MODELING AND SIMULATION OF A SELF-TUNING FUZZY LOGIC SPEED CONTROLLER OF AN INDIRECT FIELD-ORIENTED INDUCTION MACHINE DRIVE

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Abstract- **This paper presents a simple but robust model independent self-tuning scheme for fuzzy logic speed controllers. Here, the output scaling factor (SF) is adjusted on-line by fuzzy rules according to the current trend of the controlled process. Digital simulation results shows that the designed self-tuning fuzzy speed controller realises a good dynamic behaviour of the motor, with a rapid settling time, no overshoot, a good rejection of impact load disturbance, a perfect speed tracking and it deals well when parameter variations are doubled.**

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 behaviour of the system [6]. Different types of adaptive FLC's 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 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. THE INDUCTION MOTOR DRIVE

The electromagnetic torque and the mechanical equations can be written as follows:

$$T_e = \frac{3}{2} P L_m (i_{dr} i_{qs} - i_{qr} i_{ds}) \qquad (1)$$

$$j \frac{d\Omega_r}{dt} + f\Omega_r = T_e - T_L \qquad (2)$$

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 . Fig.1. shows the block diagram of the induction machine model.

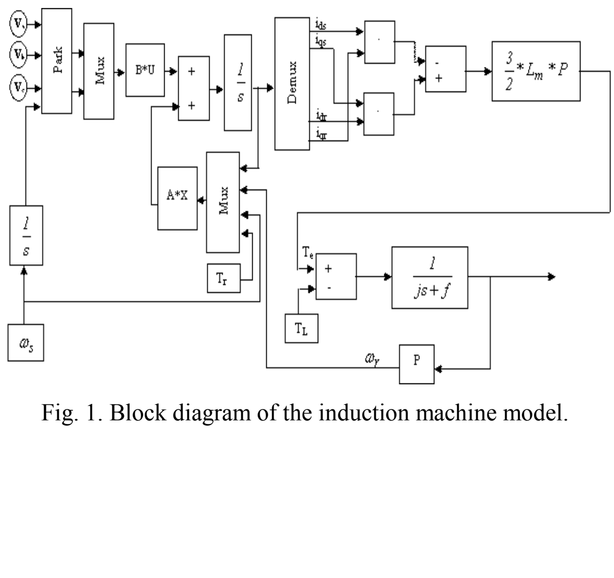


Fig. 1. Block diagram of the induction machine model.

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

$$R_r i_{qr} + \omega_{sl} \Psi_{dr} = 0 \tag{3}$$

$$R_r i_{dr} + \frac{d}{dt}\psi_{dr} = 0 \tag{4}$$

$$L_m i_{qs} + L_r i_{qr} = 0 \tag{5}$$

$$L_m i_{ds} + L_r i_{dr} = \psi_{dr} \tag{6}$$

where R_r, L_r, L_m are motor parameters, i_{dr}, i_{qr}, i_{ds}, i_{qs}, ψ_{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 (3) - (4) :

$$\omega_{sl} = \frac{L_m}{\psi_r}\left(\frac{R_r}{L_r}\right) i_{qs} \tag{7}$$

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} \psi_r i_{qs} \tag{8}$$

The torque component command T_e is generated from the speed error between the reference and the measured rotor speed through the self-tuning fuzzy logic speed controller Figure.1.

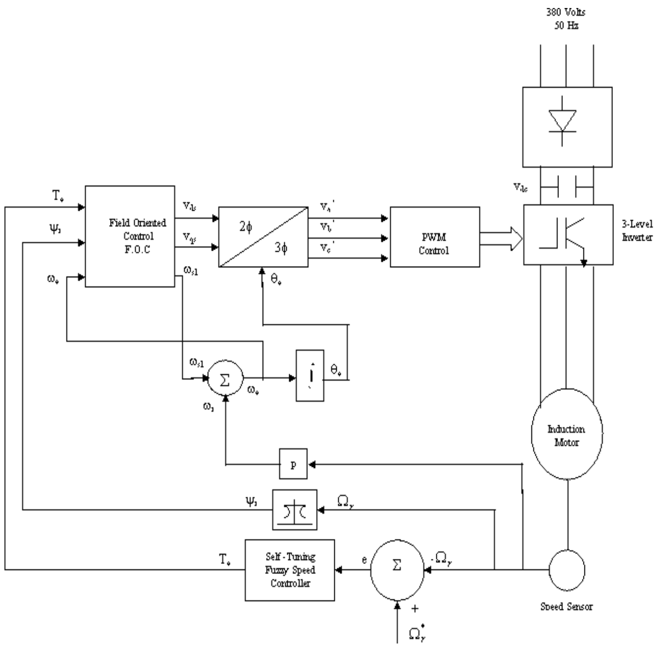


Fig .2. Block diagram of the complete system

III. THE PROPOSED SELF-TUNING FUZZY CONTROLLER

In literature fuzzy logic algorithms with adaptive characteristics can be found under various names: self-tuning, self-organising, 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 figure. 3. The output SF (gain) of the controller is modified by a self-tuning mecanism,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 Figure. 4. These input membership functions are used to transfer crisp inputs into fuzzy sets.

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 Figure.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.

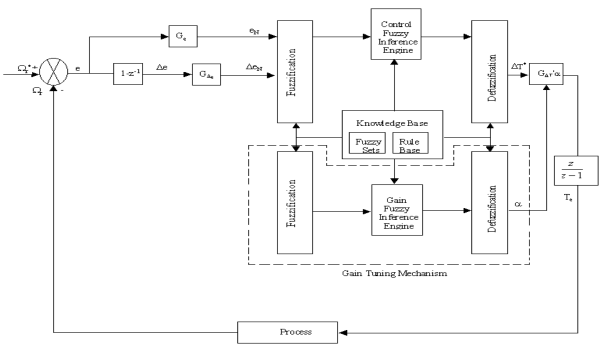


Fig .3. Block diagram of the proposed self-tuning fuzzy speed controller

The relationships between the SF's and the input and output variables of the self-tuning FLC are as follows :

$$e_N = G_e.e \quad (9)$$

$$\Delta e_N = G_{\Delta e}.\Delta e \quad (10)$$

$$T^* = \Delta T^*.\ \alpha.G_{\Delta T}^* \quad (11)$$

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 Figure.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.

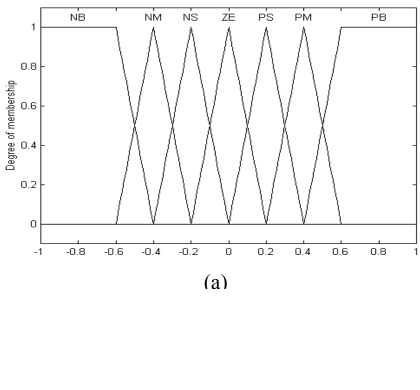
The implied fuzzy set is transformed to a crisp output by the centre of gravity defuzzification technique as given by the formula (16) , z_i is the numerical output at the ith number of rules and $\mu(z_i)$ corresponds to the value of fuzzy membership function at the ith number of rules.The summation is from one to n, where n is the number of rules that apply for the given fuzzy inputs, [1]-[2].

$$z = \frac{\sum_{i=1}^{n} z_i.\mu(z_i)}{\sum_{i=1}^{n} \mu(z_i)} \quad (12)$$

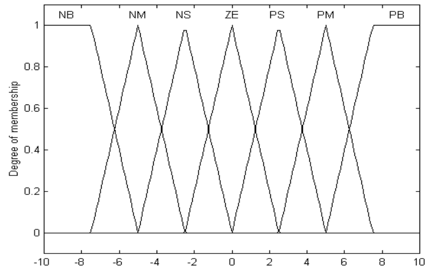
The crisp output ΔT^* is multiplied by the gain factor $\alpha.G_{\Delta T}^*$ and then integrated to give:

$$T_e(k) = T_e(k\text{-}1) + \Delta T^*.\ \alpha.G_{\Delta T}^* \quad (13)$$

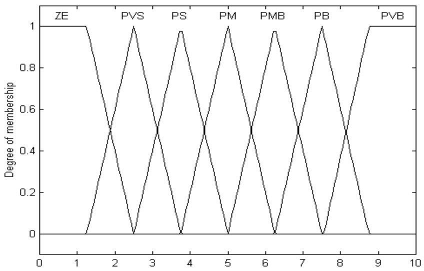
This torque component command is used as an input to the F.O.C block of Figure.2 .



(a)



(b)



(c)

Fig.4. Membership functions of (a) e and Δe; (b) ΔT^*; (c) gain updating factor (α).

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

IV. SIMULATION SCHEME OF THE PROPOSED SYSTEM

It is essential that the simulation model is designed to approach as close to reality as possible. Therefore, for the simulation of the whole drive system according to Figure.2, a mathematical model has been developed based on the induction motor. In addition, a mathematical model for all the remaining drive system units was necessary to complete the simulation model. These relations are described in the following paragraphs:

1) Voltage-Source Inverter

A three-phase three-level voltage source inverter has been used. Table 1 shows the switching states of each phase with symbols. Each phase of this inverter consists of two clamping diodes, four IGBT's and four freewheeling diodes. The switches S_{1x} and S_{4x} are the upper and lower switching devices (like a two-level inverter) respectively and S_{2x} and S_{3x} are auxiliary devices which help to clamp the output potential to the neural point with the help of the two clamping diodes.

Table 1. Switching States of a Three-Level Inverter

Switching States	S_{1X}	S_{2X}	S_{3X}	S_{4X}	Output Voltages
P	ON	ON	OFF	OFF	V_d
0	OFF	ON	ON	OFF	$V_{d/2}$
N	OFF	OFF	ON	ON	0

2) PWM Generation

The system was simulated with a space vector generator inserted between the vector controller's outputs and the machine's stator voltage inputs. A 15-KHz PWM switching rate was used with a peak output of 340 V.

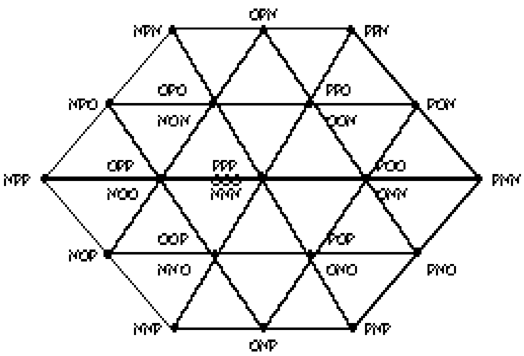


Fig. 6. Space-vector diagram of three level inverter

V. SIMULATION RESULTS

The induction motor is a three phase, Y connected, four pole, 1.5 Kw, 1420tr/mn 220/380V, 50Hz. The computer simulation results using the fuzzy controller described in section IV was carried out..The configuration of the overall control system is shown in Figure. 2. It mainly consists of a squirrel-cage induction motor ,a space vector voltage controlled pulse width modulated (PWM) inverter, a slip angular speed estimator, an inverse park, an outer speed feedback control loop and a self-tuning fuzzy speed controller . The induction motor is a three phase, Y connected, four pole, 1.5 Kw, 1420tr/mn 220/380V, 50Hz. The computer simulation results using the fuzzy controller described in section III was carried out.The machine parameters are given in appendix.

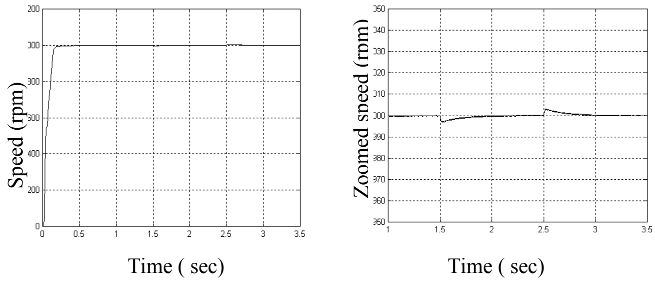


Fig . 7. ± 2 Nm Load TorqueDisturbance

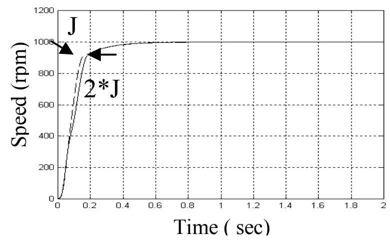


Fig . 8. Speed drive responce

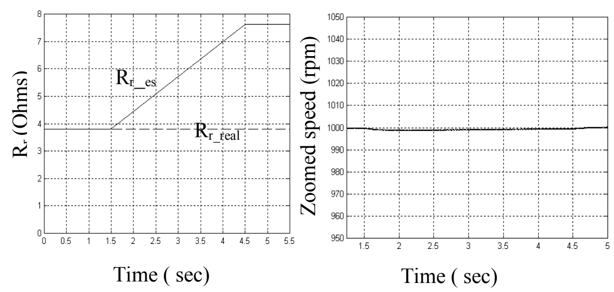


Fig.9. Effect of rotor resistance variation on the speed.

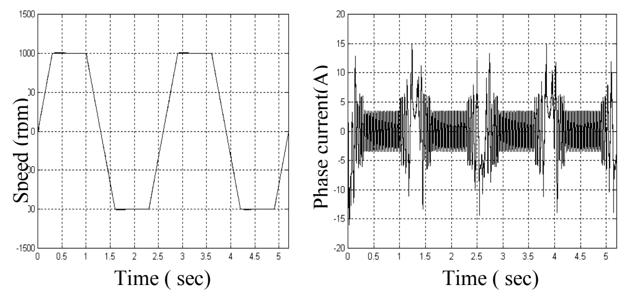


Fig . 10. Speed Tracking Performance and phase current at no load
---- Command Speed , —— Actual Speed

Figure.7. shows the disturbance rejection of self-tuning fuzzy controller when the machine is fully loaded (10 N.m) and operated at 1000 rpm and a load disturbance torque (2 N.m) is suddenly applied, first, at 1.5 s and then at 2.5 s. The fuzzy controller rejects the load disturbance rapidly with no overshoot and with a negligible steady state error and the speed is returned to its nominal value within 0.25 s with a maximum drop of speed of 3 rpm. Then we simulated our system under no load with a doubled moment of inertia Figure. 8. We notice from this figure, as the moment of inertia is twice larger than nominal, the speed error at the beginning of adaptation is negligible and at steady state is almost zero. Figure. 9. shows the effect of rotor resistance on the speed. In the actual operating conditions, the rate of change of temperature is very slow and so the resistance variation. This is covered in Figure. 9. where at 1.5 sec a ramp change of rotor resistance is applied linearly from 100% of its rated value to 200% till 4.5 sec, then, this value is maintained for 1 sec. We notice that the controller is still performing perfectly with a maximum drop of speed of 1 rpm . The last simulations in Figure. 10. show the speed tracking performance under no load . Here again the controller reacts perfectly and tracks the command speed with no steady-state error .

VI. CONCLUSION

Digital simulation results show that the designed self-tuning fuzzy speed controller realises a good dynamic behaviour of the motor, with a rapid settling time, no overshoot, a good rejection of impact load disturbance, a perfect speed tracking and it deals well when parameter variations are doubled. A speed model reference adaptive control (MRAC) system for indirect field-oriented (IFO) induction motor drives based on using fuzzy laws for the adaptive process and a neuro-fuzzy procedure to optimize the fuzzy rules is under study for the next future work .

APPENDIX

INDUCTION MOTOR PARAMETERS
USED FOR SIMULATION

$1.5Kw, 1420rpm$	$R_s = 4.85\Omega$	$L_s = 274mH$
$220/380V, 6.4/3.7A$	$R_r = 3.805\Omega$	$L_r = 274mH$
$3 phases, 50Hz, 4 pole$	$L_m = 258mH$	
$J = 0.031 \text{ kg.m}^2$	$B = 0.00114 \ kg.m^2/s$	

NOMENCLATURE

R_s, R_r	Stator and rotor resistances
L_s, L_r	Stator and rotor inductance
T_r	Rotor time constant
ψ_r	Rotor flux component
P	Number of pole pairs
T_e	Electromagnetic torque
θ_e	Stator electrical angle
ω_e	Electrical synchronous speed
ω_r	Electrical rotor speed
Ω_r, Ω_r^*	Mechanical rotor and reference speed
ω_{sl}	Slip speed
e	Speed error.
v_{ds} ,v_{qs}	d- and q- axis stator voltages
$i_{ds}, i_{qs}, i_{dr}, i_{qr}$	d- and q- axis stator and rotor currents in the stationary frame

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