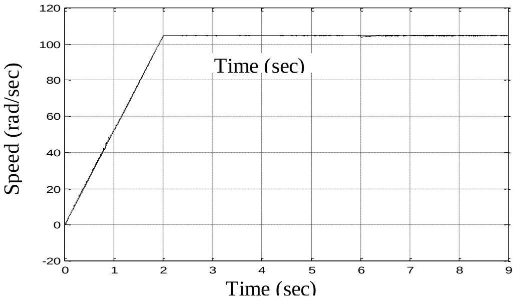


Fig . 11. Speed responce using proposed controller

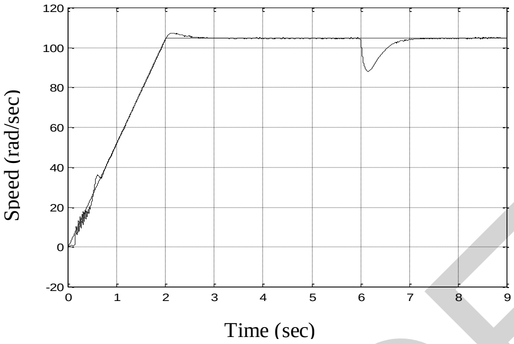


Fig . 12. Speed responce using PI controller
$(f_L= \ f_{LN})$

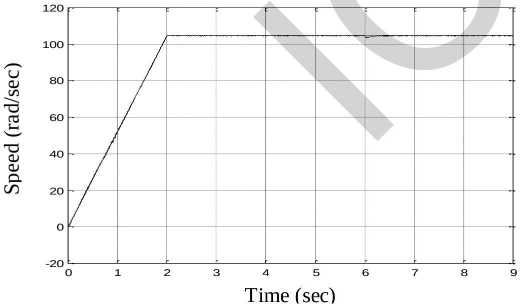


Fig . 13. Speed responce using proposed controller
$(f_L= \ 10 \ f_{LN})$

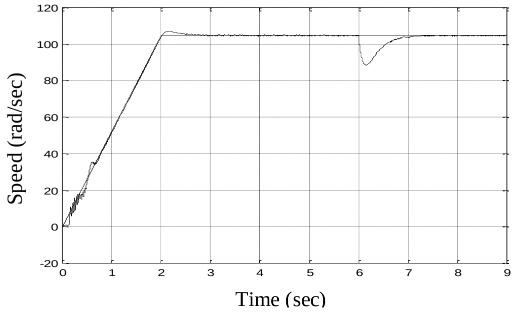


Fig . 14. Speed responce using PI controller
$(f_L= \ 10 \ f_{LN})$

"Fig.15,16"show speed tracking performance under no load. The proposed controller reacts perfectly and tracks the command speed with almost no steady state error. The PI controller is less performing especially at the starting and when changing speed from directs to reverse. A slight overshoot appears on the corners. "Fig.17, 18"show the effect of rotor resistance on the speed when its value has doubled at 6 sec and full load is applied from the beginning. However, the proposed controller is still performing perfectly with only a maximum drop of speed of 0.99 rad/sec whereas the PI controller has a drop of speed of 10 rad/s

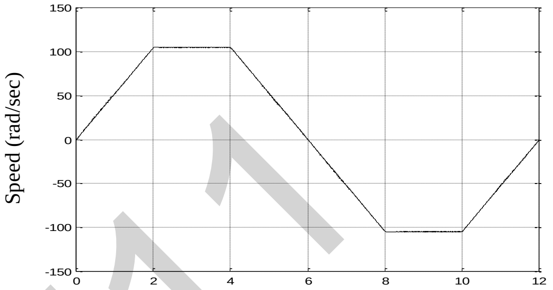


Fig . 15. Speed Tracking Performance using proposed controller

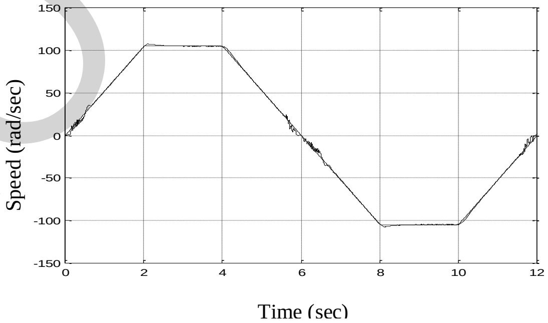


Fig . 16. Speed tracking performance using PI controller

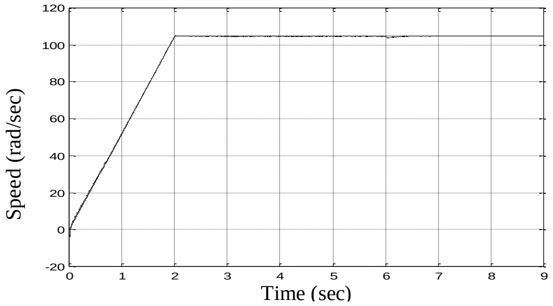


Fig.17 Effect of doubling rotor resistance on the speed using proposed controller .

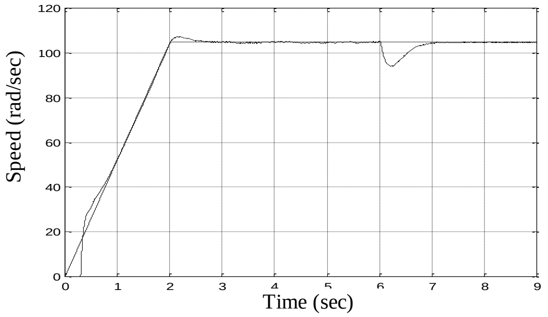


Fig.18. Effect of doubling rotor resistance on the speed using PI controller.

V. CONCLUSION

In this paper, an on-line self-tuning fuzzy logic controller for induction motor drives is presented. The structure of the proposed controller is based on the self-tuning controller that can tune its control output gain to be autonomous relating to system parameter variations.

According to simulation results using Matlab (Simulink software) and in all point of view such as variable speed characteristics, speed recovery time, inertia variation, speed tracking, viscous friction variation and effect on the speed by doubling rotor resistance, the proposed fuzzy logic controller is far better and more robust than the conventional PI controller. Actually, implementation is in progress.

To achieve more improved performances and a reduced amount of computations and complexity, a hybrid controller in which a fuzzy rule based system will modulate the output of a non fuzzy controller such as PID may be designed. The output modulation may be realized using a SF as done in the present case. This is currently under investigation.

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